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# Climate Change and Adaptation: The Case of Nigerian Agriculture

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**Abstract** The present research offers an economic assessment of climate change impacts on the four major crop families characterizing Nigerian agriculture. The evaluation is performed by shocking land productivity in a computable general equilibrium model tailored to replicate Nigerian economic development up to 2050. The detail of land uses in the model has been increased by differentiating land types per agro-ecological zones. Uncertainty about future climate is captured, using, as inputs, yield changes computed by a crop model under ten general circulation models runs. Climate change turns out to be negative for Nigeria in the medium term, with production losses and increase in crop prices, higher food dependency on foreign imports, and GDP losses in all the simulations after 2025. In a second part of the paper, a cost effectiveness analysis of adaptation in Nigerian agriculture is conducted. The adaptation practices considered are a mix of cheaper "soft measures" and more costly "hard" irrigation expansion. The main result is that the cost effectiveness of the whole package depends crucially on the possibility of implementing adaptation by exploiting low-cost opportunities which show a benefit-cost ratio larger than one in all the climate regimes.

**Keywords** Adaptation · Agriculture · CGE modelling · Climate change · Impact assessment

**JEL Classification** C68 · Q51 · Q54 · Q15

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This paper has not been submitted elsewhere in identical or similar form, nor will it be during the first three months after its submission to the Publisher.

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## 1 Introduction and Background

Developing regions, and in particular Sub-Saharan Africa, are among the most vulnerable areas to climate change. This condition derives from the combination of high exposure (high temperature increase and climatic impacts), high sensitivity (high reliance on climate sensitive sectors such as agriculture) and low adaptive capacity (IPCC 2014; Fischer et al. 2002; Parry 2009). At the same time, some countries in the area, rich in raw materials and energy sources, experiencing massive GDP growth rates and rapid structural socio-economic transformation, are increasingly aware of the need to carefully plan and govern these transitions. And, contrary to common sense view that the environment is primarily the concern of the rich nations, they are increasingly perceiving climate change as a challenge for their development.

A topical example is Nigeria. In the last decade, the country experienced a yearly GDP growth rate of 5%, reaching 7% in 2009. In the same year, the Federal Government of Nigeria produced the "Nigeria Vision 20:2020" (FGN 2010), an ambitious policy document establishing a set of socio-economic targets aiming to place the country in the world's top-20 economies within a decade. However, adverse climate change impacts can threaten the capacity of many sectors of the Nigerian economy to support this development. In this context, we focused our analysis on Nigerian agriculture which is the most important sector in the country, representing 42% of Nigeria's value added in 2010, and is particularly sensitive to climatic conditions, being almost completely rain-fed (99%). Assessing climate change impacts on agriculture can thus offer precious insights into the more general effects of climate change on the country.

The tool used for this investigation is the recursive-dynamic computable general equilibrium (CGE) model for the world economy ICES—Intertemporal Computable Equilibrium System, (Eboli et al. 2010), tailored to replicate Nigerian economic development up to 2050. With this model, we assess the economic impact of climate change on the Nigerian agricultural sector, the feedback on the entire Nigerian economy, and finally propose some adaptation measures evaluating their cost effectiveness.

The use of CGE models in assessing climate change impacts in agriculture is well established. Early works on this subject date back to Kane et al. (1991), Reilly and Hohmann (1993), Rosenzweig and Iglesias (1994), Tsigas et al. (1997). More recent contributions are e.g. Hertel et al. (2009a), Palatnik and Roson (2009), Ponce et al. (2012). CGE models are characterised by a detailed and interconnected sectoral representation which allows tracking the propagation of climate change impacts from agriculture to other sectors and, conversely, the influence of the macroeconomic context on agriculture. The "shock" transmitting mechanisms are endogenous prices, which drive domestic and international market exchanges of goods and production factors.

The CGE economic evaluation is commonly the last step of a wider integrated assessment of climate change impacts (Darwin 2004; Bosello and Zhang 2005; Reilly et al. 2007; Zhai et al. 2009). This involves, in an output-input-output chain, general circulation models (GCMs) to simulate different temperature, carbon concentration and precipitation scenarios; crop growth models to estimate changes in yield for different crops; and CGE models to provide the economic assessment. In general, these studies indicate moderate GDP losses in low-mid latitude countries, and rather strong market-driven effects from trade and factor substitution, to smooth over initial yield losses.

For instance according to Darwin (2004), under temperature scenarios ranging from +1.0 to +5.2 °C the highest loss of welfare will be observed in 2050 in Southeast Asia (−0.16 to −0.82% with respect to (w.r.t. thereafter) 1990). Bosello and Zhang (2005) find that African countries are the most affected, with a GDP loss of −0.13% in 2050 w.r.t the baseline scenario under a scenario foreseeing a 0.93 °C increase of temperature in 2050. Reilly et al. (2007) observe economic gains in tropical and southern regions where trade effects compensate for agriculture losses, and the highest damage in Southeast Asia and China, (−2.5 and −4% in 2100 w.r.t 2000) in the "high pollution scenario" ($CO_2$ concentration of 810 ppm and +2.75 °C in 2100). Zhai et al. (2009) estimate a 2.2% loss of GDP for SSA in 2080 under the A2 SRES scenario and a 29.6% drop of agricultural output against an exogenous shock on agricultural productivity between −27 and −16.6% respectively, both with and without carbon fertilisation effect.

However, two major criticisms arise when climate change impacts on agriculture are assessed through a CGE approach: the poor representation of land use dynamics in the CGE models, and the aggregated focus of the analysis. As to the first point, standard CGE models represent land as an undifferentiated input which is allocated to different crops' productions responding to changes in crop prices. Frictions in land switching are captured by an elasticity of transformation parameter that summarizes all the economic, geo-bio-chemical constraints determining imperfect land substitutability across different agricultural sectors. The second issue pertains to the typical format of input and output data in CGE models in which the sectoral detail can be very high, but the "spatial resolution" is usually at country level. This implies that input data, e.g. yield changes, that can be very detailed, especially if produced by geographically resolved crop or land use models, need to be "aggregated", with the consequent loss of information.

Different approaches are proposed for overcoming the first and partially the second of these limitations.

With the first method, the land allocation mechanisms of the CGE model are made consistent with information produced by an external source, typically a land use model. An example is Ronneberger et al. (2008). In that study, land allocated to different crops in a CGE model (GTAP-EFL) is the output of the KLUM land use model. The CGE and the land use models are "soft linked": the first uses as inputs the land supply from the land use model, while the second determines land uses from changes in crop price produced by the CGE model. The process is iterated until convergence is reached. A similar iterative approach is adopted in the LEITAP (now MAGNET) model (van Meijl et al. 2006), a CGE GTAP-based model, "soft linked" to IMAGE modelling framework. In this case, the crop production changes from the LEITAP model are inputs to the IMAGE framework which computes yield changes. These are then fed back into LEITAP with the discrepancy between the two model outputs accounting for the change of land availability due to climate change.

Alternatively, the detail of the nested CET production function for agricultural goods of the CGE models is enriched. This allows increasing the number of CET elasticities and better capturing differentiation in land uses. These "structural modifications" are for instance proposed by Burniaux (2002), and Burniaux and Lee (2003) in the GTAP-L model describing inter-sectoral land transitions to estimate greenhouse gas emissions; Keeney and Hertel (2005) in the GTAP-AGR model re-specify both the factor supply and derived demand equations by assuming separability of food from non-food commodities. Palatnik et al. (2011), develop a three-level nested structure for the CET function of their CGE model, with different parameterization for the agricultural sectors of northern and southern Mediterranean countries (for greater detail see the surveys of Palatnik and Roson 2009; Hertel et al. 2009a).

Finally, there is the agro ecological zone (AEZ) approach (Darwin et al. 1995; Fischer et al. 2002; Lee et al. 2009; Golub et al. 2009, 2012). This introduces explicit land heterogeneity within CGE models by specifying different land types that depend on the climatic characteristics, moisture levels and growth period characterizing the different AEZs. Imperfect land substitutability is, as usual, governed by a CET function. This however is AEZ-specific, while land substitution is not allowed among AEZs. This captures (and models) the fact that a crop cannot be grown everywhere within a region, but only in those AEZs where the land is geographically and bio-chemically suitable to its cultivation. In GTAP-AEZ-GHG model (Golub et al. 2009, 2012), different land inputs appear among the primary factors in crops' production functions and land supply is characterised by a two-level CET function where a lower elasticity of substitution determines the choice between cropland, livestock land and forest, and a higher one regulates the allocation of land across crops. In Hertel et al. (2009b), the CET function is characterised by three nests to diversify substitution between forestry and agriculture, crops and grazing, and between different crops.

A recent application of AEZ methodology to a single African country is Thurlow et al. (2009), who use a hydro-crop model linked to a dynamic CGE with AEZs, and assess Zambia's GDP loss under different precipitation patterns under the IPCC SRES B1a. Interestingly, the study tries to assess current climate change impacts by focussing on the 2007–2016 decade and using as a comparison a "normal rainfall scenario". Losses range between −3 and −9.9% in the decade 2007–2016, where the highest loss is associated with the lowest precipitation scenario.

The exercise proposed here adopts the AEZ approach. The climate change impact on Nigerian agriculture is represented through shocks on land productivity deriving from a crop model. This covers the whole range of variability produced by an envelope of one high resolution regional climate model and ten global climate model runs processing the A1B IPCC SRES scenario. Using AEZs allows differentiating productivity shocks in the ICES CGE model by land type and areas within Nigeria with an increase in the detail of the subsequent economic assessment. Furthermore, the ICES database itself is enriched singling out as separate agricultural industries yam and cassava, which are the most important food crops in Nigeria. The economic output consists of effects on agricultural production, prices, imports, land prices, and ultimately on Nigeria's GDP performance.

The final contribution of the present research is the analysis of adaptation, representing not only its benefits, but also the potential cost associated with both hard and soft measures in agriculture, and a comparison of the two. Explicit representation of adaptation cost in CGE models is not common. To our knowledge, it is limited to Deke et al. (2001), Darwin and Tol (2001), and Bosello et al. (2007), and only in the area of coastal protection. We apply to our analysis of agriculture an approach similar to these studies: basically, that adaptation expenditure influences the process of capital stock accumulation.

In what follows, Sect. 2 presents the model used, Sect. 3 its future baseline, Sect. 4 describes the input used, Sect. 5 introduces the results, Sect. 6 discusses adaptation, and Sect. 7 concludes.

## 2 The ICES Model

The ICES model is a recursive-dynamic CGE model for the world economy amply applied to the study of climate change impact (see e.g. Berritella et al. 2006; Bosello et al. 2006, 2007, 2011, 2012; Eboli et al. 2010); its main features are described in the dedicated "Appendix".[1] The model shares the core structure of the GTAP-E model (Burniaux and Truong 2002), and is grounded on GTAP 7 database, which gives a snapshot of world economic flows in 2004

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[1] For additional documentation about model description and application of ICES, the interested reader is also addressed to: http://www.feem.it/getpage.aspx?id=138&sez=Research&padre=18&sub=75&idsub=102.

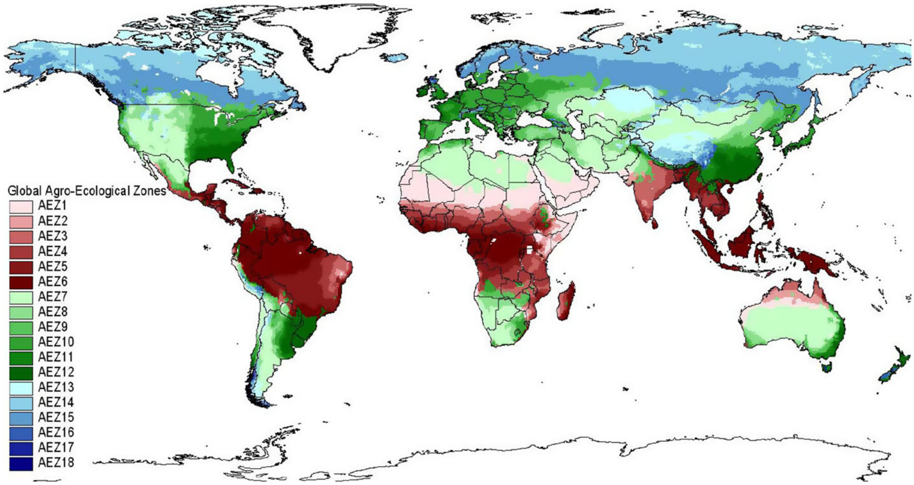

**Fig. 1** AEZ classification in the GTAP/ICES database. *Source*: Monfreda et al. (2009). (Color figure online)

(Narayanan and Walmsley 2008). The simulation period is 2004–2050, resolved in one-year time steps.

Given the agricultural sector focus of the study, more realism in land representation has been added by adopting the Agro Ecological Zone (AEZ) approach (FAO and IIASA 2000). In each country, the homogenous land endowment is replaced by 18 land types (see Fig. 1) and (imperfect) land substitutability is allowed within, but not between AEZs.

To this purpose, the ICES model database is extended linking to the GTAP-AEZ database (Avetisyan et al. 2011) which details production of 175 crops, and value of land endowment in 18 AEZs in 113 countries/regions. The linking procedure is rather straightforward, consisting in "splitting" the undifferentiated land primary input in ICES into AEZ-specific land production factors following the data from Avetisyan et al. (2011). The rest of the production structure of ICES remains unchanged.

Nigerian territory, in particular, is characterised by only 6 AEZs with different moisture regimes from arid to humid. Our analysis focuses thus on these 6 AEZs. All other AEZs are then grouped in a residual class (AEZ 7). In this set up, ICES thus considers a total of seven AEZs which means seven different land types and input to the production function.

A further improvement concerns the representation of Nigerian agricultural sectors. The original GTAP 7 database considers 8 different crop families[2]; we introduce two additional crops, cassava and yam, given their relevance for the Nigerian agriculture.[3] The production values of cassava and yam have been disentangled from the larger GTAP 7 sector "vegetable and fruits" to which they belong, compounding information on quantity produced from the GTAP-AEZ database (Avetisyan et al. 2011) with the values of production provided by Nwafor et al. (2010). Due to their lower relevance for Nigerian agriculture, the other crops have been aggregated in larger bundles. Table 1 (left) reports the final sectoral and macro-sectoral specification of the model including non-agricultural industries. Even though the

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[2] The agricultural sectors considered in GTAP 7 database are paddy rice, wheat, cereal grains, vegetables and fruits, oil seeds, sugar cane, plant based fibres, and other crops.

[3] Cassava and yam are the most important crops in terms of share of agricultural value added, building up in 2006 respectively the 16.3 and the 14.7% of it (Nwafor et al. 2010).

**Table 1** Sectoral (left) and regional (right) detail of the ICES model

| | |
|---|---|
| Rice | Agriculture |
| Cereal Crops | |
| Cassava | |
| Yams | |
| Vegetable and Fruits | |
| Other Crops | |
| Livestock and Fishing | |
| Timber | |
| Coal | Mining |
| Oil | |
| Gas | |
| Mining | |
| Electricity | Manufacturing |
| Oil Products | |
| Other Industries | |
| Private Services | Services |
| Public Services | |

| | |
|---|---|
| USA | United States |
| EUROPE | Europe |
| FSU | Former Soviet Union |
| RoA1 | Rest of Annex 1 |
| MENA | Middle East and North Africa |
| NIGERIA | Nigeria |
| SSA | Sub Saharan Africa |
| ASIA | Asia |
| LACA | Latin and Central America |

current assessment is focused on Nigeria, ICES is a world CGE model; the other countries are grouped into 8 macro-regions (Table 1 right).

## 3 The Baseline Scenario

Preliminary to the impact assessment is the construction of the social-economic baseline capturing potential economic development in Nigeria up to 2050. This baseline represents the counterfactual “without climate change” against which the impacts of climate change on crop productivity will be imposed, and the consequent effects on Nigerian GDP and sectoral performance will be evaluated.

Up to 2025 this baseline is shaped by the revised “Nigeria Vision 20:2020” produced by the Federal Government of Nigeria (FGN 2010). It assumes a sustained annual GDP growth peaking at 9% in 2025. It also sets targets to the evolution of macro-sectoral composition of value added to for 2025: 21% from agriculture (slightly less than half of the 2010 figure), 18% from mining, 15% from industry and 46% from services. ICES is thus calibrates to match these medium-term figures. Furthermore, Nigeria’s population baseline trend follows the projections of United Nations’ world population prospects, in the medium fertility variant scenario (UN 2009). Due to the lack of official projections on the economic trend after 2025, we assumed a lower GDP growth rates in the period 2025–2050 (on average 5.7%). In the post-2025, the VA shares are indeed fully endogenous, but they remain almost constant up to 2050.

Other assumptions concern specifically the agricultural sector: crop (harvested) area remains constant at the 2010 levels;[4] furthermore, irrigated land, which in the calibration

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[4] We assume neither an increase/reduction of harvested area due for example to a reduction/increase of pastureland or build-up land, nor an increase/reduction of the number of harvests per year.

year in Nigeria is negligible (lower than 1% of total cultivated area), reaches 5% of total cropland in 2025 and 20% in 2050, according to the Country irrigation master plan (JICA 1995).[5]

2010–2050 population and GDP growth rates for the "non-Nigerian" macro-regions derive respectively from UN (2009) and the A1B IPCC SRES (Nakicenovic et al. 2000).

## 4 Climate-Related Shocks on the Agricultural Sector

In the ICES model, impact scenarios are built using as inputs crop- and AEZ-specific variations of land productivity due to climate change generated in the DSSAT-CSM crop model (Mereu and Spano 2011). The DSSAT-CSM crop model uses input information from COSMO-CLM[6] (Rockel et al. 2008), a regional climate model[7] with 8 Km of horizontal resolution, which reproduces recent/present climate in Nigeria and project temperature and precipitation variables under the A1B IPCC SRES scenario (Nakicenovic et al. 2000).[8] The COSMO-CLM projections on temperature and precipitation are fed in the DSSAT-CSM model, which assesses yield changes up to 2050. This first scenario is called RCM thereafter.

In order to account for uncertainty[9] stemming from the choice of climate models (Olesen et al. 2007; Lionello 2012), the COSMO-CLM projections are also perturbed with 10 different GCMs,[10] and used to generate the corresponding 10 different alternative yield change scenarios in the crop model.

The economic results reported, refer however to just three of these climate runs/scenarios perturbing the crop model. The first is the RCM run, the other two derive from the perturbation of COSMO-CLM with the GCM from the National Center of Atmospheric Research (NCAR), and that from the Global Fluid Dynamic Lab (GFDL). These together present, respectively, the least and the most pessimistic 2050 yield changes across the whole range of perturbed climate model runs and allow us defining a sort of confidence interval for our impact assessment.

Two further notes on the data transfer process between DSSAT-CSM and ICES are:

1. The crops analysed by the DSSAT-CSM model are: cassava, yam, rice, millet, maize and sorghum. Therefore (see Table 1), a one-to-one correspondence with ICES exists just for

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[5] Information on future irrigated land per crop and AEZ is not available. The study therefore assumes its uniform development.

[6] The CMCC-MED global model is the reference GCM for the COSMO-CLM model (Scoccimarro et al. 2011).

[7] Regional Climate Models are defined as limited-area models which are used to dynamically 'downscale', global model simulations for some particular geographical region to provide more detailed information, Flato et al. (2013)".

[8] The 10 GCMs considered are all reproducing the A1B scenario. This scenario is under A1 storyline, which describes a world characterised by high economic growth and regional convergence, but we assumed a balanced use of fossil and non-fossil energy sources proper of A1B scenario (Nakicenovic et al. 2000). We consider this storyline consistent economic scenario described in the "Nigeria Vision 20:2020" (FGN 2010): high GDP growth, decreasing VA share of agricultural sector, and increasing VA share of services.

[9] In our analysis, we account only for the uncertainty due to the choice of the climate model. We are not considering the uncertainty due to emission scenarios, which is limited in the medium term according to the literature (Lionello 2012). Furthermore, the uncertainty related to the choice of the crop and the economic model is also disregarded.

[10] Among the 10 GCM simulation considered, 9 comes from the Couple Models Intercomparison Project 3 (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php): CNRM_CM3, CSIRO_Mk3.5, GFDL_cm2.1, IAP_FGOALS, CCSR_MIROC3.2, MPI_ECHAM5, MRI_CGCM_2.3.2, NCAR_CCSM3, and UKMO_HadCM3. The last simulation is from the CMCC-MED global model (0.75 ° resolution).

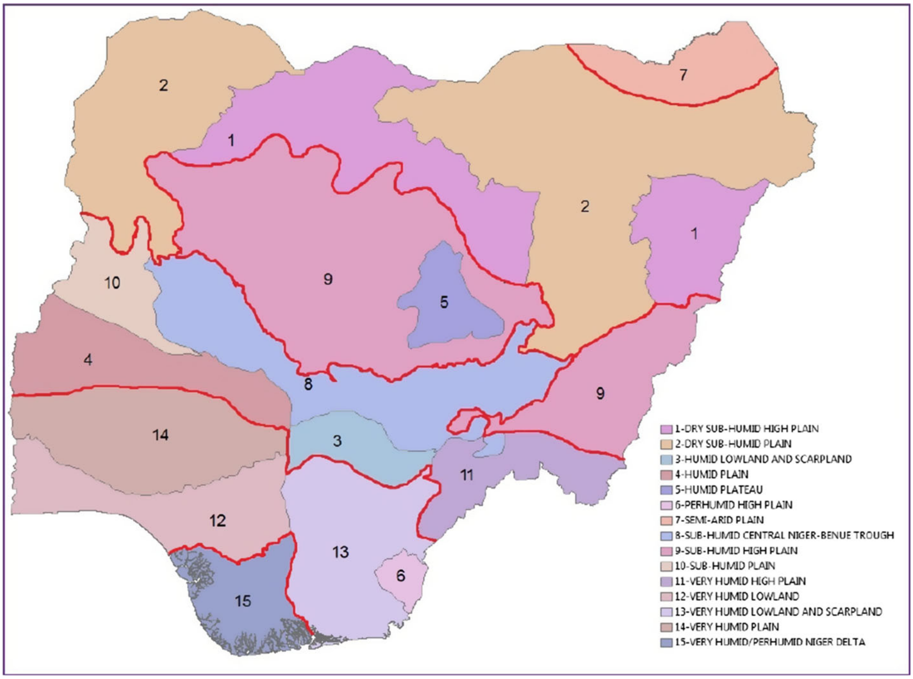

**Fig. 2** Representation of the 15 AEZs considered in the DSSAT-CSM model (numbered from 1 to 15) and of the 6 AEZs considered in ICES model (*red contours*). (Color figure online)

**Table 2** Mapping AEZs in DSSAT-CSM to AEZs in ICES

| AEZs in DSSAT-CSM | AEZs in ICES |
|---|---|
| AEZ 7 | AEZ 1 |
| AEZ 1 and AEZ 2 | AEZ 2 |
| AEZ 9 and AEZ 5 | AEZ 3 |
| AEZs 10, 8, 11, 4, 3 | AEZ 4 |
| AEZs 14, 12, 13, 6 | AEZ 5 |
| AEZ 15 | AEZ 6 |

the first three crops. Yield changes for the ICES "cereal crops" aggregate are a weighted average of the yield changes of maize, millet and sorghum. Because of lack of data, no yield changes are on the contrary imposed on the other two ICES crop aggregates: "other crops" and "vegetable and fruits".[11]

2. The agro-ecological zoning used by the DSSAT-CSM model is more detailed than that available in the ICES database: Nigeria is characterised by 15 rather than 6 AEZs (Fig. 2; Table 2). Therefore a mapping procedure was applied to DSSAT-CSM output to achieve consistency across the two different geographical resolutions.

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[11] Nonetheless, for completeness of information, production changes of these crops are also reported. But they depend upon changes in relative prices and are not directly imputable to climate-induced yield changes.

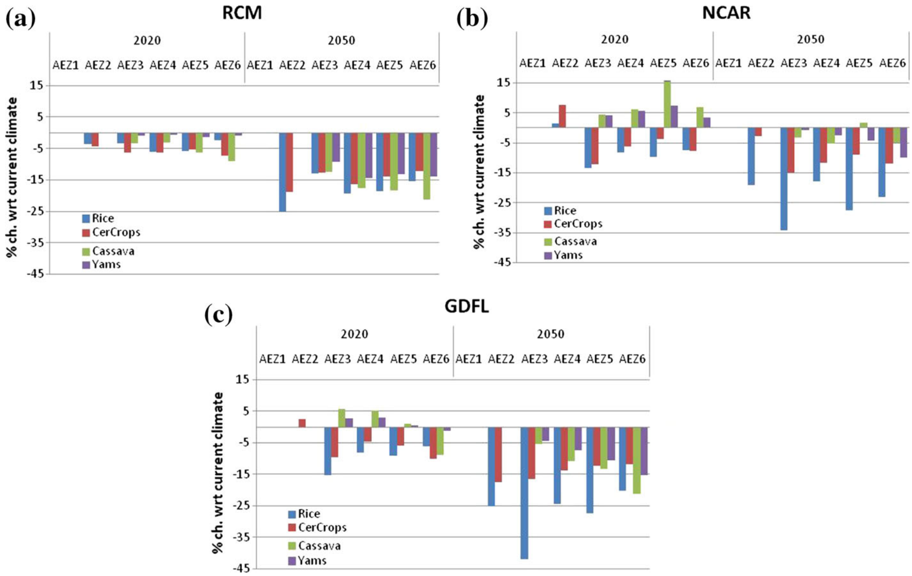

**Fig. 3** Climate change impacts on Nigerian crop yields (% change wrt current climate) per Agro-Ecological Zone (A1B SRES), **a** RCM scenario, **b** NCAR scenario and **c** GDFL scenario. *Source*: DSSAT-CSM model

The AEZs are so characterised: AEZ 1 provides a negligible contribution to Nigerian agricultural production. The AEZs 2 and 3 are the most important producers of "cereal crops", but poor of cassava and yam. These crops are concentrated in AEZ 5, 4 and 6. The AEZs 4 and 5, finally, are fundamental for rice and "vegetables and fruits" productions.

It is worth noticing that in the AEZs 4, 5 and 6, where rice, cassava and yam productions are concentrated, rice contributes only marginally (around 6%) to the agricultural value added, while cassava, yam, and other "vegetables and fruits" play a major role.

Figure 3 presents the shocks on crop yields generated by DSSAT-CSM and input for the CGE model.

In 2050, the crop model simulations highlight a general decline in yields, irrespectively of the climate model used as source data. GFDL is more pessimistic than NCAR, and both more optimistic than RCM for cassavas and yams. With the RCM scenario, the generalized decrease in crop productivity in Nigeria is particularly pronounced for yam in AEZs 4 and 6 ($-14.5$ and $-14.0$% w.r.t baseline in 2050), cassava in AEZ 6 ($-21.3$% w.r.t. baseline in 2050), and rice and "cereal crops" in AEZ 2 (respectively $-25.3$ and $-18$% w.r.t baseline in 2050). In the medium run (until 2020), productivity change across scenarios varies in magnitude and sign.

## 5 Results

Here we present a selection of ICES model results, focusing on economic impacts determined in the RCM climate model run. Furthermore, we give an overview of outcomes of the NCAR and the GFDL scenarios, which represent the uncertainty range of our impact assessment. Finally, we perform an adaptation analysis for the three scenarios, computing the cost of a mixed policy able to offset climate change-driven yield loss, and its effect on GDP.

**Table 3** Crop production, RCM scenario (% change w.r.t baseline)

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Rice | 0.0 | −1.2 | −1.3 | −1.9 | −2.7 | −3.4 | −4.5 | −5.2 | −6.0 |
| CerCrops | 0.0 | −2.4 | −3.3 | −4.9 | −6.7 | −8.3 | −10.5 | −12.3 | −14.1 |
| Cassava | 0.0 | −1.0 | −1.0 | −1.3 | −1.8 | −2.3 | −3.0 | −3.5 | −4.0 |
| Yam | 0.0 | −0.8 | −0.7 | −1.1 | −1.6 | −2.0 | −2.7 | −3.3 | −3.8 |
| VegFruits | 0.0 | −0.6 | −0.6 | −0.9 | −1.3 | −1.6 | −2.2 | −2.6 | −3.2 |
| OthCrops | 0.0 | −1.3 | −1.3 | −1.7 | −2.4 | −3.0 | −3.7 | −4.2 | −4.8 |

**Table 4** Crop production in 2050 per AEZ, RCM scenario (% change w.r.t baseline)

| | Rice | CerCrops | Cassava | Yam | VegFruits | OthCrops | Total |
|---|---|---|---|---|---|---|---|
| AEZ1 | 8.8[a] | −1.2[a] | 16.5[a] | 0.0[a] | −1.7[a] | −2.6[a] | −1.7[a] |
| AEZ2 | −11.0 | −16.9 | 15.0[a] | 0.0[a] | −2.8 | −4.3 | −13.6 |
| AEZ3 | −2.0 | −11.7 | 2.2[a] | 0.7[a] | −2.3 | −3.5 | −8.7 |
| AEZ4 | −6.3 | −14.7 | −3.1 | −4.7 | −3.0 | −4.4 | −7.1 |
| AEZ5 | −6.0 | −13.5 | −4.0 | −3.6 | −3.7 | −5.5 | −5.7 |
| AEZ6 | −3.7[a] | −12.2[a] | −6.1 | −4.0 | −3.7 | −5.5 | −4.9 |
| Total | −6.0 | −14.1 | −4.0 | −3.8 | −3.2 | −4.8 | −7.2 |

[a] Negligible presence of the crop in the AEZ ($\leq 2\%$ of the national total)

## 5.1 The RCM Scenario

The direct effect of yield losses is a generalised decline of national agricultural production (Table 3). The major contraction concerns the “cereal crops” aggregate (−14.1% w.r.t baseline 2050), followed by a smaller but non-negligible reduction in the output of rice, cassava, and yam (−6.0, −4.0 and −3.8% w.r.t baseline in 2050).[12]

In 2050, the total shrinking of Nigerian crop production amounts to −7.2% w.r.t. baseline, but it is not uniform across AEZs, denoting a worsening of the situation as we move Northward (Table 4). The northern AEZ 2 is the most adversely affected (−13.6% w.r.t. baseline), due to its dedication to “cereal crops” and rice cultivations, which experience high yield declines. A lower, but still relevant, production loss is registered in central Nigeria (AEZs 3 and 4 with respectively 8.7 and 7.1% production drop w.r.t. baseline) that again can be attributable to impacts on rice and “cereal crops” yields. The production performance of AEZ6 is strongly influenced by the cassava and “other crops” losses (−6.1 and −5.5% w.r.t. baseline).

This picture is mirrored by increase in the price of agricultural commodities (Table 5a) which in 2050 peaks to +47.2% (w.r.t. baseline) for rice. Cassava shows the second highest increase (+21.4% w.r.t. baseline), then followed by “cereal crops” and yam.

By comparing Tables 3, 5a, b, it is possible to draw some insights. For instance, rice shows a moderate drop in production, but the highest price increase across all crops due to the spike of land price in AEZ 5 where most of production takes place. Cassava shows a similar pattern. Conversely, climate change has a different impact on “cereal crops”: it

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[12] Note that the drop in production also affects the other two crop aggregates, “vegetables and fruits” and “other crops” which are not directly concerned by the yield decline. This is due to a general contraction of the Nigerian economy in the climate change scenario.

**Table 5** Crops prices (a) and land prices (b), RCM scenario (% change w.r.t baseline)

| | 2020 | 2050 |
|---|---|---|
| Crop prices (a) | | |
| Rice | 7.0 | 47.2 |
| CerCrops | 2.9 | 14.3 |
| Cassava | 7.7 | 21.4 |
| Yam | 2.2 | 15.2 |
| VegFruits | 0.3 | −1.8 |
| OthCrops | −0.1 | −0.9 |
| Land prices (b) | | |
| AEZ1 | −4.2 | −23.5 |
| AEZ2 | −0.8 | 5.7 |
| AEZ3 | 0.3 | −9.8 |
| AEZ4 | 1.6 | 3.6 |
| AEZ5 | 8.1 | 30.4 |
| AEZ6 | 11.0 | 24.4 |

determines small increase of market prices (weighted average of increase/decrease of land price in AEZs 2, 3 and 4, characteristic of these crops), but a strong drop of production. In fact, in these AEZs, it is more remunerative for the land owner to allocate land away from “cereal crops” to “vegetable and fruits”.

As we anticipated, land prices are also affected (Table 5b). In this case especially, model outcomes need to be taken cautiously, as the institutional, regulatory, administrative, and even cultural factors determining the definition of land property rights in Nigeria are not captured by the model’s mathematical structure. Nonetheless, they are still indicative of the pressures that climate change may exert on land endowment.

It can thus be noted that land value increases across different AEZs, tending to derive from a combination of climate change impact and dominance of the specific crop in the value of production of the AEZ. This applies for instance to the southern part of the country (AEZs 5 and 6) where the spike in land prices is motivated by the combined climate induced shocks on cassava and yam and by the fact that these crops represent, respectively, 55 and 70% of production value in those AEZs. On the contrary, land price variations are moderate in the central AEZs 2 and 4; where the impact on “cereal crops” is mitigated by the absence of shock on “vegetables and fruits”. Finally, AEZs 1 and 3 are experiencing a drop in land prices. This is due to relatively higher predominance of the “vegetables and fruits” aggregate. Accordingly, climate change, albeit negative for the consumer, redistributes some gains in terms of higher land rents to landowners, especially in the southern part of the country.

The lower domestic crop production and the higher prices boost net imports of food commodities, worsening the Nigerian agricultural trade balance (Table 6), and highlighting a potential stress on food dependency. Rice and cassavas are the most affected, followed by “cereal crops”, while, in the case of yams, net imports decline. However, the case of cassava and yam needs to be interpreted correctly. In fact, imports of those two goods are basically zero in the baseline and remain negligible in the climate change scenarios. Therefore, the figures reported for these two crops reflect changes in export flows. Those of cassavas decline: a higher share of the declined production is addressed to satisfy domestic rather than international demand. On the contrary, yam exports increase. Higher prices reduce domestic

**Table 6** Net-Imports of agricultural commodities, RCM scenario (% change w.r.t baseline)

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Rice | 0.0 | 4.7 | 6.2 | 10.0 | 15.9 | 23.1 | 29.5 | 36.1 | 43.7 |
| CerCrops | 0.0 | 0.3 | 2.4 | 5.4 | 6.9 | 8.0 | 9.3 | 11.3 | 13.7 |
| Cassava[a] | 0.0 | 13.0 | 12.9 | 15.2 | 20.2 | 27.0 | 31.0 | 33.2 | 35.2 |
| Yam[a] | 0.0 | −9.4 | −7.6 | −11.8 | −18.9 | −26.7 | −31.5 | −34.6 | −37.1 |
| VegFruits | 0.0 | −0.4 | −0.9 | −2.6 | −3.2 | −4.3 | −5.8 | −7.6 | −9.6 |
| OthCrops | 0.0 | −1.7 | −1.6 | −2.2 | −2.9 | −3.9 | −5.0 | −5.9 | −6.7 |

[a] Negligible quantity imported in the base year

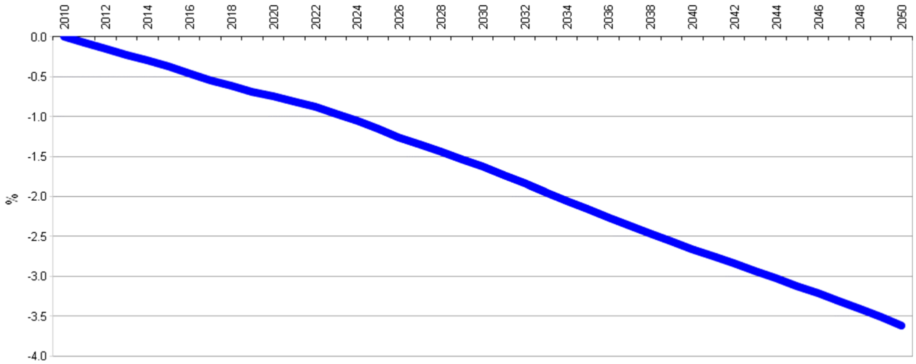

**Fig. 4** Nigerian GDP. RCM scenario (% change wrt baseline)

demand for yams which is readdressed to rice, and this makes room for an expansion of international demand.

The net impact on the country, as approximated by the GDP performance, is nonetheless negative, with a GDP loss that reaches -3.6% compared to the baseline in 2050 (Fig. 4).

## 5.2 Robustness Analysis Accounting for Impact Uncertainty

To account for impact uncertainty, the economic analysis evaluates two further sets of yield changes produced by the crop model processing the climatic data stemming from the NCAR, and the GFDL GCM simulations. As said, these two particular runs roughly span the whole range of variability produced by the 10 GCMs envelope.

Both GFDL and NCAR CGE runs register lower production losses than RCM in the medium term, with NCAR scenario showing slight increases in rice, cassava and yam production (Table 7). The, GFDL scenario highlights declines in cassava and yam production notwithstanding their increased productivity. This is the effect of the aggregated demand decline, which in turn is driven by the GDP decline (Fig. 5). In the longer term all scenarios depict decreasing production (−4.8% for NCAR and −7.4% for GFDL in 2050 w.r.t baseline), with NCAR less pessimistic and GDFL more pessimistic than RCM.

In the long term, consistent with trends in crop productions, all crops increase their prices (Table 8). Again, rice is the most severely affected, followed by “cereal crops”. Cassava and yam price changes are lower than in the RCM simulation.

**Table 7** Crop production, RCM, NCAR and GFDL scenarios (% change w.r.t. baseline)

| | 2020 | | | 2050 | | |
|---|---|---|---|---|---|---|
| | RCM | NCAR | GFDL | RCM | NCAR | GFDL |
| Rice | −1.3 | 0.2 | −1.0 | −6.0 | −5.9 | −8.2 |
| CerCrops | −3.3 | −1.6 | −2.5 | −14.1 | −9.7 | −15.7 |
| Cassava | −1.0 | 1.0 | −0.3 | −4.0 | −3.0 | −4.8 |
| Yam | −0.7 | 0.9 | −0.2 | −3.8 | −3.1 | −4.7 |
| VegFruits | −0.6 | 0.5 | −0.2 | −3.2 | −2.8 | −4.1 |
| OthCrops | −1.3 | 1.2 | −0.5 | −4.8 | −4.5 | −6.4 |
| Total | −1.4 | 0.5 | −0.6 | −7.2 | −4.8 | −7.4 |

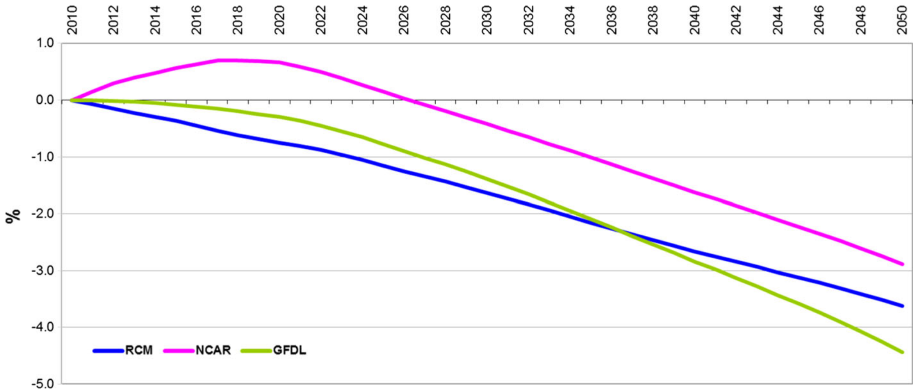

**Fig. 5** Nigerian GDP. RCM, NCAR and GFDL scenarios (% ch. w.r.t. baseline)

**Table 8** Crop prices, RCM, NCAR and GFDL scenarios (% change w.r.t. baseline)

| | 2020 | | | 2050 | | |
|---|---|---|---|---|---|---|
| | RCM | NCAR | GFDL | RCM | NCAR | GFDL |
| Rice | 7.0 | 10.2 | 8.1 | 47.2 | 91.2 | 73.2 |
| CerCrops | 2.9 | 2.5 | 3.1 | 14.3 | 14.5 | 7.7 |
| Cassava | 7.7 | 0.9 | −10.4 | 21.4 | 14.6 | 1.8 |
| Yam | 2.2 | −0.8 | −7.2 | 15.2 | 10.0 | 4.6 |
| VegFruits | 0.3 | −0.2 | −0.9 | −1.8 | −2.3 | −1.3 |
| OthCrops | −0.1 | −0.4 | −0.6 | −0.9 | −1.1 | −0.5 |

The net-import flows (Table 9) confirm the increased dependence on foreign agricultural products, especially in the GFDL run and especially for rice.

In terms of GDP, Nigeria is expected unambiguously to lose after 2025 (Fig. 5). In 2050, the loss ranges between 3 and 4.4% of GDP. In the medium term however, the two GCM runs highlight a smaller downturn in economic activity with respect to the RCM simulation and the NCAR one, projecting increases in cassava and yam production, and even predicting a potential maximum GDP gain of about 0.7% in 2017.

In summary: climate change can surely be considered a problem for the country in the medium-long term. It is more questionable, however, that this will entail relevant losses in the short-medium term (they remain lower than 1% until 2020, even in a worst-case scenario), and

**Table 9** Net Imports of agricultural commodities, RCM, NCAR and GFDL scenarios (% change w.r.t. baseline)

| | 2020 | | | 2050 | | |
|---|---|---|---|---|---|---|
| | RCM | NCAR | GFDL | RCM | NCAR | GFDL |
| Rice | 6.2 | 9.1 | 10.0 | 43.7 | 71.9 | 86.9 |
| CerCrops | 2.4 | 4.0 | 2.4 | 13.7 | 5.8 | 12.3 |
| Cassava[a] | 12.9 | −17.6 | 0.9 | 35.2 | −1.7 | 19.2 |
| Yams[a] | −7.6 | 30.1 | 2.8 | −37.1 | −13.6 | −26.8 |
| VegFruits | −0.9 | −1.1 | −1.2 | −9.6 | −8.1 | −12.5 |
| OthCrops | −1.6 | −0.2 | −1.3 | −6.7 | −5.6 | −8.7 |

[a] Negligible quantity imported in the base year

jeopardizes for instance Nigerian development goals. However, many considerations suggest caution in interpreting these short-term outcomes too positively, as the quantified negative economic impacts are probably underestimated. Indeed, only a subset, although relevant, of crops have been examined, and negative consequences can be higher when all the crops characterizing Nigeria's agricultural production have been considered. More importantly, only the agricultural sector is analysed, while it is well recognized that climate change affects many more dimensions relevant for social and economic development. Furthermore, all the adjustments in demand and supply described by the model, factor and good substitution across markets occur at no cost and without any friction. This also contributes to representing costs as being lower than they really are. Finally, acting in anticipation is often cheaper than acting in reaction. All this strongly supports proactive actions against climate change. Some of these will be discussed in the next section.

## 6 Adaptation

This section describes a methodology for a cost effectiveness evaluation of adaptation measures in the agricultural sector using the CGE approach.

The exercise applies to the agricultural sector an idea proposed by Deke et al. (2001) and Darwin and Tol (2001) to estimate the general equilibrium effects of adaptation against sea-level rise. In our case, the first step of the assessment is to quantify the total direct cost needed to completely offset projected yield decline through different adaptation practices; then to interpret this as an investment expenditure falling within the more general category of "adaptation", in adjusting consequently the capital accumulation process driving the model's recursive dynamics. In practice, the ICES model is run without imposing negative shocks on yields, but subtracting period by period the quantified adaptation costs from the Nigerian capital stock. This implicitly assumes that adaptation investment crowds out other forms of investment, thus reducing capital (services) available to produce all other goods and services in the model's production function.[13] The higher order cost of adaptation investment is the quantified difference between Nigeria's GDP performances in this case and in the baseline.

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[13] Bosello et al. (2007) noted that this procedure represents adaptation as a pure cost, neglecting the potential multiplicative effects of adaptation investment on the economy. They thus propose to trade off adaptation investment with consumption rather than with other investments. We will test this alternative formulation in a subsequent paper.

**Table 10** Production Gap Eliminated by non-irrigation options, by Year and Scenario (Percent)

| | 2020 | | | 2050 | | |
|---|---|---|---|---|---|---|
| | RCM | NCAR | GFDL | RCM | NCAR | GFDL |
| Cassava | 100 | 100 | 100 | 92.2 | 100 | 100 |
| Maize | 100 | 100 | 100 | 99.1 | 100 | 99.9 |
| Millet | 95.1 | 100 | 100 | 78.3 | 100 | 82.6 |
| Rice | 100 | 100 | 100 | 89.0 | 100 | 89.2 |
| Sorghum | 100 | 100 | 100 | 93.9 | 100 | 94.0 |
| Yams | 100 | 100 | 100 | 92.3 | 100 | 97.4 |

The economic effectiveness of adaptation, with which it is compared, is instead measured by the avoided GDP loss entailed by full adaptation, which thus coincides with the values reported in Fig. 5 and replicated in Table 12.

The estimation of direct adaptation costs derives from a detailed ad hoc study conducted within the World Bank's "Nigerian Climate Risk Analysis" (Cervigni et al. 2013). The adaptation strategy considered is a mix of "soft" and "hard" measures. The first are a combination of: shift of the sowing/planting dates, manure management to complement nutrient provision, increase of ordinary fertilisation. The second include the expansion of irrigated land through large—and small-scale irrigation plants. The analysis has therefore been conducted with regard to a range defined by a low unit cost case, and a high unit cost case. The cost per hectare of soft measures varies across climate model runs, depending on the yield loss to recover, the crop type and the measure. The sources of information used are FAO (2012), Bationo (2004), Bationo et al. (2012), Mutiro and Murwira (2004), Kamiri et al. (2011). The lowest average minimum and maximum unit costs of adaptation are obtained in the NCAR run (roughly US $20–US $100). RCM and GFDL average costs per hectares are higher and quite similar, ranging from roughly US $250–US $1,100. Concerning irrigation, large scale plants require initial investment costs ranging between US $3,700/ha and $20,000/ha for newly irrigated land, plus an annual operation and maintenance (O&M) cost of US $30/ha. For small-scale plants initial required investment is between US $2,200/ha and $5,000/ha, plus an annual O&M cost of US $40/ha (You et al. 2009), integrated with country expert personal communications).

The assumptions on the deployment of adaptation strategies are then as follows. First, non-irrigation practices are applied to all croplands. Then, if these are still insufficient to recover the production gap, irrigation expansion is used. This would occur through substitution of irrigated for rain-fed land and with a combination of large-scale (55%) and small-scale (45%) irrigation. This proportion is derived from You et al. (2009), reporting the economically viable irrigation potential of Nigeria for the two different irrigation schemes.

According to the adaptation analysis, in the long term, "soft" measures suffice to completely offset yield decline due to climate change in the NCAR run and almost completely, with the partial exception of millet and rice, in the other runs (Table 10). From 14 to 18 million hectares have to be treated with soft adaptation, whereas irrigation needs to be applied to 1.7 and 1.5 additional million hectares in the RCM and GFDL runs respectively (Table 11).

The results of the cost effectiveness analysis are summarized by Table 12.

All over the simulation period, using costs per hectare and hectares to be treated reported in Table 11, total direct adaptation costs can range from US $0.4 to US $45 billion (Table 12, 4th and 5th rows). Once the related GDP loss (Table 12, 7th and 8th rows) is computed and compared with those induced by climate change (Table 12, 2nd row), soft adaptation

**Table 11** Area of Adaptation Application by Scenario (ha, millions)

| | 2020 | | | 2050 | | |
|---|---|---|---|---|---|---|
| | RCM | NCAR | GFDL | RCM | NCAR | GFDL |
| Farm practices in rain-fed areas | 1.11 | 0.59 | 0.77 | 17.98 | 14.26 | 16.15 |
| Additional irrigation | 0.02 | 0.00 | 0.00 | 1.67 | 0.00 | 1.49 |
| Total | 1.13 | 0.59 | 0.77 | 19.65 | 14.26 | 17.65 |

**Table 12** Adaptation cost effectiveness

| | RCM | NCAR | GFDL |
|---|---|---|---|
| **GDP loss induced by climate change in 2050 (economic gains from full adaptation)** | 3.6% | 2.9% | 4.5% |
| **Direct cost of adaptation 2010–2050 total undiscounted (US$ billions)** | | | |
| Low unit cost case | 10 | 0.4 | 9 |
| High unit cost case | 45 | 1.3 | 40 |
| **GDP “cost” of full adaptation in 2050:** | | | |
| Low unit cost case | 2.6% | 0.1% | 2.3% |
| High unit cost case | 14.3% (6.8% due to soft measures, 7.2% due to irrigation) | 0.3% | 12.7% (5.8% due to soft measures, 6.9% due to irrigation) |
| **Benefit cost ratio** | | | |
| Low unit cost case | 1.38 | 29 | 1.96 |
| High unit cost case | 0.25 (0.47 w/o irrigation) | 9.6 | 0.35 (0.70 w/o irrigation) |

results as unambiguously cost effective, highlighting benefit-cost ratios much larger than one irrespective of the assumption on unit costs, in the NCAR run (Table 12, 10th and 11th rows).

However, soft measures may not be sufficient for a full recovery of production gaps, as for instance with reference to the climate scenarios replicated by the RCM and GFDL models. In this case, irrigation expansion can play a role, but due to its particularly high costs, as a residual option (i.e. on a much more limited acreage compared with soft measures). When adaptation costs are at, or can be kept reasonably close to, the lower range of values proposed by the literature, the adaptation mix still demonstrates a benefit cost ratio larger than one in all the three runs. If costs are those of the high-end estimates, full adaptation ceases to be cost-effective. The major factor responsible for this outcome is irrigation. However, even if costly irrigation expansion is abandoned, leaving the remaining adaptation measures to offset roughly 90% of damages, this would not be sufficient to raise the benefit cost ratios above one.

The main message is that it cannot be taken for granted that “any” adaptation is cost-effective: in our specific case not only irrigation expansion, but also the much cheaper soft adaptation measures, should be carefully applied to minimize implementation costs. Even though the more technical aspects are beyond the scope of the present analysis, it is worth stressing that, in addition to being cheaper, soft adaptation measures have in any case another advantage as compared with irrigation: flexibility in implementation. On the contrary, especially large irrigation infrastructure needs anticipatory planning, and once the investment is immobilized in irrigation programs it can hardly be reversible. This should constitute an additional caveat in the use of irrigation expansion in the present context of climate uncertainty (in the NCAR scenario irrigation is for instance unnecessary). A final aspect worth to considering derives from the evidence that, according to a cost-effective decision framework, a given degree of residual damage has to be accepted. This does not mean that its level and distributional implication across the society are acceptable under different criteria.

## 7 Conclusions

The present research offers an economic assessment of climate change impacts on the four major crop families of Nigerian agriculture covering more than 80% of national production. The evaluation is performed by shocking land productivity in a CGE model tailored to replicate Nigerian economic development up to 2050. The detail of land uses in the model has also been increased by differentiating land types by AEZs. Uncertainty about future climate is captured, using, as input, yield changes computed by a crop model covering the whole range of climate variability produced by the envelope of ten GCM runs for A1B IPCC SRES scenario.

Climate change turns out to be unambiguously negative for Nigeria in the long term, with production losses, increases in crop prices, higher food dependency on foreign imports, and GDP losses in all the simulations after 2025. Compared to the baseline, in 2050 total agricultural production declines between 4.8 and 7.4%, with northern Nigerian regions and cereal cultivation more penalized; crop prices increase on average between 17 and 32% (with a peak of 90% for rice); net imports of agricultural commodities increase on average between 13 and 23%. Landowners benefits from a potential increase in land rents in the southern and central part of the country, driven by the increased value of cassava and yam cultivations. Nonetheless, the projected GDP loss ranges between 3 and 4.4%. It is worth stressing that only a subset, although relevant, of crops is examined, only the agricultural sector is analysed, and all the adjustments in demand and supply described by the model are costless and frictionless. In the light of this, it can be concluded that climate change can very likely entail higher costs for Nigeria. If this is the case, climate change would seriously dampen Nigeria development potential, especially since the second quarter of the century.

Against this background, the second part of the research develops a cost effectiveness analysis of adaptation in Nigeria agriculture by comparing the GDP implication of adaptation expenditure/investment with the avoided GDP loss induced by climate change. The adaptation practices considered are a mix of cheaper “soft” measures and more costly “hard” irrigation expansion. The main result is that the cost effectiveness of the whole package crucially depends on the possibility of implementing adaptation by exploiting low-cost opportunities. In this case, all climate change damages can be offset with a benefit cost ratio larger than one in all the climate regimes. Expensive irrigation expansion should however be applied on a much more limited acreage in comparison with soft measures. If adaptation costs are those of the high-end estimates, full adaptation ceases to be cost-effective. This finding does not change even if only cheaper soft measures are used. This points out the need for careful planning and implementation of adaptation, irrespective of type, by looking for measures apt to check its unit cost. Moreover, it is worth stressing that hard measures, such as irrigation, are less flexible than soft ones. In a context of climatic uncertainty, this calls for additional caution in their use.

The current research has some limitations. First, climate change is assumed to affect only agriculture in Nigeria. Negative effects on crop productivity outside the country may well reduce the loss of competitiveness of Nigerian food commodities, but they can also further increase their prices, with a more adverse effect on Nigerian consumers. Another limitation is the very stylized representation of adaptation which appears as an undifferentiated (non-sector specific) expenditure without any additional effect with respect to damage reduction. Furthermore, the analysis focuses on aggregate agricultural variables, crop and AEZ-specific, disregarding all the underlying distributional issues on initial resource dispersion and differentiated impacts. These matters are certainly of primary interest and will be the starting point for our future research.

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## Appendix

### The Core of ICES Model

The Intertemporal Computable Equilibrium System (ICES) model[14] is multi-regional CGE model of the world economy, built upon the static GTAP-E model (Burniaux and Truong 2002), which in turn is an extension of the basic GTAP model (Hertel 1997). Industries are "typically" modelled through a representative cost-minimizing firm, taking input prices as given. In turn, output prices are given by average production costs. The production functions are specified via a series of nested CES functions. Peculiar to ICES is the "isolation" in the production tree of energy factors which are taken out from the set of intermediate inputs and are inserted as primary production factors in a nested level of substitution with capital. The following figure shows the production structure of the model.

At the top of Fig. 6, production stems from the combination of intermediate inputs (*QF*) and a value added composite including all primary factors and energy (*QVAEN*). Perfect complementarity is assumed between value added and intermediates. This implies the adoption a Leontief production function. For sector *i* in region *r* final supply (output) results from the following constrained production cost minimization problem for the producer:

$$\begin{aligned} &\min PVAEN_{i,r} QVAEN_{i,r} + PF_{i,r} QF_{i,r} \\ &s.t.\ Y_{i,r} = \min\left[QVAEN_{i,r}, QF_{i,r}\right] \end{aligned}$$

where *PVAEN* and *PF* are prices of the related production factors.

The second nested-level in Fig. 6 represents, on the left hand side, the value added plus energy composite (*QVAEN*). This composite stems from a CES function that combines four primary factors: land (*QLAND*), natural resources (*QFE*), labour (*QFE*) and the capital-energy bundle (*QKE*) using $\sigma$VAE as elasticity of substitution. Primary factor demand on its turn derives from the first order conditions of the following constrained cost minimization problem for the representative firm:

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[14] For further details about ICES model, please visit the website: http://www.icesmodel.feem.it/.

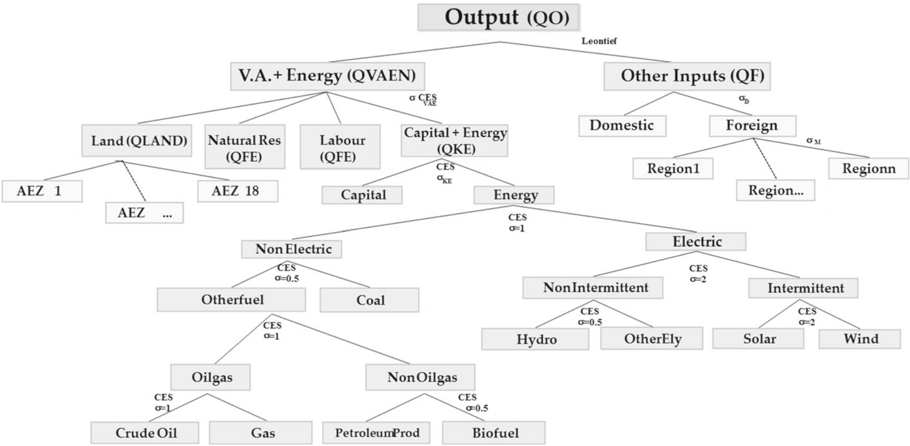

**Fig. 6** ICES nested production function

$$\min P_{i,r}^{Land} LAND_{i,r} + P_{i,r}^{NR} NR_{i,r} + P_{i,r}^{L} L_{i,r} + P_{i,r}^{KE} KE_{i,r}$$

$$s.t.\ QVAEN_{i,r,t} = \left( LAND_{i,r}^{\frac{\sigma_{VAE}-1}{\sigma_{VAE}}} + NR_{i,r}^{\frac{\sigma_{VAE}-1}{\sigma_{VAE}}} + L_{i,r}^{\frac{\sigma_{VAE}-1}{\sigma_{VAE}}} + KE_{i,r}^{\frac{\sigma_{VAE}-1}{\sigma_{VAE}}} \right)^{\frac{\sigma_{VAE}}{\sigma_{VAE}-1}}$$

In the third nested-level, the *QLAND* bundle combines the AEZ-specific land types and the *KE* bundle combines capital with a set of different energy inputs. This is a peculiarity of GTAP-E and ICES model. In fact, energy inputs are not part of the intermediates, but are combined to capital in a specific composite.

Furthermore, Energy is produced using Electric and Non Electric commodities in the Fourth nested-level, while the Non Electric commodity is produced using Coal and Otherfuel commodities. At the basic level of the production tree, there are Gas, Oil, Petroleum Products and Biofuels.

Notice that domestic and foreign inputs are not perfect substitutes, according to the so-called "Armington assumption", which accounts for—amongst others—product heterogeneity. In general, inputs grouped together are more easily substitutable among themselves than with other elements outside the nest. For example, imports can more easily be substituted in terms of foreign production source, rather than between domestic production and one specific foreign country of origin. Analogously, composite energy inputs are more substitutable with capital than with other factors.

A representative consumer in each region receives income, defined as the service value of national primary factors (natural resources, land, labour, capital). Capital and labour are perfectly mobile domestically but immobile internationally. Land and natural resources, on the other hand, are industry-specific. This income is then used to finance three classes of expenditure: aggregate household consumption, public consumption and savings as depicted in the Fig. 7.

Thus, the upper level represented in Fig. 7, mathematically translates into a Cobb-Douglas utility constrained maximization problem:

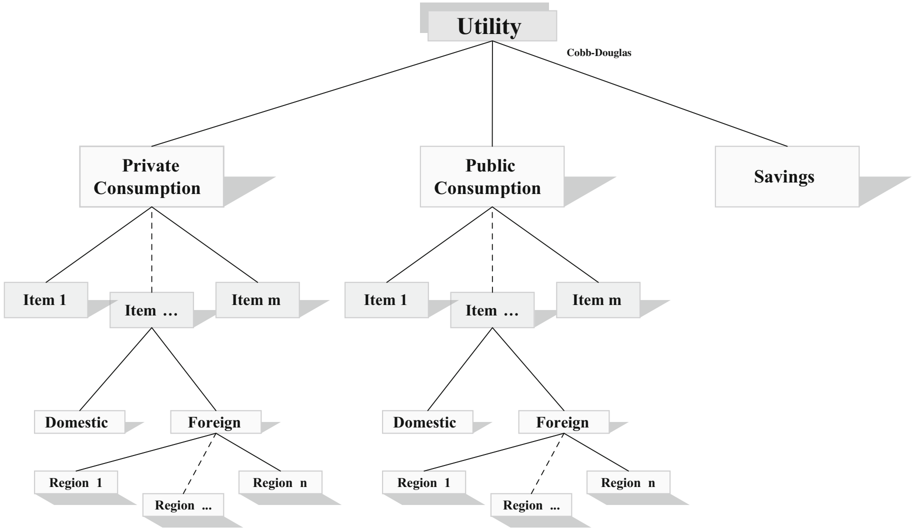

**Fig. 7** ICES nested tree structure for final demand

$$\max U = C\prod_i U_i^{B_i}$$

$$subject\ to\ X = \sum_i E_i\left(P_i, U_i\right)$$

where $U_i$ are the per capita utility from private consumption, per capita utility from government consumption, and per capita real savings; $C$ is a scaling factor and $B_i$ are distribution parameters. $X$ describes the budget constraint which must meet the sum of three types of expenditures $E_i$. $P_i$ is the expenditure-share-weighted index of commodity group price indices.

At the second level, per capita utility from private consumption is derived from the aggregation of per capita private consumption of individual commodities. This is done using the Hanoch's constant difference elasticity (CDE) demand system (Hanoch 1975).

$$1 = \sum_i B_i U^{\Upsilon_i R_i}\left(\frac{P_i}{X}\right)^{\Upsilon_i}$$

where $U$ denotes utility, $P_i$ the price of commodity $i$, $X$ the expenditure, $B_i$ are distribution parameters, $Y_i$ substitution parameters, and $R_i$ expansion parameters.

## Endogenous Dynamics

ICES model is a recursive dynamic model. This means it presents a sequence of static equilibria which are inter-temporally connected by the process of capital accumulation. Capital growth is standard along exogenous growth theory models and follows:

$$Ke_r = I_r + (1-\delta)\,Kb_r$$

where $Ke_r$ is the "end of period" capital stock, $Kb_r$ is the "beginning of period" capital stock, $\delta$ is capital depreciation and $I_r$ is endogenous investment. Once the model is solved at a given step $t$, the value of $Ke_r$ is stored in an external file and used as the "beginning of period" capital stock of the subsequent step $t + 1$.

The hearth of the model's dynamics is the endogenous determination of investment demand $I_r$. Sources of world investments are savings from households. Regional households save a given share of their income which is firstly "pooled" by a "world bank" and then redistributed back to each region following:

$$I_r = \varphi_r RGDP_r e^{[(\rho_r (R_r^E - R^w)]}$$

where RGDP is real GDP, $\rho_r$ and $\varphi_r$ are given parameters, $R_r^E$ and $R^W$ are the expected rate of return to capital in region r and the world rate of return to capital respectively. According to the previous equation, each region demands investment as long as its real GDP rises or its expected rate of return is higher than the world rate of return $R^W$. Investment demand is negatively correlated to $R^W$ which on its turn is determined by the general equilibrium condition requiring equalization between global savings and investments. The parameter $\rho_r$ reflects the flexibility of capital movement related to changes in the current rate of return. If $\rho_r$ has a small value then it will reduce the effect of the growth of the current rate of return when compared with the growth of the global rate of return; basically it can be assumed to reflect policy restrictions. $R_r^E$ needs a particular comment: ICES does not generate endogenously the expected rate of return to capital according to a fully rational expectation generation process of a forward looking agent; more simply it is assumed that the expected rate of return to capital coincides with the current observed rate of return to capital.

The world investment supply (savings) must match world investment demand, but this is not necessarily so at the regional level. Indeed a region can run a foreign debt or credit position as long as $Sr \neq Ir$. This will be reflected in disequilibrium in the trade balance.

In ICES model, also the stock of natural resource has an endogenous dynamics. As explained in Hertel et al. (2008), initial calibration values of these variables in the original GTAP database are not obtained from official statistics, but are indirectly estimated to make the model consistent with industry supply elasticity values from the literature. Then to represent in ICES availability of additional resources due to new discoveries, the price of natural resources has been fixed exogenously, making it variable over time in line with exogenous projections, while allowing the model to compute endogenously the corresponding stock levels.

## Exogenous Dynamics

Capital and natural resources are not the only factors expected to vary over time. Population stock, labour stock, labour and land productivity change over time because of natural or technological evolutionary processes. These processes have been also taken into account in the baseline. This has been done by updating exogenously year by year the initial calibration data of all the above mentioned variables according to their expected rates of change.

## GTAP Database

The model and database are calibrated for year 2004, which constitutes also the beginning year for simulations. ICES model relies on GTAP 7 Data Base (Narayanan and Walmsley 2008) with world coverage: countries are aggregated in 113 macro-regions, and all economic sectors, grouped in 57 sectors.

Furthermore, the database and the model account for main GHG emissions $CO_2$, $CH_4$ and $N_2O$. Following Burniaux and Truong (2002), $CO_2$ emissions are calculated proportionally to energy combustion. Data relative to energy volumes are also included in the GTAP 7 Data Base. Emissions of other greenhouse gases, namely methane and nitrous oxide, are also included in ICES. Data relative with emissions of these gases have been calculated starting from the GTAP non-$CO_2$ emissions database (Lee 2003).

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