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Reducing climate change impacts on agriculture: Global and regional effects of mitigation, 2000–2080

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Abstract

What are the implications for agriculture of mitigating greenhouse gas emissions? By when and by how much are impacts reduced? Where does it matter most? We investigated these questions within the new A2 emission scenario, recently developed at the International Institute of Applied Systems Analysis with revised population and gross domestic product projections. Coupling an agro-ecological model to a global food trade model, two distinct sets of climate simulations were analyzed: 1) A *non-mitigated* scenario, with atmospheric CO_2 concentrations over 800 ppm by 2100; and 2) A *mitigation scenario*, with CO_2 concentrations stabilized at 550 ppm by 2100. Impacts of climate change on crop yield were evaluated for the period 1990–2080, then used as input for economic analyses. Key trends were computed over the 21st century for food demand, production and trade, focusing on potential monetary (aggregate value added) and human (risk of hunger) impacts. The results from this study suggested that mitigation could positively impact agriculture. With mitigation, global costs of climate change, though relatively small in absolute amounts, were reduced by 75–100%; and the number of additional people at risk of malnutrition was reduced by 80–95%. Significant geographic and temporal differences were found. Regional effects often diverged from global net results, with some regions worse off under mitigation compared to the unmitigated case.

Keywords: Agriculture; Climate impacts; Mitigation; World food supply

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1. Introduction

There is concern about the impacts of climate change and its variability on agricultural production worldwide. For one, food security is prominently on the list of human activities and ecosystem services under threat of dangerous anthropogenic interference on earth's climate ([1–3]; article II, UNFCCC). Second, each country is naturally concerned with the potential damages and benefits that may arise over the coming decades from climate change impacts on its territory as well as globally, since these will affect domestic and international policies, trading patterns, resource use, regional planning, and the welfare of its people.

Current research confirms that, while crops would respond positively to elevated CO_2 in the absence of climate change [4–6], the associated impacts of high temperatures, altered patterns of precipitation, and possibly increased frequency of extreme events, such as drought and floods, will likely combine to depress yields and increase production risks in many world regions. These will widen the gap between rich and poor countries [7]. A consensus has emerged that developing countries are more vulnerable to climate change than developed countries, because of the predominance of agriculture in their economies, the scarcity of capital for adaptation measures, their warmer baseline climates, and their heightened exposure to extreme events [8]. Thus, climate change may have particularly serious consequences in the developing world, where about 800 million people are currently undernourished [9].

Many interactive processes determine the dynamics of world food demand and supply: agro-climatic conditions and land resources and their management are clearly a key component, but they are critically affected by distinct socio-economic pressures, including current and projected trends in population growth, and availability and access to technology and development. In the past three decades, for instance, average daily per capita intake has risen globally from 2400 to 2800 calories, spurred by economic growth, improved production systems, international trade, and globalization of food markets. Feedbacks of such growth patterns on cultures and personal taste, lifestyle, and demographic changes have, in turn, led to major dietary changes—mainly in developing countries, where shares of meat, fat, and sugar to total food intake have increased significantly [10].

Several integrated assessment studies have focused on quantifying the key impacts on food production from climate change, as a function of different socio-economic scenarios, including the analyses of likely adaptation strategies, such as crop management changes and economic adjustments [10–13]). As society learns to respond to climate change pressures over the coming decades, it is clear, however, that to minimize the negative impacts of climate change on human activities and ecosystems, adaptation strategies will need to be implemented in parallel with mitigation actions [14].

Yet attempts to quantify the potential benefits of climate mitigation actions on the agricultural sector have received minimal attention so far [15]. Specifically, what are the implications for global and regional agricultural production of mitigating greenhouse gas (GHG) emissions, and thus slowing climate change over time? By when and by how much are impacts reduced? Where does it matter most?

This paper investigates precisely such questions. We employed for analysis the Food and Agriculture Organization-International Institute of Applied Systems Analysis (FAO-IIASA) agro-climatic database and modeling framework known as the agro-ecological zones (AEZ) model [16] in connection with the IIASA world food system, or Basic Linked System (BLS) [17–19]). We focused on a new A2 socio-economic scenario developed at IIASA, A2r [20], to quantify global and regional socio-economic development from 1990 to 2080, with associated climate change variables computed with and without mitigation options. Overall, the focus of this paper is not to analyze policy options for mitigation–a task for which analyses of multiple scenarios from the *Special Report on Emissions Scenarios* (SRES) scenarios would be necessary–but simply to begin to assess the potential benefits of mitigation, framed within the science questions posed above. Within this context, the use of a single scenario, A2r, was considered a useful first step for analysis.

Simulation results included climate change impacts on agro-climatic resources, potential arable land, and related changes in crop production patterns. Our economic analyses assessed over the 21st century changes to food demand, production, trade and incomes, and the scale and location of risk of hunger.

2. Materials and methods

The combination of a spatially detailed biophysical–agronomic assessment tool and a global food system model provided an integrated framework for the assessment of the impacts of climate change and agricultural vulnerability within this study (Fig. 1). Brief descriptions of the key components of the IIASA modeling systems are given below.

2.1. AEZ modeling methodology

Assessment studies of the impacts of climate change on agriculture at farm to regional levels need to analyze complex interactions of climate, agro-ecosystem function, and human management. To this end, researchers typically link climate predictions of general circulation models (GCMs) to crop models and land management decision tools [21], for instance, Decision Support System for Agrotechnology Transfer (DSSAT) [22,23], Erosion Product Impact Calculator (EPIC) [24], and Terrestrial Ecosystem Model (TEM) [25].

The simulation tool used in this study was the IIASA-FAO AEZ model. It uses detailed agronomic-based knowledge to simulate availability and use of land resources, farm-level management options, and crop production potentials as a function of climate. At the same time, it employs detailed spatial biophysical and socio-economic datasets to distribute its computations at fine gridded intervals over the entire globe [16]. This land-resources inventory is used to assess, for specified management conditions and levels of inputs, the suitability of crops in relation to both rain-fed and irrigated conditions, and to quantify the expected attainable production of cropping activities relevant to specific agro-ecological contexts that characterize the study area. The characterization of land resources includes components of climate, soils, landform, and present-day land cover. Crop modeling and environmental matching procedures identify crop-specific environmental limitations under various levels of inputs and management conditions.

Specifically, AEZ employs the FAO-UNESCO Digital Soil Map of the World (DSMW) as the underlying reference for its own land-surface database, which consists of more than 2.2 million grid cells at $5'$ latitude × $5'$ longitude (i.e., with a size of about 10 × 10 km at the equator). In addition, a global digital elevation map (DEM) and derived slope distribution database are linked to DSMW. AEZ's current climate database is based on datasets developed by the Climate Research Unit (CRU, University of East Anglia). These comprise historical monthly mean data for the period 1901–1996 and include a monthly mean climatology (e.g., that describes mean monthly minimum temperature, mean monthly maximum temperature, precipitation, wet-day frequency, cloudiness, vapor pressure deficit) based on the decades 1961–1990 [26]. In AEZ, the CRU data are transformed into daily data and analyzed *vis-à-vis* crop requirements [16]. Finally, AEZ employs a land cover/land use layer that specifies distributions of aggregate land-cover classes, as derived from global 1-km land-cover datasets from, respectively, National

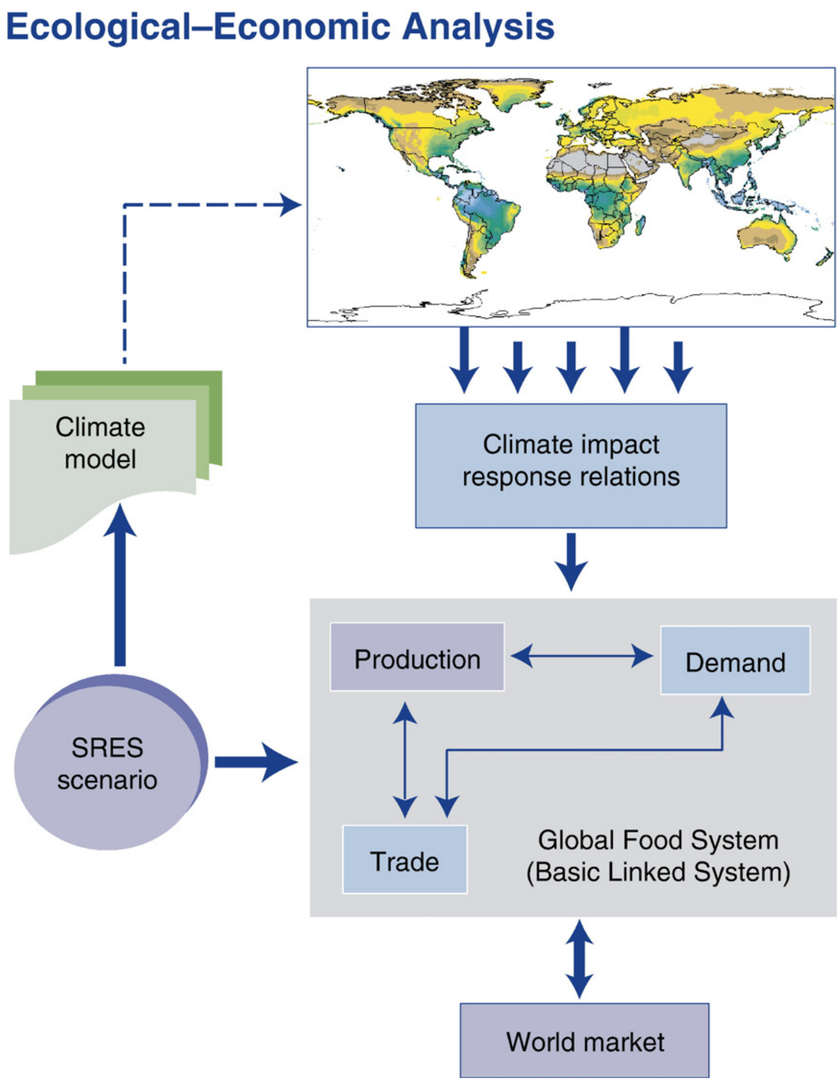


Fig. 1. Graphic illustration of the AEZ–BLS modeling framework. Socio-economic SRES scenarios determine future demographic and economic conditions and define GHG emissions and ultimately climate change under which AEZ and BLS are run. Climatic impacts on agricultural production—computed with AEZ—are passed on to the agricultural economics and trade model, BLS, to determine the overall impacts on national agricultural and world food systems.

Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA AVHRR; see http://edcsns17.cr.usgs.gov/glcc/globdoc2_0.html for details) and Global Landcover Classification (GLC2000; see http://www-gvm.jrc.it/glc2000/ for details). Based on these spatial land-cover datasets and consistent with land statistics from the FAO statistics database (FAOSTAT), the AEZ global land-resources database incorporates spatial delineation and accounting of forest and protected areas. In terms of key socio-economic datasets, AEZ employs a global population data set calibrated for the year 2000, including estimates of spatially explicit population distributions and densities for each country at 5′ latitude × 5′ longitude.

The AEZ model further classifies amounts of non-arable and arable land as a function of environmental constraints. Land is classified as having severe (too cold, too wet, too steep; or having serious soil-quality constraints), moderate, slight, or no constraints to cultivation. Classification is also made between rain-fed and irrigated land, depending on water deficits computed internally as precipitation minus evapotranspiration.

The AEZ model has been validated for use in agricultural resource assessment and employed in many studies [10,16]. It is one of the main tools used by the FAO for analyses of present and future land resources, both regionally and globally [12].

2.2. World agricultural trade and economic modeling

In addition to land-resource assessment and computation of potentially attainable yield, this analysis included an agro-economic model to estimate actual regional production and consumption, using the BLS developed at IIASA. This model comprises a series of national and regional agricultural economic models. It provides a framework for analyzing the world food system, viewing national agricultural components as embedded in national economies, which in turn interact with each other at the international trade level [18]. The BLS model consists of 34 national and regional geographic components that cover the globe, calibrated and validated over past time windows [17,27]) and successfully reproduces regional the consumption, production, and trade of major agricultural commodities in 2000. Several applications of the BLS to climate-change impact analysis have been published [1,10,13,19,18].

The individual national and/or regional models are linked together by means of a world market, in which international clearing prices are computed to equalize global demand with supply. The BLS is formulated as a recursively dynamic system that works in successive annual steps. Each individual model component focuses primarily on the agricultural sector, but attempts to represent the whole economy as necessary to capture the essential dynamics among capital, labor, and land. To enable subsequent international linkage, the production, consumption, and trade of goods and services are aggregated into nine main agricultural sectors, though individual regional models have more detail. The nine agricultural sectors include wheat, rice, coarse grains, bovine and ovine meat, dairy products, other meat and fish, protein feeds, other food, and non-food agriculture. The rest of the economy is coarsely aggregated into one simplified non-agricultural sector. Agricultural commodities may be used within BLS for human consumption, feed, intermediate consumption, and stock accumulation. The non-agricultural commodity may contribute as investment, and to process and transport agricultural goods. All physical and financial accounts are balanced and mutually consistent—the production, consumption, and financial ones at the national level, and the trade and financial flows at the global level.

Within each regional unit, the supply modules allocate land, labor, and capital as a function of the relative profitability of their different economic sectors. In particular, actual cultivated acreage is computed from agro-climatic land parameters (derived from AEZ) and profitability estimates. Once acreage, labor, and capital are assigned to cropping and livestock activities, actual yields and livestock production is computed as a function of fertilizer applications, feed rates, and available technology.

Population growth and technology are key external inputs to BLS. Population numbers and projected incomes are used to determine demand for food for the period of study. Technology affects BLS yield estimates by modifying the efficiency of production per given units of input [18]. To simulate historical periods up to the present, population data are taken from official United Nations (UN) data at country level, while the rate of technical progress can be estimated from past agricultural performance. For simulations into the future, scenarios of socio-economic development and population growth must be chosen to inform BLS computations. Another key external input to AEZ-BLS is climate and environment, which determine crop suitability and potential yields used by the economic model as an input in resource allocation. Thus, projected climate change affects BLS results indirectly yet significantly, via its impacts on agro-climatic land resources computed by AEZ.

2.3. Socio-economic scenario generation

To assess agricultural development over the 21st century, with or without climate change and with or without mitigation, it was necessary to first make some coherent assumptions about how key socio-economic drivers of food systems might evolve over the same period. For instance, plausible socio-economic development paths were specified by the IPCC SRES, with special reference to emissions of GHGs into the atmosphere [2,7,28]. Emissions of GHGs can then be translated into projections of climate change using GCMs. IIASA developed a new socio-economic scenario, A2r, from SRES A2 using revised population projections [20]. In A2r, unmitigated GHG emissions reached above 25 GtC/year–and atmospheric CO_2 concentrations were above 900 ppm CO_2–by 2100. Mitigation of emissions was shown to be possible within this scenario, stabilizing CO_2 concentrations at 550 ppm. The overall cost of mitigation was computed to be small, or 4.4% of world gross domestic product (GDP) in 2100. In other words, economic growth under mitigation would only be delayed by 2 years compared to the unmitigated case, reaching the same economic output in 2102 rather than in 2100 [29]. Therefore, as a first approximation, the two different levels of climate change–corresponding to either unmitigated or mitigated emissions–were linked to only one underlying socio-economic scenario, A2r.

In this work, we specifically focused on the impacts of climate change on agriculture under the A2r scenario, with and without mitigation. A new B1 mitigation scenario at 550 ppm CO_2 is also available from IIASA for analysis, but it is not considered herein. Climate change differences among unmitigated and mitigated scenarios would have been too small, since CO_2 concentrations between the new and the original marker B1 scenario were similar.

Analyses of socio-economic scenarios within BLS were then realized via the following steps (a more detailed technical discussion of this methodology has been published [10]). First, the A2r population projections were incorporated for each BLS country or region. To maintain consistency with the SRES structure presented within this Special Issue, the BLS 34 regions were further aggregated into 11 regions that are common to this collection of papers: North America, Latin America, Western Europe, Eastern Europe plus former USSR, North Africa and Middle East, Sub-Saharan Africa, South Asia, Southeast Asia, China and Centrally Planned Asia, Developed Pacific Asia, and Rest of the World.

We then let BLS dynamically compute the allocation of labor and capital between agriculture and non-agriculture sectors as a function of specified economic conditions. Second, BLS runs were harmonized with the larger socio-economic scenario specifications. The approach chosen was to harmonize rates of economic growth generated in the BLS with those projected in the A2r scenario, through adjustment of capital investment (saving rates) and of rates of technical progress in non-agricultural sectors. The harmonization of production factors and GDP, individually for each decade during the period 1990–2080, was carried out on a region-by-region basis.

To assess the impacts of climate change on agriculture over the 21st century, with and without mitigation, we devised the following two-step strategy. First, the impacts of socio-economic variables were analyzed against current conditions, without climate change. Second, impacts of climate change, without and with mitigation, were superimposed on the first scenario, and differences between unmitigated and mitigated climates were computed.

2.4. Climate change scenario generation

GCMs compute future climates under anthropogenic forcing (i.e., present and projected future emissions of GHGs [2]). Their use in impact assessment studies of climate change is widespread [7,30]. These models provide internally coherent climate dynamics by solving globally all climate-relevant physical equations. Yet it is recognized that GCM projections present significant uncertainties, in part through issues of scale resolution, and in part through imperfect understanding of key climate dynamics [2]. For instance, the earth climate sensitivity, defined as mean global planetary temperature response to a doubling of CO_2 levels (~560 ppm) in the atmosphere, is thought to be in the range 1.5–4.5 °C [2]. Though GCM simulations fall squarely within this range, future climate projections with GCMs that correspond to lower and upper values may be quite different in terms of projected global warming. More importantly, even among GCMs with similar temperature-change simulations, predictions of regional precipitation responses may vary significantly, in part because of the intrinsic chaotic nature of climate and in part because of differences in model approach to resolving local to regional atmospheric dynamics.

As discussed, only one socio-economic development pathway was linked to both non-mitigated and mitigated climates within the new A2r scenario. Yet, to analyze the distinct impacts of climate change on the agricultural sector of each scenario, two separate climate change projections were necessary. As no actual GCM simulation using A2r emission histories existed, approximations had to be made as follows. We observed that, although A2r and the SRES marker A2 socio-economic scenarios differed in both regional patterns of GDP and related emissions of GHGs [20], global total emissions, and thus the aggregated climate outcomes for both A2r and the SRES A2 marker scenarios were quite similar. Data developed in this Special Issue [29] and computations with the simplified climate Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) [31] showed that estimated CO_2 concentrations in 2100 were about 920 ppm for A2r. This is well within the range reported by the IPCC for the original A2 marker scenario of 760–930 ppm CO_2 [28]. As a result, the temperature consequences of the two scenarios were similar. Indeed, mean global temperature increases relative to pre-industrial times were 4.1 °C for SRES A2, compared to 4 °C for A2r. We therefore chose to use A2 SRES-based GCM runs as a proxy for A2r *unmitigated* climate change.

Similarly, computations using data from this Special Issue [29] showed that, because of similarities in aggregate emissions, CO_2 concentrations in 2100 under the A2r *mitigated* scenario (i.e., 550 ppm) were within the range of those that corresponded to the SRES B1 marker scenario of 490–680 ppm CO_2. Climate outcome between A2r *mitigated* and SRES B1 scenarios were likewise similar: computations with MAGICC showed by 2100 identical global mean temperature changes of 2.3 °C under both A2r *mitigated* and SRES B1. We therefore chose to use B1 SRES-based GCM runs as a proxy for A2r *mitigated* climate change.

In conclusion, we used GCM projections relative to SRES A2 and SRES B1 as proxy climates for assessing impacts under A2r unmitigated and mitigates scenarios, respectively. For simplicity, in the following analyses we refer to these two scenarios as A2r and A2r-mit.

Within each A2r scenario, impacts on agriculture were analyzed using climate change projections of two GCMs—Hadley CM3 (HadCM3) and Commonwealth Scientific and Industrial Research Organisation (CSIRO). Specifically, GCM climate changes were computed for each decade of interest, from 1990 to 2080, relative to a baseline reference climate (1961–1990). These were then interpolated to the AEZ grid of $0.5' \times 0.5'$ latitude by longitude, and used to generate future agronomic data.

2.5. Limitations of modeling framework

Simulation models provide a valid, and often the only available, tool to investigate complex interactions and feedbacks of many variables. As discussed, simulation impact-assessment studies are widely used to project climate change and socio-economic effects on human activities, including agriculture. A number of limitations and uncertainties characterize such exercises.

First, there is uncertainty in the magnitude of climate change and its spatial and temporal distribution. It is thus recommended that several GCM scenarios be used when assessing climate change impacts on crop production, in particular given the strong dependence of this sector on precipitation [21]. At the same time, the GCM simulations used herein do not contain increases in the frequency of extreme events; these might have further reduced crop yields compared to computations herein.

Second, the AEZ modeling simulations have been validated in many places, but the global nature of the simulations signifies that validation has not been possible at every grid point considered. In addition, AEZ computes potentially attainable, rather than actual, crop yields. Thus, wherever the gap between actual and potential yields is large, such as in many developing countries, there is uncertainty in translating AEZ-calculated impacts of climate change–subsequently used in BLS computations–into changes in actual crop productivity. In those regions with large yield gaps, AEZ may predict larger positive impacts of climate change on crop production than is actually possible in real fields. Finally, the AEZ-simulated crop response to elevated CO_2 is modeled rather simply, as a multiplier of the harvest yield obtained under current CO_2 levels. This multiplier was derived, as in other crop models, from controlled experimental data, which indicated a 25% increase in yields of C3 crops, such as wheat, rice, and soybean, and a 10% increase in the yield of C4 crops, such as maize and sugar cane, for a doubling of CO_2 levels. It is recognized that such simulated responses may, in fact, be larger than is actually possible at farm levels [21]. In the AEZ assessment these factors are applied to land units without production limitations. Where suitability is limited the multipliers are reduced proportionally to the magnitude of the limitations.

Third, our simulation results depend on BLS dynamics. Although this model has been validated for past periods, various additional and uncertain assumptions are needed to obtain food system projections (e.g., technical progress in crop yields, regional irrigation development scenarios, changes in food preferences, etc.). Nonetheless, BLS provides internally coherent socio-economic dynamics, so that its predictions represent plausible futures for scenario analysis.

Fourth, the A2r scenario employs population numbers that are at the upper range of UN projections. The results obtained herein may thus be regarded as a *worst-case scenario*, in terms of population pressures on food systems.

Finally, the same set of socio-economic assumptions was used for both A2r and A2r-mit projections (i.e., implicitly assuming no cost feedback of mitigation to both the global economy and the agricultural sector). Indeed, data from this Special Issue [20,29] indicate that impacts of mitigation are small compared to the global economy (i.e., 3.9% of total GDP in 2080). These translate into even smaller impacts on agricultural GDP (i.e., 2.6%), because of different elasticities between the global economy and the agricultural sector. Moreover, the actual costs of implementing mitigation–including mainly reductions of N_2O and CH_4 emissions via more efficient fertilizer use, and changes in livestock and manure management, and in rice cultivation–within the agricultural sector were only 0.4%, of global agricultural GDP, or about 12 billion US$ compared to BLS projections of 2.9 trillion US$ [29]. Furthermore, temporal and regional feedbacks of mitigation in the agricultural sector–which we have assumed not significant–could modify the outcome of our simulations. Preliminary calculations, however, indicate that regional dynamics would only slightly change the regional numbers of agricultural GDP, with little consequences to global dynamics.

3. Results: world food system, 1990–2080

While climate and farm management are key determinants of food production locally, agro-economics and world trade combine to shape regional productivity both regionally and globally. The following sections describe results obtained with AEZ-BLS simulations of world food systems. We first assessed the implications of the A2r socio-economic scenario for world agricultural economy. BLS simulation results without climate change represented a reference case against which climate change impacts were analyzed. To run BLS with climate change, AEZ-derived projections of changes in land production potentials and attainable yields for each future decade, from 1990 to 2080, were used to modify, in a simple multiplier fashion, production functions for BLS internal yield. Simulations started in 1990 and were carried out in yearly increments; the results are presented in 10-year intervals, from 1990 to 2080. Analyses of projected changes were made relative to the year 2000.

3.1. Impacts of socio-economic development, no climate change

We first analyzed the impacts of the A2r socio-economic scenario without climate change on the world agricultural economy. The following sections describe in detail some specific AEZ-BLS projections, from 1990 to 2080, including global and regional cereal production, arable land use, agricultural value added, and number of people at risk of hunger. Many additional variables were computed by BLS within these runs, but are not discussed herein for brevity. The interested reader can find additional results in Appendix A (e.g., for agricultural crop residues and bioenergy potentials, livestock numbers, and rice cultivation and production), which are used elsewhere in this Special Issue [29].

3.1.1. Cereal production

World cereal production was computed to be 2.1 Gt in 2000, nearly equally divided between developed and developing countries (Table 1), in agreement with current statistics. By 2080, BLS projected annual global cereal production of 4.2 Gt (i.e., twice 2000 levels). Production in the developing countries increased at a faster pace (+135%) compared to that in developed countries (+70%), so that by 2080 cereal production in developing countries was about 50% more than in developed regions.

The largest relative increase–and also one of the largest in absolute terms–was computed for Sub-Saharan Africa (i.e., a five-fold increase from 73 Mt in 2000 to 360 Mt in 2080). By contrast, the smaller relative and absolute increases were computed for Western Europe, where from 2000 to 2080 production increased by only 40 Mt because of overall decreases in cultivated land. Finally, production significantly increased in major cereal growing regions, such as North America (+80%), East Asia (+70%), and Southeast Asia (+130%).

Not surprisingly, the figures computed by BLS for cereal production were paralleled rather closely by fertilizer use. In 2000, BLS estimated world nitrogen use of roughly 83 Mt, 35% of which was in developed countries, in agreement with current statistics. Global use was projected to increase to 205 Mt N in 2080 (+145%), with usage in developing countries accounting for more than two-thirds of the increases. In Sub-Saharan Africa, fertilizer nitrogen applications were projected to increase seven-fold, although its per hectare level in the year 2000 was a mere fraction of the amounts used in other

Table 1
Projected cereal production (million tons), including wheat, rice, maize, and other coarse grains

Region	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080
WORLD	1797	2095	2371	2670	2969	3274	3550	3787	4013	4215
NAM	402	462	515	560	613	672	732	771	807	835
WEU	179	185	191	202	210	219	223	227	228	226
PAO	34	41	47	56	63	72	77	83	84	84
EEU+FSU	306	324	343	363	387	416	446	472	518	569
AFR	54	73	97	125	158	200	242	281	320	359
LAM	102	129	165	207	245	283	313	340	359	369
MEA	43	57	71	87	101	115	129	144	159	173
CPA	360	424	475	528	573	612	644	672	697	720
SAS	195	254	301	349	400	443	481	517	551	585
PAS	55	68	82	97	113	129	141	151	156	155

A2r-reference scenario (i.e., no climate change). NAM, North America; WEU, Western Europe; PAO, Developed Pacific Asia; EEU+FSU, Eastern Europe and former USSR; AFR, Sub-Saharan Africa; LAM, Latin America; MEA, Middle East and North Africa; CPA, Centrally Planned Asia; SAS, South Asia (Indian sub-continent); PAS, Southeast Asia.

regions. These increases resulted from both higher nitrogen-fertilizer application rates and an increased amount of arable land. We further computed nitrogen application rates per unit arable land, expressed in kgN/ha. Global values in 2000 were 50 kgN/ha, with values in developed countries consistent with statistics: BLS computed rates of about 55, 115, and 170 kgN/ha for the USA, Western Europe and China, respectively. Application rates in most developing regions (except for East Asia) were much lower, and almost insignificant in Sub-Saharan Africa (3 kgN/ha). Nitrogen-fertilizer application rates per unit arable land were projected to double globally by 2080, to 115 kgN/ha, while almost quintupling in Africa.

3.1.2. Cultivated land

Computations of total cultivated land were carried out by assessing the land potential with AEZ and the economic utilization with BLS. In 2000, 1.5 Gha of arable land were computed, or roughly 10% of all available land on earth, off which almost 900 Mha were in developing countries (data not shown). By 2080 under the A2r socio-economic scenario, no increase in land under cultivation was projected for developed countries, where additional production resulted from increased productivity and fertilizer input. In developing countries, by contrast, cultivated land was projected to increase by roughly 250 Mha (+27%). Most of this additional cropland is from Africa (+122 Mha, or +60%) and Latin America (80 Mha, or +45%). Arable land was, by contrast, projected to decrease in many developed regions, with the largest reductions in Western Europe (−9 Mha, or −11%).

3.1.3. Agricultural output

Aggregate agricultural production is defined herein as total agricultural value added. This quantity, which integrates over crop and livestock sectors, is expressed in constant 1990 US$. The BLS model computed global agricultural value-added in 2000 to be about 1.3 trillion US$, or roughly 5% of world GDP, with about 780 billion US$ produced in developing countries (Table 2). Sharper differences were computed between developed and developing countries in terms of share of total GDP. In developed countries, agricultural income was 2.1% of GDP; this share was roughly 16% in developing countries.

Table 2
Agricultural GDP (billion US$, constant 1990 prices), A2r-reference scenario

Region	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080
WORLD	1077	1273	1466	1684	1921	2158	2384	2586	2767	2932
NAM	148	164	176	189	205	223	241	251	258	264
WEU	122	133	143	151	159	169	177	183	186	188
PAO	41	47	52	58	65	72	78	84	88	91
EEU+FSU	79	83	87	90	95	100	105	111	121	131
AFR	55	74	95	124	160	198	239	286	330	370
LAM	123	151	185	226	269	311	347	374	391	402
MEA	46	62	79	100	124	148	173	197	218	237
CPA	212	250	283	316	347	374	398	417	435	453
SAS	138	176	212	253	299	344	390	435	482	532
PAS	55	70	85	102	119	137	149	159	166	171

These numbers were consistent with current statistics; in particular, poor countries are more dependent on agriculture, with a large fraction of their population employed on farms. In 2000, regions with highest shares of agricultural GDP were Sub-Saharan Africa (40%) and the Indian Subcontinent (28%). Regions with lowest shares, between 1% and 2%, were North America, Western Europe, and developed Pacific Asia, which includes Japan, Australia, and New Zealand.

BLS computed a significant development of the agricultural output under the A2r scenario. Globally, agricultural value-added grew by a factor of 2.3 in 2080, to almost 3 trillion US$, of which 2.2 trillion US$ were produced in developing countries. The global share of agricultural value-added to world GDP was projected to decrease to less than 2%, largely as a consequence of the increasingly larger roles of the industry, energy, and service sectors compared to agriculture. While GDP share of agriculture of developed countries diminished from about 2.1% in 2000 to 1% in 2080, the projected decrease in developing countries was much more dramatic: a factor of seven, from 15.5% in 2000 to 2.3% in 2080. In particular, agricultural value-added in Sub-Saharan Africa in this A2r scenario was projected to rise five-fold, from 74 billion US$ in 2000 to 370 billion US$ in 2080; however, shares of agriculture in total GDP decreased six-fold, from 40% to 7%. In South Asia (i.e., the Indian subcontinent) shares decreased by a similar magnitude, from 28% to 4%.

3.1.4. Food security

BLS computed the number of *people at risk of hunger* based on FAO data [32] and relying on a strong empirical correlation between the shares of undernourished in the total population and the ratio of average national food supply, including imports, relative to aggregate national food requirements (Fig. 2). For instance, Fig. 2 suggests that the share of undernourished in the total population falls below 20% for an index value of about 130 (i.e., when aggregate food supply exceeds aggregate national food requirements by 30%). Hunger is nearly eliminated for index values of food supply over requirements higher than 160. This correlation, based on current relationships between per capita calorie requirements, food supply, and food distribution, implicitly includes today's levels of inequality in access to and distribution of food resources in many developing countries. While it has been used by the FAO for projections of hunger up to 2030 [12], it is possible that improved socio-political conditions in later decades may modify the correlation for many developing countries and result in less people at risk of hunger for a given index value of demand over supply. If that were to happen, the projections below might be overestimates. However,

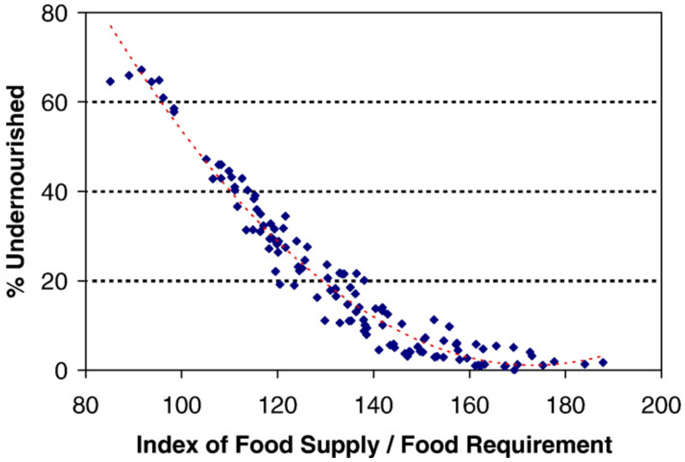


Fig. 2. Correlation between an index value that represented aggregate national food supply over requirements, and the share of undernourished people within a country, based on current data from developing countries [16,32].

worsening of political or local environmental conditions that accompany climate change might create further negative pressures on the risk of hunger.

BLS computed the total number of people at risk of hunger to be 820 million in 2000 (see Table 3), with the large majority concentrated in Asia (526 million) and Sub-Saharan Africa (188 million).

Hunger was projected to decrease globally, to about 555 million in 2080. Still, these BLS results indicate that the Millennium Development Goals of reducing hunger by half by 2015 [9] are unrealistic within the A2r scenario, unless perhaps additional specific targeted programs for hunger reduction are put in place. Further, global reductions masked diverging regional signals. While by 2080 the number of people at risk of hunger was projected to be significantly reduced in Asia, from 526 million to 'only' 73 million (a factor of about seven), the number of people at risk of hunger sharply increased in Africa, from 188 million to 410 million.

3.2. Impacts of socio-economic development, with climate change

We performed an analysis of the climate change impacts by comparing projections from two GCMs, Hadley and CSIRO. These projections were available for both A2r and A2r-mit scenarios (for SRES A2

Table 3
People at risk of hunger (million), A2-reference scenario

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080
LDCs	885	821	804	772	687	628	579	582	561	554
ASIA LDC	659	526	463	390	280	189	123	102	85	73
OTH. LDC	226	295	341	382	407	440	455	480	475	481
AFR	138	188	231	273	304	336	359	386	393	410
LAM	54	57	56	53	48	46	40	36	29	23
MEA	33	49	53	55	54	57	56	58	54	48
CPA	226	171	138	106	77	55	43	37	31	26
SAS	374	312	293	254	176	112	66	56	48	43
PAS	60	42	32	30	27	22	15	8	6	5

and B1, as previously discussed), that is, to simulate yield impacts that correspond to both unmitigated and mitigated climate changes. Three additional GCMs, Canadian, Max-Planck, and National Center for Atmospheric Research (NCAR), were also available, but only for A2r analyses. We henceforth refer to the A2r scenario without climate change as *A2r-reference*. The following sections describe the results of coupling BLS simulations of global and regional production with AEZ-derived climate change impacts on land and crop potentials. For both climate scenarios the BLS simulations were performed in yearly time steps, and the results are presented in 10-year increments from 2000 to 2080.

In general in these simulations, modifications to food production caused by climate change created crop production and market imbalances with respect to the A2r-reference scenario. This modified international prices and led to reallocation of agricultural capital and human labor among and within regions, as well as causing adjustments of consumption. As part of these reallocations, AEZ-BLS computed a number of adaptation strategies automatically, by searching for solutions that optimized new opportunities over the climate change scenarios considered. Specifically, AEZ simulations suggested new sets of crops, cropping systems, and management solutions better suited to climate change conditions, while BLS computed additional economic adjustments.

3.2.1. Cereal production

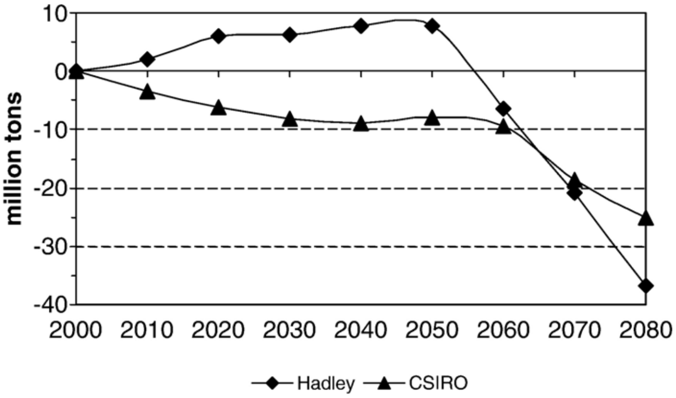
Impacts of climate change on *world aggregate* cereal production were projected to be small in absolute and relative terms, with the CSIRO and Hadley GCM scenarios suggesting a decrease of about 25 to 37 Mt in 2080, about −0.6% to −0.9% of a total production of 4.2 Gt.

Regional and temporal patterns of these impacts were, however, much more diverse and significant. First, small global reductions masked opposite impacts on developed and developing regions. Specifically, in 2080 production increased in developed countries and decreased in developing regions. While these asymmetries were smaller under A2r-Hadley (respectively, +2.7% and −3.3% compared to the A2r-reference in 2080), they were quite pronounced under the A2r-CSIRO climate (+9.0% and −7.2%); the latter scenario indicated significant absolute gains and losses of, respectively, +150 and −175 Mt (Fig. 3). Second, even within these regional groupings, BLS computed some winners and losers consistently across the two GCM scenarios. Northern Eurasia (+2.2% and +6.7%, respectively), developed Pacific Asia (+8.5% and +18.5%, respectively), Latin America (+12.5% and +5.2%, respectively), and North America (+4.0% and +13.5%, respectively) were projected as gaining cereal production under both GCM climates—in part through better growing conditions with warming. However, Africa (−3.9% and −7.5%, respectively), East Asia (−2.5% and −7.8%, respectively), and in particular South Asia (−22.1% and −18.2%, respectively) were consistent losers.

Finally, the time evolution of cereal production changes computed by BLS was quite different among regions, decades, and GCMs, with positive and negative impacts projected through time (Fig. 3). The reasons that underlie such behavior are complex, with no simple explanation possible. In BLS cereal production is an integral part of crop impacts, adaptation, and economic redistribution. However, perhaps the global and regional time patterns seen under Hadley, with increases in production earlier in the 21st century, up to 2050, followed by decreases, could be explained by assuming that the negative impacts of climate change on crops were masked in the earlier decades by the positive effects of an elevated atmospheric CO_2 on plants, more so than under the CSIRO climate. As these effects saturated later in the 21st century, while climate change became more pronounced, negative impacts to crop production resulted.

With mitigation. Under the A2r-mit scenario, BLS computed much smaller losses (for the CSIRO climate) and even increases (for the Hadley climate) of global cereal production in 2080, with small production

(a) Global impact of climate change on cereal production



(b) Regional impacts of climate change on cereal production

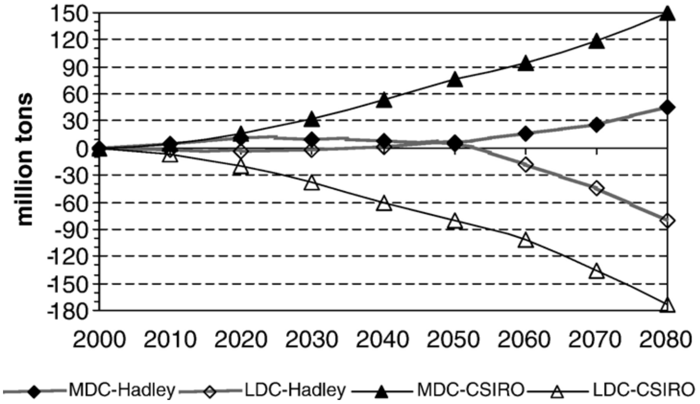
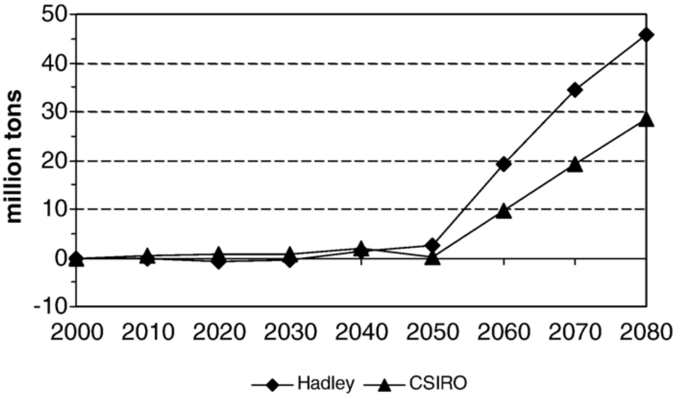


Fig. 3. Impacts of climate change on aggregate cereal production in the A2r scenario as computed by the BLS model over time, for selected decades into the future. (a) Aggregate net global impacts; (b) Data are aggregated into developing and developed regions (MDC, moderately developed countries; LDC, less developed countries).

changes of, respectively, +4 and +9 Mt, or +0.1% and +0.2% of the A2r-reference. Regional trends in differences between A2r-mit and A2r-reference are similar to those discussed for the unmitigated case, still with some asymmetries between developed and developing regions. For each region, however, the magnitude of climate impacts under A2r-mit was projected to be smaller than under A2r, but with roughly the same groups of winners and losers indicated previously. We computed the absolute differences between cereal production under A2r and A2r-mit, for both GCMs. In addition to the differences discussed so far, climate mitigation created its own set of winners and losers–on the one hand, regions that benefited from mitigation (with large reductions of negative impacts) and, on the other hand, regions that became worse off with mitigation (not fully realizing positive agronomic impacts or economic benefits)–compared with the unmitigated climate change (Fig. 4). In addition, results from BLS were consistent among the GCMs to indicate a time asymmetry in the mitigation effects, at least at the global level. Specifically, while mitigation A2r-mit increased cereal production globally by 2080 relative to A2r, its effects were even slightly negative

(a) Global effect of mitigation on cereal production



(b) Regional effects of mitigation on cereal production

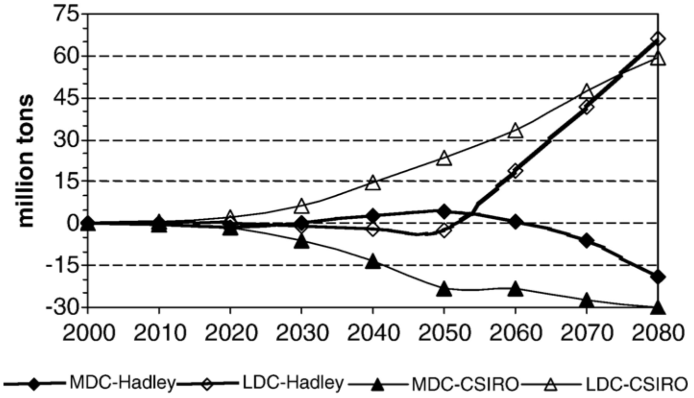


Fig. 4. Effects of mitigation on aggregate regional cereal production, defined as A2r-mit minus A2r values, as computed by the BLS model over time for selected decades into the future. Positive values correspond to *benefits* of mitigation (i.e., added production with respect to the unmitigated case) and vice-versa. (a) Net global effect of mitigation; (b) Data are aggregated into developing and developed regions.

in the early decades (i.e., global cereal production was higher under the A2r than the A2r-mit scenario) up to 2040 under Hadley, and nearly neutral up to 2050 under both GCM scenarios.

Such results can be explained, in part, by differences in elevated CO_2 between the A2r and A2r-mit scenarios. During the initial decades to about 2050, higher CO_2 levels in A2r compared with A2r-mit may have allowed crops to better compensate for climate change with no mitigation. Past 2050, the stronger climate signal of A2r, combined with the saturating effects of elevated CO_2 on plants, resulted in increasingly better relative crop-growing conditions under A2r-mit. In fact, additional simulations performed under the Hadley climate change, but with no CO_2 effects on crops within AEZ, support this hypothesis.

3.2.2. Cultivated land and fertilizer use

Impacts of climate change on land use for crop production were projected to be small globally (+9 to +12 Mha cultivated land in 2080 compared with a total of 1775 Mha in the A2r-reference, i.e., an increase of about 0.5–0.7% of total cultivated land), with relative differences smaller than 2% across regions, decades, and GCM scenarios. Similarly, climate change was projected to increase fertilizer use globally and regionally, albeit not by large amounts. For both GCMs, BLS projected an additional 18 Mt nitrogen fertilizer applied globally in 2080 (compared with 205 Mt in the A2r-reference) because of climate change, nearly a 9% increase. Much of the net increase was in developed countries, consistent with higher adaptation potentials in this region under climate change. For developing countries both positive and negative changes in fertilizer use occurred in response to climate change, which resulted in only a small net increase of less than 2.5 Mt compared with the A2r-reference. Mitigation reduced these additional amounts by roughly 50–75%, with the A2r-mit scenario using globally about 5–10 Mt of additional nitrogen fertilizer by 2080, compared to the reference.

3.2.3. Agricultural output

BLS simulated moderate changes to the aggregate global agricultural output under climate change, which reflects the overall small net impacts on crop production and successful adaptation. Compared with the A2r-reference scenario, by 2080 under the Hadley and CSIRO climates global agricultural GDP decreased to −0.9% and −0.8% annually, respectively. In absolute terms, this translated into losses of −23 to −28 billion US$ globally (1990 US$) in 2080, compared with an aggregate value of 2.9 trillion US$, with the larger impacts computed under the Hadley climate (see Table 4).

Significant regional and temporal patterns were computed. First, as for cereal production, small global differences masked opposite impacts in developed and developing regions. Specifically, in 2080, agricultural value-added increased in developed countries, while it decreased in developing regions. This asymmetry was computed under A2r-Hadley (+0.0% and −1.3%), but much more so under the A2r-CSIRO climate (+3.8% and −2.3%); the latter scenario corresponded to significant absolute gains (for developed countries) and losses (for developing countries) of +25 and −49 billion US$, respectively. Second, BLS computed specific regional winners and losers consistently across GCM scenarios. Specifically, North America, developed Pacific Asia, and Latin America were projected as gainers under both GCM climates (+2% to +8% across regions and scenarios). On the contrary, Africa, East Asia, and South Asia were consistent losers (−2% to −11% across regions and scenarios). Southeast Asia was projected to either gain or lose agricultural GDP somewhat, depending on climate scenario.

Finally, the time evolution of agricultural GDP computed by BLS also reflects asymmetries among regions and decades. For developed countries, the aggregate impact of climate change on agricultural value-added is small, but slightly positive for Hadley, and is increasingly positive over time for the CSIRO climate scenario. For developing regions, unmitigated climate change results in agricultural GDP losses of −28 to −49 billion US$ annually, respectively, for Hadley and CSIRO scenarios. While GDP losses occur in all periods for CSIRO, the Hadley scenario produces slight increases for developing countries until about 2050. As for the case of cereal production, the reasons that underlie such behavior are complex, because agricultural value-added in BLS is an integral of crop impacts, adaptation, and economic redistribution, with overall impacts apparently dominated by positive CO_2 fertilization effects.

With mitigation. BLS computed only small changes of global agricultural output under the A2r-mit scenario compared with the A2r-reference. Globally, agricultural GDP was projected to change by +6 (for Hadley) to +0 (for CSIRO) billion US$, a difference of less than 0.1% for both GCMs compared with the A2r-reference (no climate change) scenario. In fact, agricultural value-added for A2r-mit under the Hadley climate exceeds the global agricultural GDP of the A2r-reference for the entire simulation period until 2080, and it produced insignificant aggregate global differences under the CSIRO climate. Aggregate regional results showed gains in the agricultural GDP of A2r-mit under the Hadley climate for both developing and

Table 4
Projected impacts of climate change on agricultural GDP (billion US$, constant 1990 prices), A2r (non-mitigated climate change) minus A2r-reference (no climate change) scenarios

Region	2000	2010	2020	2030	2040	2050	2060	2070	2080
(a) Hadley									
WORLD	0.0	2.1	4.2	5.4	5.2	5.8	−4.7	−15.1	−27.5
MDC	0.0	1.3	2.8	2.7	1.6	0.9	0.3	−0.4	0.0
LDC	0.0	1.0	1.9	3.3	4.2	5.4	−4.7	−14.6	−27.7
ROW	0.0	−0.2	−0.4	−0.6	−0.5	−0.5	−0.4	−0.1	0.2
NAM	0.0	0.6	1.5	1.6	0.9	0.1	1.4	3.2	5.4
WEU	0.0	0.2	0.2	−0.2	−1.3	−2.0	−4.0	−6.7	−8.6
PAO	0.0	−0.1	−0.4	−0.3	0.5	1.7	1.9	2.1	2.2
EEU+FSU	0.0	0.6	1.4	1.7	1.4	1.1	1.1	1.0	0.9
AFR	0.0	0.3	0.7	0.4	−0.7	−2.1	−5.4	−8.7	−14.4
LAM	0.0	0.8	1.7	3.0	4.5	6.4	7.3	9.3	12.2
MEA	0.0	−0.3	−0.7	−1.0	−0.7	−0.3	−2.0	−3.3	−4.5
CPA	0.0	0.1	0.1	0.4	1.1	2.3	−0.1	−3.7	−8.2
SAS	0.0	−0.7	−1.7	−3.0	−4.8	−6.7	−10.2	−13.7	−18.2
PAS	0.0	0.7	1.8	3.4	4.8	5.9	5.8	5.6	5.4
(b) CSIRO									
WORLD	0.0	−0.5	−1.5	−1.8	−1.2	−2.3	−9.2	−14.9	−22.7
MDC	0.0	0.6	1.5	3.5	5.9	8.4	11.4	16.8	25.3
LDC	0.0	−0.9	−2.4	−4.6	−6.7	−10.6	−20.8	−32.2	−48.8
ROW	0.0	−0.3	−0.6	−0.7	−0.5	−0.1	0.2	0.5	0.8
NAM	0.0	0.6	2.0	5.0	9.6	14.1	17.0	19.4	22.0
WEU	0.0	−0.9	−2.4	−4.4	−7.1	−10.1	−11.4	−10.0	−5.6
PAO	0.0	0.2	0.5	0.6	0.9	1.4	2.1	2.8	3.6
EEU+FSU	0.0	0.7	1.5	2.2	2.5	3.1	3.8	4.6	5.2
AFR	0.0	−0.5	−1.5	−3.5	−5.1	−8.6	−18.1	−28.3	−40.9
LAM	0.0	0.9	2.4	3.9	5.1	6.6	11.6	18.0	24.7
MEA	0.0	1.4	3.4	5.0	5.3	5.2	2.4	−0.5	−3.9
CPA	0.0	−1.2	−3.1	−5.0	−6.6	−8.0	−9.7	−12.9	−17.7
SAS	0.0	−1.0	−2.6	−3.8	−4.8	−5.6	−6.2	−7.1	−9.2
PAS	0.0	−0.4	−1.0	−1.1	−0.5	−0.3	−0.8	−1.5	−2.0

developed regions, with the largest global increase occurring around 2050. For the CSIRO climate, the gains of developed countries under A2r-mit increase gradually throughout the entire simulation period, mirroring increasingly larger losses over time for developing countries. For each regional group, however, the magnitude of climate impacts was projected to be smaller under A2r-mit than under A2r, but with roughly the same regional sets of winners and losers discussed for the A2r scenario.

We also compared losses and/or gains in agricultural income because of climate change with and without mitigation (Table 5). Globally, we computed total GDP benefits from mitigation in the range 23–34 billion US$ (at constant 1990 prices) annually in 2080. These benefits are greater than the global costs of mitigation in agriculture, estimated at about 12 billion US$ by Riahi et al. [29]. For developed countries a small (insignificant) positive balance was maintained for Hadley, and overall gains of 25 billion US$ in the (unmitigated) A2-CSIRO scenario were reduced by 12 billion US$ in response to mitigation. At the same time, losses of developing countries that amounted in (unmitigated) A2 to −28 to −49 billion US$ were

Table 5
Impacts of climate mitigation on agricultural GDP (billion US$, constant 1990 prices), A2r-mit (mitigated climate change) minus A2r (non-mitigated climate change) scenarios

Region	2000	2010	2020	2030	2040	2050	2060	2070	2080
(a) Hadley									
WORLD	0.0	−0.2	−0.2	0.0	0.4	1.9	12.3	22.0	33.7
MDC	0.0	−0.1	−0.3	0.1	0.9	2.3	1.6	−0.1	0.9
LDC	0.0	−0.1	0.0	−0.2	−0.4	−0.3	11.0	22.7	33.6
ROW	0.0	0.0	0.0	0.0	0.0	−0.1	−0.3	−0.6	−0.9
NAM	0.0	−0.1	−0.2	0.2	1.0	2.3	0.8	−1.2	−3.6
WEU	0.0	0.0	0.0	0.2	0.5	1.1	1.4	1.0	3.8
PAO	0.0	0.0	0.0	−0.2	−0.7	−1.4	−1.1	−0.6	0.0
EEU+FSU	0.0	−0.1	−0.2	−0.1	0.2	0.4	0.6	0.7	0.8
AFR	0.0	0.0	−0.1	0.2	1.0	2.1	4.2	7.2	9.1
LAM	0.0	−0.1	−0.2	−0.5	−1.1	−1.9	−1.3	−2.3	−4.2
MEA	0.0	0.0	0.1	0.0	−0.5	−1.0	0.6	2.4	4.4
CPA	0.0	0.0	0.0	−0.4	−0.9	−1.4	1.7	6.0	11.1
SAS	0.0	0.1	0.3	0.9	2.0	3.3	6.0	8.6	11.6
PAS	0.0	−0.1	−0.2	−0.5	−1.0	−1.4	−0.3	0.8	1.7
(b) CSIRO									
WORLD	0.0	0.1	0.1	0.1	−0.1	0.1	8.5	16.4	22.9
MDC	0.0	0.0	−0.1	−0.7	−1.6	−3.1	−4.8	−6.4	−12.2
LDC	0.0	0.1	0.1	0.8	1.7	3.7	14.0	23.6	36.1
ROW	0.0	0.0	0.1	0.0	−0.2	−0.5	−0.7	−0.9	−1.0
NAM	0.0	0.0	−0.2	−1.1	−2.9	−5.2	−5.1	−4.7	−4.3
WEU	0.0	0.1	0.3	0.8	1.9	3.1	1.7	0.9	−4.9
PAO	0.0	0.0	0.0	−0.1	−0.2	−0.4	−0.6	−1.1	−1.5
EEU+FSU	0.0	−0.1	−0.2	−0.3	−0.3	−0.6	−0.8	−1.4	−1.6
AFR	0.0	0.0	0.1	0.7	1.3	2.7	9.5	17.3	24.8
LAM	0.0	−0.1	−0.3	−0.4	−0.5	−0.8	−3.6	−8.9	−14.3
MEA	0.0	−0.1	−0.3	−0.4	0.0	0.6	3.9	7.3	11.8
CPA	0.0	0.1	0.3	0.5	0.6	0.7	2.2	4.2	7.5
SAS	0.0	0.1	0.1	0.4	0.7	1.3	2.1	3.2	5.0
PAS	0.0	0.0	0.1	0.0	−0.5	−0.8	0.0	0.5	1.3

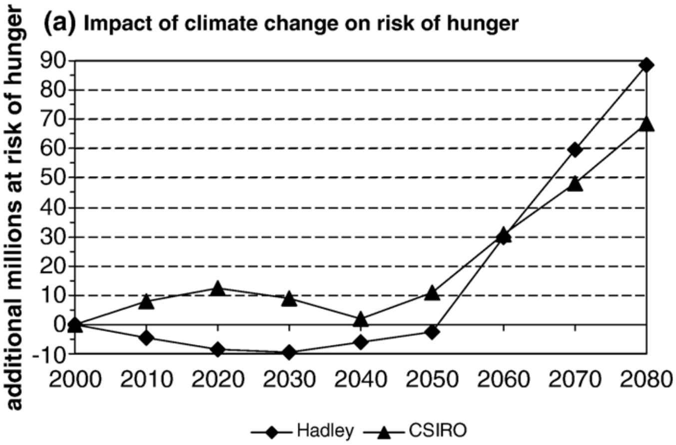
reduced by 34 to 36 billion US$ (even producing a surplus under the Hadley A2r-mit compared with the A2r-reference). As well as the differences discussed so far, climate mitigation created its own sets of 'winners' and 'losers' (i.e., regions that, at any given decade, were either better or worse off with mitigation, compared to the unmitigated climate change). In this sense, climate mitigation is clearly beneficial to agricultural outcomes in Africa and the Asian regions, but may produce fewer benefits than the unmitigated case for resource-rich regions such as South and North America or developed Pacific Asia.

3.2.4. Food security under climate change

Under the A2r-reference scenario considered herein, the number of people at risk of hunger was projected to be high throughout the entire simulation, though it declined somewhat over the period, from 821 million in the year 2000 to 555 million in 2080. Climate change increased already high reference values, with an additional 70–90 million people projected as at risk of hunger from climate change in 2080, depending on

GCM, with respect to the reference. These numbers correspond roughly to a 12–16% increase relative to the 555 million at risk in the A2r-reference (data not shown). Important trends in the geographic distribution of such results were similar among the GCMs considered. First, in terms of the absolute number of people, the bulk of the increases were in Sub-Saharan Africa (+43 to +53 million), followed by the Middle East and North Africa region (+14 to +20 million). These projected increases in the numbers of people at risk of hunger by 2080 were not homogeneous through time, and the values are highly dependent on the GCM used. Under Hadley, BLS computed *decreases* across all regions in the early decades, up to the late 2040s. Increases only started in 2050—possibly because of more severe climate change and the saturated effects of CO_2 on plants. Under the CSIRO climate, by contrast, the total number of people at risk of hunger showed increases in all decades compared to the A2r-reference, but slight decreases were still visible in specific early decades up to the 2040s for Latin America, the Middle East, and Southeast Asia.

(a) Impact of climate change on risk of hunger



(b) Effect of mitigation on risk of hunger

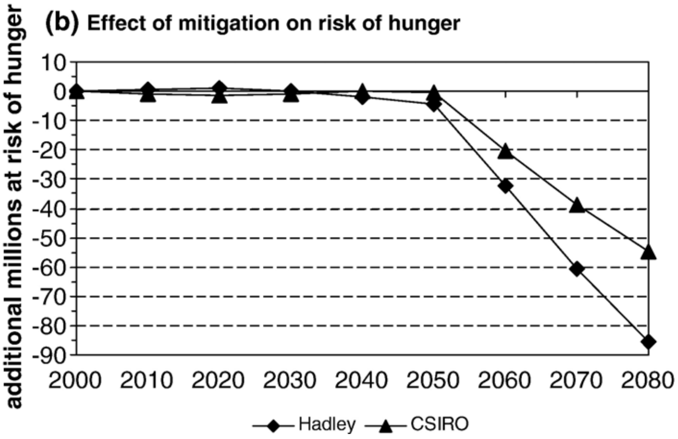


Fig. 5. Impacts of climate change and effects of mitigation on numbers of people at risk of hunger, as computed by the BLS model over time, for selected decades into the future. Data are aggregated globally, and represent contributions mainly from Sub-Saharan Africa, Asia, and Latin America. (a) Impacts of climate change, defined as A2r minus A2r-reference values; (b) Effects of mitigation, defined as A2r-mit minus A2r values. Negative values indicate *benefits* of mitigation (i.e., a decrease in the numbers at risk of hunger with respect to the unmitigated case) and vice-versa.

With mitigation. BLS computed the numbers of additional people at risk of hunger in 2080, under the A2r-mit scenario compared with the A2r-reference, to be in the range 3–14 million people, depending on the GCM used (data not shown). Geographic trends in 2080 were roughly similar to those in the A2r scenario, with the highest additional number of people at risk being in Sub-Saharan Africa (+3 to +9 million) and the Middle East and North Africa (+1 to +3 million), and small decreases in other regions. We compared the effects of mitigation by computing differences in numbers of people at risk of hunger in the A2r-mit and A2r unmitigated scenarios. Similarly to the previous analyses for cereal production, mitigation reduced hunger in 2080 by about 55–85 million globally (i.e., 80–95% of the A2r unmitigated increases); it also significantly altered the time evolution of impacts in complex ways, with outcomes depending on the GCMs used (Fig. 5). Under Hadley, BLS computed that increases in the numbers of people at risk of hunger in the decades up to 2030 would be slightly higher in the A2r-mit compared with the unmitigated A2r case. As discussed for cereal production, the reason for these dynamics might be caused by fewer crop benefits from elevated CO_2 under the A2r-mit scenario, with climate change levels in the early decades similar to those in the A2r scenario. These dynamics were less pronounced under the CSIRO climate, for which BLS projected reductions in the numbers of people at risk of hunger in all decades relative to the unmitigated A2r climate. Yet, benefits from reducing the numbers of people at risk of hunger by 10 million or more, compared with the A2r-CSIRO scenario without mitigation, only occurred after 2050 under the A2r-mit scenario.

4. Discussion: effects of mitigation

BLS reference results indicated that socio-economic development–in this study represented by the A2r scenario–significantly impacts global agriculture. Against the current backdrop of about 2.1 Gt of cereal production worldwide, BLS computed by 2080 about 4.2 Gt. These projections represented a doubling of current global production, in response to the projected rise in population and incomes. The context behind these figures is that, globally, land and crop resources, together with technological progress, appear to be sufficient to feed a world population projected in A2r to reach nearly 12 billion people in 2080, although serious problems of equity and distribution remain. Of particular relevance to regional food security is the case of Sub-Saharan Africa, in which a growing share of people considered undernourished is currently located, and where BLS projected three-quarters of the malnourished in 2080.

Importantly, this study quantified the potential benefits of mitigation to the agricultural sector as a whole. Results can be summarized as follows—the ranges indicate GCM differences:

1) *Global annual agricultural output benefits of mitigation in 2080 were 23–34 billion US$*, measured as differences in agricultural GDP (at constant 1990 prices) between the mitigated and unmitigated scenarios. These figures represent only 0.8–1.2% of agricultural GDP in 2080; in relative terms, but mitigation actions entirely eliminated the projected global costs of climate change to agriculture. The geographic redistribution of these changes was found to be complex, in some cases, varying over time, heterogeneous across regions, and dependent on GCM scenario.
2) *Mitigation benefits developing regions, but may reduce the possible gains of export-oriented developed countries*. Specifically, under the Hadley GCM climate we projected gains from mitigation for developing countries (+34 billion US$ annually in 2080)–mainly for South Asia (+12 billion US$), East Asia (+11 billion US$), and Sub-Saharan Africa (+9 billion US$)–while developed countries maintained agricultural value-added under mitigation (+1 billion US$). Under CSIRO, projections produced somewhat smaller global benefits from mitigation: developing countries again gained with

mitigation (+36 billions US$ annually in 2080, i.e., recovered nearly 75% of the losses computed in the non-mitigated scenario relative to a scenario with no climate change). Developed countries, however, lost about half of the gains computed for climate change without mitigation (i.e., gained 'only' +13 billion US$ compared with +25 billion US$ gained in the unmitigated A2r-CSIRO scenario).

3) *Humanitarian savings of mitigation, in terms of the reduced numbers of people at risk of hunger in 2080, were 70–90 million people*. These figures represent 12–16% of the total numbers of people at risk of hunger projected by BLS in 2080 under the A2r-reference scenario. In relative terms, humanitarian savings of mitigation represent a reduction by 80–95% of the additional numbers of people at risk of hunger through non-mitigated climate change, nearly two-thirds of this reduction being realized in Africa.
4) *The time evolution of key variables was by no means constrained by the 2080 end results*. For instance, agricultural GDP gains from mitigation computed by BLS were small until 2050 under both GCMs. They were rather insignificant for decades up to the mid-century, and sometimes even negative (e.g., globally up to 2030 under the Hadley climate). In addition, mainly through production benefits caused by the CO_2 fertilization of plants, the numbers of people at risk of hunger *can at times be higher* (by small amounts) under the mitigated than under the non-mitigated climate change scenario. For instance, results for the early decades up to about the 2030s showed more people at risk with mitigation for the Hadley climate than without.

The trends seen in the time evolution of both risk of hunger and cereal production computed by BLS were further analyzed. As discussed, the complex interaction of climate change and CO_2 atmospheric levels, together with changes in international markets and in regional comparative production advantages, are responsible for the computed dynamics and the differences between the unmitigated and the mitigated climate scenarios. Specifically, while the magnitude of climate change between unmitigated and mitigated scenarios hardly differed in the first half of the 21st century, lower atmospheric CO_2 levels in the mitigated scenario possibly led to lower plant productivity, especially between 2010 and −2030. This resulted, at times, in *net* negative effects of mitigation on crop yields, compared with the non-mitigated case. Only in the second half of the 21st century, with non-mitigated climate change significantly more severe and CO_2 effects on crops leveling off, did benefits of mitigation become significant and grow rapidly.

Naturally, these results arise from a simulation exercise, so they are subject to uncertainties linked to model performance and data. In particular, if differences in CO_2 concentrations drive the transitory effects of mitigation in the coming decades–given similar climate changes up to about 2040 in both non-mitigated and mitigated scenarios–the relative impacts of mitigation will depend on the real-world strength of elevated CO_2 effects on crop plants and the chosen pathways of GHG mitigation (i.e., reduction of CO_2 emissions versus reduction of non-CO_2 GHG emissions). If these CO_2 fertilization effects are large and the reduction of CO_2 emissions contributes a large fraction to the mitigation efforts, some transitory negative effects of mitigation on agriculture may be felt in the early decades. If, conversely, the CO_2 effects are small, mitigation actions should always be beneficial, even prior to 2050, compared with no mitigation. We confirmed this conclusion in a special simulation run for the Hadley A2r climate in which we assumed no additional CO_2 fertilization effects on plants. In addition, while simulating the impacts of changes in mean climate, our simulations did not consider the impacts of increased climate variability on crops. These might reduce or limit the CO_2 effects on plants, which results in increased relative advantages of mitigation in any given decade.

Finally, the computed impacts were relatively small when compared with the dynamic changes between 2000 and 2080 that result from the socio-economic scenario alone, both population and income growth. Hence, scenario-dependent changes in socio-economic pressures (e.g., lower-than-assumed economic growth in some regions or alternative demographic development) could alter the computed dynamics of climate change impacts and benefits from mitigation significantly.

5. Conclusions

In summary, our simulation results suggest the following:

- *First*, the effects of mitigation on key agricultural variables may be significant in reducing the negative impacts of an unmitigated climate, with very sizable reductions of both economic and humanitarian costs.
- *Second*, the regional implications of mitigation can be quite divergent from the global outcomes, with some regions experiencing positive impacts from mitigation while others may experience reductions relative to the unmitigated case; details of such regional heterogeneities are somewhat GCM dependent.
- *Third*, the time dynamics of these changes are also significant, and mitigation impacts in the early decades may diverge from the global and regional outcomes at the end of the 21st century.

Mitigation can and should play an important role in lessening the impacts of climate change on the agricultural sector, both globally and regionally. Importantly, our results highlight possible trade-offs between long-and short-term objectives that are of great relevance to decision making and planning. While stabilization of GHG concentrations in the atmosphere requires long-term targets, a global focus, and very early actions, our results indicate that the intended end-of-the-century global effects may be unevenly distributed among regions and decades. Importantly, this uneven distribution cannot be predicted a priori, because of key uncertainties in both regional climate dynamics and crop responses to increased atmospheric CO_2 concentrations. At least for agriculture, therefore, mitigation appears to be associated with complex consequences, as some new winners and losers may arise from the effects of mitigation itself. Thus, countries that implement regional and global mitigation actions should also create, at the same time, additional resources to help those regions in which the intended benefits do not materialize. These resources should be used to develop a range of adaptation options—particularly in developing countries that are already vulnerable today to climate and other environmental pressures.

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Appendix A. Additional results from BLS

We publish below a set of additional simulation results obtained with BLS for the mitigation scenarios, in addition to those discussed herein. These include bioenergy potentials from agricultural residues, livestock numbers, production and harvested area for rice, and fertilizer use. They were used by several authors [29].

Although these data were not important to the main focus of this paper, they were used to compute specific GHG emissions and overall energy contributions from the agricultural sector by Riahi et al. [29].

A discussion on the derivation within BLS of numbers on the supply of crop residues, livestock energy requirements, and digestible energy has been published [33]. Bioenergy potentials from crop production and their prices (Tables A5 and A6) were derived by applying the following simplified methodology to each BLS region and time horizon. First, 50% of the residue amounts were considered to be re-applied to the field at the end of each growing season—a typical practice necessary to maintain soil quality and nutrient levels. The remaining 50% was converted into energy values by using a conversion factor of 18 MJ/kg dry matter, typical for most crop plants. Second, the total energy content of residues was first reduced by subtracting total livestock digestible energy requirements (minus those already satisfied via primary crop feeds). The remaining amounts represented the potentially available bioenergy. As for prices, initial values in the range $15–40 (US1990) were chosen for 1990, with the lower and upper bounds representing prices in developing and developed countries, respectively. Finally, a simple assumption was made that the residue prices would scale with their associated crop prices—as computed by BLS, both regionally and over time.

Table A1
Rice area (Mha), A2r-reference scenario

Region	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080
WORLD	152.3	163.8	174.4	185.3	195.7	204.2	211.1	216.5	219.6	220.4
MDC	4.7	4.5	4.6	4.6	4.6	4.7	4.8	4.8	4.8	4.8
LDC	147.3	159.0	169.5	180.5	190.8	199.2	206.0	211.4	214.5	215.3
ROW	152.3	163.8	174.4	185.3	195.7	204.2	211.1	216.5	219.6	220.4
NAM	1.4	1.6	1.7	1.7	1.8	1.9	2.0	1.9	1.9	1.9
WEU	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.4	0.4
PAO	2.3	2.2	2.1	2.0	1.9	1.9	1.9	1.9	1.9	2.0
EEU+FSU	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
AFR	4.6	5.6	6.9	8.5	10.1	12.0	13.7	15.8	17.5	19.0
LAM	9.1	11.0	12.8	14.5	16.1	17.7	18.9	19.6	19.8	19.8
MEA	1.3	1.5	1.7	1.9	2.1	2.3	2.6	2.8	3.1	3.3
CPA	45.3	46.4	47.0	47.6	47.9	48.3	48.2	47.7	47.2	46.4
SAS	62.4	67.8	72.8	78.1	83.3	86.2	88.9	91.0	92.1	92.5
PAS	24.5	26.7	28.3	29.9	31.2	32.6	33.7	34.5	34.8	34.3

Table A2
Rice production (Mt, milled equivalent), A2r-reference scenario

Region	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080
WORLD	337.7	406.8	471.6	543.1	614.7	678.0	729.6	771.2	802.2	822.7
MDC	18.2	19.1	20.3	21.2	22.3	23.6	24.7	25.5	25.9	26.0
LDC	318.8	387.0	450.5	520.9	591.4	653.3	703.7	744.5	775.0	795.4
ROW	0.7	0.7	0.8	0.9	1.0	1.1	1.2	1.2	1.3	1.3
NAM	5.4	6.3	6.9	7.5	8.2	8.9	9.6	9.9	10.0	10.2
WEU	1.0	1.0	1.4	1.7	1.9	2.0	2.2	2.2	2.1	1.9

Table A2 (*continued*)

Region	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080
PAO	10.5	10.4	10.5	10.6	10.8	11.0	11.3	11.6	11.8	11.9
EEU+FSU	1.3	1.4	1.5	1.5	1.5	1.6	1.7	1.8	1.9	2.1
AFR	5.2	7.6	10.6	14.4	19.0	24.1	29.3	35.9	42.4	48.6
LAM	13.2	17.1	21.6	26.5	31.7	37.2	42.2	46.8	50.3	53.3
MEA	3.1	4.4	5.9	7.2	8.3	9.6	11.3	13.2	15.2	17.7
CPA	154.8	176.6	195.6	214.8	231.0	243.4	251.4	257.4	262.3	264.9
SAS	98.5	126.1	149.9	177.4	208.0	234.1	256.1	271.8	282.8	290.5
PAS	44.0	55.2	66.9	80.7	93.4	104.8	113.5	119.5	122.0	120.3

Table A3
Bovine and ovine livestock (million head, cattle equivalent), A2r-reference scenario

Region	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080
WORLD	1709	1772	1907	2071	2241	2432	2598	2728	2841	2930
MDC	438	387	393	403	415	427	439	449	456	459
LDC	1207	1321	1456	1614	1776	1957	2112	2234	2341	2429
ROW	64	64	59	54	50	49	47	45	44	43
NAM	109	113	115	117	118	118	118	119	117	114
WEU	113	100	103	108	114	122	130	139	146	151
PAO	69	65	70	78	87	97	106	114	122	129
EEU+FSU	167	126	125	127	129	131	133	135	137	139
AFR	189	196	219	255	296	355	400	432	470	504
LAM	348	368	418	469	519	563	597	614	619	616
MEA	66	75	87	101	114	128	139	148	155	160
CPA	147	184	192	198	203	208	212	215	218	221
SAS	403	451	487	530	575	625	678	729	776	816
PAS	33	31	33	35	36	37	38	37	37	36

Table A4
Pig and poultry meat, eggs, and fish production (Mt, protein equivalent), A2r-reference scenario

Region	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080
WORLD	21.0	25.0	28.9	33.1	37.6	42.1	46.4	50.3	54.2	58.2
MDC	10.0	10.9	11.5	12.1	12.6	13.2	13.7	14.1	14.6	15.1
LDC	9.6	12.5	15.5	19.0	22.7	26.6	30.3	33.7	37.0	40.4
ROW	1.4	1.7	1.9	2.0	2.2	2.3	2.5	2.6	2.6	2.7
NAM	2.8	3.0	3.1	3.2	3.4	3.5	3.7	3.9	4.1	4.3
WEU	2.7	3.1	3.3	3.4	3.6	3.7	3.8	3.8	3.8	3.8
PAO	1.8	2.1	2.3	2.5	2.6	2.8	2.8	2.9	2.9	2.9
EEU+FSU	2.7	2.8	3.0	3.1	3.2	3.4	3.6	3.8	4.1	4.5
AFR	0.7	0.9	1.3	1.7	2.3	3.0	3.6	4.2	4.8	5.3
LAM	1.5	1.9	2.4	2.9	3.5	4.1	4.7	5.2	5.6	6.0
MEA	0.5	0.8	1.1	1.6	2.1	2.6	3.1	3.6	4.1	4.6
CPA	5.2	6.5	7.7	9.1	10.4	11.7	13.0	14.1	15.4	16.8
SAS	0.7	1.0	1.3	1.6	2.0	2.3	2.7	3.1	3.5	3.9
PAS	1.0	1.3	1.6	2.0	2.3	2.6	2.9	3.1	3.3	3.5

Table A5
Usable bioenergy potential from crop residues (TJ), A2r-reference scenario

Region	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080
WORLD	16,423	18,732	20,712	23,007	24,956	27,499	29,709	31,228	33,142	34,922
MDC	6826	7542	7950	8509	8771	9474	10,063	10,331	10,858	11,372
LDC	8968	10,733	12,312	14,031	15,725	17,548	19,158	20,397	21,756	22,994
ROW	629	689	735	805	841	902	945	976	1008	1030
NAM	3223	3533	3752	4032	4186	4564	4881	4960	5139	5289
WEU	1152	1222	1295	1387	1443	1532	1598	1649	1666	1669
PAO	266	307	339	391	431	488	536	585	615	634
EEU+FSU	2390	2480	2564	2699	2710	2890	3048	3137	3438	3780
AFR	959	1250	1574	1955	2426	2931	3431	3995	4521	4999
LAM	1340	1657	2041	2518	2924	3376	3714	3927	4085	4141
MEA	432	570	702	865	999	1168	1332	1470	1621	1760
CPA	2991	3437	3785	4162	4381	4648	4849	4922	5108	5283
SAS	2504	2924	3140	3275	3558	3803	4085	4270	4552	4923
PAS	538	664	784	918	1057	1197	1289	1337	1391	1414

Table A6
Bioenergy price of biomass residues (1990US $/GJ), A2r-reference scenario

Region	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080
NAM	2.2	2.1	2.2	2.5	2.9	3.3	3.7	4.1	4.2	4.3
WEU	2.2	2.1	2.2	2.5	2.8	3.2	3.5	3.9	3.9	4.0
PAO	2.2	2.1	2.2	2.5	2.9	3.3	3.7	4.1	4.0	4.0
EEU+FSU	1.3	1.0	1.1	1.3	1.7	2.2	2.6	3.0	3.1	3.1
AFR	0.9	0.9	0.9	1.0	1.2	1.4	1.6	1.8	1.9	1.9
LAM	1.1	1.1	1.1	1.3	1.5	1.8	2.0	2.3	2.4	2.5
MEA	1.2	1.1	1.2	1.4	1.6	2.0	2.3	2.5	2.6	2.6
CPA	0.9	1.0	1.1	1.4	1.8	2.4	3.0	3.5	3.6	3.6
SAS	0.9	0.9	1.0	1.1	1.3	1.5	1.8	2.0	2.2	2.2
PAS	1.0	1.0	1.1	1.3	1.5	1.8	2.1	2.3	2.3	2.4
ROW	2.0	1.8	1.8	2.0	2.3	2.7	3.0	3.3	3.4	3.5

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