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THE IMPACTS OF CLIMATE CHANGE, CO_2, AND SO_2 ON AGRICULTURAL SUPPLY AND TRADE:

AN INTEGRATED ASSESSMENT

Günther Fischer and Cynthia Rosenzweig

WP-96-05
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IIASA International Institute for Applied Systems Analysis • A-2361 Laxenburg • Austria
Telephone: +43 2236 807 • Telefax: +43 2236 71313 • E-Mail: info@iiasa.ac.at

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Abstract

The analysis of the impacts of alternative future energy paths on the regional supply and trade of agricultural commodities is part of an integrated assessment study undertaken at IIASA. For the agricultural study, results from the energy models (i.e., 11R and MESSAGE III) of IIASA's Environmentally Compatible Energy Strategies project and from the regional air pollution model RAINS developed by IIASA's Transboundary Air Pollution project were compiled to define the economic and environmental conditions for a number of simulation experiments with the BLS model.

This paper examines the impacts of climate change and altered concentrations of CO_2 and SO_2 in the atmosphere, on crop yields and regional food supply. Three different emission abatement scenarios are tested, representing a range of possible economic development and regulatory pathways.

Emission abatement, in terms of agricultural and environmental impacts, is a regional issue much more than a global one. While there is relatively little difference between outcomes at the global level, regional results vary greatly between scenarios.

1. Introduction

Changes in climate and the atmosphere will alter the agricultural production potential in various regions of the world. Rising levels of atmospheric carbon dioxide (CO_2) will result in increased agricultural productivity and enhance the crop water-use efficiency. Global warming will tend to expand the agro-ecological potential polewards and into higher altitudes. These positive effects, however, will be constrained by altered temperature, precipitation, and evaporation. In addition, other anthropogenic changes in the chemical composition of the atmosphere and lithosphere, could further alter or even reduce regional agricultural productivity. For instance, the air pollutants most damaging to agricultural crops are sulfur dioxide (SO_2), the oxides of nitrogen (NO_x), and ozone (O_3). This study examines the impacts of climate change and altered concentrations of CO_2 and SO_2 in the atmosphere, on crop yields and regional food supply. Three different emission abatement scenarios are tested, representing a range of possible economic development and regulatory pathways.

One incontestable fact is the rising concentration of CO_2 in the Earth's atmosphere. An additional certainty is the soundness of the basic greenhouse theory: the composition of the gas mix in the atmosphere strongly affects the planet's radiation balance. Based on this theory, experiments with coupled general circulation models (GCMs) suggest that the range of emission scenarios described by the Intergovernmental Panel on Climate Change (IPCC), the IS92 scenarios (IPCC, 1992), could produce a 1° C to 4.5° C increase in global temperature by year 2100[1] (IPCC, 1995).

The complexity of the problem at hand requires an analysis that takes into account the relevant physical and economic relationships that govern the world food system. IIASA's research has provided a framework for analyzing the world food system, viewing national agricultural systems as embedded in national economies which in turn interact with each other at the international level.

Section 2 reviews the body of information on the complex and multifaceted effects of increased atmospheric CO_2 concentrations and climate change on crop productivity. The possible impact of air pollutants, in particular of SO_2, on crops and grasses are discussed in Section 3. Then, in Section 4, we turn to a brief description of IIASA's global model of the world food system, known as the Basic Linked System (BLS), and we explain how the macro-economic model 11R (Manne and Richels, 1992) of the world energy system has been linked with the BLS. We also discuss how sulfur deposition, obtained with the RAINS-Asia model (Amann, 1993), was incorporated into the agricultural analysis. Section 5 presents a summary of BLS simulation results based on a coal intensive high emission unabated energy scenario (HER) and derived from two emission abatement scenarios (MOM and MIS energy model runs). Finally, in Section 6 we present some conclusions that can be drawn from this integrated analysis.

2. Effects of increased CO_2 concentrations and climate change on crops[2]

Temperature, solar radiation, water and level of CO_2 concentration are the main climate and atmospheric variables important for agriculture. Detailed understanding of plant response is important for better prediction of climate change impacts on agriculture. Responses of plants to climate change on the micro-level, e.g., the individual leaf, does require translation to macro scales, such as the field level for an entire cropping season.

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[1] When incorporating the possible effects of future changes of anthropogenic aerosol concentrations implied by the IS92 scenarios the best estimate for year 2100 is a temperature increase in the range of 1° to 3.5° C, somewhat lower than earlier projections reported by IPCC.

[2] Summarized and adapted from draft report of IPCC, WGII Subgroup D, Agriculture II.B (August 1994), and *CO_2 and Biosphere* (Rozema *et al.* (eds.), 1993).

Climate change will most likely result in new combinations of soil, climate, atmospheric constituents, solar radiation, and pests, diseases and weeds. First observations of the physiological effects of CO_2 on plant growth date back to the beginning of the 19th century (e.g., see Kimball *et al.*, 1993). However, most systematic experimental analyses of the interactions of temperature, moisture availability and increased CO_2 on plant growth have been undertaken during the last three decades.

In the process of photosynthesis, carbon dioxide and water are combined in plant leaves utilizing sunlight to produce carbohydrates and oxygen. Plants differ in what kind of intermediate steps and compounds are produced in the photosynthetic process. One major group of plants is referred to as C_3 plants because one of the first intermediate compounds has three carbon atoms (phosphoglyceric acid). Most agricultural crops, notably wheat, rice, barley, soybeans and potatoes, belong to the C_3 group. Similarly, a second group of plants, termed C_4 plants, produces a compound with four carbon atoms (oxaloacetic acid). C_4 plants of economic importance include maize, sorghum, millet, and sugarcane.

Plant species vary in their response to CO_2 in part because of these differing photosynthetic mechanisms. C_3 plants use up some of the solar energy they absorb in a process known as photorespiration. In this process, which occurs only in the light, a considerable fraction of the carbon initially reduced from CO_2 and fixed into carbohydrates is re-oxidized to CO_2, reducing the net amount of carbohydrates being accumulated. C_3 species tend to respond readily to increased CO_2 levels because photorespiration is suppressed in these conditions. In C_4 plants, on the other hand, CO_2 is trapped inside the leaf and then concentrated in the cells which carry on photosynthesis. These plants are photosynthetically more efficient than C_3 plants under present CO_2 levels, but have been found to be less responsive to CO_2 enrichment.

Another important physiological effect of CO_2 enrichment is the closure of stomates, the small openings in leaf surfaces through which CO_2 is absorbed and water vapor released. Accordingly, a rise in atmospheric CO_2 may reduce transpiration even while promoting photosynthesis. This dual effect may improve water-use efficiency. Thus, by itself, increased CO_2 can increase yield and reduce water use per unit of biomass.

Some of the interactions of temperature, moisture availability and increased CO_2 on plant growth have been investigated for a range of environmental conditions through crop response models. These models have been widely used to assess yield response to climate change at many different sites around the world and have produced valuable insights into these interactions. The crop models used in this study account for the physiological effects of increased atmospheric CO_2 concentrations on crop growth and water use (Peart *et al.*, 1989). Ratios were calculated between rates of daily photosynthesis and evapotranspiration measured for a canopy exposed to high CO_2 doses compared to current levels, based on published results (Allen *et al.*, 1987; Cure and Acock, 1986; and Kimball, 1983), and the ratios were applied to the appropriate variable in the crop models on a daily basis[3].

The promising picture of improved food production under higher atmospheric CO_2 is modified by other factors and by uncertainty about the validity of extrapolations. First, most of our understanding of the positive effects on crops relies on short-term and controlled studies at the individual plant level. Extrapolations and generalizations to large-scale field conditions or to long-term global food production are still uncertain. Also, since crop responses to climate change are site-specific and species-dependent, the knowledge of one kind of grouping or plants may have little relevance to other species or groupings. Second, under conditions of limited soil nutrients or solar radiation (e.g., through enhanced cloud cover), higher CO_2 does little to improve yields; in much of the world such stress conditions are the rule rather than the exception (FAO, 1994).

As simulated by crop models, the direct effects of CO_2 may bias yield changes in a positive direction, since there is uncertainty regarding whether experimental results will be observed in the open field under conditions likely to be operative when farmers are managing crops. Plants growing in experimental settings are often subject to fewer environmental stresses and less competition from weeds and pests than are likely to be encountered in farmers' fields. Still, recent field free-air release studies have found overall positive CO_2 effects under current climate conditions (Hendrey *et al.*, 1993).

2.1 Effects of increased CO_2 levels

Generally there is agreement that increase of CO_2 levels leads to an improvement in plant productivity. C_3 plants, when exposed to atmospheric CO_2 concentrations of twice the current level under good water and nutrient supply, show an increased productivity of about 30-40%. Response, however, depends on crop species and also on nutritional and fertility conditions. C_4 plants produce a much less pronounced response than the C_3 crops, on the average in the order of 5-10%. In general, higher CO_2 concentrations lead to improved water-use efficiency of both C_3 and C_4 plants.

[3] The photosynthesis ratios (555 ppmv CO_2/330 ppmv CO_2) for soybean, wheat, rice, and maize were 1.21, 1.17, 1.17, and 1.06, respectively. Changes in stomatal resistance were set at 49.7/34.4 s/m for C3 crops and at 87.4/55.8 s/m for C4 crops, based on experimental results by Rogers *et al.* (1983).

Established trends of plant responses to increased CO_2 concentrations on the basis of experiments, in terms of plant growth, plant water-use efficiency and quantity and quality of harvested produce are summarized below:

2.1.1 Plant growth

- The rate of photosynthesis increases immediately following exposure to increased CO_2 concentrations.
- An initial strong response to increased CO_2 concentrations is often reduced under long-term exposure to higher CO_2 levels.
- Increased leaf area production induced by higher CO_2 levels, leading to an earlier and more complete light interception, stimulates biomass increases.
- Higher biomass requires higher energy supply for maintenance, expressed in higher total respiration, partly compensated by lower relative respiration.
- Leaf turn-over rate increases due to self-shading and decrease of specific leaf surface. Both these effects tend to reduce photosynthesis per leaf.
- C_3 plants (temperate and boreal) show a pronounced response to increased CO_2 concentrations.
- C_4 plants (warm tropical) show only limited response to increased CO_2 concentrations.
- C_3 plants with nitrogen fixing symbionts tend to benefit more from enhanced CO_2 supplies than other C_3 plants.

2.1.2 Water use efficiency

- Increased CO_2 levels reduce stomatal conductance and transpiration rate. Note, however, that water consumption on a ground area basis is much less effected.
- Many studies report an increase in crop water use efficiency in terms of dry matter produced per unit of water transpired.
- As a consequence of the reduced transpiration, leaf temperature will rise and may lead to enhanced plant development and considerable increase in leaf area development, especially in the early crop growth stages.
- Reduced transpiration and resulting higher leaf temperature leads to an accelerated aging of the leaf tissue.
- Overall effects of a leaf temperature rise will depend upon whether or not optimum temperatures for photosynthesis are approached.

2.1.3 Harvest index and quality of produce

- Biomass and yield increased in almost all experiments under controlled conditions.
- Dry matter allocation patterns change differently for C_3 an C_4 crops and root/shoot ratios increase.
- The content of non-structural carbohydrates generally increases under higher CO_2 while the concentration of mineral nutrients is reduced. Food quality of leaf tissue declines which may lead to an increased requirement of biomass by herbivores.

- Weeds compete with crops for resources essential for growth. Unless controlled, weeds always reduce potential crop yields in agro-ecosystems. Differences in response of C_3 and C_4 plants to increases in atmospheric CO_2 are of importance to weed-crop competition. In fact, most of the important food crops are C_3 plants, while most weeds are C_4 plants.

2.2 Effects of climate change

Trends of plant responses to changes of temperature, precipitation, humidity and (potential) evapotranspiration are summarized below. Climatic variability with regard to specific climatic conditions cannot be predicted with any certainty, and discussion of such eventual effects on crop production is therefore rather speculative at this stage (and was omitted here).

2.2.1 Temperature effects

- There is a clear temperature effect on the level of CO_2 fertilization, especially for C_3 plants. Temperature rise has been found to enhance the physiological effects of increasing CO_2.
- Higher mean temperatures during the cold season allow earlier planting, and cause earlier ripening of annual crops. Reduced growth duration diminishes annual crop yields. The reduced growth cycle duration of crops in some cases might lead to more crops per year and extension of the growing season for perennials and grasses.
- Temperature influences the rate of growth and partitioning of dry matter.
- For annual crops, shortening of the growing season is not fully compensated by a changed ontogenetic development and by enhanced growth vigor at a higher temperature. Therefore, ceteris paribus, a net yield loss will occur. The duration of the vegetative growth and the light interception during the reproductive stages largely defines the occurrence of net yield losses.
- Higher temperatures in mountainous areas will provide more plant growth at high altitudes.
- Higher temperatures might affect phenological development of crops or induce temperature stresses (e.g., risk of reversed vernalization in wheat, or the risk of increase of spikelett sterility in rice).
- Climate is a major factor in determining habitats available to insect communities thus affecting insect survival rates. Changes in habitat generally leads to increased mortality but may also lead to higher reproduction rates, changes in diapause, migration, or even to genetic adaptation.
- Crop diseases are primarily related to climate and soil conditions. Their incidence and vigor may increase under warmer and wetter conditions.

2.2.2 Precipitation, Humidity and Evaporation

- Climate change projections point to an intensification of the hydrological cycle: higher evaporation, humidity and precipitation.

- Under equal temperature conditions and increased CO_2 levels, rates of potential evapotranspiration might decrease due to reduced crop transpiration; actual rates are partly compensated by an increase in leaf area index.
- Higher precipitation and humidity might improve moisture balances in semi-arid and sub-humid areas in favor of natural vegetation and crop yields. In humid and per-humid areas increased precipitation and humidity might lead to extending of periods with excess moisture and indirectly to hampered field operations, increased incidence of pests and diseases, all of which may depress crop yields.

3. Effects of increased SO_2 concentrations[4]

Airborne chemicals have multiple effects on human society. Cowling (1985) lists eight types of effects:

- Human health effects due to inhalation of airborne chemicals;
- Human health effects due to ingestation of airborne or soilborne chemicals via drinking water, fish, or other food products, caused by atmospheric deposition or leaching;
- Acidification of lakes, streams, ground waters, and soils;
- Fumigation of crops and forests near point sources of pollutants;
- Regional change in the health and productivity of forests;
- Damage to engineering materials, monuments, and other cultural resources;
- Increased haze in the atmosphere;
- Fertlization of crops, forests, and surface waters.

Cowling (1991) notes that all of these effects, except to some degree the last item, are detrimental to the interests of society. SO_2 emissions are involved in all eight effects. In the scenarios discussed later on in this paper, only the direct effects of sulfur dioxide on agricultural crops have been taken into account. It is important, therefore, to note that only a partial valuation of the possible damages from increasing regional SO_2 concentration levels is included in the high emission energy scenario (HER).

The air pollutants that are most damaging to agriculture are sulfur dioxide (SO_2) and the oxides of nitrogen (NO_x), which can be categorized as acid pollutants, and ozone (O_3) together with other photochemical oxidants. Air pollution can cause serious losses to crop and animal husbandry, although the levels of loss under different circumstances are difficult to assess experimentally. Especially in crop experiments, there have been problems of ensuring comparability of environmental conditions, and of separating out the interactions with soil and climatic factors.

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[4] Summarized and adapted from Fitter and Hay (1987), Conway and Pretty (1991), and Ashmore and Wilson (eds.) (1992).

The nature and amount of damage caused to plants by air pollutants depends on three key factors - the inherent toxicity of the particular pollutant gas, the proportion that is taken up by the plants and their physiological reaction. These, in turn, are affected by the environment in which the crop is growing, including the presence of other pollutants.

Sulfur dioxide and nitrogen oxides are prime causes of acid pollution. These have been prevalent in industrialized countries, particularly in parts of Europe and northeastern USA, primarily as a result of the burning of fossil fuels. While such emissions have been declining in developed regions, the highest rates of increase of SO_2 emissions in recent years have occurred in countries that are rapidly industrializing, notably in China (Chameides *et al.*, 1994). When dissolved in water, these gases produce acid. From the air they are deposited onto farmers' fields, directly as dry deposition, or in the form of rain or snow as wet deposition, or are taken up by plants from fog or clouds, as occult deposition. Apart from these chemical interactions, SO_2 aerosols may also affect the radiation and temperature environment in which crops grow through scattering of incoming solar radiation.

3.1 Dry deposition

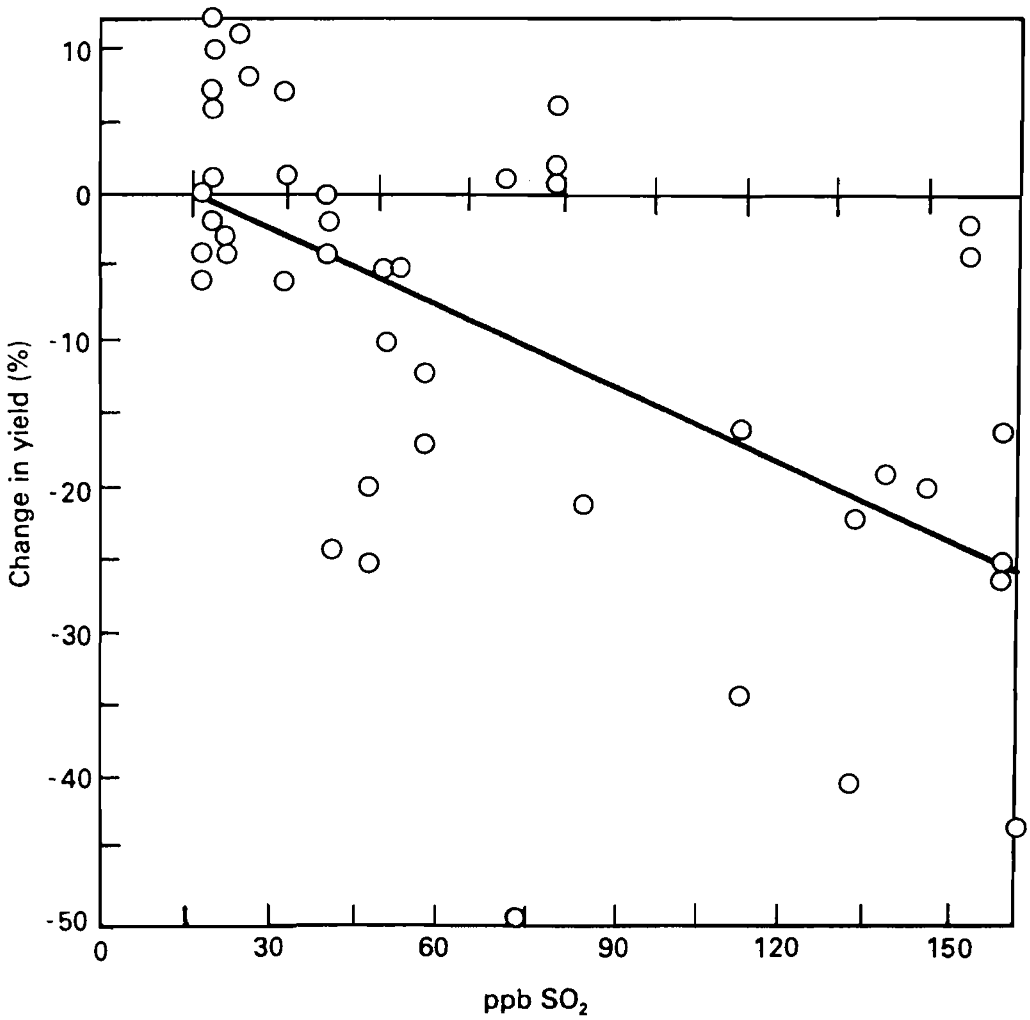
Early research was mainly concerned with acute injury of plants. Conditions under which visible damage of plant foliage occurs have been studied for almost one hundred years. Such visible injury is closely correlated with yield losses and can occur when SO_2 levels exceed 500 ppbv[5] for a few hours. However, with the adoption of efficient dispersion mechanisms (i.e., tall smokestacks for heavy polluters) such conditions are hardly observable nowadays, and acute injury of agricultural crops from dry deposition is unlikely.

In the last decades the research focus has shifted towards the effects of low to moderate concentrations of pollutants on arable crops and grasses (Figure 1). Experiments and field studies have shown that most reductions in yield occur without signs of visible injury. Impacts at doses comparable to levels typically observed in rural areas in Europe and USA

[5] Concentrations of gaseous pollutants are usually expressed either on a volume to volume basis, such as parts per billion (ppbv), or on a mass to volume basis, such as micrograms per cubic meter (μgm^{-3}). Conversion between measures depends on pressure, temperature and molecular weight of the gas. At a temperature of 20° C and a pressure of 1 atmosphere, the respective conversion factor for sulfur dioxide is: 1 ppbv ≈2.67 μgm^{-3}.

have been found to be highly variable and results were sometimes even conflicting. Nevertheless, a few general conclusions have been formulated (see, e.g., Ashmore and Wilson, 1993). There is now good evidence that SO_2 -induced chronic injury is greatly enhanced when plants are growing slowly, such as in higher altitudes or during winter months. Low light intensity, short days and low temperature produce slow growth which makes plants more vulnerable to SO_2.

Figure 1 Effects of long-term exposure (20-200 days) to SO_2 on the grass *Lolium perenne*



Source: Roberts, T.M., "Long-term effects of sulphur dioxide on crops: an analysis of dose-response relations", Phil. Trans. R. Soc. Lond. **B 305** (1984) pp. 299-316.

Evidence from filtration and low concentration fumigation experiments indicates that critical levels for SO_2 might be lower in the presence of nitrous oxide or ozone. On the other hand, reduction in stomatal conductance by enhanced atmospheric CO_2 could potentially reduce the effects of SO_2 and ozone (Allen, 1990). The experimental results are, however, complicated and sometimes even conflicting, making it impossible to predict what type of interaction will happen when a crop is subjected to a given combination of pollutants. Mixtures of toxic gases are most harmful to plants under stress, and may reduce their ability to withstand such environmental stress, for instance, their ability to tolerate freezing. Plants with the C_3 photosynthetic pathway tend to be more susceptible to air pollution than C_4 plants. There is some evidence to suggest that soil type does not have a major influence on the response of crops to pollutants when grown in adequately fertilized soils (Sanders, 1993). In the studies of critical loads of pollutants in Europe (see Bell, 1993), it is noted that in the case of agricultural and horticultural crops adverse effects are not observed for annual mean SO_2 concentration levels below 30 μgm^{-3}. The overall dose or average concentration of pollutant gases appears to be the primary factor controlling effects, rather than intermittent peaks in exposure levels.

3.1 Wet deposition

Most investigations into the effects of wet deposition, commonly termed acid rain, have focused on damages to forests and water bodies. Studies on crops indicate that the usual ambient concentrations of acids in rainfall are insufficient to produce acute injury except in the immediate vicinity of intense sources of emissions. Plant damages have been reported for pH values below 3.5, a concentration of acids in rainfall rarely achieved even in highly polluted areas. Some general findings are that broadleaf plants are more susceptible than grasses, and root and leafy vegetables are more susceptible than forage, grain and fruit crops. Overall, the effects of wet deposition of pollutants on plants are even less well understood than those of gaseous pollutants (Fitter and Hay, 1987).

Much attention has also been given to studying indirect effects of sulfur deposition, for instance on the dynamics of soil and surface water acidification. Reduction in pH, below a pH level of 4.2, eventually leads to an increase in toxic aluminum concentration in the soil enhancing the potential for damage to vegetation and affecting soil fertility and vegetation structure. This has been a major concern with regard to less intensively managed ecosystems, such as forests, but seems of less importance for agro-ecosystems where mitigating management practices, e.g., liming of agricultural land, can neutralize even high rates of acidic deposition, albeit at increased costs of agricultural production.

4. Linking the BLS with 11R, MESSAGE and RAINS

The analysis described in this report is part of an integrated assessment study involving several models developed by different IIASA projects. To achieve consistency among the various research groups, the assessment models have been harmonized through an approach that we term soft-linking. A first critical step in this process is linking the results of the macro-economic energy model 11R (Manne and Richels, 1992) and IIASA's model of the world food and agriculture system, the BLS (Fischer, *et al.*, 1988). Second, the climate change yield component of the BLS is parameterized according to emissions projected by the energy model MESSAGE III (Messner and Strubegger, 1995) and global temperature changes derived from MAGICC (Wigley and Raper, 1992; Hulme *et al.*, 1995). Third, results from RAINS (Regional Acidification INformation and Simulation model; Amann, 1993; Amann *et al.*, 1995; Cofala and Dörfner, 1995) have been utilized to derive regional yield damage functions in the BLS to account for the effects of increasing SO_2 emissions and deposition in the high emission energy scenario (HER) used in this study.

4.1 The world agriculture model system BLS

The Basic Linked System of National Agricultural Policy Models (BLS) is a world level general equilibrium model system developed by the Food and Agriculture Program of the International Institute for Applied Systems Analysis. It consists of some thirty-five national and/or regional models: eighteen national models, two models for regions with close economic cooperation (EC-9 and Eastern Europe & former Soviet Union[6]), fourteen aggregate models of country groupings, and a small component that accounts for statistical discrepancies and imbalances during the historical period. The individual models are linked together by means of a world market module. A detailed description of the entire system is provided in Fischer *et al.* (1988). Earlier results obtained with the system are discussed in Parikh *et al.* (1988) and in Fischer *et al.* (1990, 1994, 1996).

The general equilibrium approach upon which the BLS is constructed necessitates that all economic activities are represented in the model. Financial flows as well as commodity

[6] The political changes as well as changes in national boundaries of the recent past are not captured in the BLS, although the model formulation has been adjusted, away from centrally planned economies to more market oriented behavior.

flows within a country and at the international level are consistent in the sense that they balance. Whatever is produced will be demanded, either for human consumption, feed or intermediate input; it might be traded or put into storage. Consistency of financial flows is imposed at the level of the economic agents in the model (individual income groups, governments, etc.), at the national as well as the international level. This implies that total expenditures cannot exceed total income from economic activities and from abroad, in the form of financial transfers, minus savings. On a global scale, not more can be spent than what is earned.

The country models are linked through trade, world market prices and financial flows. The system is solved in annual increments, simultaneously for all countries. It is assumed that supply does not adjust instantaneously to new economic conditions. Only supply that will be marketed in the following year is affected by possible changes in the economic environment. A first round of exports from all the countries is calculated for an initial set of world prices, and international market clearance is checked for each commodity. World prices are then revised, using an optimizing algorithm, and again transmitted to the national models. Next, these generate new domestic equilibria and adjust net exports. This process is repeated until the world markets are cleared in all commodities. Since these steps are taken on a year-by-year basis, a recursive dynamic simulation results.

Although the BLS contains different types of models, all adhere to some common specifications. The models contain two main sectors: agriculture and non-agriculture. Agriculture produces nine aggregated commodities. All non-agricultural activities are combined into one single aggregate sector. Production is critically dependent on the availability of the modeled primary production factors, i.e., of land, labor and capital. The former is used only in the agricultural sector, while the latter two are determinants of output in both the agricultural and the non-agricultural sectors.

For agricultural commodities, acreage or animal numbers and yield are determined separately. Yield is represented as a function of fertilizer application (crops) or feeding intensity (livestock). Technological development is assumed to be largely determined by exogenous factors. Technical progress is included in the models as biological technical progress in the yield functions of both crops and livestock. Rates of technical progress were estimated from historical data and, in general, show a decline over time. Mechanical technical progress is part of the function determining the level of harvested crop area and livestock husbandry.

Several factors cause consumers and producers to adjust their behavior over time to political changes, altered economic and technological conditions. For consumers, it is mainly the formation of taste and habit, and changing prices and incomes that alter their responses. Producers are most affected by their past investment decisions, by technological innovations, or – as in this study – changes in productivity due to climate change, increased atmospheric concentrations of CO_2, and sulfur deposition.

Information generated by simulating with the BLS contains a variety of variables. At the world market level these include prices, net exports, global production and consumption. At the country level the information generated varies between different models, including generally the following variables: producer and retail prices, level of production, use of primary production factors (land, labor and capital), intermediate input use (feed, fertilizer, and other chemicals), level of human consumption, stocks and net trade, gross domestic product and investment by sector, population number and labor force, welfare measures such as equivalent income, and the level of policy measures as determined by the government (e.g., taxes, tariffs).

4.2 Linking BLS with 11R and MESSAGE III

11R is an eleven world region adaptation of the Global 2100 model (Manne and Richels, 1992). This model, in several variants, has been widely used for economic studies of the global implications of CO_2 reductions. 11R is a dynamic nonlinear macroeconomic optimization model used for the analysis of long-term CO_2-energy-economy interactions. Its objective function is the total discounted utility of a single representative producer-consumer. The maximization of this utility function determines trajectories of optimal savings, investment, and consumption decisions. Savings and investment drive the accumulation of capital stocks. Available labor, dependent on demographic change, and energy inputs determine the total output of the economy according to a nested constant elasticity of substitution (CES) production function.

11R generates internally consistent projections of global and regional gross domestic product (GDP), as well as trajectories of regional investment, labor, and primary energy consumption. A high degree of correspondence with the BLS in key variables for modeling the economy makes it feasible to harmonize the scenario analysis undertaken with the 11R and BLS models. One possible approach would have been to directly impose projections of GDP, labor, investment and technological progress as exogenous inputs to the BLS. This alternative was dropped, however, as it would have constrained the BLS in a very rigid manner, in effect by-passing its representation of the interdependencies between the agriculture and non-agriculture sectors.

To keep these interdependencies intact, the approach chosen for linking was to harmonize rates of economic growth generated in the BLS with those projected by 11R through adjustment of production factors and of assumed technical progress. Growth rates in the national models of the BLS are endogenously determined based on three elements: (a) capital accumulation through investment and depreciation, related to a savings function that depends on lagged GDP levels as well as balance of trade and financial aid flows; (b) dynamics of the labor force as a result of demographic changes; and (c) (exogenous) technical progress. The thirty-four model components of the BLS were aggregated into eleven world regions as closely matching the regionalization of 11R as possible. Then, the harmonization of production factors and GDP for the period 1990 to 2050 was carried out on a region by region basis.

Regional GDP and investment generated by 11R are shown in Tables 3 and 4, respectively. Economic growth is highest - between 4 to 6 percent average annual growth - in the three developing Asian regions. Developed regions grow by a little less than 2 percent. This model calibration resulted in a BLS reference scenario (BLS/REF3) specifically designed to derive projections of the world food system which are consistent with the basic economic assumptions used in 11R. As a benchmark run against which to compare alternative energy scenarios, reference scenario BLS/REF3 assumes current climate, and current levels of atmospheric CO_2 and SO_2 concentrations.

Another cornerstone of the integrated assessment exercise is MESSAGE III, a dynamic systems engineering optimization model used for medium to long-term energy system planning and energy policy analysis. MESSAGE III uses a bottom-up approach to describe the full range of technological aspects of energy use, from resource extraction, conversion, transport and distribution, to the provision of energy end-use services. The model keeps a detailed account of pollutant emissions such as of CO_2 and SO_2.

The emissions projections arrived at by iteration over 11R and MESSAGE III scenario runs are input to MAGICC (a Model for the Assessment of Greenhouse-gas Impacts and Climate Change; Hulme *et al.*, 1995) that has been widely used for assessments reported by the IPCC. MAGICC accounts for the climate feedback due to CO_2 fertilization, and for negative radiative forcing due to sulphate aerosols and stratospheric ozone depletion. Emissions are converted to atmospheric concentrations by gas models, and the concentrations are converted to radiative forcing potentials for each gas. The net radiative forcing is then computed and input into a simple upwelling-diffusion energy-balance climate model. This produces global[7] estimates of mean annual temperature (see Carter *et al.*, 1994). The global climate and emission characteristics of three scenarios used in this study are shown in Table 10. The analyses compare the results of a high emission energy scenario (HER) with the outputs from two alternative emission abatement scenarios. These are the MIS (Mitigation Including Single-purpose options) and the MOM (Mitigation Only with Multi-purpose strategies) abatement scenarios.

4.3 Temperature and CO_2 yield impacts

A projection of global temperature change only, as calculated by MAGICC, provides insufficient information to assess the impact of climate change on agriculture. Therefore, we employed geographically detailed information generated within earlier climate impact studies to estimate crop yield changes from the three scenarios (see Rosenzweig and Parry, 1994; Rosenzweig and Iglesias (eds.), 1994; Fischer *et al.*, 1994, 1996; ASA, 1995; Smith and Strzepek (eds.), 1995).

The original yield change estimates referred to well defined conditions of climate and CO_2 concentrations according to the results of doubled CO_2 simulations of three general circulation models (GCMs). The GCMs used were those from (see Table 11 for GCM run characteristics):

GISS: Goddard Institute for Space Studies (Hansen *et al.*, 1983),

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[7] MAGICC estimates temperature change separately for the northern and southern hemispheres.

GFDL: Geophysical Fluid Dynamics Laboratory (Manabe and Wetherald, 1987), and UKMO:United Kingdom Meteorological Office (Wilson and Mitchell, 1987).

The simulated temperature changes of these GCM scenarios (+4° to +5.2°C) are near the upper end or above the range (+1° to +4.5°C) projected for doubled CO_2 warming by the IPCC (IPCC, 1995). The temperature changes generated in the GCM experiments are well above the temperature changes projected by MAGICC using the emission scenarios of the current study.

For the crop modeling part of the original study (Rosenzweig and Parry, 1994), climate changes from doubled CO_2 GCM simulations are utilized with an associated level of 555 ppmv CO_2, somewhat higher than the CO_2 levels occurring in the HER energy scenario (i.e., 538 ppmv in year 2050).

For the specification of yield impact scenarios we use the yield impact as estimated for different GCM climate scenarios. Let ΔT_{GCM} denote the temperature change associated with any particular GCM experiment. The level of CO_2 concentrations in the atmosphere, of the control run (i.e., approximately current levels) and for an effective doubling of greenhouse gases, is indicated by $c_{GCM}^{\Delta T}$ and c_{GCM}^{0}, respectively. Furthermore, let $\Delta y_{GCM}^{t,j}$ denote the yield changes in region j of the BLS, and $\Delta y_{GCM}^{c,j}$ is a vector of respective yield changes from CO_2 fertilization at CO_2 level $c_{GCM}^{\Delta T}$. These vectors of yield impacts can be derived from the agronomic results produced in the crop modeling study (Rosenzweig and Iglesias, 1994) as follows: (i) the vectors $\Delta y_{GCM}^{t,j}$ of climate change induced yield effects are captured in the *climate-change-only* experiments, and (ii) vectors $\Delta y_{GCM}^{c,j}$ can be calculated as the difference between *climate impacts with physiological effects of elevated* CO_2 and *climate-change-only* scenarios. For global climate conditions resulting from any particular energy scenario *s*, i.e., a combination of projected temperature change and increase of CO_2 concentration $(\Delta t_s, \Delta c_s)$, the effective yield impact is calculated by linear interpolation:

$$\Delta y_{GCM}^{j}(\Delta t_s, \Delta c_s) = \Delta y_{GCM}^{t,j} \cdot \frac{\Delta t_s}{\Delta T_{GCM}} + \Delta y_{GCM}^{c,j} \cdot \frac{\Delta c_s}{c_{GCM}^{T} - c_{GCM}^{0}} \qquad (1)$$

The respective changes in global temperature and the level of CO_2 concentrations for the high emission energy run (HER scenario) and two alternative abatement scenarios

(MOM and MIS scenarios) are shown in Table 10. Temperature changes were applied separately for the northern and southern hemispheres as calculated in MAGICC.

This approach, which mixes equilibrium climate and transient CO_2 projections, is the best that can be done given the lack of availability of GCM transient climate change simulations consistent with the assumed emission scenarios.

4.4 SO_2 yield impacts

RAINS is a modular simulation system originally designed for integrated assessment of alternative strategies to reduce acid deposition in Europe (Alcamo *et al.*, 1990). The model quantifies sulfur emissions from given activity levels in the energy sector, both production and end-uses, traces the fate of these emissions using atmospheric transport and chemical transformation models, calculates the amount of sulfur deposition and estimates their impacts on soils and ecosystems. RAINS generates results in a geographically explicit manner on a grid of 1×1 degree along latitude and longitude. To parameterize the yield damage caused by dry deposition of SO_2, the gridded estimates of sulfur deposition and SO_2 concentrations for south and east Asia projected by RAINS-Asia were evaluated, using a linear damage function:

$$\Delta y_s^{S,j}(x) = -\max\left(0, \frac{e(x)-30}{2.67} 0.01\right) \quad (2)$$

where

x	geographic location (i.e., pixel of 1×1 degree along latitude and longitude);
$e(x)$	mean annual SO_2 concentration in μgm^{-3} at location x;
$\Delta y_s^{S,j}(x)$	yield change caused by SO_2 at mean annual concentration of $e(x)$.

From the discussion in Section 3 it is obvious that the quantification of SO_2 impacts on crops is difficult and controversial. Nevertheless, it was decided to attempt quantifying possible damages from sulfur deposition in the BLS runs, because omitting these effects would have created an unacceptable bias in the assessment. However, there is great uncertainty as to the magnitude of the possible SO_2 damage. In equation (3), we use an SO_2 concentration threshold of 30 μgm^{-3} as established for Europe (see Ashmore and Wilson, 1993). In accordance with experiments cited in Fitter and Hay (1987) and Conway and Pretty (1991), we have adopted the assumption that crop yield damage increases linearly when SO_2 concentration levels exceed the threshold such that yield is reduced by

10 percent for each 10 ppbv (i.e., each 10 ppbv ≅ 26.7 μgm^{-3}) increase of mean annual sulfur dioxide concentrations beyond the critical level. The estimates of crop damage by grid-box were then aggregated for the main agricultural areas of major countries in the study region of RAINS-Asia (e.g., China, India, Pakistan, etc.). In addition to South and East Asia (CPA, PAS and SAS regions[8]), estimates of crop damage from SO_2 deposition were also included for the former Soviet Union (FSU) and North America (NAM) using the regional trajectories of sulfur emissions calculated by MESSAGE III in the HER energy scenario. Consequently, the yield impact equation (1) discussed above was amended to also include a term accounting for SO_2 damage.

$$\Delta y^{j}_{GCM}(\Delta t_s, \Delta c_s, e_s) = \Delta y^{t,j}_{GCM} \cdot \frac{\Delta t_s}{\Delta T_{GCM}} + \Delta y^{c,j}_{GCM} \cdot \frac{\Delta c_s}{c^{T}_{GCM} - c^{0}_{GCM}} + \Delta y^{S,j}_{s}(e_s) \qquad (3)$$

The individual yield impact components of climate, CO_2 fertilization and SO_2 damage, and the resulting net impact for each energy scenario variant at global and broad regional level are listed in Table 12.

4.5 Scenario analysis with the BLS

The evaluation of the potential impacts of alternative energy futures on production and trade of agricultural commodities, in particular on food staples, is carried out by comparing the results of corresponding climate change scenarios to a reference projection, scenario BLS/REF3, that represents a future when current climate and atmospheric conditions would prevail.

Data on crop yield changes were estimated for different scenarios of climate change and increases of atmospheric CO_2 and SO_2 concentrations, based on the emissions resulting from three alternative energy runs. Data were compiled for each of the thirty-four components representing the world in the BLS. Most models included in the BLS distinguish yield and acreage functions. Yield variations caused by climate change and sulfur deposition were introduced into the yield response functions of the BLS country models by means of a multiplicative factor impacting upon the relevant parameters in the mathematical representation. This implies that both average and marginal fertilizer productivity are affected by the imposed yield changes. Therefore, changes of yield

[8] The mapping from BLS components to agreggate world regions is given in the Appendix.

obtained in simulations with the BLS that include economic adaptation will deviate somewhat from productivity changes derived from crop modeling results since input levels adjust accordingly.

There is uncertainty to what extent the positive physiological effects of CO_2 observed in crop experiments will materialize in farmers' fields (e.g., see FAO, 1994), and to what extent negative impacts from climate change can be mitigated by farmers' adaptation to changing conditions. For this reason, two scenario variants, labeled V1 and V2, where simulated.

Finally, we accounted for the consequences of increased investment requirements in the abatement runs. Additional investment required for emission abatement is determined by MESSAGE III. The results, calculated by world region, were input to the BLS as percentage of GDP used for additional energy investment (and thus not available for other purposes). This defined another set of scenario experiments including the runs MISb, MIS.V1b, MIS.V2b, MOMb, MOM.V1b and MOM.V2b. The underlying idea is that additional investment requirements for energy emission abatement will also affect capital accumulation in other sectors, including agriculture. Averaging over decades, the global investment required in scenarios MOM and MIS is about 0.5 percent of GDP. The investment requirements differ significantly between developed and developing regions. The following investment coefficients, i.e., percent of GDP required for investing in abatement, were used in the respective BLS simulation runs: 0.1% (NAM), 0.05% (WEU&ODE), 0.10% (PAO), 1.2% (AFR), 0.6% (LAM), 0.6% (WAS), 0.8% (SAS), 1.0% (CPA), and 0.85% (PAS).

A description of the acronyms of sixteen scenarios, which were specifically designed and simulated for this study, is given in Table 9.

4.6 Static yield impacts

Before assessing the impacts of introducing a set of climate change and CO_2-induced yield modifications through simulation with the BLS, it is useful to ask what distortion such an exogenous change in agricultural productivity would imply for the world food system. We refer to this measure of distortion as *static* climate change yield impact as it describes a hypothetical effect without taking into account adjustments of the economic system. To obtain for any particular year τ an estimate of the *static* climate change yield impact, say $\Lambda_s(\tau)$, for scenario s, we apply the above estimated crop-wise yield changes, $\lambda^j(s,\tau) = \Delta y^j_{GCM}(\Delta t_s(\tau), c_s(\tau))$ to the yield and production levels as observed in a BLS reference projection in year τ. For cereals these impacts can be added up without weighting. To arrive at static impact estimates for other groups of crops and the entire sector, world market prices of year τ as simulated in the respective reference projection are used. In mathematical notation,

$$\Lambda^R_s(\tau) = \{\sum_{j \in R}\sum_{i \in C} P^W_{i\tau} \cdot Q^j_{i\tau} \cdot \lambda^j_i(s,\tau)\} / \{\sum_{j \in R}\sum_{i \in C} P^W_{i\tau} \cdot Q^j_{i\tau}\} \tag{4}$$

where

$\Lambda^R_s(\tau)$ static climate change yield impact of scenario s on region R in year τ.

$\lambda^j_i(s,\tau)$ climate change yield impact of scenario s, for crop i, in country j, in year τ.

$P^W_{i\tau}$ world market price of commodity i in year τ of BLS/REF3 projection.

$Q^j_{i\tau}$ production of commodity i, in country j, in year τ of BLS/REF3 projection.

Table 12 shows *static* impacts on cereals and total crop production estimated for the global and regional level. The effects are indicated for the three basic energy runs (HER, MOM and MIS scenarios) and two sets of sensitivity scenarios. In sensitivity variant 1, i.e., scenarios HER.V1, MOM.V1 and MIS.V1, we assume that the effect on farmers' fields will be only two-thirds of the beneficial impacts of increased CO_2 levels derived from crop experiments. Scenario variant 2 (HER.V2, MOM.V2 and MIS.V2) assumes that only two-thirds of both climate and CO_2 effects materialize under open field conditions. The aggregate yield impacts in high emission scenario variants shown in Table 12 include estimates of damages from increased sulfur deposition. These were derived utilizing results from the RAINS model.

5. The agriculture sector in the BLS/REF3 reference scenario

The reference scenario BLS/REF3 is a long-term projection of agricultural supply, demand and trade that serves as a neutral point of departure for studying potential impacts of alternative energy scenarios on productivity changes in agriculture. The reference scenario adopts the economic growth patterns calculated by the energy model 11R according to the assumptions in the high emission (unabated) energy run, scenario HER. We discuss here the characteristics of the reference scenario BLS/REF3 for comparison with the impacts assessed later on. It represents a future when current climate conditions would prevail.

Effective demand for food grows substantially owing to higher incomes and larger populations. This increase in demand is met at somewhat decreasing world market prices for agricultural products, consistent with historical trends. Table 5 shows global production of agricultural commodities in the BLS/REF3 scenario. Average annual growth rates of production during the period 1980 to 2050 (and hence effective demand) for agricultural commodities range from 1.0 to 1.4 percent per annum implying a two- to three-fold increase compared to 1980 levels. Gross agricultural production[9] increases on average 1.3 percent per annum, i.e., by year 2050 it reaches about 2.5 times the 1980 level. This compares favorably to the projected average population increase of less than 1.2 percent annually during this 70 year period from 1980 to 2050.

Global trade in the reference scenario increases somewhat faster than global agricultural production. For cereals, the share of net exports in global production is estimated to increase from just above 12 percent in 1980 to almost 15 percent in 2050. Wheat exports show a 2.4-fold increase, and coarse grains and rice reach a threefold increase in trade levels. In general, the share of global trade in global production of commodity aggregates increases gradually over time indicating a growing specialization in production. Increasing demand in developing countries, due to rising incomes and growing populations, leads to a deterioration in the level of agricultural self-sufficiency for this group of countries, which changes from a net surplus of about 3 percent in 1979/81 into a 1 percent deficit by the year 2050 caused by increasing net imports of cereals and dairy products.

Global cereal production in 1979/81 is estimated to amount to 1.5 billion tons (note that rice is included in milled form). Production is projected to increase to about 2.1 billion tons by the year 2000 and some 3.4 billion tons by year 2050, implying an average annual increase of 1.2 percent per annum over a period of 70 years (Table 7). This matches approximately the projected population growth. The share of developed countries in global production of cereals is projected to decline steadily between 1980 to 2050, from 55 percent to 42 percent by the end of the simulation period. Over the same period the share of developed countries in the global demand of cereals declines from 52 percent in 1980 to 33 percent in 2050, resulting in an increased net flow of cereals into developing countries, mainly in Africa (AFR), Western Asia (WAS), and China (included in the CPA region)

[9] Gross agricultural production, labeled *Agriculture* in Table 5 is calculated at constant 1970 world market

(Tables 6 and 8). North America remains the principal bread basket of the world in scenario BLS/REF3, producing about 20 percent of the global cereal harvest, twice its projected demand.

6. Scenario results

Table 10 shows the effects of the three energy scenarios on climate, CO_2 concentrations and SO_2 emissions. Although the carbon dioxide concentration is highest in the HER scenario, the projected temperature increase is less than in the abatement runs, MOM and MIS, due to lower radiative forcing caused by the high amount of aerosols. Since increased temperature, at least at an aggregate regional level, leads to negative yield impacts, and increased CO_2 to sizable positive yield impacts, the HER scenario would clearly be the best option for agriculture if one were to ignore possible damage from SO_2. The magnitude of the different factors contributing to changes in crop productivity and the net effects estimated for year 2050 are shown in Table 12, calculated on the basis of crop experiments derived according to patterns of climate change in GISS 2× CO_2 GCM experiments. Effects were also quantified for GFDL and UKMO GCM results.

Even when taking SO_2 damage to crops into account, estimates of aggregate global crop productivity in the HER scenario are comparable to the estimates for the abatement cases. When assuming that the beneficial physiological effects of CO_2 in the open fields will on average be only two-thirds of the magnitude determined in crop experiments, due to various constraints pointed out by researchers that would limit the CO_2 effects, the abatement scenarios become superior for agriculture (scenario variants MOM.V1 and MIS.V1). This conclusion is further strengthened in scenario variant V2 where we assume that the climate effect will also be limited to two-thirds of the level determined in the crop experiments (an estimate of adaptation measures by farmers).

Table 13 shows BLS simulation results by world region (see Appendix 1 for information on aggregation of BLS country/region models to world regions) for year 2050, of the dynamic impacts on cereal production based on the three energy-climate runs. The results take into account economic adjustments triggered by the changes in crop productivity. Table 14 presents aggregate impacts calculated for all crops. Outcomes are

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prices.

clearly more beneficial for developed regions than for developing countries. However, for both groups, the magnitude of the impacts falls into a fairly broad range, with the most positive results for the regions including the former Soviet Union (EEU&FSU), Pacific OECD (PAO) and Western Europe (WEU&ODE). The highest losses occur in Latin America (LAM) and Africa (AFR).

When the response impact of CO_2 on crop yields is reduced to two-thirds of the response measured in crop experiments (scenario variant V1), the global impact on crop production becomes almost negligible. The regional impacts vary between -6 percent to +12 percent (Table 15). When both the CO_2 effect and the climate impact are reduced to two-thirds of the magnitude derived from crop modeling experiments (scenario variant V2), the situation changes somewhat, producing a net benefit in the order of +1 percent (see Table 17).

The dynamic impacts on crops for V1 and V2 scenarios, respectively, are shown in Table 16 and in Table 18, referring to scenarios variant V1b and V2b. There is, of course, no difference in results for the coal-intensive energy scenario HER between Table 15 and Table 16, since no additional investment is required. Earmarking additional energy investment requirements for abatement causes a reduction of crop output and GDP of agriculture by about 0.3-0.4 percent. The percent change in GDP of agriculture relative to the reference case BLS/REF3 for all scenario variants is shown in Table 19. The results demonstrate that abatement to avoid damage from SO_2 pollution clearly matters to regional output of agriculture.

The impact on world prices is fairly moderate in all BLS scenarios presented here. As a consequence of a modest increase in crop productivity relative to the reference scenario BLS/REF3, mainly due to the physiological effects of CO_2 on plants, prices of agricultural commodities are generally lower when considering changes in climate and the atmosphere.

7. Discussion and Conclusions

World population is expected to almost double between 1990 and 2050 from 5 to about 10 billion. This will require major increases in the level of economic activities, in energy consumption and food production. The analysis presented starts from economic projections that stipulate a more than tenfold increase of GDP in developing regions between 1990 to the middle of next century. Undoubtedly, such dramatic demographic and economic changes will put heavy demands on resources and will require the application of more efficient and environmentally benign technologies.

The analysis of the impacts of alternative future energy paths on the regional supply and trade of agricultural commodities is part of an integrated assessment study undertaken at IIASA. For the agricultural study, results from the energy models (i.e., 11R and MESSAGE III) of IIASA's Environmentally Compatible Energy Strategies project and from the regional air pollution model RAINS developed by IIASA's Transboundary Air Pollution project were compiled to define the economic and environmental conditions for a number of simulation experiments with the BLS model.

The choice of future energy sources and technology will greatly impact on the level of greenhouse gases and aerosols in the atmosphere and is expected to alter the prospects for crop cultivation through changes in climate as well as in levels of CO_2 concentrations and airborne pollutants. The projected increase in global temperature by year 2050 is lowest - about 1.1° C - in the carbon intensive high emission energy scenario (HER), compared to 1.3° C and 1.4° C warming, respectively, under alternative abatement scenarios (MOM and MIS). Despite having the highest level of CO_2 concentration (in year 2050, estimates are: 538 ppmv CO_2 in HER, 474 ppmv and 488 ppmv in MOM and MIS scenarios, respectively), the total radiative forcing is lower in the HER scenario because of the cooling effect due to much higher levels of aerosols.

Crop experiments and studies of the impact of climate change on crop productivity have resulted in the understanding that global warming (i.e., the climate effect only), on a broad regional level, will have negative impacts on agriculture. This effect is mitigated and will often be more than compensated by beneficial effects on plants of increasing CO_2 levels, through enhancing photosynthesis and water use efficiency. For a number of reasons, agriculture in temperate zones is expected to fare better under climate change than tropical agriculture.

When looking <u>only</u> at the projected climate and CO_2 effects of the three alternative energy and emission scenarios, conditions in the HER scenario are more beneficial to agriculture than the abatement scenarios. This perhaps counterintuitive finding derives from the projected conditions, namely that the HER scenario produces the highest CO_2

level (a positive effect) and causes the least warming (a negative impact) of the three cases analyzed.

However, the high emission of pollutants in the HER scenario, notably of SO_2, poses a number of environmental risks not included in this analysis. The detrimental impacts of airborne chemicals include human health effects, acidification of soils and water bodies, fumigation of crops and forests, and damage to buildings and engineering materials. While the cost of abatement measures is determined by rather well-specified investment requirements, the damage caused by SO_2 and related pollutants is complex, of multiple forms, and widespread.

The projected differences in energy investments between abatement scenarios (both MOM and MIS) and the coal intensive HER scenario amount to about ½ percent of global GDP, and more than 1 percent of GDP in east Asia (CPA region). It is justified, therefore, to carefully analyze the regional and global consequences of a failure to implement emission abatement in the energy sector.

Unlike in the debate on climate change impacts where the regions mainly responsible for the increase in atmospheric CO_2 concentration may be different from those most affected by it, the damage caused by air pollution stays more closely with the region of origin, at least when analyzing the effects in terms of broader world regions.

The simulation experiments with the BLS, computed to analyze the impacts of alternative energy futures on agriculture, suggest a few general conclusions:

- Overall effects are small due to moderate climate sensitivity and negative radiation forcing by sulfate aerosols.
- Productivity in agriculture at the aggregate global level increases in simulations for all three energy scenarios, compared to present climate and CO_2 concentration levels mainly because of the positive physiological effects of increased CO_2 levels on crop performance.
- The aggregate impact for the group of developed countries is clearly positive in all simulated cases. The aggregate impact on developing countries is likely to be negative.

- Emission abatement, in terms of agricultural and environmental impacts, is a regional issue much more than a global one. While there is relatively little difference between outcomes at the global level, regional results vary greatly between scenarios.
- Global impacts on agriculture alone, and on the basis of the single pollutant taken into account here (i.e., SO_2), do not seem to provide sufficient economic justification for abatement. Yet, regional impacts on agriculture of a coal-intensive high emission scenario (HER) could be substantial, especially in regions where agricultural production is located near industrial areas as in China and India. Hence, from a regional perspective, abatement appears to be foremost in the interest of the polluters themselves.

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Appendix: Aggregation of BLS country modules to world regions

Economic group	Region	BLS Component[10]
DEVELOPED	NAM	Canada, United States
	WEU+ODE	Austria, EC-9, Rest of the world (916)
	EEU+FSU	Eastern Europe & USSR
	PAO	Australia, Japan, New Zealand
DEVELOPING	AFR	Kenya, Nigeria, Africa Oil Exporters (901), Africa medium income/calorie exporters (902), Africa medium income/calorie importers (903), Africa low income/calorie exporters (904), Africa low income/calorie exporters (905)
	LAM	Argentina, Brazil, Mexico, Latin America high income/calorie exporters (906), Latin America high income/calorie importers (907), Latin America medium income (908)
	WAS	Egypt, Turkey, Near East Asia oil exporters (912), Near East Asia medium-low Income (913).
	SAS	India, Pakistan, Asia low income (911)
	CPA	China, Far East Asia high-medium income/calorie importers (910)
	PAS	Indonesia, Thailand, Far East Asia high-medium income/calorie exporters (909)

[10] For details of country grouping in the BLS see Fischer *et al.* (1988)

Table 1: Population in BLS/REF3 reference scenario

	Population (billions)				Growth rate (% p.a.)		
	1980	2000	2030	2050	1980 -2050	1980 -2000	2000 -2050
WORLD	4.4	6.1	8.7	9.9	1.2	1.7	1.0
DEVELOPED	1.2	1.3	1.5	1.5	0.3	0.6	0.2
DEVELOPING	3.2	4.8	7.2	8.4	1.4	2.0	1.1

Table 2: Regional population share in BLS/REF3 reference scenario (percent)

	1980	2000	2030	2050
DEVELOPED	27.1	21.9	17.1	14.9
DEVELOPING	72.9	78.1	82.9	85.1
NAM	5.7	4.8	3.8	3.3
WEU+ODE	9.8	7.7	5.9	5.1
EEU+FSU	8.6	6.9	5.6	5.0
PAO	3.1	2.5	1.8	1.5
AFR	9.4	12.4	17.7	20.6
LAM	8.0	8.5	8.9	8.7
WAS	4.3	5.3	6.5	7.3
SAS	20.5	22.8	24.2	24.6
CPA	24.8	23.2	20.0	18.4
PAS	5.9	6.0	5.7	5.6

Table 3: Economic growth in 11R coal intensive high emission energy scenario (HER)

	GDP (billion US $ of 1990)				Growth rate (% p.a.)		
	1990	2000	2030	2050	1990 -2010	1990 -2030	1990 -2050
WORLD	20870	27168	59346	97532	2.65	2.65	2.60
DEVELOPED	18390	22887	41121	58210	2.14	2.03	1.94
DEVELOPING	3420	5482	19848	41451	4.62	4.49	4.25
NAM	6070	7794	14253	19070	2.38	2.16	1.93
LAM	1080	1498	3631	6889	3.13	3.08	3.14
WEU	7010	8995	15876	21199	2.32	2.06	1.86
EEU	300	239	920	2249	0.37	2.84	3.41
FSU	790	597	1896	5447	-0.44	2.21	3.27
MEA	570	839	2459	5077	3.69	3.72	3.71
AFR	260	350	1001	2540	2.94	3.43	3.87
CPA	470	1085	6240	13592	7.44	6.68	5.77
SAS	380	533	1558	4288	3.33	3.59	4.12
PAS	660	1177	4959	9065	5.93	5.17	4.46
PAO	3280	4061	6553	8116	2.00	1.75	1.52

Table 4: Investment in 11R coal intensive high emission energy scenario (HER)

	Investment (billion US $ of 1990)				Growth rate (% p.a.)		
	1990	2000	2030	2050	1990 -2010	1990 -2030	1990 -2050
WORLD	4020	5460	11570	18810	2.72	2.68	2.61
DEVELOPED	3230	4260	7360	10550	2.32	2.08	1.99
DEVELOPING	800	1210	4220	8260	4.05	4.25	3.97
NAM	1140	1520	2480	3220	2.31	1.96	1.75
LAM	210	290	680	1410	2.73	2.98	3.22
WEU	1400	1830	2850	3640	2.05	1.79	1.61
EEU	10	20	230	530	11.61	8.15	6.84
FSU	90	110	690	1810	4.80	5.22	5.13
MEA	140	180	550	1010	2.29	3.48	3.35
AFR	40	60	210	570	3.53	4.23	4.53
CPA	180	300	1540	2750	5.24	5.51	4.65
SAS	70	100	320	1020	3.14	3.87	4.57
PAS	160	280	920	1500	5.65	4.47	3.80
PAO	590	780	1110	1350	2.08	1.59	1.39

Table 5: Global agriculture production in BLS/REF3 reference scenario[11]

	Production level in year				Growth (% p.a.)		
	1980	2000	2030	2050	1980 -2000	2000 -2050	1980 -2050
WHEAT	455	660	897	1037	1.9	0.9	1.2
RICE, MILLED	272	416	605	706	2.1	1.1	1.4
COARSE GRAINS	759	1067	1476	1685	1.7	0.9	1.1
BOV.&OVINE MEAT	65	84	117	133	1.3	0.9	1.0
DAIRY PRODUCTS	471	617	830	959	1.4	0.9	1.0
OTHER MEAT	17	25	38	46	2.0	1.2	1.4
PROTEIN FEEDS	36	52	72	82	1.8	0.9	1.2
OTHER FOOD	224	327	494	594	1.9	1.2	1.4
NON-FOOD	26	34	45	51	1.3	0.8	1.0
AGRICULTURE	312	449	659	784	1.8	1.1	1.3

[11] Units of measurement: wheat, rice, coarse grains in million tons; bovine + ovine meat in million tons carcass weight; dairy products in million tons whole milk equivalent; other animal products, protein feed in million tons protein equivalent; other food, non-food in billion US dollars of 1970.

Table 6: Cereal demand in BLS/REF3 reference scenario

	Total demand (million tons)				Demand per capita (kg/cap)			
	1980	2000	2030	2050	1980	2000	2030	2050
WORLD	1491	2143	2977	3425	340	350	344	348
DEVELOPED	768	938	1079	1129	648	701	731	767
DEVELOPING	722	1205	1899	2296	226	252	264	274
NAM	220	292	336	342	880	1001	1009	1054
WEU+ODE	187	236	279	289	437	501	549	573
EEU+FSU	320	364	412	445	856	859	857	900
PAO	41	46	51	52	308	302	334	355
AFR	69	131	275	370	168	173	180	183
LAM	91	143	228	261	258	274	296	307
WAS	67	116	208	267	356	358	371	373
SAS	155	255	396	481	173	183	189	199
CPA	298	489	681	783	274	344	394	432
PAS	43	71	110	133	165	194	222	243

Table 7: Cereal production in BLS/REF3 reference scenario

	Total production (mill. tons)				Production per capita (kg/cap)			
	1980	2000	2030	2050	1980	2000	2030	2050
WORLD	1487	2143	2977	3428	340	350	344	348
DEVELOPED	822	1070	1327	1448	693	799	899	984
DEVELOPING	665	1074	1650	1979	208	224	230	236
NAM	317	467	623	693	1272	1600	1872	2133
WEU+ODE	197	227	253	268	461	482	499	531
EEU+FSU	275	334	394	427	735	789	820	863
PAO	32	41	56	61	238	269	361	413
AFR	52	91	188	255	127	121	123	126
LAM	84	136	234	271	240	260	304	318
WAS	52	71	118	144	277	219	210	202
SAS	147	256	390	487	164	183	186	201
CPA	287	449	604	690	265	317	349	381
PAS	43	70	117	132	165	191	236	241

Table 8: Regional cereal net exports and self-sufficiency in BLS/REF3 reference scenario

	Net exports (million tons)				Self-sufficiency (percent)			
	1980	2000	2030	2050	1980	2000	2030	2050
WORLD	183	281	438	510				
DEVELOPED	54	131	248	319	107	114	123	128
DEVELOPING	-56	-131	-248	-317	92	89	87	86
NAM	98	175	287	350	144	160	185	202
WEU+ODE	10	-9	-26	-22	106	96	91	93
EEU+FSU	-45	-30	-18	-18	86	92	96	96
PAO	-9	-5	4	9	77	89	108	117
AFR	-17	-39	-87	-116	76	70	68	69
LAM	-6	-7	6	9	93	95	103	104
WAS	-15	-45	-91	-122	78	61	56	54
SAS	-8	1	-5	6	95	100	99	101
CPA	-10	-40	-77	-93	97	92	89	88
PAS	0	-1	7	-1	100	99	106	99

Table 9: BLS scenarios analyzed in the study

Scenario	Scenario characteristics
REF3	Reference scenario: UN 1992 medium growth population scenario; economic growth by region calibrated through adjustment of production factor dynamics to approximately match growth characteristics of 11R results in high emission energy scenario; agricultural protection is reduced between 1990 and 2020 by 50 percent; climate and levels of CO_2 and SO_2 concentrations remain at base year level.
HER	High emission scenario: basic assumptions as in REF3; yield changes parameterized according to temperature changes and increases in CO_2 and SO_2 levels (see Table 10) derived from emissions in high emission energy scenario, using MAGICC and RAINS-Asia and scaling yield impacts calculated in EPA climate impact study; spatial pattern of climate change derived from doubled CO_2 GCM experiments using results published for GISS, GFDL and UKMO general circulation models.
MOM	Abatement variant 1: basic assumptions as in REF3; yield changes parameterized according to temperature changes and increases in CO_2 levels (see Table 10) derived from emissions in an energy scenario that implements mitigation through abatement measures according to multi-purpose strategies, using MAGICC and scaling yield impacts calculated in EPA climate impact study; spatial pattern of climate change derived from doubled CO_2 GCM experiments using results published for GISS, GFDL and UKMO general circulation models.
MIS	Abatement variant 2: basic assumptions as in REF3; yield changes parameterized according to temperature changes and increases in CO_2 levels (see Table 10) derived from emissions in an energy scenario that implements mitigation through abatement measures according to single-purpose (i.e., SO_2 mitigation) options, using MAGICC and scaling yield impacts calculated in EPA climate impact study; spatial pattern of climate change derived from doubled CO_2 GCM experiments using results published for GISS, GFDL and UKMO general circulation models. Mitigation Including Single-purpose options.
MOMb	as MOM, but in addition assuming that investment for abatement measures affects capital accumulation.
MISb	as MIS, but in addition assuming that investment for abatement measures affects capital accumulation.
HER.V1	as HER, but assuming that CO_2 fertilization effects in farmers' fields is limited to two thirds of experimental results.
MOM.V1	as MOM, but assuming that CO_2 fertilization effects in farmers' fields is limited to two thirds of experimental results.
MIS.V1	as MIS, but assuming that CO_2 fertilization effects in farmers' fields is limited to two thirds of experimental results.
MOM.V1b	as MOM.V1, but in addition assuming that investment for abatement measures affects capital accumulation.
MIS.V1b	as MIS.V1, but in addition assuming that investment for abatement measures affects capital accumulation.
HER.V2	as HER, but assuming that both the climate and CO_2 fertilization effects in farmers' fields are limited to two thirds of experimental results.
MOM.V2	as MOM, but assuming that both the climate and CO_2 fertilization effects in farmers' fields are limited to two thirds of experimental results.
MIS.V2	as MIS, but assuming that both the climate and CO_2 fertilization effects in farmers' fields are limited to two thirds of experimental results.
MOM.V2b	as MOM.V2, but in addition assuming that investment for abatement measures affects capital accumulation.
MIS.V2b	as MIS.V2, but in addition assuming that investment for abatement measures affects capital accumulation.

Table 10: Climate and emission characteristics of three energy scenarios

HER		1990	2010	2030	2050	2100
dT north	°C	0	0.23	0.48	0.83	1.87
dT south	°C	0	0.34	0.75	1.24	2.60
dT global	°C	0	0.30	0.65	1.07	2.34
CO_2 concentr.	ppmv	355	398	458	538	810
SO_2 emissions	Mty^{-1}	142	198	272	348	498

MOM		1990	2010	2030	2050	2100
dT north	°C	0	0.54	1.00	1.50	2.71
dT south	°C	0	0.41	0.82	1.28	2.47
dT global	°C	0	0.43	0.85	1.30	2.50
CO_2 concentr.	ppmv	355	391	425	474	622
SO_2 emissions	Mty^{-1}	142	100	80	72	76

MIS		1990	2010	2030	2050	2100
dT north	°C	0	0.59	1.11	1.60	2.88
dT south	°C	0	0.44	0.89	1.37	2.64
dT global	°C	0	0.47	0.93	1.39	2.67
CO_2 concentr.	ppmv	355	395	434	488	656
SO_2 emissions	Mty^{-1}	142	92	68	72	76

Table 11: GCM climate change scenarios

GCM	Year[12]	Resolution latxlong	CO_2 ppmv	Change in average global temp. °C	Change in average global precip. %
GISS	1982	7.83°×10°	630	4.2	11
GFDL	1988	4.4°×7.5°	600	4.0	8
UKMO	1986	5.0°×7.5°	640	5.2	15

[12] when calculated

Table 12: Static impact on crop productivity (percent), year 2050

GISS		Cereals			Crops		
	Impact of	WORLD	DVLPD	DVLPG	WORLD	DVLPD	DVLPG
HER	Climate	-5.8	-3.0	-7.9	-6.4	-2.2	-7.8
	CO_2	13.8	13.3	14.2	18.1	17.0	18.5
	SO_2	-6.7	-7.2	-6.4	-5.5	-6.8	-5.0
	Net total	1.3	3.2	-0.1	6.3	8.0	5.7
MOM	Climate	-7.4	-5.2	-9.1	-7.5	-3.8	-8.7
	CO_2	9.0	8.7	9.2	11.8	11.0	12.0
	SO_2	0.0	0.0	0.0	0.0	0.0	0.0
	Net total	1.6	3.5	0.1	4.3	7.3	3.3
MIS	Climate	-7.9	-5.5	-9.7	-8.0	-4.1	-9.3
	CO_2	10.0	9.7	10.3	13.2	12.4	13.4
	SO_2	0.0	0.0	0.0	0.0	0.0	0.0
	Net total	2.1	4.2	0.6	5.2	8.3	4.1
HER.V1	Climate	-5.8	-3.0	-7.9	-6.4	-2.2	-7.8
	CO_2	9.2	8.9	9.5	12.1	11.3	12.4
	SO_2	-6.7	-7.2	-6.4	-5.5	-6.8	-5.0
	Net total	-3.3	-1.3	-4.8	0.3	2.3	-0.4
MOM.V1	Climate	-7.4	-5.2	-9.1	-7.5	-3.8	-8.7
	CO_2	6.0	5.8	6.2	7.9	7.4	8.0
	SO_2	0.0	0.0	0.0	0.0	0.0	0.0
	Net total	-1.4	0.6	-2.9	0.4	3.6	-0.7
MIS.V1	Climate	-7.9	-5.5	-9.7	-8.0	-4.1	-9.3
	CO_2	6.7	6.5	6.8	8.8	8.2	9.0
	SO_2	0.0	0.0	0.0	0.0	0.0	0.0
	Net total	-1.2	0.9	-2.9	0.8	4.2	-0.3
HER.V2	Climate	-3.9	-2.0	-5.2	-4.2	-1.5	-5.2
	CO_2	9.2	8.9	9.4	12.1	11.3	12.3
	SO_2	-6.7	-7.2	-6.4	-5.5	-6.8	-5.0
	Net total	-1.4	-0.3	-2.2	2.4	3.0	2.1
MOM.V2	Climate	-4.9	-3.5	-6.0	-5.0	-2.5	-5.8
	CO_2	6.0	5.8	6.1	7.8	7.4	8.0
	SO_2	0.0	0.0	0.0	0.0	0.0	0.0
	Net total	1.0	2.3	0.1	2.9	4.8	2.2
MIS.V2	Climate	-5.3	-3.7	-6.5	-5.3	-2.7	-6.2
	CO_2	6.7	6.5	6.8	8.8	8.2	9.0
	SO_2	0.0	0.0	0.0	0.0	0.0	0.0
	Net total	1.4	2.8	0.4	3.5	5.5	2.8

Table 13: Dynamic impact on cereal production under alternative GCM variants (% change), year 2050

Scenario	GISS			GFDL			UKMO			AVERAGE		
	HER	MOM	MIS	HER	MOM	MIS	HER	MOM	MIS	HER	MOM	MIS
WORLD	0.8	0.9	1.2	0.3	0.3	0.5	1.2	1.5	1.7	0.8	0.9	1.1
DEVELOPED	5.2	4.9	5.5	3.5	2.5	2.9	4.9	4.8	5.4	4.5	4.1	4.6
DEVELOPING	-2.3	-2.0	-2.0	-2.0	-1.4	-1.3	-1.5	-1.0	-1.0	-1.9	-1.5	-1.4
NAM	-2.1	-0.1	-0.2	0.3	1.2	1.3	-2.7	-0.5	-0.6	-1.5	0.2	0.2
WEU+ODE	9.3	3.5	3.8	7.8	2.0	2.3	9.1	3.3	3.6	8.7	2.9	3.2
EEU+FSU	13.2	13.9	15.9	4.0	3.3	4.3	13.8	14.9	17.0	10.3	10.7	12.4
PAO	12.7	5.0	4.4	17.0	9.7	9.9	10.0	1.1	-0.1	13.2	5.3	4.7
AFR	-1.4	-5.5	-5.8	-2.2	-5.8	-6.0	-0.1	-3.8	-3.9	-1.2	-5.0	-5.2
LAM	-8.2	-11.7	-12.7	-4.4	-7.0	-7.8	-7.0	-11.1	-12.2	-6.5	-9.9	-10.9
WAS	6.5	-1.5	-1.3	7.0	-2.0	-1.8	7.4	-0.1	-0.4	7.0	-1.2	-1.2
SAS	0.2	-0.8	-0.6	-0.6	-0.5	-0.4	1.4	0.3	0.5	0.3	-0.3	-0.2
CPA	-4.6	1.9	2.4	-4.9	1.3	1.7	-4.1	2.8	3.3	-4.5	2.0	2.5
PAS	0.4	-1.4	-1.4	3.9	2.5	2.8	-0.2	-0.6	-0.6	1.4	0.2	0.3

Table 14: Dynamic impact on crop production under alternative GCM variants (% change), year 2050

Scenario	GISS			GFDL			UKMO			AVERAGE		
	HER	MOM	MIS	HER	MOM	MIS	HER	MOM	MIS	HER	MOM	MIS
WORLD	2.3	1.6	1.9	2.0	1.2	1.5	2.9	2.2	2.6	2.4	1.7	2.0
DEVELOPED	5.9	6.6	7.3	4.3	3.8	4.3	5.3	6.2	6.8	5.2	5.5	6.1
DEVELOPING	1.1	-0.1	0.2	1.2	0.3	0.6	2.0	0.9	1.2	1.4	0.4	0.7
NAM	-3.5	-0.6	-0.9	-1.6	0.2	0.1	-4.2	-1.3	-1.5	-3.1	-0.6	-0.8
WEU+ODE	9.5	4.1	4.5	8.0	2.0	2.3	8.9	3.7	4.1	8.8	3.3	3.6
EEU+FSU	12.9	15.9	17.8	7.3	8.1	9.4	12.9	16.0	18.0	11.0	13.3	15.1
PAO	5.2	1.8	1.0	8.5	5.3	5.0	2.2	-1.7	-2.8	5.3	1.8	1.1
AFR	4.8	-0.2	0.2	2.9	-1.5	-1.4	5.3	0.6	0.8	4.3	-0.4	-0.1
LAM	0.5	-4.3	-4.7	3.3	-0.5	-0.5	1.2	-3.8	-4.2	1.7	-2.9	-3.1
WAS	6.3	-0.6	-0.3	5.6	-1.9	-1.6	7.0	0.6	0.9	6.3	-0.6	-0.3
SAS	2.3	1.2	1.6	1.7	1.0	1.4	3.6	2.5	3.1	2.5	1.6	2.0
CPA	-3.1	2.3	2.7	-3.4	1.7	2.1	-2.6	3.1	3.6	-3.0	2.4	2.8
PAS	-1.8	-2.1	-2.0	-1.1	1.8	2.2	1.6	-0.7	-0.5	-0.4	-0.3	-0.1

Table 15: Dynamic impact on crop production in GISS.V1 runs (% change), year 2050

Scenario	Cereals			Crops		
GISS.V1	HER	MOM	MIS	HER	MOM	MIS
WORLD	-0.9	-0.2	-0.1	0.0	0.1	0.3
DEVELOPED	3.1	3.6	4.0	3.7	5.2	5.7
DEVELOPING	-3.9	-3.0	-3.2	-1.3	-1.6	-1.5
NAM	-0.8	0.6	0.7	-1.5	0.8	0.8
WEU+ODE	7.9	2.6	2.8	8.6	3.4	3.7
EEU+FSU	4.2	8.3	9.4	4.6	10.4	11.7
PAO	18.2	8.5	8.8	12.2	6.2	6.2
AFR	-1.7	-5.7	-6.3	3.7	-0.7	-0.7
LAM	-4.1	-8.9	-9.8	1.4	-3.8	-4.1
WAS	3.7	-3.8	-3.9	3.6	-2.5	-2.5
SAS	-2.3	-2.4	-2.5	-1.9	-1.5	-1.4
CPA	-7.8	-0.1	0.1	-6.2	0.2	0.4
PAS	-1.1	-2.2	-2.3	-5.2	-4.1	-4.2

Table 16: Dynamic impact on crop production in GISS.V1b runs (% change), year 2050

Scenario	Cereals			Crops		
GISS.V1b	HER	MOM	MIS	HER	MOM	MIS
WORLD	-0.9	-0.5	-0.4	0.0	-0.2	-0.1
DEVELOPED	3.1	3.3	3.8	3.7	5.0	5.6
DEVELOPING	-3.9	-3.3	-3.5	-1.3	-2.0	-2.0
NAM	-0.8	0.5	0.7	-1.5	0.9	0.9
WEU+ODE	7.9	2.6	2.8	8.6	3.6	3.9
EEU+FSU	4.2	7.6	8.7	4.6	9.7	11.0
PAO	18.2	8.4	8.7	12.2	6.3	6.3
AFR	-1.7	-6.5	-7.3	3.7	-1.6	-1.7
LAM	-4.1	-9.2	-10.1	1.4	-4.2	-4.5
WAS	3.7	-4.2	-4.1	3.6	-2.9	-2.9
SAS	-2.3	-2.9	-2.9	-1.9	-1.8	-1.7
CPA	-7.8	-0.2	0.0	-6.2	0.1	0.3
PAS	-1.1	-2.5	-2.5	-5.2	-4.7	-4.7

Table 17: Dynamic impact on crop production in GISS.V2 runs (% change), year 2050

Scenario	Cereals			Crops		
GISS.V2	HER	MOM	MIS	HER	MOM	MIS
WORLD	-0.3	0.6	0.7	0.8	1.1	1.3
DEVELOPED	2.5	3.3	3.7	2.7	4.4	4.9
DEVELOPING	-2.3	-1.4	-1.4	0.2	-0.1	0.1
NAM	-1.7	0.0	0.0	-2.9	-0.4	-0.5
WEU+ODE	7.6	2.5	2.6	7.6	2.8	3.0
EEU+FSU	4.5	9.1	10.4	4.5	10.5	11.8
PAO	14.6	3.5	3.2	8.3	1.3	0.8
AFR	0.2	-3.9	-4.1	4.5	0.0	0.1
LAM	-2.4	-8.0	-8.9	2.5	-3.0	-3.3
WAS	5.8	-0.9	-0.8	5.0	-0.4	-0.3
SAS	-0.2	-0.6	-0.4	0.5	0.8	1.1
CPA	-7.0	1.3	1.6	-5.5	1.6	1.9
PAS	0.7	-0.9	-0.9	-2.3	-1.5	-1.4

Table 18: Dynamic impact in on crop production in GISS.V2b runs (% change), year 2050

Scenario	Cereals			Crops		
GISS.V2b	HER	MOM	MIS	HER	MOM	MIS
WORLD	-0.3	0.3	0.4	0.8	0.7	0.9
DEVELOPED	2.5	3.1	3.4	2.7	4.3	4.7
DEVELOPING	-2.3	-1.7	-1.7	0.2	-0.5	-0.4
NAM	-1.7	0.0	-0.1	-2.9	-0.3	-0.4
WEU+ODE	7.6	2.4	2.6	7.6	3.0	3.2
EEU+FSU	4.5	8.4	9.7	4.5	9.8	11.1
PAO	14.6	3.5	3.0	8.3	1.5	1.0
AFR	0.2	-4.7	-4.8	4.5	-1.0	-1.0
LAM	-2.4	-8.3	-9.2	2.5	-3.3	-3.5
WAS	5.8	-1.2	-1.1	5.0	-0.8	-0.7
SAS	-0.2	-1.0	-0.9	0.5	0.4	0.7
CPA	-7.0	1.2	1.5	-5.5	1.4	1.7
PAS	0.7	-1.1	-1.2	-2.3	-2.0	-2.0

Table 19: Dynamic impact on agriculture sector GDP (% change), year 2050

GDPA % change compared to REF3						Variant V1[13]					Variant V2				
	HER	MOM	MIS	MOMb	MISb	HER	MOM	MIS	MOMb	MISb	HER	MOM	MIS	MOMb	MISb
WORLD	1.9	1.3	1.6	0.9	1.2	0.0	0.1	0.2	-0.3	-0.1	0.7	0.9	1.1	0.5	0.7
DEVELOPED	4.6	5.3	5.8	5.2	5.7	2.6	3.9	4.4	3.8	4.3	2.0	3.5	3.9	3.4	3.8
DEVELOPING	1.0	0.0	0.2	-0.5	-0.4	-0.9	-1.2	-1.2	-1.7	-1.7	0.2	0.0	0.1	-0.5	-0.4
NAM	-3.7	-0.8	-1.1	-0.7	-1.0	-1.9	0.5	0.5	0.6	0.6	-3.1	-0.5	-0.7	-0.4	-0.6
WEU+ODE	7.5	3.7	4.1	3.9	4.4	5.9	2.6	2.9	2.8	3.2	5.5	2.5	2.8	2.8	3.0
EEU+FSU	11.0	13.8	15.4	13.1	14.8	3.8	9.0	10.1	8.4	9.5	3.7	9.1	10.3	8.5	9.6
PAO	1.8	0.8	0.7	1.1	1.0	3.1	1.6	1.7	1.8	2.0	2.3	0.6	0.5	0.9	0.8
AFR	4.3	0.1	0.4	-0.8	-0.8	3.4	-0.3	-0.2	-1.2	-1.3	4.0	0.3	0.4	-0.8	-0.9
LAM	0.1	-3.6	-3.9	-4.0	-4.3	1.1	-2.9	-3.1	-3.4	-3.6	1.9	-2.5	-2.7	-2.8	-3.1
WAS	5.4	-0.1	0.1	-0.8	-0.6	3.0	-1.8	-1.8	-2.4	-2.4	4.1	-0.1	0.0	-0.7	-0.6
SAS	1.8	1.0	1.3	0.6	0.9	-1.7	-1.3	-1.2	-1.6	-1.6	0.2	0.6	0.9	0.3	0.5
CPA	-2.5	1.8	2.1	1.6	1.9	-5.0	0.2	0.3	0.0	0.1	-4.3	1.2	1.5	1.0	1.3
PAS	-1.8	-1.9	-1.8	-2.6	-2.4	-5.0	-3.9	-3.9	-4.5	-4.6	-2.4	-1.3	-1.3	-1.9	-1.9

Table 20: Dynamic impact on world market prices (% change), year 2050

% price change compared to REF3						Variant V1					Variant V2				
	HER	MOM	MIS	MOMb	MISb	HER	MOM	MIS	MOMb	MISb	HER	MOM	MIS	MOMb	MISb
Cereals	-15	-10	-12	-10	-12	5	4	3	4	3	-4	-7	-9	-6	-8
Other crops	-24	-15	-17	-15	-17	-9	-3	-5	-3	-5	-15	-11	-12	-10	-12
All crops	-21	-13	-15	-13	-15	-4	-1	-2	-0	-2	-11	-9	-11	-9	-11
Agriculture	-15	-9	-11	-9	-11	-3	-0	-1	0	-1	-8	-7	-8	-6	-7

[13] For an explanation of acronyms and scenario variants refer to Table 9.