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Assessing Climate Change Impacts Agriculture

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Summary
The economy-wide implications of climate change on agricultural sectors in 2050 are estimated using a static computable general equilibrium model. Peculiar to this exercise is the coupling of the economic model with a climatic model forecasting temperature increase in the relevant year and with a crop-growth model estimating climate change impact on cereal productivity. The main results of the study point out on the one hand the limited influence of climate change on world food supply and welfare; on the other hand its important distributional consequences as the stronger negative effects are concentrated on developing countries. The simulation exercise is introduced by a survey of the relevant literature.

Keywords: Climate change, Computable General Equilibrium Models, Agriculture

JEL Classification: D58, C68, N50, Q54

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1. Introduction

The relationships between climate change and agriculture are complex and manifold. They involve climatic and environmental aspects, social and economic responses. These last can take either the form of autonomous reactions or of planned economic or technological policies. This picture is complicated further: indeed climate change and agriculture interdependencies evolve dynamically over time, they often span over a large time and space scale and are still surrounded by large uncertainties.

In what follows we review how the relevant scientific literature approached the problem, starting from the first studies in the early nineties to today's large coupling exercises, emphasizing the different solutions and methodologies used to respond to the different challenges.

Section 2 presents the main issues characterizing the relationship between climate change and agriculture, section 3 offers an historical background introducing when and why these different issues arose in the debate, section 4 describes the different analytical methodologies used, while section 5 summarizes the results obtained highlighting the main findings.

Section 6 proposes a simple integrated assessment simulation exercise coupling a climate model, a crop-growth model and a CGE model to assess the systemic general equilibrium effect of a hypothetical climate change on the agricultural industries in 2050.

Section 7 concludes.

2. Climate change and agriculture: Issues in modeling.

The environmental and the socio-economic dimensions are strongly intertwined in modeling the relationship between climate change and agriculture. Both need to be accurately taken into account in order to eventually produce a reliable picture of the complexities involved. The subsequent sub sections present the most relevant aspects to be considered.

2.1. Environmental issues

- **The role of temperature**. Higher temperatures will influence production patterns. Directly, as some plant growth and health may benefit from fewer freezes and chills, while some other crops may be damaged by higher temperatures; or indirectly through the temperature effect on water demand and supply, on the expansion of insects and plant diseases, on weeds expansion into different-latitude habitats.

- The interaction between soil moisture and changing precipitation patterns (extreme events). Based on a global warming of 1.4 to 5.8 °C over the next 100 years, climate models project that both evaporation and precipitation will increase, as will the frequency and intensity of rainfalls. While some regions may become wetter, in others the net effect of an intensified hydrological cycle will be a loss of soil moisture and increased erosion. Some regions that are already drought-prone may suffer longer and more severe dry spells. Moreover with changes in precipitation patterns soil moisture will decline in some mid-latitude continental regions during the summer, while rain and snow will probably increase at high latitudes during the winter.

- The interaction between carbon dioxide concentration and crops' productivity. In principle, higher levels of CO2 should stimulate photosynthesis in certain plants as they tend to suppress their photo-respiration. This should be true for the majority of species globally and especially in cooler and wetter habitats, including wheat, rice, barley, cassava and potato. Positive, but smaller effects on yields should be observed for tropical crops as maize, sugar cane, sorghum and millet, which are important for the food security of many developing countries, as well as pasture and forage grasses.

- Interaction with rangelands, pastures and livestock. For example, livestock would become costlier if agricultural disruption leads to higher grain prices or can depreciate where it depends more fully on the productivity and quality of the rangelands, which may become degraded.

- The feedback of agriculture on climate change. In general, agriculture contributes marginally to total GHG emissions. This apport is consistently reduced if the forestry sector - usually acting as a negative emitter providing a source of sinks for CO2 - is considered part of agriculture. Nonetheless, the agricultural sector remains the main emitter of nitrous oxide, coming from fertilizers and manure and methane coming from livestock and wetland or paddy rice farming. Moreover, deforestation is the second largest source of carbon dioxide. Accordingly any effect of climate change on agriculture and forestry inevitably feeds back to the climate system.

2.2. Socioeconomic issues

Agriculture is one of the most important human activities. It is still one of the main sources of income and productive sector in developing countries. In developed countries, notwithstanding its reduced share in the total economic activity, it still provides a fundamental contribution to welfare and socioeconomic development.

Accordingly, a relevant shock affecting the agricultural sector is likely to originate a whole set of responses in the socio-economic system. These responses span from the farm level up to the world economic level. They can be considered adaptation processes to the changing environment; in some cases they are autonomous reactions driven by self-regulatory mechanisms, in some other cases they respond to specific and planned policy interventions.

- Adaptation at the farm level. In history there are numerous examples of farmers' adaptation to changing climatic conditions. These possibilities are today increased by technological development and availability of information. Adaptation strategies vary from changing cultivation timing, mix and location, to preservation of the original environmental conditions (e.g. irrigation programs to counterbalance water scarcity or greenhouses to preserve humidity), to research and development (e.g. selection/production of more climate-change resistant varieties, improved warning system for extreme events etc.).

- Adaptation at the national level. Agriculture and forestry are economic sectors part of national economic systems. A climate-change induced shock on agricultural inputs (e.g. land or water) or outputs (e.g. on quantity/quality of crop production) propagates to the rest of the economy: changing prices reflecting changes in scarcity induce an autonomous substitution process between all factors of production, all goods demanded and all goods produced. The higher the flexibility of the economic system the lower is the final effect compared to the direct impact.

- Adaptation at the global level. Like sectors, countries cannot be considered in isolation: they are part of the world economic system. Linkages are provided by international flows of factors of production, goods and services. Climate-change shocks on agriculture are likely to be different in the different countries because of nation-specific environmental, socioeconomic and institutional factors. These asymmetries translate in different price changes for domestic goods and factors stimulating international trade flows. These mechanisms may benefit some countries and damage others working both as buffers or multipliers of the initial impact.

- The role of policy and of planned adaptation: At each of the three levels described above, autonomous socioeconomic reply can be strengthened or corrected by specific planned strategies decided by policy decision makers. National and international economic regulation, sectoral development strategies, environmental concerns can influence rural development and shape particular path for adaptation.

Summarizing, a modeling effort devoted to investigate the effect of climate change on the agricultural sector should in principle:

- consider changes in climate variables: temperature increase and variability, increase in CO2 concentration, changes in precipitation patterns,
- consider a set of additional climate-change induced environmental consequences: changes in land quality, water availability, frequency and intensity of extreme events,
- determine the physiological effects on crops' rate of growth and diffusion,
- consider at least the principal farm-level adaptation strategies: changes in cultivation timing, mix and location,
- consider the impact on/of main economic adjustment mechanisms at the national and international level: price effects, shifts in domestic and international supply and demand,
- finally, possibly take into consideration the feedback of the changed conditions on climate.

As can be seen the task is challenging. In particular, it is obvious that such an effort cannot rely on just one kind of modeling tool. On the contrary a comprehensive picture should couple Global Circulation Models (GCM), environmental impact models, crop growth models, land use models and economic models.

In the following sections we are going to analyze how all these issues have been dealt in the relevant literature.

3. Climate change and agriculture: Main Topics.

Since the beginning of an agricultural activity (traditionally placed after the last ice age 10,000 years ago), the role of environmental conditions in influencing soil properties, crops' growth and then land productivity and production has always been a paramount interest to farmers and then, much later, to agricultural scientists.

In modern times the empirical and experimental observation has been backed by the use of mathematical models for descriptive and simulation purposes.

Nonetheless these modeling exercises and typologies started to leave the restricted field of agricultural sciences to enter as a fundamental component the larger family of socioeconomic researches only in the 80s of this century.

Two important facts contributed to this process:

- Firstly the growing recognition of a demographic/poverty issue. Early warnings came from the 1972 “Meadows Report” and the 1974 UN-FAO World Food Conference in Rome. Subsequently, with a world population projected to increase to more than 8.9 billions by 2050, with about 85% of that population living in developing countries, it appeared crucial to study food production and security both under the perspective of adequacy of total supply to an increasing demand and in term of its socially equitable/sustainable distribution among richer and poorer world regions.
- Secondly the recognition of a global climate change issue. Since the beginning of the 1980s, many climatologists predicted significant global warming in the coming decades due to increasing atmospheric concentration of carbon dioxide and other trace gases. In 1988 the Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations Environmental Programme (UNEP) and the World Meteorological Organization (WMO) to assess the scientific, technical and socioeconomic information relevant for the understanding of human induced climate change, its potential impacts and options for mitigation and adaptation. Major possible changes in atmospheric, soil and hydrological regimes were forecasted to occur with a direct impact on food supply and demand.

The need to answer to the concerns posed by population growth and climate change on food production with their implications for welfare and socioeconomic development induced a flourishing modeling literature characterized, since its beginning, by the attempt to melt ecological and economic aspects. With the increasing knowledge accumulated on socioeconomic and environmental dynamics as well as the development and improvement of computational capacity of computers, modeling exercises became wider in scope and finer in methodology.

Food security was the main issue in earlier 1990s (Kane et al., 1992) and the investigation was generally focused on regional or domestic agricultural impact. (see e.g.: Louise, 1988; Martin et al., 1988; Adams et al., 1990; Sian Mooney and Arthur, 1990). Quite soon the recognition of the global nature of climate change and of the interdependencies between economies led successively to various attempts to introduce international trade into the picture (see e.g.: Rosenzweig et al., 1993; Reilly, 1994; Fischer et al., 1993; Adams et al., 1990). The mid 90s saw two further important steps toward reality. The first was the explicit consideration of adaptation opportunities. The previous researches only considered the passive impact of climate change on agriculture assuming no changes in farmers behavior (the so-called “dumb-farmer hypothesis”). Ignoring adaptation is obviously inadequate and can lead to serious misjudgment of the likely impact. Farmers' response to the climate and natural environmental change was thus taken into account (see e.g.: Mendelsohn 1994, 1999, Reilly 1994, Adams et al., 1988, 2000). The second, was the recognition of the physical and economic relationship of the agricultural sector with the rest of the economy. Competing uses of typical agricultural inputs like water and land were introduced (see e.g.: Darwin, 1995; Tsigas, 1996; Darwin, 1999).

Finally sustainability, vulnerability and uncertainty appeared in the research agenda. Latter studies examined vulnerability defined in terms of yield, farm profitability, regional economy and hunger explicitly considering uncertainty about future climate-change impacts (Reilly, 1999; Schimmelpfennig et al., 1996). The measure of uncertainty related to extreme events and optimal risk management is one of the main topics under this line. In particular, with the increasing accumulation of meteorological evidence, the role of extreme events in particular of El Niño and La Niña Southern Obscillation (ENSO) driven phenomena appeared into the investigation (see e.g. Adams et al., 1999; Adams et al., 2003).

4. Climate change and agriculture: comparing methodologies

Since the first modeling exercises to the last studies, many different methodological approaches and techniques have been used. Notwithstanding differences two broad categories appeared: what can be called "agriculturally oriented" and "economically oriented" researches. The first strand of studies concentrates on the ecological and biological response of soils and crops to climatic variation, considering economic interactions only partially and in a very simplified form. The second emphasized market mechanisms, analyzing agriculture as an industry part of the economic system necessarily oversimplifying the natural mechanisms at the base of crop growth and reaction to climate.

It is however important to stress how today the increasing tendency to a wider multidisciplinarity has blurred this distinction. As said, seminal studies already interfaced climatic information, crop growth models and at least some economic feedback. Then, the development in computer capacity and software flexibility allowed to build increasingly large and complex modeling frameworks called Integrated Assessment models (see e.g. the IMAGE model (IMAGE team, 2001), the IGSM-MIT model (Prinn et al., 1999), the AIM model (Kainuma et al. 2002)). Within these models, in which agriculture is only a part of the picture, Global Circulation Models, environmental impact models and economic models are linked together in a balanced and coherent manner. In principle this approach allows either specificity or a bottom-up perspective, as any sub model can be developed to a high level of detail, and comprehensiveness or the top-down view, given that no impact on any sector is considered in isolation and a general picture can be drawn.

4.1. The treatment of crops' response.

The first step in assessing the climate change impact on agriculture is to describe and simulate the bio-physical reactions of different crops to changing environmental conditions. As said, in the literature both a bottom-up and a top-down vein can be identified.

The first is based on the use of plant physiology models and of vegetation distribution models. The first set of models, considering a wide range of environmental and plant characteristics, basically describes how a given vegetal specimen grows and reproduces, the second on the basis of different climatic factors describes how vegetation distributes. Jointly these models can thus simulate how crops' varieties change their rate of growth and diffusion across the cultivated land responding to climate. Examples of plant physiology models are: CERES–Maize (Ritchie et al., 1989), CERES-Wheat (Godwin et al., 1989), SOYGRO (Jones et al., 1988) for major grains, SIM-POTATO (Hodges et al., 1992) for potatoes.

Examples of vegetation models are MAPPS (Neilson, 1993, 1995), DOLY (Woodward et al., 1995) and LPJ model (Criscuolo et al., 2004).

Impact assessment exercises using this approach are for example: Adams et al. 1995; Adams et al. 1999.

The top-down approach does not model directly the physiological mechanism driving plant reaction, but infers evolution in crop productivity through observation. Observing different yields of the same crops at different latitudes or during different periods of the year it is possible to derive what crops reaction would be to changing climatic conditions. This approach called *spatial analog* is based on statistical estimation and uses cross sectional data. Accordingly it depends on the data reliability and representatives and on the ability of statistical analysis to isolate confounding effects (Schimmelpfennig et al., 1996).

The method of spatial analogs is widely used see e.g.: Mendelsohn et al., 1994, Chen et al. 2000, Darwin et al., 1995, 1999, 2001.

4.2. The treatment of human response.

The crucial aspect of human responses at the farm level has been incorporated in most advanced agricultural studies only recently.

Basically two approaches can be identified.

The first is the above mentioned spatial approach. Already used to simulate crops' responses as an alternative to crop models, it has been applied to describe human reactions as well. The second is referred to as the "structural" approach. The distinction is not always clear in the literature; moreover those labels are somewhat misleading as both approaches share the "analogous regions concept" (Darwin, 1999): by looking at the choices, strategies and technologies being adopted now by farmers in different locations under different climatic regimes, it is possible to infer how farmers are likely to respond to a changing climate when it will take analogue characteristics. Consequently it is also possible to consider the capacity of these adaptation strategies to reduce the initial negative impact (or to enhance the positive one) in term of land values.

The true difference between the two approaches relies on the way this information is used.

In spatial analogue models, no matter how farm-level adaptation is estimated (trough cross-sectional statistic and econometric techniques like e.g. in Mendelsohn et al (1994), (1996), Chen et al. (2000) or through geographic information systems like in the FARM GIS exercise (Darwin, 1999)), the consequent variation in land values is assumed to reflect exactly the welfare implication of climate-change impacts on agriculture. In other words it is assumed that the crop and farmer responses to climate are already present in the observed data such that the biophysical and economic adjustments imposed by climate change have been made across the landscape or time. This methodology would present the advantage of bypassing the need to accurately model yield and water demand and supply physical implications of climate change as well as economic adjustments (McCarl et al. 2001). According to Mendelsohn et al., (1996) this can be legitimate if changes in land prices would not feed back on agricultural prices and on the prices of all the other inputs and outputs in the rest of the economy. Nevertheless this is unrealistic and constitutes also one of the major drawbacks of this approach if used in isolation. Indeed neglecting price changes, the feedback on domestic and foreign supply and demand are completely lost.

The structural approach, on the contrary goes one step further as changes in land values are fed into more or less sophisticated economic modules to explicitly consider the responses of all the economic agents. This methodology requires a sufficient structural detail on farm management practices and becomes particularly problematic when it has to be applied to the large scale (region, country or macroregion) as usually only few existing observations have to be considered representative of behaviors and adjustments in vast areas (Schimmelpfennig et al., 1996).

Next section will explicitly focus on the way the economic dimension has been treated by the structural approach.

Here we conclude reporting three important criticisms common to the two approaches, related to the nature of the "analog region concept" highlighted by Schneider (1997). This procedure can be reliable only if: variations across time and space are equivalent, only one steady state occurs per set of exogenous conditions and the - by necessity - limited amount of climatic variables usually considered, is able to capture all the relevant information about climate change and its impacts on agriculture. All these three conditions are unlikely to hold therefore this calls for additional cautiousness in interpreting results.

4.3 The treatment of the economic dimension

In the treatment of the economic dimension, it is possible to identify a progressive shift from a partial equilibrium view to a general equilibrium approach.

Studies can be partial in sectoral and/or geographical coverage.

There are studies offering a worldwide coverage, but modeling only the agricultural sectors. In these cases, changes in crops production and productivity – typical supply-side shocks in economic terms – influence agricultural commodity prices affecting domestic demand and import-export fluxes. These on their turn feed back on agricultural production and demand through world food trade models. Usually these studies provide a high disaggregation in term of crop varieties and offer a detailed description of substitution processes within agricultural industries. Nonetheless they fail to capture the crucial aspect of factor reallocation and demand shifts toward sectors different from agriculture. Examples of such studies are e.g. Kane et al. 1992 and Reilly et al. 1994, using the SWAPSIM world food model. This model identifies supply and demand of 20 agricultural commodities for 36 world regions including international trade fluxes, but abstracts from other economic sectors and does not explicitly incorporates resource inputs.

A slightly different class of partial equilibrium researches does consider extensively the role of intersectoral economic effects, but focuses only on the implication for world food production by the agricultural sector. Accordingly results reported do not (and are not intended to) provide a comprehensive assessment of all the welfare effects. Studies like e.g. Fisher et al. 1993 and

Rosenzweig and Parry 1994 belong to this vein. Their assessment of climate change impacts on world food supply is based on the IIASA BLS framework which is a general equilibrium economic system composed by 35 interlinked regional and national models representing all the major economic sectors. Nevertheless the analysis is then confined to impacts on agriculture and the implications for the rest of the economic system are put aside.

Other studies are partial both in the sectoral and geographical coverage as they analyze the agricultural sector in a particular country or region. International allocation movements of goods and factors are usually highly simplified and limited to import/export of agricultural commodities. Climate change impacts on US agricultural sector are the most represented in this strand of literature (see e.g. Adams et al. 1995a, 1999, 2001). Relatively few national studies exist on developing countries (see e.g. Butt et al., 2004; Butt, 2002, Downing, 1992). Typical exercises of this kind have been performed also to evaluate the economic consequences for agriculture of extreme climate-related events (see e.g. Adams et al., 1999 for ENSO consequences for the US agriculture and Adams et al., 1995b and 2002 to assess the value to farmers of an early warning system for extreme events in the US and Mexico respectively).

Finally there are studies treating comprehensively the economic part. Common tools used for this purpose are General Equilibrium Economic Models (GEMs).

GEMs describe the economy through the behaviour of optimising producers and households which demand and supply goods and factors. Adjustment processes to excess demand and supply determine equilibrium prices in all markets. Profit maximisation under perfect competition and free market entrance guarantee zero profits and the optimal distribution of resources. All markets being linked, the main feature of GEMs is exactly the ability to capture the propagation mechanism induced by a localized shock onto the international context via price and quantity changes and vice versa.

At the beginning, GEMs were developed mainly to analyze international trade policies and relationships. Soon, because of their great flexibility, they become a common tool for economists to investigate the consequences of the most diverse economic perturbations including those provoked by climate change. Indeed, notwithstanding their complexity, those consequences can be represented as changes in productivity, production or demand for the different inputs and outputs. This kind of information can be processed by GEMs and the final welfare implications can be determined.

In the specific case of the economic evaluation of climate change impacts on agriculture, the empirical literature proposes different solutions.

The simpler is to impose directly the observed change in the production factor(s) – typically land - stock and/or productivity as an exogenous shock to the economic model. The change in the quality/quantity of the input in the production function generates a readjustment to price and quantity changes whose final result can be measured in terms of welfare and utility. This is for example the approach followed by the study presented in the next section, but also by e.g. Deke et al.(2002) and Darwin and Tol (2001)[1] using respectively the GTAP (Hertel, 1997), DART and FARM economic general equilibrium models.

Often land is considered as a homogeneous production factor. In fact, because of climate and soil characteristics, land in different locations has specific properties and there are limits to crops' switching. One possibility to account for this is to differentiate land according to agro-climatic zones (see e.g. Lee, 2004). In this case there are different land inputs which are imperfectly substitutable in the production function within, but not across climatic zones. Accordingly the reaction of the economic system to prices and quantity is exposed to one more rigidity.

Instead of building land differences "inside" the economic model, another possibility is to do this "outside" the model, developing autonomous modules accounting for different land characteristics and uses. This is the route followed e.g. by the FARM-GIS exercise (Darwin, 1999) where a half-degree grid Geographic Information System is used to identify six land classes and thresholds in crop production possibilities. This module can evaluate changes in land rent due to climatic variation; this information is then processed by the FARM-CGE economic model.

Finally, an alternative methodology couples the yield and economic information with a land use model. These models, starting from prices, predict how land is allocated among competing uses. These are not limited to different cultivation types, but include also urban development. In this way the additional feedback from land/crop prices to land allocation is added. In principle the process should be iterated until a reasonable convergence can be found. This route is computationally and modeling demanding, usually it is pursued in large integrated assessment exercises like the abovementioned IGST, IMAGE, AIM. Each of this exercise couples a land use model with a CGE (respectively EPPA, WORLDSCAN, AIM-CGE).

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[1] In these two studies the negative shock on agricultural land stock was a consequence of sea level rise, but the reasoning is exactly the same of a cultivation loss induced directly by climate change.

5. Climate change and agriculture: Comparing results

Table 1: Climate Change Impacts on Agriculture, Selected Studies

Reilly et al., 1994			
	Climate Change Impact on Welfare - Millions of 1989 US $ - 2 X CO2		
	No CO2 fert. effect no adaptation	CO2 fert. effect no adaptation	CO2 fert. effect and adaptation
Region 1: <$500/capita	-56,692 to –121,063	-2,070 to -19,827	-210 to -14,588
Region 2: $500-$2000/capita	-26,171 to -48,095	-1,797 to 15,010	-429 to -10,669
Region 3: >$2000/capita	-3,870 to -6,661	-603 to -1,021	-328 to -878
E.EUROPE/USSR	-12,494 to -57,471	1,885 to -10,959	2423 to -4,875
OECD	-13,453 to -21,485	2,674 to -15,101	5,822 to -6470
WORLD	-115,471 to -248,124	-126 to 61,225	7,003 to -37,623

Fischer et al., 1993			
	Climate Change Impact on Crop Productivity - % change - 2 X CO2		
	No CO2 fert. effect no adaptation	CO2 fert. effect no adaptation	CO2 fert. effect and adaptation
Dvl.ped Countries	-19.27	0.97	6.23
Dvl.ping Countries	-29.57	-7.07	-2.17
WORLD	-26.83	-5.3	-0.07

Rosenzweig et al. 1994			
	Climate Change Impact on Cereal Productivity - % change - Projection for 2060		
	No CO2 fert. effect no adaptation	CO2 fert. effect and minor changes to existing agric. system	CO2 fert. effect and major changes to existing agric. system
Dvl.ped Countries	4.50	4.50	6.50
Dvl.ping Countries	-10.50	-6.50	-10.40
WORLD	-4.50	-0.60	-2.50

Kane et al. 1992		
	Climate Change Impact on Welfare - % change - (from moderate to very adverse). 2 X CO2	Climate Change Impacts on Crops Productivity - % change - (from moderate to very adverse). 2 X CO2
US	0.005 - -0.31	-15 - -40
Canada	-0.047 - -0.21	-20 - -5
EEC	-0.019 - -0.40	-15 - -10
Other Europe	-0.010 - -0.10	10 – 15
Japan	-0.062 - -0.29	-5
Austria	0.038 - 0.04	-10 - -15
USSR	0.032 - -0.52	-15
China	1.280 - -5.48	-20 - -10
Brazil	-0.017- 0.22	No Change
Argentina	0.120 - 2.82	No Change
Pakistan	-0.153 -1.63	No Change
Thailand	-0.081 - 1.22	No Change
ROW	-0.002 - -0.84	-10
WORLD	0.01 - -0.47	

Table 1: Climate Change Impacts on Agriculture, Selected Studies (continued)

Tsigas et al. 1997

	Climate change impacts on crop productivity - % change - 2 X CO2		Climate change impacts on Welfare - % change - 2 X CO2	
	Without CO2 Fertilisation Effect	With CO2 Fertilisation Effect	Without CO2 Fertilisation Effect	With CO2 Fertilisation Effect
Canada	-3.00	24.00	-0.02	0.50
USA	-17.00	2.00	-0.56	0.04
Mexico	-43.00	-24.00	-6.70	-2.78
EU	-9.00	11.00	-1.02	0.29
China	-17.00	3.00	-7.23	0.54
ASEAN	-34.00	-11.00	-7.59	-1.73
Australia	-16.00	8.00	-0.21	0.26
ROW	-22.00	-1.00	-2.48	-0.12
WORLD			-1.75	0.01

Rosenzweig and Iglesias, 1994

	Climate Change Impacts on Crops' Productivity - % Change - 2 X CO2		
	Rice	Maize	Wheat
Indonesia	-2.5% - + 5.4%	-40%	
Malaysia	-22% - -12%	0%	
Pakistan			-60% to -10%
Sri Lanka	-2.1% to +3%		
Bangladesh	-6% t0 +8%		
Mongolia			-74.3% to + 32%
Kazakhstan			-56% to + 44%
Czech Republic			-3% to + 16%
United Kingdon	5% to 15%		
The Bambia		-26% to -15%	
Zimbabwe		-13.6% to -11.5%	
Brazil	-27% to -7%		-46% to –17%
Argentina	-17% to +4%		-12% to + 6%
Uruguay			-31% to - 11%
United States	-23% to 1%	-29% to -15%	-14% to - 2%

Harasawa et al., 2003

	Climate Change Impacts on Crops Productivity - % Change – (*)				Social Welfare - % Change – (*)
	Rice	Wheat	Other Grains	Other Crops	
Japan	0.11	-6.6	-15.56	0.11	0.022
China	-0.25	-3.97	-1.39	0.07	-0.21
India	-1.76	-7.64	-1.33	-4.25	-4.89
Canada	105.99	115.07	89.41	-2.26	0.343
Usa	0.23	2.87	-4.04	0.25	0.009
Eu	2.03	-3.64	-6.50	-0.03	0.003

(*) % change 1990-2100 in the IS92a IPCC emission scenario.

Table 1: Climate Change Impacts on Agriculture, Selected Studies (continued)

Adams et al. 1999b		
	Benign Case (*)	Adverse Case (**)
	Climate Change Impacts on Welfare - % change Without Adaptation – 2060 Projections	
USA TOTAL	2.70	0.01
	Climate Change Impacts on Welfare - % change With Adaptation – 2060 Projections	
USA TOTAL	2.73	0.42
USA REGION	Climate Change Impacts on Crop Production - % Change in Regional Index Number Without Adaptation – 2060 Projections	
Northeast	44.59	83.49
Lake States	165.91	122.66
Corn Belt	106.28	82.99
Northern Plains	113.54	148.75
Appalachia	96.48	59.02
Southeast	138.65	98.26
Delta States	91.30	70.68
Southern Plains	75.17	59.00
Mountain States	121.97	115.75
Pacific Coast	134.64	129.76
(*) 2.5°C, +7% Precipitation, 530 ppm. CO2 (**) 5°C, +0% Precipitation, 530 ppm. CO2		
Adams et al. 1999a		
	Estimated Costs of Strong El Niño and La Niña Events (Millions of 1990 $)	
USA	- 2543	-6455
Adams et al. 2003		
	Net Present Value of Early Warning System for ENSO Phenomena (Millions of 2001 $)	
	19-year Period	51-year Period
Mexico	227.5	233.6

1- <u>Climate change impacts on agriculture are of limited extent.</u>

The main finding emerging from the literature is that climate change impacts on agriculture are quite “small”. This is true either under the perspective of impacts on yields and accordingly on food supply and availability or considering more extensively general equilibrium and welfare implications. This outcome is particularly robust as it is confirmed by the most diverse studies endorsing both the spatial and the structural view, adopting a national or a global perspective, considering simplified or complex adaptation procedures. Global studies reviewed, report for the world as a whole a loss ranging from the –2.5% to the –0.07% in term of food production and ranging from the –0.047% to the 0.01% in term of welfare in case of a doubling CO2 concentration. In regional studies, welfare changes range between the –5.48% and the +2.73% .

It is interesting to note that in general national and partial equilibrium studies report higher impacts respect to global, general equilibrium studies. As said this confirms the role of intersectoral and international substitution processes as smoothers. There is however an additional subtler reason for that: a general equilibrium approach naturally takes into account the welfare of all the agents within the economic system, and usually losses to one agents turn out to be gains for another. Typical example is a decrease in consumers' surplus that is automatically balanced by the increase in producers'. The net effect is thus reduced.

2- Crucial Role of Adaptation.

It is particularly important to highlight that the limited influence of climate change on agriculture is mainly due to natural or human adaptation mechanisms. In general strong negative impacts highlighted by exercises neglecting adaptation turn into much smaller losses or even slight gains when proper adaptation options are modeled. Interestingly, when it is explicitly taken into account (see e.g. Reilly et al. 1994; Fischer et al. 1993, Rosenzweigh et al. 1994), the fertilization effect due to the increased CO2 concentration - that can be considered as an autonomous natural adaptation process – contributes more to damage reduction than human adaptation. All the studies confirm in any case the fundamental role of economic adaptation in smoothing adverse climatic effects.

It is worth to stress here the uncertainty surrounding the modeling of CO2 fertilization effect and especially of human adaptation options. There are various views about adaptation. Scientists disagree whether the rate of change of climate and the required adaptations would add significantly to the disruption that farming will experience form future changes in economic conditions, technology and resource availabilities (see e.g. Kane and Reilly, 1993; Reilly 1994). Indeed there are many questions still puzzling regarding to adaptation. For example: how can agriculture adjust? Rapidly and autonomously, slowly and only with careful guidance? Is there little scope for adjustment? Does response of the system require planning by farmers specifically taking into account climate change, and if so what is their capability to detect change and respond (Reilly, 1999)?

This is an important qualification of the highlighted results. Should adaptation be less effective, strong adverse consequences of climate change on agricultural production and welfare cannot be excluded.

3- Uneven Distribution of Effects

Agricultural sectors in different regions are likely to be affected and to respond differently to climate change. In particular results highlight a higher vulnerability of the developing world. On the one hand this is due to a purely physical fact: the latitude where most part of developing countries are located. Though employing different methods and scenarios, most studies (see e.g. Rosenzweig, et al. 1994, Kane et al. 1992, Darwin et al., 1995) generally support the conclusion that low latitude yields will fall and middle and northern latitude yields will rise with a doubling of CO2 levels.

On the other hand this is related to their lower capacity to adapt[2].

Again, negative impacts are not “big”, but this outcome needs to be carefully qualified: apart from uncertainties, many developing countries are already experiencing severe risk of hunger and malnutrition problems. Accordingly even a slight worsening of an already dramatic situation is a worrying eventuality.

4 – Role of Extreme Events

When climate change is considered only as a variation in average conditions, impacts on agriculture can be positive and negative. They become unambiguously negative when extreme events, representing changes in extreme conditions, are taken into account (Adams et al., 1998; Solow et al., 1998, Chen et al., 2000). Also agriculture reflects this typical characterization of the relationship between climate change and adaptation: average change is slow and usually falls within the “coping range” of systems, extreme change is abrupt and often outside this coping range.

6. The modeling exercise

As an introduction of the modeling exercise performed, we firstly describe the approach used and place it in the stream of the reviewed literature.

6.1. The modeling approach.

Our investigation is an integrated assessment exercise, conducted at the world level, coupling with the so-called “soft-link” approach a GCM, an agricultural sub-model and an economic model. The GCM used is a reduced-form of the Schneider-Thompson GCM: starting from CO2 emissions, it provides information on the expected increase in average world temperature and CO2 concentration in the atmosphere. This average data is then disaggregated into 22 geo-climatic zones following Giorgi and Mearns (2002) and fed into a crop productivity change module. This module (Tol, 2004) extrapolates changes in yields respect to a given scenario of temperature increase. It is based on data from Rosenzweig and Hillel, 1998 which report detailed results from an internally consistent set of crop modeling studies for 12 world regions and 6 crops' varieties. The role of CO2 fertilization effect is explicitly taken into account. Finally changes in yields are used as input in the global economic model in order to assess the systemic general equilibrium effects.

To do this, we made an unconventional use of a standard multi-country world CGE model: the GTAP model (Hertel, 1996), in the version modified by Burniaux and Truong (2002), and subsequently extended by ourselves.

In a first step, we derived benchmark data-sets for the world economy "without climate change" at some selected future years (2010, 2030, 2050), using the methodology described in Dixon and Rimmer (2002). This entails inserting, in the model calibration data, forecasted values for some key economic variables, to identify a hypothetical general equilibrium state in the future.

Since we are working on the medium-long term, we focused primarily on the supply side: forecasted changes in the national endowments of labour, capital, land, natural resources, as well as variations in factor-specific and multi-factor productivity.

We obtained estimates of the regional labour and capital stocks by running the G-Cubed model (McKibbin and Wilcoxen, 1998) and of land endowments and agricultural land productivity from the IMAGE model version 2.2 (IMAGE Team, 2001). We ran this model by adopting the most conservative scenario about the climate (IPCC B1), implying minimal temperature changes.

In the second step we imposed over these benchmark equilibria the climate change shock on agriculture that we model as a change in the productivity of land devoted to the production of the different crops in the different regions.

Tsigas et al. 1997, perform a similar exercise measuring general equilibrium effect of climate change in agriculture using the GTAP model. The basic differences between their and our approach are: firstly the climate scenario, they refer to a doubling of CO2, while we project directly the temperature increase consistent with the emissions from the economic model;

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[2] Lower capacity does not mean lower knowledge, skill or ability. Rather it refers to the usually lower amount of resources available for adaptation options or to stronger technological or market constraints to

secondly the economic benchmark, they use the model calibrated in 1997, while as said, we pseudo-calibrated the model in 2050; thirdly the economic shocks, they implemented climate change as a Hicks neutral technical change in the crop sectors in each region, that is productivity changes affect uniformly all the production factors used by the agricultural industries while, in our case climate change intervenes, we believe more realistically, only on land-productivity-augmenting technical change.

This exercise suffers also from some major limitations. We mention the following:

- firstly an analysis at the world level requires heroic simplifications and generalizations of both climatic conditions and crop responses. A very narrow number of observations is used to provide information on vast areas inducing an unrealistic uniformity,
- secondly - apart from temperature and CO2 fertilization effects - other important impacts of climate change on agriculture are missing, primarily interrelations with water availability and with livestock,
- thirdly adaptation at the farm level is partly disregarded especially decisions on cultivation timing as the exercise is purely static. Moreover there is not a land use model defining the optimal allocation of land among competing alternatives; land is a production factor used only by the agricultural sector and not for instance by the residential or the industrial sectors, as a consequence also the mechanism governing the decision on cultivation location results highly simplified,
- finally the exercise concentrates only on few kinds of cereal crops.

Nonetheless, the exercise is particularly useful in highlighting substitution mechanisms and transmission channels within and between economic systems. It allows to represent and disentangle those adaptation mechanisms at work in the modern economies that can amplify or smooth an initial shock and produce a final effect largely different from the original stimulus.

This crucial role of autonomous national and international socioeconomic adaptation is the matter of the next subsection.

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the adoption of adaptation opportunities in developing countries respect to developed economies.

6.2. Results and comments.

In what follows we are reporting results for 2050 when, according to our calculations, temperature is expected to increase 0.93°C respect to year 2000. Results for the other benchmark years are qualitatively similar.

As can be seen (tab. 2) the productivity of land used for the cultivation of rice and wheat, generally increases benefiting of the improved fertilization effect due to higher CO2 concentration. The opposite happens to cereal cultivation. RoA1, CHIND and RoW are partly different: the first two show an increased while the last a decreased land productivity in all crops.

As expected the price of different crops moves in opposition to productivity (tab. 4).

Firstly it is worth noticing that direct productivity shocks are bigger than final general equilibrium effects on GDP. This because the economy can substitute land for other inputs (e.g. capital), or vice versa.

Then, in line with all the more recent literature, effects on GDP are generally small, (negative for USA, EEx and RoW, positive for the other regions) and relatively more negative for developing countries. What is interesting to note here, is how the change in land productivity propagates to GDP and to international capital flows. It is firstly worth recalling the rather peculiar mechanism GTAP uses to allocate capital internationally: a central bank collects savings from the regional households that save a given amount of their income and then proceeds to redistribution. The engine of the entire process is the equalization of the expected rate of return to (price of) capital in all regions. As shown by table 2, GDP is positively (negatively) affected when the net effect on land productivity is an increase (decrease). In the GDP gaining (loosing) regions the positive(negative) aggregate result fosters(depresses) the demand of all inputs including capital, capital increases(decreases) its real price (tab. 4) and subsequently capital inflows(outflows) are stimulated (tab.2).

Also a substitution effect is at play here: when land productivity increases, land prices tend to decrease as a given agricultural output can be produced with a lower amount of land. This causes a substitution away from relatively costly factors, capital and labor, to the cheaper land. Capital price decreases and capital tends to exit the region. (The same reasoning applies, reversed, in case of a land productivity decrease).

If we consider capital prices and flows, due to the (low) degree of substitution between capital and land, the aggregate effect always prevails.

Nevertheless this is not generally true considering the land price where the productivity effects dominate the aggregate effect. An example particularly clear is CHIND: here land productivity unambiguously increases with a positive effect on GDP, but land price decreases.

Note also that generally terms of trade effects act as smoothers: a relative decrease in GDP induces a shift toward domestic goods by domestic and foreign consumers attracted by decreasing prices. This decreases the price of imports and increases the price of exports. Again this is not always the case. In three regions terms of trade effects amplify rather than smooth the GDP result: USA, where changes in terms of trade strengthen the negative performance of production and JPN and CHIND where they reinforce the positive one.

The interplay between terms of trade and capital flows explains also the different sign that sometimes is observable in the household utility index respect to GDP.

Finally tab. 3 reports industrial production. In general positive GDP and productivity changes translate in similar changes in production level, particularly of agricultural industries.

Tab. 2

	Exogenous Shocks on Land Productivity in Different Agricultural Industries (% change w.r.t. baseline)			Endogenous Responses (% change w.r.t. baseline)				
	Rice	Wheat	Cereal Crops	GDP	Private Utility Index	Co2 Emissions	Terms of Trade	Internat. Capital Flows
USA	1.214	1.497	-1.702	-0.023	-0.047	-0.056	-0.183	-0.152
EU	1.811	1.046	-1.134	0.006	-0.005	-0.004	-0.048	0.019
EEFSU	1.856	3.641	-0.822	0.011	0.008	0.001	-0.016	0.037
JPN	0.973	0.399	-1.999	0.004	0.012	0.035	0.023	0.082
RoA1	6.624	8.993	3.619	0.067	0.046	0.032	-0.080	0.1
EEx	1.349	2.063	-1.659	-0.013	0.047	0.010	0.214	-0.002
CHIND	3.962	5.068	0.870	0.212	0.215	0.012	0.095	0.98
RoW	-1.791	-1.599	-4.891	-0.126	-0.099	-0.175	0.076	-0.35

Tab. 3

Endogenous Responses: Industry Output by Region (% change w.r.t. baseline)								
	USA	EU	EEFSU	JPN	RoA1	EEx	CHIND	RoW
Rice	-0.581	-0.498	0.045	-0.086	1.867	-0.015	0.461	-0.505
Wheat	-1.025	-0.507	0.513	-3.835	5.851	-0.94	0.715	-2.604
CerCrops	-0.523	0.867	0.794	0.511	5.304	0.228	1.7	-3.335
VegFruits	-0.386	0.379	0.129	0.206	0.08	-0.111	0.352	-0.355
Animals	-0.348	0.112	0.096	0.024	0.182	-0.077	0.4	-0.435
Forestry	-0.011	0.023	0.023	-0.022	-0.057	0.022	-0.082	0.01
Fishing	0.126	-0.033	0.017	0.004	-0.11	-0.01	0.082	0.032
Coal	0.05	-0.021	-0.012	-0.127	-0.079	-0.008	-0.153	0.194
Oil	0.08	0.005	-0.003	-0.079	-0.071	-0.004	-0.223	0.205
Gas	0.089	0.018	-0.016	-0.053	-0.191	-0.012	-0.666	0.438
Oil_Pcts	-0.077	-0.006	0.015	0.01	0.078	-0.014	0.162	-0.04
Electricity	0.02	-0.006	-0.013	-0.012	-0.135	0.002	-0.051	0.094
Water	0.004	0.003	0.006	-0.008	0.016	0.035	-0.037	0.008
En_Int_ind	0.145	-0.027	-0.042	-0.094	-0.276	-0.076	-0.332	0.257
Oth_ind	-0.165	0.027	0.032	0.058	-0.072	-0.054	0.284	-0.345
MServ	0.015	-0.012	-0.012	-0.002	-0.018	0.007	0.082	0.085
NMserv	0.004	-0.004	0.005	-0.008	0.022	0.034	-0.076	0.017

Tab. 4

Endogenous Responses: Primary Input (Real) Prices by Regions (% change w.r.t. baseline)								
	USA	EU	EEFSU	JPN	RoA1	EEx	CHIND	RoW
Land	1.948	-0.003	0.422	-0.399	0.873	1.091	-0.745	2.156
Lab	-0.121	-0.037	-0.02	0.015	0.003	-0.088	0.977	-0.414
Capital	-0.121	-0.038	-0.023	0.016	0.034	-0.096	1.04	-0.451
NatlRes	0.304	-0.046	-0.043	-0.048	-0.414	-0.108	-0.103	0.061
Endogenous Responses: Industry Prices by Regions (% change w.r.t. baseline)								
Rice	-0.932	-2.311	-1.726	-0.826	-4.646	-0.916	-4.924	3.515
Wheat	-1.586	-1.569	-3.067	-1.776	-4.37	-1.488	-5.439	0.911
CerCrops	3.374	1.976	1.568	1.761	-0.409	2.635	-0.315	4.395
VegFruits	0.9	0.247	0.335	0.157	0.521	0.618	-0.017	0.73
Animals	1.653	0.181	0.297	0.6	0.495	0.648	-0.113	0.782
Forestry	-0.048	0.058	0.072	0.104	0.034	0.048	0.744	-0.357
Fishing	-0.079	0.053	0.062	0.115	0.031	0.023	0.354	-0.275
Coal	-0.157	-0.011	0.031	0.068	0.083	0.018	0.486	-0.091
Oil	-0.088	0.013	0.034	0.069	0.028	0.015	0.323	-0.085
Gas	-0.21	0.012	0.032	0.109	0.04	0.016	0.55	-0.343
Oil_Pcts	-0.072	0.015	0.033	0.085	0.033	0.017	0.336	-0.089
Electricity	-0.214	0.005	0.029	0.124	0.12	0.017	0.655	-0.339
Water	-0.18	0.007	0.038	0.132	0.125	0.023	0.754	-0.381
En_Int_ind	-0.163	0.018	0.044	0.123	0.095	0.05	0.43	-0.2
Oth_ind	0.131	0.092	0.087	0.093	0.129	0.131	0.069	0.187
MServ	-0.188	0.015	0.045	0.131	0.118	0.037	0.52	-0.339
NMserv	-0.178	0.017	0.046	0.131	0.115	0.055	0.625	-0.293

7. Conclusions

In this paper we offered a survey of the various approaches used to describe, model and measure the complex relationships between climate change and agriculture. The main message that can be grasped from the relevant literature is that climatic, agricultural and economic information need to be consistently melted in order to provide a reliable and sound impact assessment analysis in this field. This is witnessed by the constant effort to expand the comprehensiveness of the investigation that has recently led to the construction of large modeling frameworks coupling global circulation models, crop growth models, land use models and economic, usually general equilibrium, models. A robust finding of all these modeling efforts is that climate change impact on food supply and on welfare are of limited extent. Nevertheless this outcome is largely determined by the working of socio-economic autonomous and planned adaptation processes, whose real costs and potential in limiting adverse consequences from climate change are highly controversial and uncertain. Another robust result is that, notwithstanding adaptation, agricultural sectors in the developing world will be adversely affected with negative consequences either in terms of food availability or of welfare. Considering the already dramatic situation faced by many developing countries even “small” worsening can lead to serious threats to their socio-economic development. This also raises the crucial issue of proper re-distributional policies from developed to developing countries.

Finally we proposed an integrated assessment exercise to evaluate climate change impact on agriculture. As it is standard to the approach we coupled a global circulation model, with a crop-growth model, with an economic model. Original to our approach is the determination of the climatic scenario, endogenously produced by the economic model and the benchmarking of the economic model itself, reproducing a hypothetical world economic system in 2010, 2030 and 2050. The results we get are in line with the existing literature confirming both the limited impact of climate change on agricultural sectors, largely determined by the smoothing effect of economic adaptation, but also the relative higher penalization of the developing world.

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