Global Journal of Agricultural Economics and Econometrics

ISSN: xxxx-xxxx Vol. 1 (1), pp. 040-050, November, 2013. © Global Science Research Journals

Review

Measuring the effect of climate change on agriculture: A literature review of analytical models

Maria De Salvo[1], Diego Begalli[1]* and Giovanni Signorello[2]

[1]Department of Business Administration, University of Verona, via Della Pieve, 70, San Pietro in Cariano, Verona, Italy. [2]Department of Agri-food and Environmental System Management, University of Catania, via Santa Sofia, 100, Catania, Italy.

Accepted 14 October, 2013

This article provides a short overview of the principal models that can be used to estimate the effects of climate change on agriculture. The models are classified in relation to the following criteria: the specific impacts they aim to assess, their ability to measure production and/or economic losses, and the adoption of social indicators of the effects and responses. The weaknesses and strengths of the models are also identified and discussed. The most relevant factors for the choice of the most appropriate model are analysed. Through a comparative analysis of the literature, an easily adoptable scheme for selecting the most appropriate method to estimate the effects of climate change according to the characteristics of the case study is identified. The adopted classification scheme demonstrates that one model is capable of simultaneously considering many aspects related to climate change and classifying these in different class.

Key words: Climate change, impacts, agriculture, models.

INTRODUCTION

Agriculture is one of the sectors most affected by ongoing climate change. The wide range of literature on this subject demonstrates that damages caused by climate change can be relevant to both cropping and livestock activities (IPCC, 1990; Adams et al., 1998). Climate change will have a significant effect on the rural landscape and the equilibrium of agrarian and forest ecosystems (Walker and Steffen, 1997; Bruijnzeel, 2004). In fact, climate change can affect different agricultural dimensions, causing losses in productivity, profitability and employment. Food security is clearly threatened by climate change (Sanchez, 2000; Siwar et al., 2013), due to the instability of crop production, and induced changes in markets, food prices and supply chain infrastructure. Moreover, because of the multiple socio-economic and bio-physical factors affecting food systems and, consequently food security, the capacity to adapt food systems to reduce their vulnerability to climate change is not uniform from a spatial point of view (Gregory et al., 2005).

However, besides its primary role in producing food and fibres, agriculture performs also other functions, such as the management of renewable natural resources, the construction and protection of landscape, the conservation of biodiversity, and the contribution to maintain socio-economic activities in marginal and rural areas. Climate change could affects also this multifunctional role of agriculture (Klein et al., 2013).

*Corresponding author. E-mail: diego.begalli@univr.it, Tel: +390456835622. Fax: +390456835673.

The ongoing effects of climate change require the individuation of mitigation policies to reduce greenhouse gas emissions and identify appropriated adaptation strategies that aim to contain agricultural losses both in market goods and environmental services (such as protection of biodiversity, water management, landscape preservation and so on). These strategies can easily be identified and applied if the economic effects of climate change on agriculture are assessed. However, creating models that are able to assess these effects accurately can present difficulties for several reasons. The first is data availability: while data are frequently available, they are often not disaggregated on the necessary temporal and/or spatial scales. Another reason is that research about the effects of climate change involves multidisciplinary skills and competencies because analyses of the effects of climate change involve many factors such as the consideration of (Bosello and Zang, 2005):

1. Climate and other induced climate-change environmental aspects,
2. Biological and plant physiology aspects,
3. Technical and socioeconomic factors,
4. Strategies to coping with the effects of climate change,
5. Impacts on/of the main economic adjustment mechanisms at the national and international level,
6. Feedback of the changed conditions on climate.

Economic and agricultural policies play an important role in such analyses, as does the geographical scale (e.g. local, regional or international) considered for the analysis. In addition to these aspects, it is also important to consider the temporal and spatial variability of the events which in turn causes a difficult predictability of future scenarios.

Considering all these aspects simultaneously is problematic. For this reason the literature proposes several models that are suitable for estimating the effects of climate change on agriculture addressing specific research issues. In light of this the present article offers an overview of the models most used to estimate the effects of climate change on agriculture (section 2) aimed to classify these models and to propose a logical scheme to help researchers in the selection of the model that best suits their research goals (section 3). The fourth section presents the conclusions.

LITERATURE REVIEW

The literature suggests that various models can be employed to assess the effects of climate change on agriculture. Each model has advantages and shortcomings, and presents different levels of complexity and completeness in relation to the specific aspects considered in its analysis. These peculiarities are discussed below for each models category.

The effects of climate change were evaluated by several scholars with consideration given only to the changes in the production of specific crops (principally maize, rice, cotton and soybean), using the so-called ‘crop simulation models’. These models restrict the analysis to crop physiology, and simulate and compare crop productivity for different climatic conditions (Eitzinger et al., 2003; Torriani et al., 2007a). Crop models are considered ‘agriculture oriented’ because the analysis of these models is focused on the biological and ecological consequences of climate change on crops and soil. In these models, farmers’ behaviour is not captured and the management practice is considered fixed. Moreover, they are crop and site specific, and they were calibrated only for the major grains and for a limited number of places (Mendelsohn and Dinar, 2009).

Others scholars estimated the sensitivity of yields to climate using empirical yield models that apply the production–function approach (Terjung et al., 1984; Eitzinger et al., 2001; Isik and Devadoss, 2006; Lhomme et al., 2009; Poudel and Kotani, 2013). The basic idea of this approach is that the growth of agricultural production depends on soil-related and climatic variables that are implemented as explanatory variables in the model for estimating the production function. Changes in climate scenarios are usually simulated using the general circulation model (GCM) (Chang, 1977; Randall, 2000).

In the production function approach, the economic dimension is of secondary importance and is considered in a partial and simplified manner (Bosello and Zang, 2005), even if these models produce important information for larger model frameworks that consider economy, later discussed. Some studies explicitly assess the economic impact of climate change through the estimation of the economic production function (Adams, 1989; Rosenzweig and Parry, 1994). However, other research evaluates the economic effects of climate change by implementing the results of agronomic analyses or of empirical yields models in mathematical-programming models (Kaiser et al., 1993; Finger and Schmid, 2007).

The main weakness of the production–function model is that it is crop and site specific. It endorses the so-called ‘dumb-farmer’ hypothesis, which excludes from analysis the plausible adoption by farmers of strategies for coping with the effects of climate change, for example, strategies that replace crops that are most sensitive with others that are less so (Rosenzweig et al., 1993; Reilly et al., 1994).

To overcome this limitation, Mendelsohn et al. (1994) proposed the Ricardian model. The principal characteristic of the Ricardian model is that it treats adaptation to climate change as a ‘black box’. In fact it estimates the relationship between the outcomes of farms and climate normals using cross-sectional data and including, among regressors, appropriate control variables. As such, it implicitly considers farmer adaptation strategies without the need to implement such strategies as explicit exploratory variables (Mendelsohn and Dinar, 2009).

However, this aspect could also represent a weakness in the model if the aim of the analysis were to estimate the effect of farmer adaptation strategies on climate change. Due to this weakness in analysis, models have been proposed that use mathematical programming to consider specifically farmer adaptation strategies (Adams et al., 1990; Kaiser et al., 1993; Mount and Li, 1994), especially concerning irrigation (Medellín-Azuara et al., 2010). However, these applications often suffer the limitation of considering hypothesised and simulated strategies that can be derived by incorrect simulation of the farmers' goal function.

The latest applications of the mathematical-programming model use positive mathematical programming (PMP) (Qureshi et al., 2010, 2013; Howitt et al., 2012). These surpass the traditional limitations of linear-programming methods, for example, the unavailability of detailed information about the relationship between inputs and yields through the function cost. In the field of the assessment of climate change impacts on agriculture this model is particularly suitable for analysis of the effects of drought on agriculture because it allows different aspects related to the use and availability of water to be explicitly treated. However, given that this model needs to consider data that can be difficult to collect (e.g. water cost by considering the source of water, the water requirements of crops, and the availability of water resources), its applicability is also limited.

More recently, other research has attempted to overcome the limitations of the Ricardian model in considering farmer adaptation strategies[1] by using econometric models estimated on farm survey data. These applications explicitly treat farmer adaptation strategies by using their proxies as explanatory variables (Di Falco and Veronesi, 2013a, b; Oluwasusi, 2013) or by modelling adaptation as the dependent variable (Gebrehiwot and Van Der Veen, 2013). These applications have the advantage of being able to estimate using the available data.

Moreover, they are suitable to be specified through sophisticated models that can consider specific characteristics of the database such as endogeneity, stratified samples, spatial correlation, and panel and time-series data. With such applications, it is also possible to hypothesise different equation functional forms (e.g. linear, log-linear, quadratic, Box Cox) as well as different distributions for the error term (e.g. normal, Weibull, probit, logit) while at the same time, using the most suitable estimator (e.g. ordinary least squares, maximum likelihood estimator) according to the specific model. However, the predictive ability is strongly connected with the accuracy of the model specification and the data quality. On this last aspect impacts the impossibility to consider strategies that are new. In fact in the past we did not have climate change so in the future new approaches need to be developed.

All the models that have been discussed focus on the agricultural sector, its specific branches, or crops without considering the relationships with other economic sectors. For this reason, further research developed general equilibrium economic models (GEMs) (Darwin et al., 1995; Borsello and Zang, 2005; Calzadilla et al., 2010a, b). GEMs examine the economy as a complex system composed of interdependent components (e.g. industry, factors of production, institutions and international economic conditions). GEMs have the advantages: to capture economy-wide and global changes, and to measure the effects of climate change on other economic sectors. Conversely, they are limited in that they aggregate in a single entity different sector characterised by specific economic and spatial dimensions. For example, agriculture is generally considered as an aggregate sector at the national level without considering its local specificities. Similarly, production factors (including irrigation water) are implemented in the model as undifferentiated commodities. Further, GEMs do not consider farmer adaptation to climate change or all dimensions, skills, and competencies that should be involved in the analysis of the effects of climate change (Mendelsohn and Dinar, 2009).

Consequently, researchers developed integrated assessment models (IAMs)[2] that combine the use of GCM with data on crop growing, soil usage, and economic models (Prinn et al., 1999; Kainuma et al., 2003). IAMs describe the causes and effects of climate change, integrating knowledge from different academic disciplines into a single framework to generate useful information for policymakers (Dinar and Mendelsohn, 2011).

The integration of such varied skills and disciplines means IAMs are often particularly complex. Moreover, interactions between agriculture and land usage with climate are only partially treatable in such models and the accuracy of this model is subject to the treatment of complex interactions (e.g. the availability and the competitive use of water between economic sectors). Another limitation is that productivity is treated as an exogenous variable, even if it is strongly correlated with the climate (Dinar and Mendelsohn, 2011). Tables 1 and 2 summarises the advantages and limitations for each of the models that have been discussed in the literature review.

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[1] Seo and Mendelsohn (2008) propone a multiple-stage model called the structural Ricardian model that first estimates an adaptation model on farmer choice, and then estimates the conditional income for each choice using a traditional Ricardian formulation.

[2] For more information on IAMs, see: IMAGE (http://www.mnp.nl/en/themasites/image/index.html) or IGSM-MIT (http://globalchange.mit.edu/igsm/).

Table 1. Principal models used to estimate the effects of climate change on agriculture.

Model	Brief description	Advantages	Limitations
Crop simulation			

Production Function

This model restricts the analysis to crop It is based on a deep understanding of Analysis is focused physiology, and simulate and compare crop agronomic science consequences of clim productivity for different climatic conditions

It is suitable to integrate effects of carbon Economic dimensions dioxide fertilization be coupled with oth

It is calibrated to local condition

dimension.

In the traditional form and the farmer's man

Some researchers co

It do not consider crop

It is crop and site spec

Ricardian

It was calibrated for number of places

Yields sensitivity to climate is estimated Easy to estimate

Crop specific

assessing a empirical production function that links water, soil, climate and economic input to

It is possible to measure the effect of Social and econom

weather on yields over time considered of second yields for specific crops.The effect of

climate coupled with other change is assessed by considering yield dimension.

variations comparing two alternative scenarios. Future climate scenarios are usually simulated using a GCM.

Assumption of the adaptation strategies

Calibrated for a spe representative, can pr

This model treats the full range of farmer Does not assume the 'dumb-farmer' Omitted variables, su adaptation strategies as a black box by hypothesis characteristics could

performing a cross-sectional regression of land Easy to estimate

magnitude

values of net revenues on climate normals and other contro

Possible to consider spatial correlations In the traditional form

variables. Climate normals are calculated as averages in a long-term

and to analyse panel data are considered but no

scenario (usually 30 years). The effects of climate change

Possible to elicit farmer adaptation in In the traditional form

are assessed in terms of farm outcome

estimation if a multinomial logit model considered. More re (e.g. a structural

Ricardian model) is used. among the regress variations, comparing the current situation to endogenously and simulated scenarios.

adequately considere

Analysis is focused agriculture and only biological and social)

Assumes a partial equ relationships with othe

Assumesthe output a not measure adjustme

Table 1. Contd**.**

PMP	This is an economic management model estimated by solving a mathematical-optimisation problem using farm data. The pay-off function can be formulated considering the profit (to be maximised) or the cost (to be minimised). The latter, known as the Positive Mathematical Programming, surpasses the traditional limitations of linear-programming methods such as the unavailability of detailed information on the relationships between inputs and yields through the dual function cost.	Useful for assessing the economic effects of climate change, especially in the simulation of irrigation-farmer adaptation options and/or water policies, including water markets and irrigation efficiency improvement.	Difficult to estimate Often difficult to find limiting production fac Assumes simulated f observed choices in s
GEM	These look at the economy as a complex of interdependent components (e.g. industry, production factors, institutions).	Assumes a general economic equilibrium, considering all economic sectors Captures economy-wide and global changes such as those linked to input and output prices Provides information on the effect of climate change in different regions Measures the effect of climate change on other economic sectors.	Difficult to estimate Aggregates into one in economic and spati Production factors, considered in the mod Difficult to analyse far Doesnot allow consi phenomena.
IAM	These are based on the joint use of General Circulation Model, crop growing, soil usage, and economic models. These models integrate different skills and competencies.	Analysis simultaneously considers all agricultural dimensions Generates useful information for policymakers.	Difficult to estimate These models can be In some cases the req

CLASSIFICATION OF MODELS, RESEARCH QUESTIONS TO BE ANSWERED, AND CRITERIA FOR CHOOSING THE MOST SUITABLE MODEL

To assess the effect of climate change on agriculture, the choice of the most appropriate model depends on the following factors:

1. The level at which the analysis needs to be conducted—this could be the agricultural sector; whole, or one crop, or a particular agricultural

Interaction between
climate are only partia

Accuracy of model
complex interaction
concerning water usa

Productivity is treated

branch[3]
2. The (tempora

[3] The literature discu
effect of climate cha
2006), viticulture (Tat

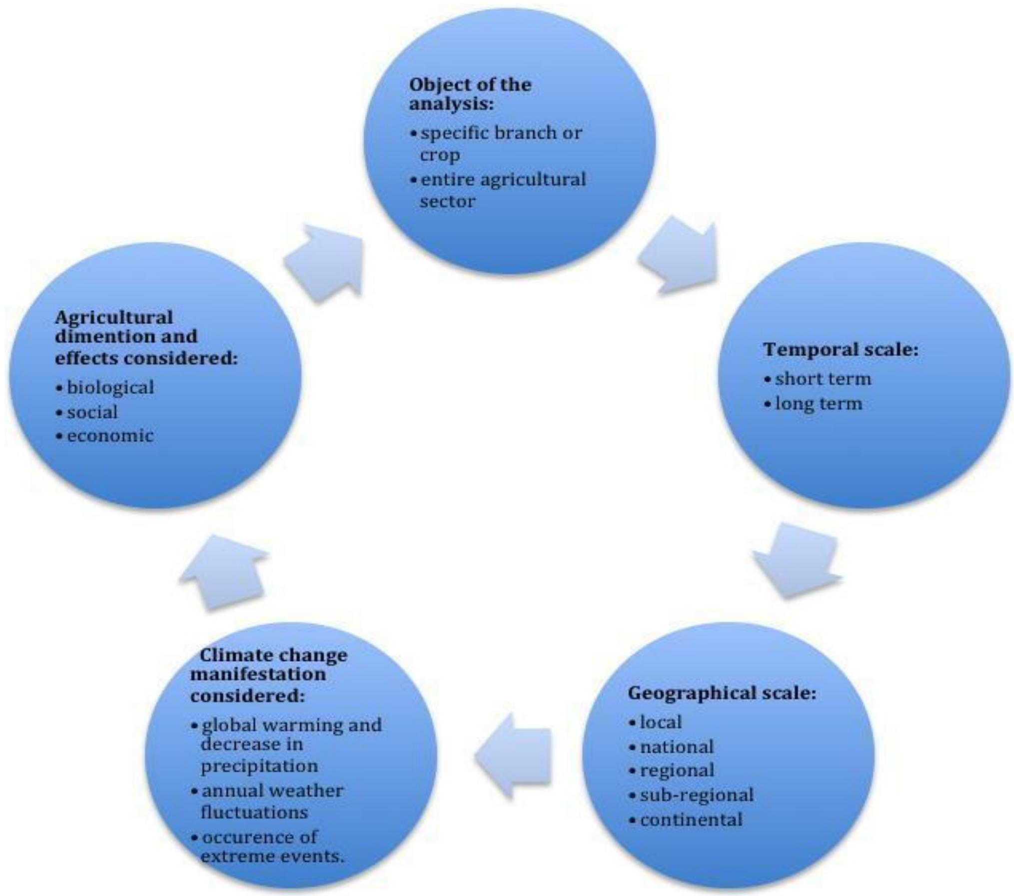

Figure 1. Aspects that influence the choice of model to be used; Source: Authors' elaborations.

whole, or one crop, or a particular agricultural branch[4];

3. The climatic phenomenon used to measure the analysed climate change (Tate, 2001; Bernetti et al., 2012), and livestock (Seo, 2008; Reynolds et al., 2010; Kimaro and Chibinga, 2013);

4. The agricultural dimension (biological, social or economic) with respect to which climate change impacts are assessed.

Figure 1 summarises the hierarchical links between these elements. The first aspect (the level of the analysis) and the fourth aspect (the agricultural dimension to be considered for estimating the effects of climate change) are connected. In fact, the models devoted to the analysis of the biological dimension of agriculture are crop specific; consequently, they concern only a single crop or branch. Conversely, the models devoted to assessing the effect of climate change on the social or economic dimensions of agriculture can consider the agricultural sector as a whole or one of its branches.

In reference to the scale of analysis it can concern cross-sectional, panel, or time-series data. In the latter case the length of the time period to be considered depends on the analysed scenario. The spatial scale can be very significant when the empirical evidence demonstrates that the magnitude of the effect of climate change varies significantly according to the location and the size of the areas studied. Previous research has highlighted that agriculture in warmer areas is more affected by climate change than agriculture in colder areas (Mendelsohn et al., 1994; Schlenker et al., 2005). However, the effects can vary dramatically on international, national and local scale (Bindi and Olesen, 2011). This variation in the effects is due to differences in adaptation strategies, which correlate highly with the local cultural, institutional and environmental conditions.

Another important issue to be considered is the specific manifestation of climate change that the model considers in calculating its effect on agriculture. This issue may concern:

1. A general increase in temperatures, accompanied by a decrease in precipitations characterising a long-term scenario (climate warming and precipitations change);

[4] The literature discusses numerous applications that estimate the effect of climate change on permanent cultivations (Lobell et al., 2006), viticulture (Tate,

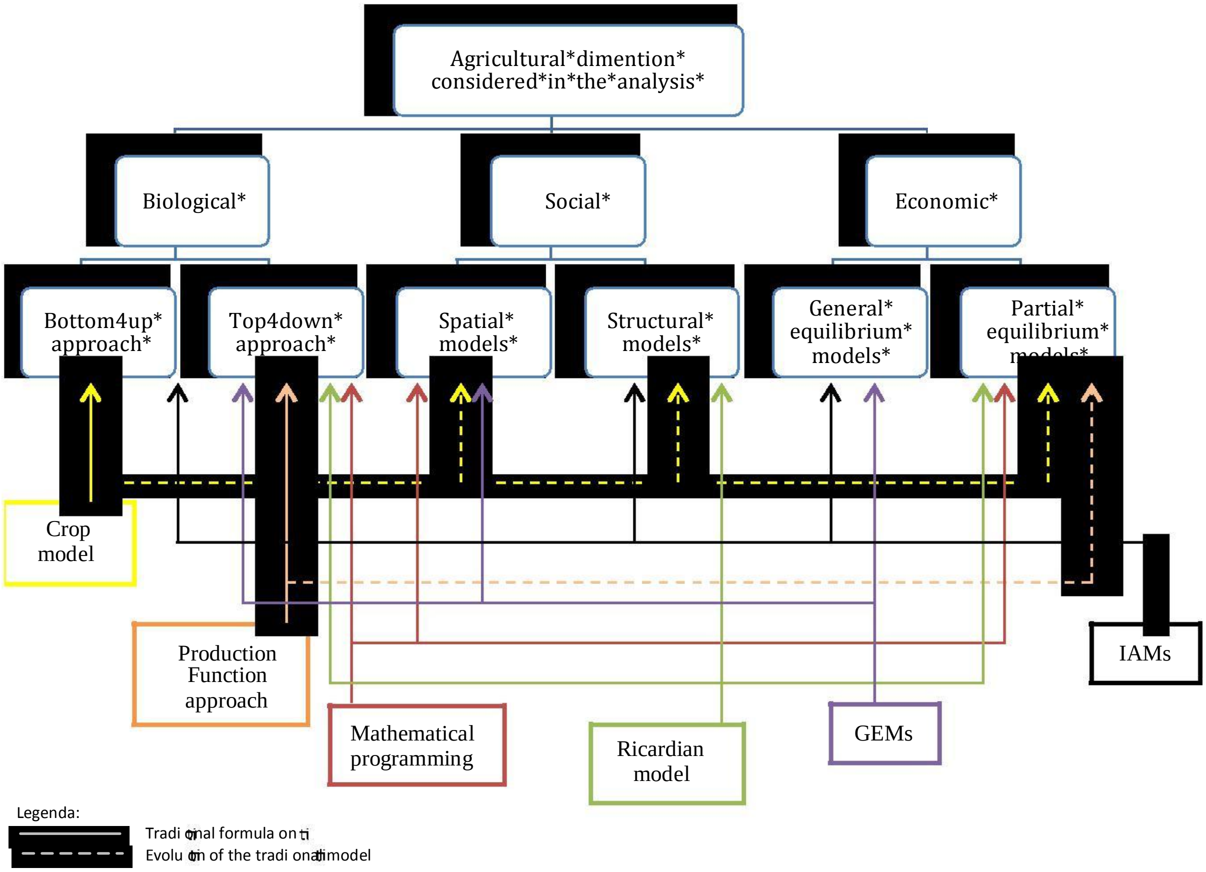

Figure 2. Classification of models by agricultural dimension, Legend: Traditional formulation; Evolution of the traditional model; Source: Authors' elaborations.

2. Annual fluctuations in the weather in terms of temperature and precipitations;

3. The frequency of extreme weather events such as droughts or floods.

Each of these aspects plays a different role and causes different effects on agriculture. The issue that has been the subject of most research is the effect of climate change in a long-term scenario. This has been widely analysed using the Ricardian model. The other two forms of the effects of climate change have been less investigated. Annual fluctuations in the weather were examined by Kelly et al. (2005) and Deschenes and Kolstad (2011). The effects of drought were analysed by Trnka et al. (2010, 2011) and of cyclones by Dasgupta et al. (2011). Figure 2 presents a classification of models that consider the biological, social, and economic dimensions of agriculture.

As demonstrated in Figure 2, if the focus is on the effects in terms of production change, by considering the biological aspects and their dynamics, it is possible to implement plant-physiology models that correlate the production output to climate variables or vegetation distribution behaviours. As such, it is possible to explain the spatial distribution of crops in relation to the climate scenario. In this case the model adopted is a bottom-up model (Bosello and Zang, 2005). Alternatively, it is possible to use a top-down model (or spatial analogue), which analyses crop reaction to climate change based on the productivity values in different temporal and spatial scenarios.

Further, in the assessment of the social effects, it is possible to distinguish spatial versus structural models (Bosello and Zang, 2005). Through the analysis of choices, strategies, and technologies used in different climatic and geographic scenarios, both of these models provide the possibility of forecasting behaviours will be adopted by farmers to face climate change.

Spatial models analyse variations in a farm's performance when dealing with climate change without considering farmer adaptation. This type of model hypothesises that such variations do not affect the prices of agricultural commodities and inputs. Consequently, this model does not consider the effects of climate change on agricultural demand and supply. Moreover, spatial models implicitly assume the absence of progressive farmer adaptation processes through changes in production cost in the short-term and medium-term scenarios. It follows that it is not possible to differentiate climate-change adaptations endorsed by the

Table 2. Characteristics demonstrated by the most commonly used models to assess the effects of climate change on agriculture.

Model	**Object of the analysis**	**Temporal scale**	**Geographical scale**	**Climate change manifestation**	**Agricultural dimension**		
					Biological	**Social**	**Economic**
Crop simulation	A specific crop	Short time	Local	Weather annual fluctuation	Treated	Not treated in the traditional formulation. It is possible to treat it exogenously.	Not treated in formulation. possible to model with frameworks economy.
Production function	A specific crop, a group of crops or a particular ecosystem	Both short term and long term	All possibilities	All possibilities	Not explicitly treated	Treated in a secondary manner.	In the formulationtre secondary m studies es economic function. Oth model with frameworks economy.
Ricardian	The whole agricultural sector or a particular branch or crop	Long term	All levels, providing enough climatic variability is assured	Global warming and precipitations decreasing	Not explicitly treated	Not explicitly treated in the traditional formulation but explicitly treated in the structural Ricardian model	Treated
Econometric model	The whole agricultural sector or a particular branch or crop	Both short term and long term	All levels, especially local, national or regional	All possibilities	This depends on the model formulation	This depends on the model formulation	This depends formulation
PMP	The whole agricultural sector or a particular branch	Both short term and long term	All levels, especially local, national or regional	All possibilities	Not explicitly treated in the traditional formulation. Some researchers treat it explicitly coupling this model with a crop simulation model	Treated	Treated

Table 2. Contd.

GEMs	The whole agricultural sector or a particular branch if appropriately formulated	Long term	All levels, especially national or higher	All possibilities	Not explicitly treated	Not explicitly treated	Treated
IAMs	The whole agricultural sector or a particular branch if appropriately formulated	Long term	All levels, especially national or higher	Global warming and precipitations decreasing	Treated	Treated	Treated

agricultural sector from those deployed by the economy as a whole, and neither is it possible to separate these adaptations from those put in place to deal with factors other than climate change (Molua and Lambi, 2007).

The structural models through which the physical, social, and economic responses of agriculture to climate change are analysed overcome these limits. However, the application of these models is sometimes hampered by a need for detailed information on business-management practices.

By focusing only on the economic dimension, applicable models can consider a partial equilibrium or a general equilibrium in sectorial and/or geographical terms. GEMs, or economy-wide models, were used to estimate the economic effect of climate change on agriculture (e.g. Darwin et al., 1995; Borsello and Zang, 2005; Calzadilla et al., 2010a, b). These applications look at the whole economy and consider the relationships between sectors. However, they present some limitations (Table 1) that are overcome by the partial equilibrium models, which focus on a part of the economic system, consisting of a single market or a set of markets or sectors (Deressa, 2007).

The microeconomic partial equilibrium models can omit important aspects of the issue being considered, for example:

1. The re-allocation of production factors,
2. Changes in demand for agricultural products,
3. The interrelation of the economic sectors,
4. The dynamics of international markets,
5. The endogenous nature of market prices for agricultural products and inputs.

Moreover, the partial microeconomic equilibrium models can be divided into two broad categories: models based on the simulation of the crop-growth processes (crop-growth simulation models) and econometric methods (Kurukulasuriya and Rosenthal, 2003; Deressa, 2007) that also include the widely used Ricardian models. The choice of the best model to assess economic effects depends heavily on the specific aspects that the analysis has to consider and on the level of detai

Conclusion

The assessmen on agriculture a better suite the area for sever always availabl necessary temp such research professional co analyses have physiological asp features; and a farmers and br Third, a relevan to economic an geographical (l scale of the ana consider the te climate; the unce and the feedba climate change.

Consequently, the selection of the most appropriate model should consider different aspects of the research problem, for example:

1. The specific object of the analysis,
2. The temporal and geographical scales,
3. The specific forms of climate change that are being considered (e.g. climate warming, weather fluctuations or extreme climatic events),
4. The magnitude of the effects expressed according to the agricultural dimensions (biological, social and/or economic) that the analysis aims to consider.

The choice of the model to be implemented is one of the most important steps in a assessment project. In the analysis of the effects of climate change on agriculture, the literature offers a multitude of applicable methods and tools, each of them with specific advantages and disadvantages. Consequently, the choice of the best model can be difficult due to a lack of perfect knowledge of all the possible alternatives. The choice of the model to apply for analysis often follows the trend of the moment, and is applied without detailed analysis of all the assumptions and hypotheses underlying the model. Choosing incorrect models causes a bias of results and an increase in unexplained variability that worsens the analytical framework of an already very complex area issue.

This article attempts to address this lack of information by offering to researchers a useful tool with which to identify all the possible alternatives of models analysing the effects of climate change on agriculture. This article has reviewed the literature and discussed the most popular analytical methods that are presented in the literature, and that are: the Crop Simulation Models, the Production-Function Model, the Ricardian Model, the Mathematical Programming, the General Equilibrium Model (GEMs) and the Integrated Assessment Models (IAMs). It has classified methods of analysis according to the principal aspects that have to be considered in when selecting a model, with particular emphasis on the dimensions under which the effects of climate change should be expressed. The adopted classification scheme demonstrates that one model is capable of simultaneously considering many aspects related to climate change and classifying these in different classes.

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