Issues in Modelling Agriculture Response to Climate Change

Singh, Amarendra Pratap and Narayanan, Krishnan

IIT Bombay, IIT Bombay

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Amarendra Pratap Singh[1] and Krishnan Narayanan[2]

Abstract

Agriculture stands as most sensitive economic activity to climate variations. Modelling climate-agriculture relationship is one of the most researched issues in recent times. This paper reviews some of the issues regarding modelling agriculture response to climate change.

Key words: yield, temperature, Ricardian technique

1. Introduction

Green House Gases (GHGs) driven climate change is one of the leading issues in current environment-development debate. Recent continuation of extreme climatic events across the Globe has increased awareness towards GHGs induced global *Climate Change*[3]. Monitoring and analysing Climatic Change (temperature, rainfall, precipitation) and its impact on global as well as regional scale have received special importance at policy making level. There are clear evidences of change in mean and extreme temperature, rainfall and other climatic activities across the world (IPCC, 2007). Precision of the estimate and predictions are still debatable issues but the reality of climate change is equivocally supported.

Agriculture and allied activities represent a human managed ecosystem generally known as agricultural system. *Agricultural system*[4] is the most vulnerable and sensitive economic sector to climate change/variation due to its critical link with nature (IPCC, 2007). Growth and development of plants and vegetation cover directly depends on local climate conditions and environmental quality. Not only crop sector but other allied activities of agriculture (livestock, forestry, and fishery) are also highly responsive to changing climatic conditions. The cascading effects of climate change driven ecological change on farm environment have a direct relationship with growth, equity and poverty (Gadgil and Gadgil, 2006). Quantification and prediction of climate change impact on welfare is an important area of

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[1] PhD student, IIT Bombay.

[2] Professor in Economics, IIT Bombay.

[3] *Climate Change* is defined as a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use (UNFCCC). Source: http://unfccc.int/essential_background/convention/background/items/2536.php

[4] An agricultural system is an assemblage of components which are united by some form of interaction and interdependence and which operate within a prescribed boundary to achieve a specified agricultural objective on behalf of the beneficiaries of the system (FAO concepts and definitions).
Source: http://www.fao.org/docrep/w7365e/w7365e04.htm

research for suggesting useful policies. Literature identified four major ways in which climate would have an impact on agriculture.

First, change in temperature and precipitation suggests a pole ward shift in agro-ecological zones of the world (IPCC, 2007). Zilberman et *al*. (2004) also modelled climate change as a homogenous shift in agro-ecological zones. Changes in soil moisture and content and the timing and length of growing seasons will be affected in various ways due to changing climate. Countries situated at middle and higher latitudes will benefit from lengthening of growing seasons and expand crop producing areas towards pole. In contrast, in lower latitudes, it is expected that higher temperatures will adversely affect growing conditions, especially in areas where temperatures are optimal or close to it for crop growth. Availability of irrigation water and crop water demand may also increase due to changes in temperature and rainfall.

Second, increasing level of carbon dioxide is expected to have a positive impact on crop yield. These effects are strong for plants having C3 photosynthetic pathway, which include crops such as wheat, rice, and soybean. Carbon dioxide enrichment is also positive but relatively lesser for C4 plants such as maize, millet, and sorghum, and many grasses (and thus weeds). Water use efficiency of plants is also supposed to increase in presence of high CO_2 concentration (Rogenberg, 1981). This effect is known as *fertilization effect*[5] in literature.

Third, change in temperature is likely to increase plant water demand especially in warmer regions. Change in rainfall pattern has potential to redistribute the allocation and availability of water across the globe. Water availability and plant water demand is a critical factor in determining the impact of climate change on agricultural system.

Fourth, climatic variation increases the probability of occurrences of extreme events like drought and flood. A higher frequency of droughts is likely to increase pressure on water supplies. In contrast, increases in rainfall intensity in other regions can lead to higher rates of soil erosion, leaching of agricultural chemicals, and runoff that carries livestock waste and nutrients in water bodies.

Measuring climate sensitivities for agriculture, both at *system* level and *component* level is well established idea in the field of agriculture and environment economics. System level studies are inclined to measure welfare impact of climate change on entire agricultural system that exists in a geographical unit. However, component level studies prefer to estimate climate change impact on various components of agricultural system (biological and

[5] These details are taken from Rosenberg (1981).

economical). These sensitivities are then used to measure *impact*[6] of climate change on agricultural system and its components.

Furthermore, some human response to minimize the magnitude of damage to climate change cannot be ignored by impact studies. Humans as a profit maximizing agent, put a lot of efforts, both at individual and collective levels, to minimize the negative impact of Climate change. Human responses to curb the negative impact are termed as *adaptation* in literature. However, these responses neither materialize without bearing some *transaction costs*[7] nor are cost free (adaptation costs). Therefore, impact assessment cannot be viewed as an isolated idea that links climate to agriculture performance. A feasible impact assessment methodology must incorporate market as well as non market impacts including adaptations that emerge due to changes in underlying biological and economic structure (Antle, 1996). One can divide impact studies in two categories based on the generalised technique used for studying impact. These are agronomic studies and econometric studies. Econometric methodologies are used measure impact both at system (Mendelsohn et *al*. 1994) and component level (Schlenker and Roberts, 2009).

In this report, our attempt is to critically review existing methodologies pertaining to measure impact of climate change on agriculture with a special focus on econometric studies. Section 2 develops a conceptual scheme to identify various factors that contribute to impact assessment. Section 3 briefly reviews studies that meant to capture impact of climate on crop yield. Section 4 devoted to understand conceptual building and economic idea behind Ricardian technique. Section 5 presents some criticism and developments in Ricardian model and estimation approach. Final section devoted to summarize findings of review.

2. Impact of Climate Change on Agriculture

Callaway et *al.* (1982) defined *impact* in reference to agriculture as the broad range of effects that changes in the atmospheric concentration of GHGs may have on the physical and natural environments in which agricultural production takes place.[8] This is a broader definition with limited functional applicability. A functional definition of impact can be given following Mendelsohn, et *al*. (1994) and others. They defined *impact* as the change in the quantity/net value of production or some farm asset (Land).

[6] *Impact* denotes changes in the physical environment or biota resulting from climate change which have significant deleterious effects on the composition, resilience or productivity of natural and managed ecosystems or on the operation of socio-economic systems or on human health and welfare.

[7] There is always a time lag between identifying the source of impact and evolving and implementing corrective measures. Early adaptation can minimize transaction cost.

[8] From here onwards, we use the term “impact” in this specific sense.

A comparative framework for measuring *impact* can be formulated using difference in profit before and after climate change. If we use subscripts 0 and 1 to represent period before climate change and after climate change then following set of equation shows the net impact of climate change on agriculture,

$$I^{gross} = P_1 - (P_0 + I_{0,1}^{fertlization})$$

$$I^{net} = P_1^A - (P_0 + C_{0,1}^A + I_{0,1}^{fertilization})$$

$$I^{adj} = (P_1^A - P_1) - C_{0,1}^A$$

$$I^{adj} = A_{0,1} - C_{0,1}^A$$

In this system of equation, *I* refers magnitude of impact, *P* is value of production, *A* and *C* stands for adaptation and cost respectively. We assumed that adaptation costs are equal to the change in production costs between two periods and adaptation being one time cost. Transaction cost is included separately to introduce the impact of cost incurred due to lag between realization of impact and formulating and implementing decisions to minimize the magnitude of negative impact.

2.1. Conceptualizing interaction between agriculture and climate

Climate change impact on agriculture is not unidirectional and it depends on complex interaction among human and nonhuman actors that participate in agricultural production. These interactions can be understood by developing a causal link between various component of agricultural system and climate. In this direction, Callaway et *al.* (1982) separated the impact of GHGs induced climate change on agriculture in terms of *first order* and *second order* effects.[9] However, the *impact* cannot be measured considering first order and second order effects separately. Moreover, most of the second order impacts are still unknown and it is still not clear how to incorporate these impacts in an economic framework.

[9] First order effects refer to those GHGs induced environmental change that affect physiological conditions necessary for plant growth. These include change in atmospheric concentration of CO_2, increase in temperature, and change in precipitation. Second order effects include response of agricultural inputs (land, water, biodiversity) to climate change.

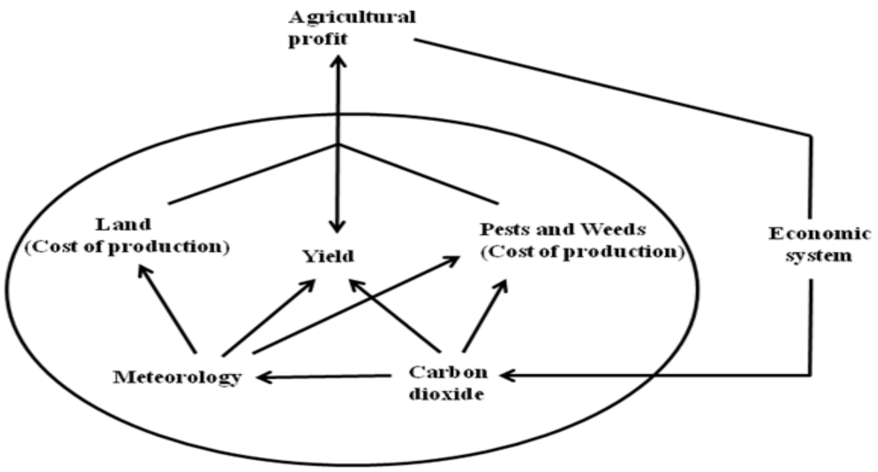

Figure 1: A path diagram of agriculture climate interaction

A simple path diagram is presented in figure (1) that shows some of the effects of climate change on agriculture. However, both effects doesn't takes place separately and a framework to understand the complex interaction of variables in measuring impact must incorporate first and second order effects jointly.

The relationship illustrated in figure (1) can be written in following functional form,

$$\pi = p(Q)Q(z, CO_2) - C(Q(z, CO_2)) \qquad (2.1)$$

Here, *p* is the price, *Q* is the quantity, *C* is the cost of production. *z* and CO_2 denote climate at the location and level of carbon dioxide in atmosphere respectively. It is helpful to assume that farmer doesn't change choice of crops that is grown at the location in order to maintain consistency in prices.

Differentiating eq. (2.1) with respect to z,

$$d\pi/dz = Q(dp/dQ * dQ(z, CO_2)/dz) + p(dQ(z, CO_2)/dz) - dC/dQ * dQ(z, CO_2)/dz \qquad (2.2)$$

Rearranging, we get

$$d\pi/dz = [(Q\,dp/dQ) + (p - dC/dQ)](dQ(z, CO_2/dz) \qquad (2.3)$$

We can write output produced as product of yield of crops and land area cultivated,

$$Q(z, CO_2) = Y(z, CO_2) * L(z) \qquad (2.4)$$

Where *Y* is the yield and *L* is the area under cultivation. Differentiating equation (2.4) with respect to *z*,

$$dQ(z, CO_2)/dz = L * \left[\partial Y/\partial z + \frac{\partial Y/\partial CO_2}{dz/dCO_2} \right] + Y\,dL/dz \qquad (2.5)$$

Combining equation (2.5) and equation (2.3), we get an expression for *impact*

$$d\pi/dz = [(Q\,dp/dQ) + (p - dC/dQ)]\left[L\left(\partial Y/\partial z + \frac{\partial Y/\partial CO_2}{dz/dCO_2}\right) + Y\,dL/dz\right] \qquad (2.6)$$

However, without apriori knowledge of functional relationship and direction of causality among the variables, we cannot estimate impact. Tentative expression derived here, does incorporate a few indirect impacts along with direct impacts. Equation (2.6) suggests that *impact* is not linear; rather, it depends on the complex interaction of various factors.

Deschenes and Greenstone (2007) analyzed the change in profit due to annual fluctuations in weather; however, their work was concentrated to capture long run losses only (equation 2.3).[10] In equation 2.3, $Q\,dp/dQ$ shows short run effect and is supposed to vanish in the long run due to difference in elasticity of supply of agricultural commodities in short and long run.[11] In short run, change in production due to change in climate will be entirely due to changes in yield. Fertilization effect and change in agricultural land use is not supposed to be effective in short run. This implies that economic system may suffer major losses in short run. Distribution of short run losses between agricultural system and rest of the economy depends on the change in prices of agricultural goods due to climate change (through change in quantity). In long run, term $(p - dC/dQ)$ that shows marginal conditions for profit maximization will determine profit. Long run impact will be zero that reflects perfect adaptation to climate change by farmers.

However, dynamics of the term in second parentheses of the left hand side of equation (2.6) may cause under/over estimation the market impact. Increase in temperature due to global warming is supposed to have a negative effect on crop yield. Cascading effect of increasing temperature on yield will be further reflected in shrinking agricultural land under particular crop. However, some of the impact of climate change on agricultural land is supposed to be mitigated due to CO_2 fertilization effect (see, equation 2.6). Mendelsohn et *al*. (1996) accepted that land area under production cannot be assumed constant in wake of changing climate and corrected their estimates to remove possible bias due to this factor.[12] Rise in sea level will also cause declining land area under agriculture especially in islands and coastal areas.

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[10] Their analysis assumes that crop choice of farmers remains unchanged during the period of analysis which is a contestable assumption.

[11] We are assuming that, in the long run, quantity adjustment will take place as more farmers inclined to produce that commodity whose price is rising which leaves $\frac{\partial p}{\partial Q} = 0$ (see, Deschenes and Greenstone, 2007).

[12] They introduced area under production as weight in regression analysis to address area effect.

In summary, equation (2.6) identifies *yield of crops*, *land area under crop production*, *prices of agricultural commodities and inputs* as main factors to determine impact of climate change on welfare. A systematic framework based on the production analysis can be used to quantify impact.

To illustrate the analysis, consider a situation where a farmer produces crops using purchasable inputs (X_i), fixed allocable inputs (L_i) and climate at the location (z). The technology of a farm at any specific location producing output Q_i ($i=1,2,3,...n$) can be expressed as

$$Q_i = f_i(X_i, L_i, z) \quad (2.7)$$

$$X_i = (X_{i1}, X_{i2}, X_{i3} ..., X_{ij}) \quad (2.7.1)$$

$$L_i = [L_{i1}, L_{i2}, L_{i3}, ..., L_{im}] \text{ subject to } \sum_{i=1}^{n} L_i = \overline{L} \quad (2.7.2)$$

$$z = (z_1, z_2, z_3, ..., z_k) \quad (2.7.3)$$

In this set of equations, Q is the quantity of output i produced at the farm, X_i is the vector of j purchased inputs used for producing i^{th} output, L_i is a vector of allocated fixed inputs (e.g. land, machinery etc.) allocated among n commodities and z is the vector of k exogenously determined environmental inputs.

It is widely accepted that crop yield is nonlinear in climate variables (Schlenker and Roberts, 2009). Yield first increases with increasing temperature till a threshold reached and then started decreasing till it becomes zero (Zilberman et *al*. 2004). Keeping the land under crop constant, production of particular crop must also show similar kind of relationship with climate.

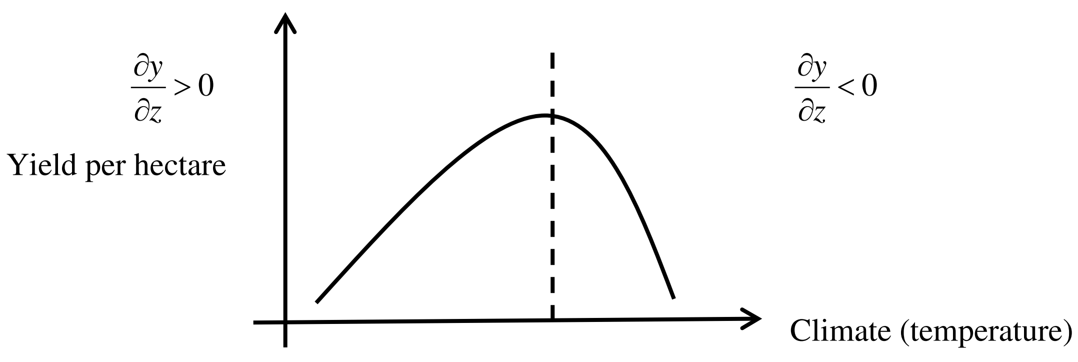

Figure 2: A hypothetical yield response curve

The assumed objective of a rational farmer is to maximize its profit. To do this cost function for the farmer should also be specified properly. As we have shown in equation (6) that production costs are not independent of climate variables, therefore, any analysis of impact must also consider interaction of cost with climate. Short run cost function related to some specified level of production can be given as

$$C = C_i(Q_i, \omega, z) + FC \tag{2.8}$$

$$\omega = [\omega_1, \omega_2, \omega_3, ..., \omega_j, ..., \omega_m]$$

Where, C is the cost of production for commodity i and ω is a vector of input prices. Now it is important to consider the impact of climate on cost of production. If climate change is helping to reduce cost of production $(i.e. \frac{\partial C}{\partial z} < 0)$ as one can observe in case of increasing rainfall, profit will increase. However, if cost of production is increasing due to changing climate $(i.e. \frac{\partial C}{\partial z} > 0)$ then profit will fall. A relevant example is rapid growth in weeds due to fertilization effect forces farmer to allocate additional labour (pesticide) cost to maintain production.

Following equation (2.7) and equation (2.8), profit function for maximization problem can be given as,

$$\max \pi_i = [p_i Q_i - C_i(Q_i, \omega, z) + FC] \tag{2.9}$$

$$s.t. \sum_{i=1}^{n} L_i = \overline{L}$$

Where, π_i is the profit and p_i is the price of commodity i. Following agronomic studies, profit is also assumed to follow a nonlinear path as suggested in figure (2) with the change in climate.

There may be various approaches to explore the link between different aspects of agricultural system (yield, land, profit, land values etc.) and climate. One can clearly demarcate between two approaches that are widely used for impact assessment. First of the two approaches is inclined to measure physical impact of changing climate on agricultural productivity and resources. Later approach advocates to measure monetary impact of climate change on societal welfare. While the first is limited to agricultural system only; later is more inclusive in the sense that it meant to capture change in welfare (both consumer and producer) due to climate change. In the next sections, we will present a brief review of two approaches as well as their strengths and weaknesses.

3. Methods for Modelling Yield Response to Climate Change

Estimating the impact of meteorological variable on crop yield is not a new phenomenon in literature. Since the beginning of 20th century, meteorologists started research in this direction but exact relationship between crop yield and weather remains a subject of debate. Early studies in this direction were more concentrated on measuring physical impact of climate change on agriculture. The modelling approach in these models was fairly based on multiple regression analysis to determine the impact of a vector of independent climatic and non climatic variables on the yield of a crop.

However, these models used statistical technique to forecast impact of climate change on crop yield; theoretical support is borrowed from agronomic literature. According to agronomic literature, effect of heat on relative plan growth is cumulative over time and that yield is proportional to total plant growth (Schlenker and Roberts, 2009). Plant growth *g(h)* at any location for some crop depends nonlinearly on heat and thus relationship between heat and yield can be given as,

$$Y = \int_{\underline{h}}^{\overline{h}} g(h)\varphi(h)dh \qquad (3.1)$$

Where $\varphi(h)$ is the time distribution of heat over the growing season, *Y* is the yield and *g(h)* is the growth of plant. $\underline{h}$ and $\overline{h}$ are the lower and upper bound of the observed temperature at the location.

One of the early attempts to study crop technology and weather interaction was by Thompson (1975). Thompson (1975) used a reduced form specification to estimate the impact of yield and technology on corn yield. Later, many studies applied Thompson's (1975) approach to predict[13] impact of climate/weather[14] on yield. Econometric model used for yield prediction by Thompson includes (1975) level and squared terms of 6 weather variables and technology trend variable to check possible nonlinearity. Weather variables introduced in the model were not considered in level rather deviation from *normal*[15] form. Improved specifications of Thompson's model introduced nitrogen use as a proxy for technology. The econometric specification under Thompson (1975) approach is given as,

$$Y = \alpha_0 + \sum_{i=1}^{m} \alpha_i z_i + \sum_{i=1}^{m} \beta_i z_i^2 + \varphi_1 t_1 + \varphi_2 t_1^2 + \varphi_3 t_2 + \varepsilon$$

Where m =12 is the number of meteorological variables, t_1 and t_2 are technological trend variables.

[13] Yield was predicted for a given year based on regression parameters fitted with the data for the period ending previous year.

[14] Early meteorological studies used weather information. Deschenes and Greenstone (2007) were also of the view that annual weather fluctuation is better measures than climate normals.

[15] Normal is defined as moving average of climate (temperature, precipitation, rainfall) data over a long period of time.

Nelson and Dale (1978) adopted Thompson's (1975) approach to estimate effect of weather on corn yield using both general (OLS) and stepwise regression technique. Stepwise regression was justified to improve the predictive strength (adjusted R^2) of the model. Two variants of the Thompson's model were estimated for two different specifications of technology. They used data of Tippecanoe County (US) between the years 1941 to 1975. Results of stepwise regressions were interpreted as its results showed less variability to change in data. Major issue that the study brings forth was about using trend variable as a proxy for technology in absence of information on technology. Their estimates showed that results of the model with nitrogen use as a technology variable was superior to that of model with technology trend variable.

In statistical studies, adj. R^2 and mean square error (MSE) of the estimated model becomes very important as we cannot attach any physical meaning to estimated coefficients of a model. Increasing predictive strength of the model remained most important aim of statistical studies in this area. Due to this reason, early studies applied step wise regression to increase the predicative strength of the estimated results. Other limitations of regression framework include correlated climate variables.

A problem attached with OLS framework is their results lack any physical interpretation. Shlenker and Roberts (2009) modified regression framework by replacing temperature by heat units. They argued that such transformation helped them to incorporate whole distribution of weather outcomes during growing season in regression analysis. To represent heat units in a regression framework, they used the concept of *growing degree days*[16]. Heat distribution over the time is approximated using dummy variable for each three degree temperature interval. All the time a plant is exposed to temperature above higher threshold are lumped into one category. Simulated heat distribution was also used to study crop response. Following regression model was used for estimating crop sensitivities,

$$Y_{it} = \sum_{j=0,3,6,9,...}^{39} \gamma_j z_{it,j} + \delta x_{it} + c_i + \varepsilon_{it}$$

$$z_{it,j} = \left[\varphi_{it}(h+j) - \varphi_{it}(h)\right]$$

Results of the study suggested an inverted U relationship between crop productivity and heat, irrespective of the process used for converting monthly average temperature into its heat equivalent. Study reported significant negative impact on wheat, corn and cotton of climate change.

[16] Growing degree days are defined as sum of the degree above a lower baseline and below an upper threshold during the growing season.

3.1. Importance of climate variability in measuring impact

Developing a framework that can capture climate change appropriately is an important element in predicting physical/monetary impact (Callaway et *al*. 1982). In this regard, any measure of climate change must involve *climate variability* along with the climate change to measure the impact. Climate variability is an integral part of any *climate response function* because of the stochastic nature of climate variables and farmer's attitude towards risk (Callaway et *al*., 1982).

To establish the importance of climate variability on yield prediction, we use following formulation for yield of a crop,

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i z_i + \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} z_i z_j \qquad (3.2)$$

Where, Y is the yield of crop, z_i and z_j are the climatic variables and β_0, β_i and β_{ij} are the parameters that explain relationship between yield and relevant climate variables. Climate variables are assumed to be stochastic and climate at any location can be assumed to be given by the joint distribution of these climatic variables. The expected value of yield can be expressed as,

$$E(Y) = \beta_0 + \sum_{i}^{n} \beta_i E(z_i) + \sum_{i=j=1}^{n} [E(z_i)^2 + \text{var}(z_i)] + \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} [E(z_i)E(z_j) + \text{cov}(z_i z_j)]$$

(3.3)[17]

Covariance between two variables is given as the product of standard deviations between climate variables z_i and z_j multiplied with correlation coefficient between z_i and z_j. If two climate variables are independent to each other, correlation coefficient of these variables will become zero. In such a case, covariance term in equation (3.3) will become meaningless. Equation (3.3) establishes that variability in climate matters for predicting crop yield if separability of climate variables doesn't hold. Callaway et *al*. (1982) argued that by taking a strictly linear crop response function, we assume that climate variables are non-stochastic in nature.

Furthermore, increasing number of extreme events (increased climate variability) increase the possibility of wild fluctuation in yield or crop failure. However, at the same time, expected yield (long run average) of the crop may be fairly stable. In such a case, farmers at an affected location may opt to grow that crop which yield less mean income per acre but are more tolerant to climate variability to reduce risk (Callaway et *al*., 1982).

[17] See appendix.

4. Methods for Modelling Aggregate Agricultural Response to Climate Change

Advance approaches in climate change and agricultural studies emerged to capture aggregate impact of climate change on agricultural sector. Adams et *al*. (1998) classified system level studies as 'structural' and 'spatial-analogue' models. Structural (agronomic) models to assess the impact are interdisciplinary in nature and are highly based on mathematical simulations. Simulations models are borrowed from other disciplines to measure impact of climate change on agriculture. Multi stage Simulations are performed in structural procedure. Basically, simulation based studies followed following steps,

Step 1: Defining likely changes in global climate due to change in CO_2 concentration level and further to model how these change in CO_2 levels are manifested in temperature, precipitation, and other climatic variables across different agricultural regions.

Step 2: The second step incorporates modelling the changes in yields, water availability and crop water demand due to change in climatic variables. In this way, result of first step modelling becomes the input of second stage.

Step 3: Once quantifies, yield and irrigation effects act as inputs for the third stage. In this stage some agricultural sector model (ASM) is used that allows the physical and biological effects of climate change to be translated into economic effects on producers and consumers. The economic effect are seek to either minimize cost or maximize consumer and producer welfare subject to climatic and other constraints. However, usefulness of structural approach is limited due to difficulties to identify and incorporate possible adaptations in these models which may vary across time and space.

Spatial analogue models estimate the long run impact of climate change on agriculture based on the differences in agricultural production and climate between regions (Adams et *al*., 1998). Spatial analogue models assume that farmers as rational economic agents maximize profit and thus adaptation becomes an important component of analysis. Early evidence of spatial analogue model is found in the work of Mandelsohn et *al*. (1994) popularly known as the Ricardian technique. Under this technique *impact* is defined as the changes in the land values with changing climate.

4.1. Addressing adaptation to climate change in impact models

Assessing impact of climate change on agriculture cannot be considered solely as an economic problem because a number of biological processes are also involved in determining agricultural production (Antle, 1996). These biological processes itself are supposed to be influenced by changing climate. Antle (1996) suggested that there may be adaptation from non human species to climate change, either evolutionary or non evolutionary, depending on the organism and time scale involved and these changes cannot be captured easily.

Furthermore, it is naive to assume that farmer is unable to counter the negative impact of climate change on farm profit. Over time, humans are supposed to evolve ways to adapt agricultural system for external and internal shocks. These adaptations range from *incremental* to *transformational* adaptations and can be perceived as a part of development process (Kates et *al*., 2012).[18] Technological advancement, changing crop mixes and cultivated acreages, and changing institutional arrangements are some ways to accomplish adaptation (Antle, 1996).

4.1.1. Adaptation as viewed in Ricardian studies

Ricardian technique developed by Mendelsohn et *al*. (1994) is superior to production function based agronomic studies in the sense that it captures all possible adaptations by including behavioural responses of farmers in modelling framework.

The argument for adaptation that Mendelssohn et *al*. (1994) presented to justify their approach is given in figure (3). In the figure, net revenue from land or land value is measured along the vertical axis and temperature, proxy to climate is measured along horizontal axis. We assume that a farmer initially producing crop *X* as climate is believed to be favourable for this crop. Value of land under crop *X* increases first as the temperature increases and after attaining a maximum starts declining with further increase in temperature (see figure 2). Structural models assume that farmer will keep on growing crop *X* irrespective of declining land value due to increasing temperature. However, Mendelsohn et *al*. (1994) argued that once farmer realizes declining land values under crop *X*, farmer will switch to crop *Y* which is more suitable to new climatic conditions. This adaptation decision by farmer holds farm values much higher than what is expected when land is allocated to crop *X* under changed climate.

[18] Incremental adaptations can be defined as the extensions of current actions and behaviors that already reduce the losses or enhance the benefits of natural variations in climate and extreme events. On the contrary, there are at least three classes of transformational adaptations those that are carried out at much larger scale or intensity, those that are new to a region or resource system, and those that transform places and shift locations. It is possible that over the long run, the cumulative incremental changes may appear as a transformational adaptation.

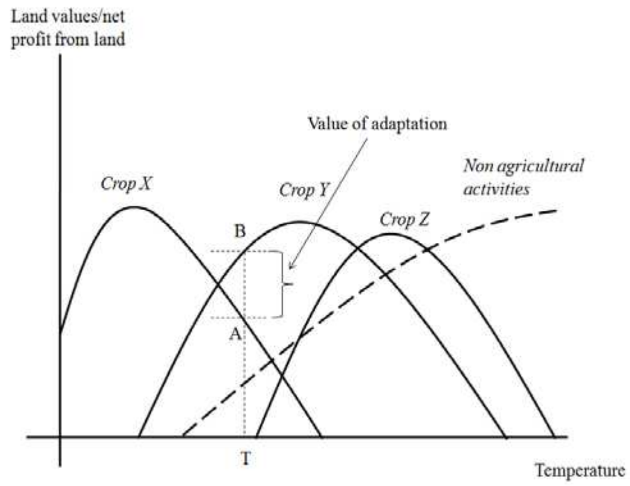

Figure 3: Land values under changing climate (Mendelsohn et *al*., 1994)

Argument proposed by Mendelsohn et *al*. (1994) (figure 3) is a simple representation of adaptation that is available to farmer merely by self realization and thus can be termed as autonomous. However, there are a number of adaptation opportunities, autonomous as well as induced, available to farmer to minimize the negative impact of climate change on farm profit. Autonomous adaptation decisions are dependent on climate and other ecosystem properties specific to a location (Antle, 1996). Spatial characteristics of an agricultural region serve as limiting factors as far as diffusion of autonomous adaptations are concerned. In this regard, crop switching decisions, background of Ricardian technique, are essentially local in nature.

A major shortcoming of Mendelsohn et *al*. (1994) is that they assumed land area available for agricultural production remains unchanged despite changing climate. Three possibilities can be discussed if we relieve assumption of constant land area under cultivation,

1. Area under cultivation can decline and thus less area will be available to crop Y after switching. Rest of the land can be left as fallow, pasture that has less economic value. Agricultural production can decline assuming that yield of crop Y is less than yield of crop X at every level of temperature (figure 3).[19]

2. Farmer can devote entire land to plantation or non agricultural activities. However, in lack of proper infrastructural support, there is no reason to believe that value of land under non agricultural activities will be higher than value of land under agriculture. Second, such investment usually have 4-5 year gestation period and demand huge initial investment. In that case, such adaptation is ruled out for small holders in developing countries. Only after

[19] Reverse can also happen especially in areas that currently fall into cold climatic regions. However, we are more concerned about normal cases than such extreme cases.

ensuring the availability of well established infrastructural and financial support, allocation of land to such activities can be profitable. This case is shown by dotted line in figure (3).

3. The most general case is that area under cultivation remains intact and farmer allocate land to multiple activities ranging from crop production to other agricultural non agricultural activities.

Considering these possibilities, we can suggest that land use diversification is virtuous activity from the farmers' side in the case of changing climate. Following these aspects of a representative farmer's behaviour, we propose that crop diversification will increase with changing climate. However, as farmer will identify next best crop that suits to changed climate, crop diversification will decline in long run.

It is argued that diversification of many forms (genetic variety, species, structural) and over different scales (within crop, within field, landscape level) is an important *resilience*[20] strategy for agricultural system (Lin, 2011). This concept of resilience is linked to *insurance hypothesis*[21] (Yachi and Loreau, 1999). However, insurance hypothesis is basically an ecological concept but it has important economic implications in wake of climate variability that took place in short run. Important implication that we confer after relieving the assumption of constant land area is that however, in long run farmer will switch land to a new activity; increased crop diversification cannot be ruled out in short run.

Evolution of new policies and institutions increases the adaptation options available to a farmer by providing necessary incentives. Evolution of adaptation friendly policies and institutions cannot be viewed in separation to the economic development. Considering the wide range of adaptation options available to farmer, the *climate response function* for a crop will be different from what is expected under controlled experiments (Mendelsohn et *al*. 1996). Correcting for farmers actions to adapt to climate change, actual crop response will be more moderate (figure 4).

Therefore, any impact methodology cannot undermine the role of adaptation, a combative strategy applied at individual as well as collective level, to moderate the negative impact of climate change on agriculture. Intuitive logic of Ricardian technique is appealing; however, it doesn't capture adaptation entirely, especially future development in policy and institutions.

[20] Here resiliency refers to the ability of a system to absorb infrequent disturbance of varying magnitudes and then return to its pre-disturbance state, but have done little to change the basic organization of the system. Long-term adaptation, however, is the ability of a system to change form and function in response to repeated disturbance (Easterling, 1996).

[21] This hypothesis proposes that crop diversification by increasing biodiversity provides insurance against climate fluctuations because different species respond differently to change.

What it provides climate change impact on net farm revenue considering others things constant.

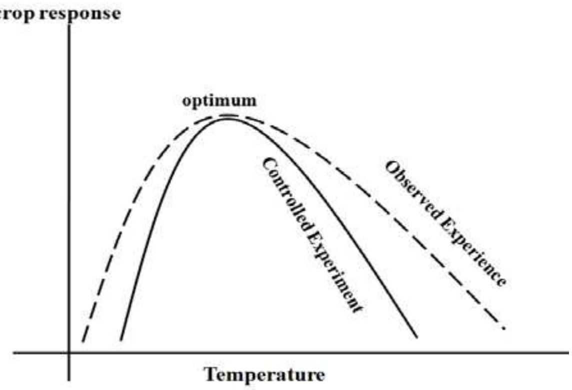

Figure 4: Impact of climate on crop productivity with and without adaptation (Mendelsohn et *al*., 1996)

4.2.Ricardian model

The intuitive idea of Ricardian technique is that impact of climate change will be reflected in changing land values. It is argued that unlike the agronomic studies, Ricardian technique captures the real response of the farmer as shown in figure (3). As stated earlier, change in climate affect agricultural system from the production side. However, end effect is partially shared by the consumer due to changing prices of the commodities. Furthermore, a rational farmer always tries to reallocate different quantities of inputs in production according to the new economic and climatic conditions. Ricardian model proposed in Mendelsohn et *al*. (1996) captures climate change impact and farmer's adaptation through changing land values at a location.

Given the agricultural technology and prices constant, there may be number of agricultural commodities which can be produced using different amount of inputs. Consider a set of well behaved production functions that links purchased inputs and climatic inputs with output Q produced at some location:

$$Q_i = f(X_i, z); i = 1,2,3...n \quad (4.1)$$

$\boldsymbol{X_i} = (X_{i1}, X_{i2}, X_{i3},...X_{ij})$ is a vector of quantities of j $(j=1,2,3,4...j)$ inputs used for producing commodity i. $z= (z_1, z_2, z_3...,z_m)$ is a vector of environmental and climatic inputs that are determined exogenously. $\boldsymbol{p}=[p_1,p_2,p_3,...,p_n]$ and $\boldsymbol{q}=[q_1,q_2,q_3,...,q_j]$ are sets of price of agricultural commodities as well as of purchased inputs respectively. The long run cost function given the environmental factors of a piece of land can be given as,

$$C_i = C(Q_i, q, z) \quad (4.2)$$

Now, objective function of a profit maximizing farmer can be given as,

$$\text{Max } p_i Y_i - C(Q_i, q, z) \quad (4.3)$$

A Production function approach follows a static technology assumption by partitioning environment and purchased inputs to estimate final production function. In this approach, we first estimate how change of climate affects agricultural yield and then use this estimated yield as a supply shift parameter in production function. Ricardian approach is a modification on this static approach as it relies on the derived crop response function. Crop response function reflects the frontier of different land use functions which arises from the dynamics of farmer's adjustment to minimize losses due to climate change (see, figure 3).

Because our focus is to use change in land value as a measure of climate change impact on agriculture, it is useful to separate land values from cost function given in equation (4.2). We assume that land as a heterogeneous input and denote it by L_i. By heterogeneity of land, we mean to say that productive capacity of different piece of land differs spatially according to the socio-climatic conditions (for some given region, particular crops are cultivated by farmers). If a representative piece of land denoted by L_i has annual cost or rent p_L, then maximization problem will look like,

$$\max \; p_i Q_i - C(Q_i, q, z) - p_L L_i \qquad (4.4)$$

We assume that agricultural land markets are fairly competitive and thus long run profit will be zero.

$$p_i Q_i - C(Q_i, q, z) - p_L L_i = 0 \qquad (4.5)$$

$$p_L = \frac{[p_i Q_i - C(Q_i, q, z)]}{L_i} \qquad (4.6)$$

According to the Ricardian rent theory, if land is allocated to the best use then rent from the land will be equal to profit earned from that piece of land.

Land value will be discounted present value of the stream of revenue from the land over time. Assuming a perfect capital market, the land value will be given as,

$$V_L = \int_0^\infty p_L e^{-rt} dt = \int_0^\infty \frac{[p_i Q_i - C(Q_i, q, z)]e^{-rt}}{L_i} dt \qquad (4.7)$$

Where, r is the rate of interest prevailing in the market. The essence of Ricardian model is described in equation (4.7). This equation describes the changes in the production and cost of production due to climate change. It also inherently captures the farmer's behaviour in a changing climate. Finally these all changes in farming parameters determine net land revenue. Long run accumulation of land revenues determines land values.

5. **Recent Developments in Ricardian Technique**

Neither the assumptions of the Ricardian model (MNS, 1994[22]) nor the estimation technique left without criticism since the publication of Mendelsohn et *al*. (1994). Later research in this direction has succeeded to relieve some theoretical and technical assumptions of the basic model (MNS, 1994) to generate robust estimates.

Cline (1996) argued that Ricardian approach reduced to be a partial equilibrium analysis due to assumed constancy of prices. It undermines the fact that agricultural activities are not possible beyond a certain level of temperature. Such a situation necessarily implies contraction in supply of food and other agricultural products. In reply to this criticism, Mendelsohn et *al*. (1999) argued that change in taste and preferences and international trade in agriculture will keep prices constant in long run. Another criticism of Ricardian technique in this direction is that it captures impact of climate change on crop system only and doesn't consider the contribution of allied (livestock) activities to land values (Darwin, 1999).

Economic adjustments to climate change are not cost free. If we incorporate adaptation costs in Ricardian estimates, monetary valuation of impact will further increases. Therefore, Ricardian approach by assuming zero adjustment cost provides a lower bound to the actual cost (Quiggin and Horowitz, 1999). On the contrary, production function based studies gives an upper bound estimate of cost of climate change as these studies assume infinite adjustment costs (no adjustment scenario). Furthermore, time distribution of climate change is another important issue that affects magnitude of impact. Quggin and Horowitz (1999) pointed out that a t^0C increase in temperature in an immediate year and t^0C increase in temperature over the period of *N* years would have different impact on adjustment cost. In other words, an immediate rise of t^0C in temperature in coming year will raise adjustment cost to infinity. On the other hand, similar increase in temperature distributed over the period of *N* years (where *N* tends to infinity) will make adjustment cost approaching to zero.

Irrigation is an important component of economic adaptation considering the fact that increasing temperature has potential to create water scarcity in agricultural regions. High temperature and low precipitation in growing season increases the requirement of investment in irrigation capital. Global warming also supposed to increase crop water demand. These factors will escalate cost of production. Cline (1996) argued that ignoring future rise in irrigation costs created a downward bias in MNS (1994) impact estimates. Darwin (1999) also criticized MNS (1994) for neglecting importance of irrigation. Darwin (1999) suggested

[22] This abbreviation is used for Mendelsohn et *al*., 1994.

that precipitation and temperature in adjacent counties should be incorporated separately in the model.[23]

Schlenker et *al*. (2005) proposed a model that shows the inherent bias in original Ricardian model due to neglecting importance of irrigation. They modelled profit as a quadratic function of climatic and non-climatic inputs assuming that too much of any input is harmful for plant. Schlenker et *al*. (2005) proposed following formulation,

$$\pi = \begin{bmatrix} x' & z' \end{bmatrix} \begin{pmatrix} A_{xx} & A_{zx} \\ A_{xz} & A_{zz} \end{pmatrix} \begin{bmatrix} x \\ z \end{bmatrix} - \omega' x - C \qquad (5.1)$$

Where π is for profit, z is a vector of climatic inputs and x is a vector of purchased inputs. A_{xx}, A_{xz}, A_{zx}, and A_{zz} are the coefficients of the quadratic production function, ω is the set of price of purchased inputs and C is the fixed cost of production. A rational farmer will maximize profit by choosing optimal x^*. Solving the matrix for profit maximization gives,

$$\pi = (z' A_{zz} z + z' A_{zx} x + x' A_{xz} z + x' A_{xx} x) - \omega' x - C$$

By symmetry,

A_{xz}=A_{zx}

Therefore,

$$\pi = A_{xx} x^2 + 2A_{xz} xz + A_{zz} z^2 - \omega x - C \qquad (5.2)$$

Differentiating equation (9) with respect to z and solving for maximization,

$$\frac{\partial \pi}{\partial z} = 2A_{xz} z + 2A_{xx} x - \omega'$$

$$x^* = A_{xx}^{-1} \left[\frac{\omega}{2} - A_{xz} z \right] \qquad (5.3)$$

Transferring profit maximizing x^* in equation (5.2),

$$\pi = A_{zz} z^2 + 2A_{zx} A_{xx}^{-1} \left(\frac{\omega}{2} - A_{xz} z \right) z + \left[A_{xx}^{-1} \left(\frac{\omega}{2} - A_{zx} z \right) \right]^2 A_{xx} - \omega \left[A_{xx}^{-1} \left(\frac{\omega}{2} - A_{zx} z \right) \right] - C$$

$$\pi = A_{zz} z^2 - A_{xz}^2 A_{xx}^{-1} z^2 - A_{xx} \frac{\omega^2}{4} + \omega A_{xz} A_{xx}^{-1} z - C \qquad (5.4)$$

$$\pi = z' \left[A_{zz} - A_{zx} A_{xx}^{-1} A_{xz} \right] z + \omega' \left(A_{xx}^{-1} A_{zx} \right) z - \omega' \left(\frac{1}{4} A_{xx}^{-1} \right) \omega - C \qquad (5.5)$$

Put,

[23] Higher temperature in other areas supposed to reduce the availability of irrigation water on average because they reduce runoff by increasing evapotranspiration in other areas. Statistically, this indicates possibility of spatial autocorrelation.

$\left(A_{zz} - A_{zx}A_{xx}^{-1}A_{xz}\right) = A_1$

$\left(A_{xx}^{-1}A_{zx}\right) = A_2$; and'

$\left(\frac{1}{4}A_{xx}^{-1}\right) = A_3$

We get,

$$\pi = z^{'}A_1 z + \omega^{'}A_2 z - \omega^{'}A_3\omega \qquad (5.6)$$

Equation (5.6) shows that cost of some purchased input can be affected due to the interaction of purchased inputs with climatic inputs (z) through A_2. For example, in regions where irrigated agriculture is in practice contrary to regions relying on rain fed agriculture, price of irrigation affects profit. Schlenker et *al*. (2005) concluded that considering rain fall and irrigation as substitute inputs, the coefficient on rainfall will be shifted by the varying prices of irrigation water.

Availability of land and other natural resources in a region also important to determine aggregate net agricultural loss of that region due to climate change. Countries being large in area may suffer less aggregate losses relative to countries smaller in size. Larger geographical area of a country provides it the benefit to shift production of a particular crop from one area to other areas. Small and island countries lacks this cheaper adaptation than international trade.[24] Furthermore, due to large area, loss of crop in certain state can be compensated from the gain in other areas (Quiggin and Horowitz, 1999).

Kumar and Parikh (2001)[25] is the early attempt to apply Ricardian technique in a developing country framework. Instead of using land values they defined net revenue per hectare as a proper proxy for land values. Study used a pooled data set covering years from 1972 to 1980 instead of using a cross sectional framework. As far as model specification is concerned, Kumar and Parikh (2001) were first to incorporate agricultural price variable in the regression model. Base model and two variants of base model with additional information on climate variability and commodity prices were estimated. On the basis of F test results, base (MNS, 1994) model estimates and first variant estimates were rejected against the estimates of second variant of the base model.[26]

[24] However, if we follow free trade assumption there will be no area advantage left.

[25] Their estimates are ridden from the problem of same sign to level and squared terms (January temp., July temp., October rain and their squares). This problem is also evident in MNS (1994).

[26] First variant model includes climate variability as an independent variable; second variant model also includes commodity prices as independent variable.

Polski (2004) was first to discuss the problem of spatial correlation and heterogeneity in MNS (1994) estimates. He argued that boundary between two agricultural systems remains porous due to the spatial interaction among the systems. Similar argument holds in case of temporal interaction among the systems. Similarly some agricultural reasons are more productive than others due to difference in respective endowments of economic, technological and ecosystem properties. This creates a spatial heterogeneity bias in the estimates. Polski (2004) used Information from the Great Planes, USA, to evaluate the predictive strength of the Ricardian estimates (MNS, 1994). To test for a spatial interaction, weighed sum of land values in neighbouring cross sectional units was introduced by Polski (2004) as a new term in basic Ricardian model (MNS, 1994). Similarly GHET term was also included in the model to capture group-wise heteroscedasticity.

The estimation results in Polski (2004) showed the presence of bias in original model (MNS, 1994) due to presence of spatial autocorrelation and group-wise heteroscedasticity. Cross sectional analysis in Polski (2004) indicated that model estimates for different year's shows different impact on agricultural land values for US Great Plains.

In Polski (2004) the special variance term (GHET) to capture group-wise heteroscedasticity was incorporated using information on irrigation status of the counties. Schlenker et al., (2005) tested the hypothesis that these are no significant difference between Ricardian estimates for irrigated and non-irrigated counties i.e. spatial pooling of counties is justified. To correct their model for another potential source of bias, level of urbanization, they kept urbanized counties out of the sample. Sample of non urban counties was then divided into irrigated and non irrigated counties. Regression results of subsample, representing non urbanized and non irrigated counties, were used to simulate the future impact.

6. Summary and Discussion

Climate acts as a vital input for agricultural production. Majority of the population in developing countries still rely on agriculture and allied activities as a source of livelihood. Changing climatic cycles across the Globe and expected future loss to agricultural production due to it raises serious concerns for global food security. Indian economy is still an agricultural economy as far as contribution of agriculture in employment is concerned. Agriculture and allied activities accounts for providing livelihood for 60 percent of India's population.

Considering these facts, impact assessment becomes an important research issue. In this review, we have made an attempt to summarize two broad approaches that have been used by researchers for impact assessment. Both the approaches use OLS framework to estimate climate sensitivities. This similarity in estimation framework allows us to compare the strength and weaknesses of two approaches. However, physical impact studies have been performed on Indian agriculture (for a review see, Mall et al., 2006) but these studies are mostly concentrated to cereals. The biophysical impact on some of the important crops like sugar cane, oilseeds and pulses has not been studied.

Another important issue that we encounter regarding Ricardian technique is the increasing importance of spatial factors while performing sensitivity analysis. Recent studies have chosen study areas very cautiously to ensure environmental homogeneity (see, Polski, 2004 and schlenker, 2005; 2006). Antle (1996) also endorsed this factor while measuring climate change impact on agriculture. Equally important issue with Ricardian technique is that it assumes a smooth and continuous climate response function for land values. Such an assumption leads to a situation of perfect adaptation (Quiggin and Horowitz, 1999). We argue that if argument of MNS (1994) holds then crop diversification will increase with climate change and eventually start decreasing when a farmer identifies a crop that suits changed climate conditions (see, section 4.1).

Appendix:

Interaction of climate variables includes two different cases. First, when both variables reflect same meteorological phenomenon (temperature or rainfall) and second, when both variables reflect different metrological phenomenon (temperature and rainfall). In the first case, we need to compute expected value of square of some meteorological phenomenon while in the second case we need to compute expected value of interaction of two different meteorological phenomenons. Final results can be computed as follows,

$$\mathrm{var}(X) = E[X - E(X)]^2$$
$$= E[X^2 - 2E(X)E(X) + [E(X)]]^2$$
$$= E(X^2) - [E(X)]^2$$
$$E(X^2) = \mathrm{var}(X) + [E(X)]^2$$

Similarly,

$$\mathrm{cov}(XY) = E[(X - E(X))(Y - E(Y))]$$
$$= E[XY - XE(Y) - YE(X) + E(X)E(Y)] = E(XY) - E(X)E(Y)$$
$$E(XY) = \mathrm{cov}(XY) + E(X)E(Y)$$

References:

Adams, R.M., B. H. Hurd, S. Lenhart and N. Leary, "Effects of global climate change on agriculture: an interpretative review," *Climate Research*, 1998, 11, 19–30.

Antle, J. M., “Methodological issues in assessing potential impacts of climate change on agriculture,” *Agricultural and Forest Meteorology*, 1996, 80, 67-85.

Callaway, J. M., F. J. Cronin, J. W. Currie and J. Tawil, “An analysis of methods and models for assessing the direct and indirect economic impacts of CO_2- induced environmental changes in the agricultural sector of the U.S. Economy,” U.S. Department of Energy, Report No. PNL-4384, 1982.

Cline, R., “The Impact of Global Warming of Agriculture: Comment,” *American Economic Review*, 1996, 86 (5), 1309-1311.

Darwin, R., “The Impact of Global Warming on Agriculture: A Ricardian Analysis: Comment,” *American Economic Review*, 1999, 89 (4), 1049-1052.

Deschênes, O. and Greenstone, M., “The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather,” *American Economic Review*, 2007. 97 (1), 354-385.

Easterling, W. E., “Adapting North American agriculture to climate change,” *Agriculture and Forest Meteorology*, 1996, 80 (1), 1-53.

Gadgil, S. and S. Gadgil, “The Indian Monsoon, GDP and Agriculture,” *Economic and Political Weekly*, 2006, 41 (47), 4887-4895.

IPCC, “Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007. Retrieved from http://www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html

Kates, R. W., W. R. Travis and T. J. Wilbanks, “Transformational adaptaion when incremental adaptations to climate change are insufficient,” *Proceedings of National Academy of Sciences*, 2012, 109 (19), 7156-7161.

Kumar, K. S. K. and J. Parikh, “Indian agriculture and climate sensitivity,” *Global Environmental Change*, 2001, 11, 147-154.

Lin, B. B., “Resilience in Agriculture through Crop Diversification: Adaptive Management for Environmental change,” *Bioscience*, 2011, 61 (3), 183-193.

Mall, R. K., R. Singh, A. Gupta, G. Srinivasan and L. S. Rathod, “Impact of climate change on Indian agriculture: A review,” *Climatic Change*, 2006, 78, 445-478.

Mendelsohn, R. and W. D. Nordhaus, “The Impact of Global Warming on Agriculture: A Ricardian Analysis: Reply,” *American Economic Review*, 1999, 89 (4), 1046-48.

Mendelsohn, R., A. Dinar and A. Sanghi, “The effect of development on the climate sensitivity of agriculture,” *Environment and Development Economics*, 2001, 6, 85-101.

Mendelsohn, R., W. D. Nordhaus and D. Shaw, "Climate impacts on aggregate farm value: accounting for adaptation," *Agricultural and Forest Meteorology*, 1996, 80, 55-66.

Mendelsohn, R., W. D. Nordhaus and D. Shaw, "The Impact of Global Warming on Agriculture: A Ricardian Analysis," *American Economic Review*, 1994, 84 (4), 753-771.

Nelson, W. L. and R. F. Dale, "Effect of trend or technology variables and record period on prediction of corn yields with weather variables," *Journal of Applied Meteorology*, 1978, 17, 926-933.

Polski, C., "Putting Space and Time in Ricardian Climate Change Impact Studies: Agriculture in the U.S. Great Plains, 1969-1992," *Annals of the Association of American Geographers*, 2004, 94 (3), 549-564.

Quiggin J.C. and J. K. Horowitz, "The Impact of Global Warming on Agriculture: A Ricardian Analysis: Comment," *American Economic Review*, 1999, 89 (4), 1044-45.

Rosenberg, N. J., "The increasing CO_2 concentration in the atmosphere and its implication on agricultural productivity," *Climatic Change*, 1981, 3, 265-279.

Schlenker, W. and M. Roberts, "Nonlinear temperature effects indicate severe damages to US crop yields under climate change," *Proceedings of National Academy of Sciences*, 2009, 106 (37), 15594-15598.

Schlenker, W., W. M. Hanemann and A. C. Fisher, "Will U.S. Agriculture Really Benefit from Global Warming? Accounting for Irrigation in the Hedonic Approach," *American Economic Review*, 2005, 95 (1), 395-406.

Thompson, L. M., "Weather variability, climate change and grain production," *Science*, 1975, 118, 535-541.

Zilberman, D., X. Liu, D. R. Holst and D. Sunding, "Economics of climate change in agriculture," *Mitigation and Adaptation Strategies for Global Change*, 2004, 9, 365-382.