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The potential impact of climate change on Taiwan's agriculture

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Abstract

This paper intends to estimate the potential impact of climate change on Taiwan's agricultural sector. Yield response regression models are used to investigate the climate change's impact on 60 crops. A price-endogenous mathematical programming model is then used to simulate the welfare impacts of yield changes under various climate change scenarios. Results suggest that both warming and climate variations have a significant but non-monotonic impact on crop yields. Society as a whole would not suffer from warming, but a precipitation increase may be devastating to farmers. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Agriculture has been a central focus of policy discussions and research projects dealing with economic effects of greenhouse gas emission control strategies. Climate is a major determinant of both the location and productivity of agricultural activities. Significant research efforts are now underway to investigate agriculture's ability to adapt, because it is important to "understand how much to control global greenhouse gas emissions and to gauge what actions would make agriculture more resilient" (Reilly, 1999, p. 4).

Considerable progress has been made in evaluating the potential effects of climate change on global agriculture (Kane et al., 1992; Rosenzweig and Parry, 1994; Darwin et al., 1995). However, significant uncertainties remain (Reilly, 1995) and concern has shifted to regional effects (e.g. Adams et al., 1990, 1993; Mendelsohn et al., 1994 on US agriculture) or farm-level impacts (e.g. Kaiser et al., 1993; Easterling et al., 1993). Adams et al. (1998) provides a thorough review on the similarities and differences in the research of climate change on agriculture. In general, the economic effects vary across both crops and regions, just as the changes in physical crop yields do. Including human adaptive responses is critical to a valid assessment and in some cases even reverses the direction of the net economic effect.

The literature reviewed by Adams et al. (1998) concentrates on the CERES family of crops (Ritchie et al., 1989) produced in North and Latin American countries, because empirical assessment for other crops produced elsewhere in the world is sparse. While the consensus is that the potential for crop yield reduction is greatest in warmer, lower latitude areas and semi-arid areas of the world (cited in Rosenzweig and Iglesias, 1994; IPCC, 1996 and Smith et al., 1996),

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the economic consequences of crop yield reductions in these areas are largely unexplored. To fill this empirical gap, this study evaluates the potential impacts from climate change on the agricultural sector of an economy located in the semi-tropical area—Taiwan. The results illustrate not only the sensitivity of agriculture to climate change in this area, but also the possible economic outcomes which can assist us in understanding the importance of the adaptive behavior that is available to cope with these changes.

Taiwan is situated between 21.7 and 25.5° northern latitude and has a total area of 3.6 million ha. A central mountain chain runs along the vertical axis of the island, with the land rising from a 100 m foothill to a mountain range of 3000 m being only within a horizontal distance of 50–60 km. Thus, the location of this mountain chain determines the distribution of agricultural land. The total cultivated land in 1996 was 0.87 million ha, or 24% of the total land area, with paddy fields amounting to 0.46 million ha and dryland 0.41 million ha. Of all the paddy fields, about 75% are in the irrigated area managed by the irrigation association.

Taiwan's subtropical weather permits the growing of a great variety of crops. In the summer months the temperature in southern and northern Taiwan is almost identical (27–28 °C). During the winter months, the mean temperature is about 5 °C higher in the south (20 °C) than that in the north (15 °C). Although, the rainfall distribution is profoundly affected by topography, the annual rainfall in the main crop production area ranges from 1500 to 2000 mm, with rainfall abundant throughout the island from May to October. During the winter months, the rainy season prevails in the northern and eastern regions while the central and southern parts of the west coast have dry and sunny weather. Given warm and humid weather, many kinds of crops can be grown to produce a wide variety of farm products on the island (Cheng, 1975).

In this study we will adopt the "structural" approach in Adams et al. (1999) which incorporates the yield effects of climate change directly into a sector-wide economic model with various levels of farm adaptation possibilities. We start by using multiple regression models to investigate the impact of climate change on Taiwan's crop yields. The coefficient estimates are used to predict yield changes under alternative climate change scenarios. An empirical Taiwan agricultural sector model (hereafter called TASM) is then employed to evaluate the impact of crop yield changes on agricultural production, land use, welfare distribution, as well as the potentials for agriculture to adapt to climate changes.

This paper is organized as follows. Section 2 presents the empirical results of the crop yield response regressions. In Section 3 an overview of the structure and data of TASM are illustrated. In Section 4 the welfare implications of alternative climate change scenarios are evaluated and Section 5 summarizes the results.

2. Yield response regression

Several previous studies have estimated the impact of climate on crop yields, however, most studies have focused on selected crops (e.g. Andresen and Dale, 1989; Dixon et al., 1994; Kaufmann and Snell, 1997 on corn; Wu, 1996 on rice). Inter-crop comparisons are not available. To facilitate our sector-wide evaluation, a comprehensive crop yield response study for 60 crops is conducted for Taiwan.

Crop yield response models are typically estimated from field data using the measurement of climate and non-climate-related variables to identify the physical effect of climate change on yield. To consider farmers' adaptation, this paper adopts a multiple regression model for crop yields that integrates the physical and social determinants of yield. Average yields from 15 sub-regions (or prefectures) in Taiwan for the years 1977 through 1996 are used in our regressions. The general form of this model is given by Eq. (1) as follows: [1]

$$\text{yield} = f(\text{climate, technology, management, land})$$

[1] Price variables are not included in our model, because we did not adopt the duality approach as done in Segerson and Dixon (1999). Therefore, our yield estimates should be viewed as short-term predictions. No adaptation in management practices to offset the negative impact of climate change is considered here. Therefore, some overestimation on the negative effect (or underestimation on the positive) of climate change might occur. However, adaptations are allowed in terms of changing crop mixes in the later part of our analysis when TASM is used to simulate the effect of climate change on land usage and welfare distribution.

where yield is per acre yield, climate and land represent climate and soil conditions and do not lend themselves to control by decision makers.

In this study average temperature and precipitation are considered as the major climate factors, with the average slope being used as a proxy for the characteristics of land. Both technology and management are considered as systematic factors under the control of producers. Time trend is used to represent the level of technology. The management factor associated with crop yield is proxied by the ratio of full-time farm households to total farm households in the area. This variable intends to capture the extent to which farm operators in a given area devote their effort to farming and derive their livelihood from it (Segerson and Dixon, 1999).

Under the general setup, a seasonal regression model is specified to reflect the relationship between weather and the growth stage of crops as follows:

$$Y = f(\mathrm{TEMP}_s, \mathrm{TEMP}_s^2, \mathrm{RAIN}_s, \mathrm{RAIN}_s^2, \mathrm{VTEMP}_s, \mathrm{VRAIN}_s, \mathrm{MANA}_s, \mathrm{TIME}, \mathrm{SLOPE})$$

where subscripts s ($s = 1$–4) are the seasonal identifiers. The explanatory variables include: TEMP_s, seasonal mean of monthly average temperature (°C); RAIN_s, seasonal mean of monthly average precipitation (mm); VTEMP_s, variation of seasonal mean temperature from 20 years seasonal average; VRAIN_s, variation of seasonal mean precipitation from 20 years seasonal average; MANA, percentage of full-time in total farm households (%), TIME, time trend; and SLOPE, land slope (%).

This model adopts a non-linear specification for each climate variable where linear and quadratic terms are used as regressors, reflecting the effect of a physiological optimum on yield. For example, a positive coefficient for the linear term and a negative coefficient for the quadratic term indicate that an intermediate value has the greatest positive effect on yield (Kaufmann and Snell, 1997). It also allows for a non-monotonic relationship between climate and yield, i.e. a warming up might increase crop yields in cooler areas but decrease yields in warmer regions (Segerson and Dixon, 1999). However, collinearity problems arise from inclusion of these quadratic terms. Therefore, the results should be interpreted carefully and the significance level of the coefficient estimates are unreliable.

Table 1
Regional and sub-regional specifications

Region	Sub-region
North	Taipei, Taoyuan, Hsinchu, Miaoli
Central	Taichung, Nantu, Changhua, Yunlin
South	Chiayi, Tainan, Kaohsiung, Pingtung
East	Ilan, Hualian, Taitung

Variations on temperature (VTEM_s) and precipitation (VRAIN_s) from their historical means are also included to capture the effect of an extreme event on yield.[2] Previous studies (e.g. Shaw et al., 1994; Mendelsohn et al., 1996) show that omitting the variation terms biased the effect of the global warming. Therefore, these climate variation terms are added in our yield regression model.

A semi-logrithmic functional form is used where all the independent variables (except the time trend variable) are transformed by taking their logs. The model is estimated with pooled time-series and cross-sectional data for 59 crops from 15 sub-regions over the period 1977–1996. Table 1 displays the regional and sub-regional specifications. Taiwan is divided into four major crop regions by geographical locations, and within each region there are 3–4 sub-regions. The data on crop yields are drawn from the Taiwan Agricultural Yearbook. Monthly weather data on temperature and precipitation are obtained from Taiwan's Central Weather Bureau. Annual data on the number of full-time and total farm households are taken from the Taiwan Agricultural Yearbook. Data on slopes are calculated by averaging the data reported in The Statistics and Graphical Summary of the Soil Conditions and Proper Cropping Systems in Taiwan's Cultivated Land (Lin and Tsai, 1994).

[2] It should be noted that there exist alternative specifications for the climate variation variable. The variables used in our study are measured differently from those in Mendelsohn et al's. (1999) study. We calculate the deviations of seasonal average temperatures and precipitation from their corresponding sample means for each sample period, while Mendelsohn et al. (1999) use the difference between the highest and lowest monthly temperatures and precipitation over the entire sample period in their cross-section study. Although, the main concern in both studies is about the extreme event, the measures differ due to differences in model scope and data availability.

Table 2
Summary statistics of data used in yield response regressions

	Mean	Standard error
Non-climate		
MANA	0.13	0.05
SLOPE	0.05	0.03
Climate		
$TEMP_1$	17.04	2.42
$TEMP_2$	22.25	2.16
$TEMP_3$	27.88	1.51
$TEMP_4$	24.02	1.93
$RAIN_1$	91.48	96.12
$RAIN_2$	163.91	84.71
$RAIN_3$	293.57	130.14
$RAIN_4$	208.44	229.79
Climate variations		
$VTEMP_1$	0.50	0.66
$VTEMP_2$	0.43	0.52
$VTEMP_3$	0.20	0.27
$VTEMP_4$	0.24	0.28
$VRAIN_1$	1978.71	4622.38
$VRAIN_2$	3627.25	5641.49
$VRAIN_3$	12995.31	24262.19
$VRAIN_4$	13580.60	37149.20

The summary statistics are presented in Table 2. Over the past 20 years, the temperature variation is obviously less dramatic than the variations in precipitation. In Figs. 1 and 2, regional differences on annual average temperature and precipitation are presented. Both the southern and eastern regions have above average temperature, while their precipitation levels are mostly below average.

Since the pooling data is used, the error terms may be correlated across time and individual units. Thus, the error terms consist of three components: a cross-section, a time-series, and a combined error component. We adopt the assumption that the error terms are cross-sectionally independent, but are timewise autocorrelated. A generalized least square procedure described in Kmenta (1986, pp. 618–622) is used to obtain consistent estimates.[3]

For most crops, the model tends to have pretty good explanatory power as measured by the Buse Raw-moment R^2, including rice. However, for wheat, sorghum, soybeans, potato, several vegetables (scallop bulb, cabbage, etc.) and fruits (grape, apple, coconut, etc.), the model does not perform very well.

For the non-climate variables, the management factor (i.e. the percentage of full-time farms) has a very significant and positive impact on yields for most crops. Steeper land slopes are harmful to many crop yields, in particular vegetables. Technology has, as expected, a positive and significant effect on yields in most cases.

As for the climate variables, since both linear and quadratic terms are included in the model, elasticities are calculated to identify their marginal yield impacts at the sample means. The results are shown in Table 3. For rice (Taiwan's most important staple crop), warmer temperatures and increased precipitation are mostly yield-decreasing. A number of studies are also conducted on the impact of climate change on rice yield using the data from field and/or laboratory controlled-experiments and various crop simulation models for many different countries. Matthews et al. (1995) conclude that many uncertainties exist due to uncertainties in climate predictions, limited sites for which historical weather data are available, and quality of the crop simulation models. Nevertheless, the result that a warming up would adversely affect rice yield is quite consistent with those in Horie (1991) for Japan and Wu (1996) for Taiwan.

A warming up also tends to be harmful to soybeans, adzuki beans, sugarcane, and many fruits like bananas, pineapples, grapes, apples, etc. As for vegetables, temperature increases in the first and fourth quarters are mostly favorable, but while it is not in the second quarter. Too much rain is also unfavorable to their yields. Tomato yields are found to positively related to a temperature increase, and this is quite similar to the pattern used in Adams et al's. (1999) study for US agriculture.

The climate impacts on citrus fruit vary by species. A temperature rise is favorable for ponkan, tankan and wentan, but not for liucheng, lemon and grapefruits. The yield changes used in Adams et al. (1999) (originally estimated by Ben-Mechlia and Carroll (1989a,b) using the crop simulation models) for citrus produced in the US show that a warming up may cause some decreases in the southern regions, but shows increases at more northerly sites. Our results suggest that differences in species should also be taken into account beside locations.

[3] Data and detailed estimation results are available upon request.

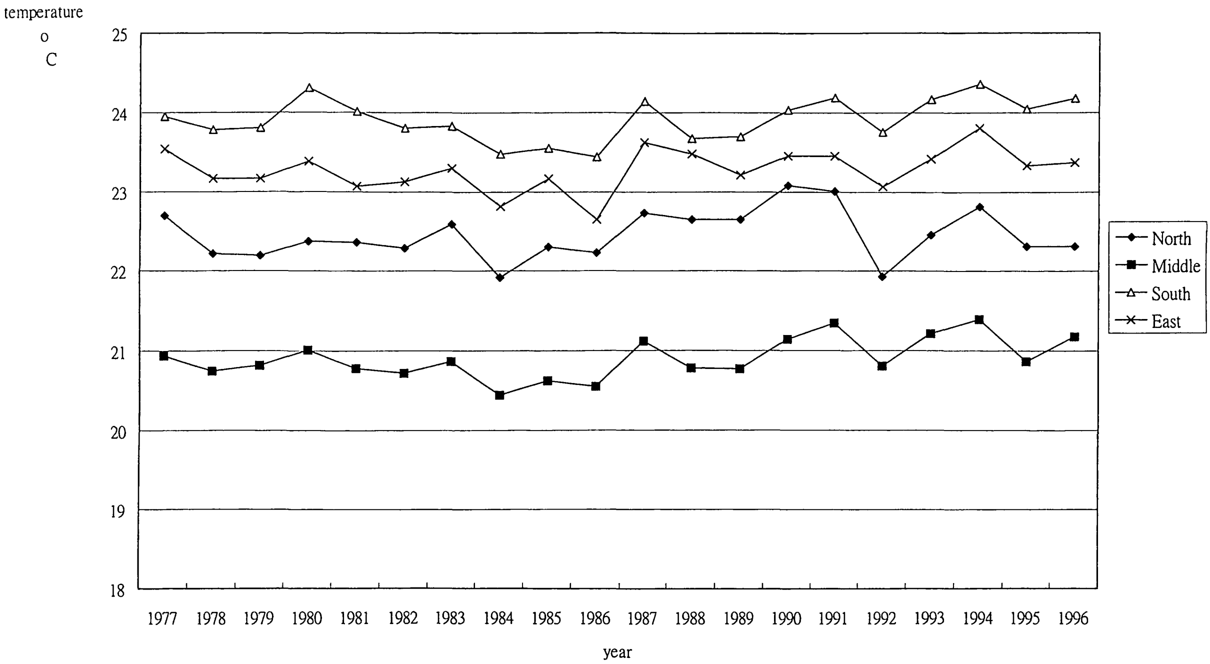

Fig. 1. Annual mean of monthly average temperature by region in Taiwan, 1977–1996.

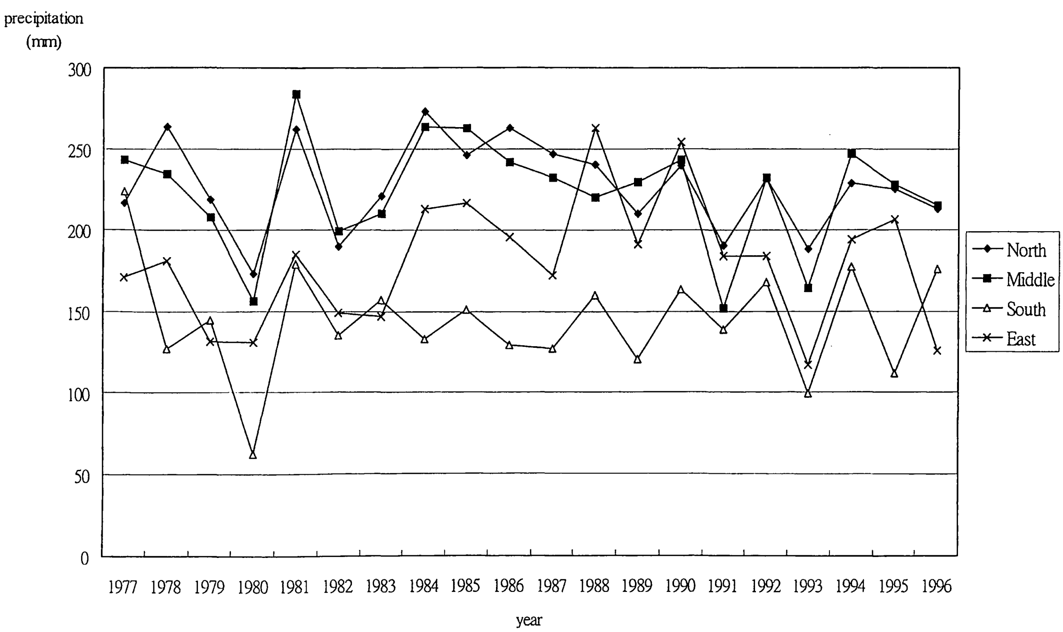

Fig. 2. Average mean of monthly average precipitation by region in Taiwan, 1977–1996.

Table 3
Elasticities of yields in response to climate change

	Temperature change by season				Precipitation change by season			
	First	Second	Third	Fourth	First	Second	Third	Fourth
Cereal								
Rice	−0.075	−0.003	−0.198	−0.052	−0.014	−0.080	0.027	0.008
Corn	−0.002	0.078	−0.778	0.367	−0.003	−0.035	−0.059	−0.004
Wheat	0.035	0.150	0.158	−0.360	−0.002	0.068	−0.051	0.004
Sorghum	−0.120	−1.113	1.769	1.498	−0.035	0.095	0.510	−0.009
Pulses								
Soybean	−0.250	−0.048	0.264	−0.234	−0.047	−0.116	0.505	0.105
Peanut	−0.167	0.397	0.097	−0.126	−0.010	−0.080	0.003	0.061
Adzuki bean	−0.336	−0.536	0.734	−1.337	−0.003	0.069	−0.270	0.076
Roots								
Sweet potato	0.163	0.200	−0.674	0.261	−0.003	−0.028	−0.206	−0.009
Potato	−0.056	−0.248	−0.383	1.115	0.000	−0.331	−0.362	0.091
Special								
Tea	0.023	0.593	−1.181	0.644	0.022	−0.241	0.020	0.007
Cane for proc	−0.097	−0.233	0.039	−0.325	0.030	0.354	−0.256	0.055
Cane fresh	−0.097	−0.233	0.039	−0.325	0.030	0.354	−0.256	0.055
Sesame	0.322	−0.513	−1.489	0.383	−0.105	−0.002	0.448	−0.075
Vegetables								
Radish	0.011	0.021	0.093	−0.044	0.003	0.068	0.030	0.017
Carrot	0.145	−0.255	1.536	0.146	−0.006	0.059	−0.277	0.015
Ginger	0.181	0.406	0.445	−0.116	−0.001	0.069	0.016	0.004
Scallion	0.072	−0.170	1.310	0.586	0.001	−0.032	−0.105	0.026
Scallion bulb	0.120	0.299	−1.210	0.940	−0.059	0.189	−0.055	0.091
Garlic bulb	−0.047	−0.384	−1.042	1.484	0.005	0.293	0.055	0.229
Leek	0.064	0.636	−0.723	0.751	0.001	−0.114	−0.135	0.007
Bamboo	0.088	0.061	0.459	0.258	−0.005	−0.069	−0.090	−0.066
Asparagus	−0.093	−1.045	−0.436	0.794	−0.043	−0.061	0.413	0.041
Water bamboo	−0.093	−1.045	−0.436	0.794	−0.043	−0.061	0.413	0.041
Cabbage	0.076	−0.072	0.053	0.164	−0.018	0.172	−0.299	0.007
Cauliflower	0.076	−0.072	0.053	0.164	−0.018	0.172	−0.299	0.007
Pickling	0.197	0.097	−0.343	−0.389	−0.006	0.010	−0.288	−0.043
Cucumber	−0.066	−0.106	−0.163	0.115	−0.006	0.032	−0.216	−0.008
Bitter	0.036	−0.087	0.717	0.718	−0.090	−0.160	0.214	−0.020
Tomato	0.046	−0.086	0.165	0.313	−0.043	−0.045	−0.037	−0.054
Pea	0.188	−0.510	1.012	−0.903	−0.009	−0.082	0.125	−0.048
Vegetable soybean	0.188	−0.510	1.012	−0.903	−0.009	−0.082	0.125	−0.048
Watermelon	0.149	0.029	0.649	−0.307	0.014	0.245	−0.636	0.031
Cantaloupe	0.022	0.024	−0.959	0.825	−0.012	0.063	0.185	0.018
Mushroom	0.461	−0.115	−1.561	0.367	−0.038	−0.078	−0.030	−0.020
Fruits								
Banana	−0.231	−0.495	−0.223	−0.125	−0.035	−0.065	−0.003	−0.004
Pineapple	0.118	−0.274	−1.316	−0.553	−0.009	0.168	−0.071	−0.013
Ponkan	0.177	−0.593	0.595	−0.003	0.007	0.225	−0.323	0.040
Tankan	0.123	−0.069	1.074	0.546	0.044	−0.239	0.031	0.039
Wentan	0.198	0.028	0.540	−0.011	0.039	0.043	−0.004	0.063
Liucheng	0.267	−0.255	−0.189	0.064	0.007	0.116	0.208	−0.038
Lemon	−0.216	0.103	−0.495	−0.260	0.016	0.021	0.147	0.026
Grapefruit	−0.158	0.409	−1.235	−0.102	0.008	−0.137	0.122	−0.060

Table 3 (*Continued*)

	Temperature change by season				Precipitation change by season			
	First	Second	Third	Fourth	First	Second	Third	Fourth
Mango	−0.164	0.236	0.735	−0.182	−0.073	−0.377	−0.396	0.059
Betel	−0.210	0.444	−1.759	0.013	−0.030	0.268	−0.182	−0.072
Guava	−0.070	−0.294	0.087	0.149	0.020	0.094	−0.049	0.008
Wax apple	−0.068	0.240	0.456	−0.164	−0.012	−0.123	0.021	−0.041
Grape	−0.029	−0.837	−1.387	1.366	0.015	0.353	0.292	0.029
Loquat	0.039	0.841	−0.083	−0.375	−0.006	−0.120	−0.154	0.043
Plum	0.227	0.005	−0.259	0.407	−0.012	−0.054	0.259	0.033
Peach	0.242	−0.119	0.377	0.365	0.019	−0.102	0.057	−0.100
Persimmons	0.197	0.232	0.337	−0.563	0.009	−0.127	−0.262	−0.056
Apricot	−0.242	−0.183	−0.602	0.116	0.015	0.200	0.167	0.060
Liche	0.181	−0.531	0.952	−0.853	−0.014	−0.003	0.089	0.018
Carambolas	−0.058	−0.172	0.385	0.096	−0.008	−0.002	−0.270	0.004
Pear	−0.064	0.335	−0.648	0.714	0.006	−0.194	0.229	−0.035
Apple	−0.147	−0.134	−2.720	0.647	0.009	−0.044	0.295	−0.047
Papaya	0.039	−0.331	0.368	0.036	0.023	−0.137	−0.178	−0.066
Sugar apple	−0.103	−0.214	0.363	−0.733	−0.055	−0.115	−0.002	−0.141
Passion fruit	−0.236	0.131	−0.483	0.039	−0.052	0.063	0.069	0.064
Coconut	0.039	−0.071	0.102	−0.532	0.007	0.063	−0.203	−0.095

Climate variations are lastly found to have a significant yield impact on many crops like corn, peanut, sorghum, sugarcane, sesame, scallop bulb, bamboo, cucumber, cantaloupe, banana, etc. Relatively speaking, temperature variations seem to be more favorable to yields, while precipitation variations are mostly yield-decreasing. The latter is, to some extent, consistent with the findings in Shaw et al. (1994) and Mendelsohn et al. (1996). In other words, changes in rainfall patterns can be beneficial over some ranges, but detrimental over others.

In the review article by Adams et al. (1998), they compare the climate effects on grain crops in Latin and North America derived from various crop simulation models. Their comparison indicates that an important regional trend exists. They also point out that crop productivity in large areas of Latin America is negatively affected by the inter-annual variability and the occurrence of extreme events. Since both warming and greater climate variability are found to have a significant impact on many crop yields in Taiwan, their concern on the regional food supply and welfare redistribution are potentially important and, thus, should be explored. In the following sections we will investigate the economic implications of these yield changes.

3. Structure of TASM

In this study a price-endogenous spatial equilibrium model (TASM) is used to evaluate the impact of crop yield changes on regional production, land use, welfare distribution, as well as the potentials for agriculture to adapt to climate changes. This section describes the structure of TASM. The TASM is formulated in a multi-product partial equilibrium framework based on the previous work of Baumes (1978); Burton and Martin (1987); McCarl and Spreen (1980); Chang et al. (1992); Coble et al. (1992) and Tanyeri-Abur et al. (1993). The empirical structure has been adapted to Taiwan and used in a number of policy-related studies, e.g. Chang and Chen (1995) and Chang (1999). The current version of TASM accommodates more than 90 commodities for four major production regions which can be further divided into 15 sub-regions.

Under the perfect competitive and price-taking assumptions, price-dependent product demand and input supply curves are used to replicate market operations. First, we assume that there exists I agricultural commodities which are produced in K regions through production activities ($i = 1, 2, \ldots, I$; $k = 1, 2, \ldots, K$). The unit of each activity is a hectare. The total production in each region can be calculated by multiplying per hectare yield with. For product demand, we assume all commodities are sold in the wholesale markets. The prices faced by consumers can be represented by the national average of wholesale prices. Assume demand functions are integrable and can be represented by the following inverse demand functions:

$$P_i^Q = \psi(Q_i), \qquad i = 1, 2, \ldots, I \tag{1}$$

where Q_i is the total quantity of consumption and P_i^Q the average wholesale price of commodity i.

In the input markets we assume each production activity must apply M regional inputs (such as land and labor) and N inputs purchased from the non-farm sector (such as fertilizer and chemicals). The prices of N purchased inputs are exogenous. However, the prices of M regional inputs are endogenously determined by the derived demand from the production activities and regional supply functions. Assume regional supply functions are integrable as follows:

$$P_{mk}^L = \alpha_k(L_{mk}), \qquad m = 1, 2, \ldots, k \tag{2}$$

where P_{mk}^L are user prices of regional inputs and are the quantity supplied.

The objective function which maximizes the sum of consumers' surplus plus producers' surpluses is used to simulate a perfectly competitive market equilibrium following Samuelson (1952); Takayama and Judge (1964). It is defined as the area between the product demand and factor supply curves to the left of their intersection as follows:

$$\begin{aligned} \max : &\sum_i \int \psi(Q_i)\,\mathrm{d}Q_i - \sum_i \sum_k C_{ik} X_{ik} \\ &- \sum_k \int \alpha_{mk}(L_{mk})\,\mathrm{d}L_{mk} \end{aligned} \tag{3}$$

The constraints are:

$$Q_i - \sum_k Y_{ik} X_{ik} \le 0 \qquad \text{for all } i \tag{4}$$

$$\sum_i f_{imk} X_{ik} - L_{mk} \le 0 \qquad \text{for all } k \tag{5}$$

where C_{ik} is the purchased input cost in region k used in producing the ith commodity, Y_{ik} the per hectare yield of ith commodity produced in region k, and f_{imk} the demand for the mth regional input in region k. Terms P^L, P^Q, L_K, and X_{ik} are endogenous variables while C_{ik}, Y_{ik}, and f_{imk} are known parameters.

The following two sets of policy variables are also added into the model. The first set is used to reflect the government rice purchase program under a guaranteed price which is above the market equilibrium price. An import ban is used to assure farmers a reasonable return. A high guaranteed price and tight restriction on rice imports stimulate excess production resulting in a rapid accumulation of surplus rice, a shortage of elevator space, and an escalating government deficit. Per hectare limits on rice purchases have been implemented since 1977. Letting P_r^g be the weighted government guaranteed purchases price and the total amount of government purchase, the objective function becomes

$$\begin{aligned} \max : &\sum_i \int \psi(Q_i)\,\mathrm{d}Q_i + P^g Q^g \\ &- \sum_i \sum_k C_{ik} X_{ik} - \sum_k \int \alpha_{mk} L_{mk}\,\mathrm{d}L_{mk} \end{aligned} \tag{6}$$

The constraints are also modified into:
subject to:

$$Q_r + Q^g - \sum_k Y_{rk} X_{rk} \le 0 \qquad r \text{ is rice product} \tag{7}$$

$$Q_j - \sum_k Y_{jk} X_{jk} \le 0$$

$$j \text{ is other products excluding rice} \tag{8}$$

$$\sum_i X_{imk} - L_{mk} \le 0 \qquad \text{for all } k \text{ and } m \tag{9}$$

The total amount from the government rice purchase program ($P_r^g Q_r^g$) is added into the objective function as additional revenues for the farmers. Eq. (7) represents the modified supply–demand balance condition for rice and Eq. (8) is for other products. Eq. (9) remains unchanged.

The second set of policy variables relates to the trade protection instruments in Taiwan. Taiwan's import/export share in the world market is very small. Therefore, import and export prices are assumed to be exogenously determined by supply and demand in the world market. The net trade balances are added into the objective function directly to reflect the welfare

Table 4
List of commodities in TASM[a]

Primary Products (75)									Secondary Products (17)
Crops (60)						Floral Crops (5)	Livestock (7)	Forest (3)	
Cereals (4)	Pulses (3)	Roots (2)	Special (4)	Vegetables (21)	Fruits (26)				
Rice, maize, wheat, sorghum	Soybeans, peanuts, adzuki beans	Sweet potatoes, potatoes	Tea, sugarcane, sugarcane for processing, sesame	Radishes, carrots, ginger, scallion, scallion bulbs, garlic bulbs, leek, bamboo shoot, asparagus, water bamboo, cabbage, cauliflower, oriental picking melons, cucumbers, bitter gourds, tomatoes, field peas, vegetable soybeans, watermelons, cantaloupe, mushroom	Bananas, pineapples, citrus-ponkans, citrus-tankans, wentan pomelos, citrus-liuchengs, lemons, grapefruits, mangoes, guavas, wax apples, lichees, carambolas, papayas, betel nuts, loquats, grapes, Plums, peaches, persimmons, Japanese apricot, pears, apples, sugar apples, passion-fruits, coconut	Chrysanthemum, gladiolus, rose, baby's-breath, others	Cattle, hogs, goats, geese, duck, broiler, eggs	Conifers, hardwoods, bamboo	Soybean oil, soybean power, Wheat flour, wheat bran, corn oil, corn starch, hogs feed, cattle feed, goats feed, chicken feed, duck feed, geese feed, sugar, pork, pork belly, conifer timber, hardwood timber

[a] The numbers of commodities within the group are in parentheses.

effects from international trade. The model is further extended into:

$$\max : \sum_i \int \psi(Q_i)\,\mathrm{d}Q_i + \sum_f P_f^x Q_f^x - \sum_f P_f^m Q_f^m - \sum_i \sum_k C_{ik} X_{ik} - \sum_m \sum_k \int \alpha_{mk}(L_{mk})\,\mathrm{d}L_{mk} \tag{10}$$

subject to:

$$Q_f + Q_f^x - Q_f^m - \sum_k Y_{fk} X_{fk} \le 0$$

f is imported/exported product (11)

$$Q_j - \sum_k Y_{jk} X_{jk} \le 0$$

j is other non-imported/exported products (12)

$$\sum_i X_{imk} - L_{imk} \le 0 \qquad \text{for all } k \text{ and } m \tag{13}$$

In Eq. (10) the net trade values are added into the objective function, where P^m and P^x are import and export prices, and Q^m and Q^x are export and import quantities, respectively. There are two types of commodity balance equations, one for traded and the other for non-traded products. In Eq. (11) the demand of a traded product is the sum of domestic demand (Q_f) and export demand (Q_f^x), where the supply side includes the import supply (Q^m)and domestic supply ($\sum_k Y_{fk} X_{fk}$). Eq. (12) represents the demand–supply balance of non-traded goods as Eq. (13) remains the same.

Currently, two trade protection instruments (quota and tariff) are used to protect domestic farm products. The quota systems are imposed on the imports of rice, sugar, pork, and poultry, etc. The import of beef and fruits are under a tariff protection system. In the model the former is handled by imposing an upper bound for the import quantity while the latter is treated by adding an import tax upon domestic prices.

The TASM includes 60 crops, 5 floral crops, 7 livestock, 3 types of forests (conifers, hardwoods, and bamboo) and 17 secondary commodities (including two timber products: conifer-timber and hardwood-timber). The total value of the primary commodities accounts for 85% of Taiwan's total value of agricultural product. Table 4 provides the list of commodity coverage. Sub-regional production activities are specified in the model for each commodity. Crop, livestock and forestry mixes activities and constraints are also specified at the sub-regional level, but the input markets for cropland, pasture land, forest land, and farm labor are specified at the regional level.

The data sources largely come from published government statistics and research reports, which include the Taiwan Agricultural Yearbook, Production Cost and Income of Farm Products Statistics, Commodity Price Statistics Monthly, Taiwan Agricultural Prices and Costs Monthly, Taiwan Area Agricultural Products Wholesale Market Yearbook, Trade Statistics of the Inspectorate-General of Customs, Forestry Statistics of Taiwan. Demand elasticities of agricultural products comes from various sources. They are listed in the Appendix of Lin (1996).

The empirical model is validated based on the comparison between the equilibrium solution and actual statistics. The year 1994 was chosen as the baseline to construct the database, and we use both the total production and prices as the basis to validate our model. It is found that most of the discrepancies between model results and 1994 data are within 5% range and thus the model should be valid for our simulation.

4. Climate change simulation

The estimated elasticities of the quarterly model in Table 3 are used to predict yield changes. Table 5 lists 11 combinations of alternative climate change

Table 5
Description of climate change scenarios

Scenario	Temperature (°C)	Precipitation (%)
1	0	−10
2	0	+7
3	0	+15
4	+1.5	−10
5	+1.5	0
6	1.5	+7
7	+1.5	+15
8	+2.5	−10
9	+2.5	0
10	+2.5	+7
11	+2.5	+15

scenarios, which include 0, +1.5, +2.5 °C for temperature and −10, 0, +7 and +15% for precipitation. Because the data used in our study do not allow for an estimation of the effects of changes in CO_2, all scenarios assume no change in the CO_2 level and thus include no CO_2 fertilization effects. We also assume that the temperature or precipitation change occurs in all four seasons. Thus, in each scenario all seasonal variables are adjusted simultaneously by the same amounts. Floral crops in TASM are assumed to be unaffected by climate changes since most of them are cultivated inside greenhouses. Livestock and poultry production in Taiwan has been transformed from backyard sideline operations into large business enterprises and mostly produced in the confined environment. Due to limited exposure to the outside environment, their yields as such are also assumed to be unaffected by climate changes.

Another major impact of climate change involves input adjustment related to yield levels. Input usage is adjusted by the percentage change in yield times an output elasticity expressing the response of input usage to a percentage change in yield. Arc elasticity of input for selected crops in each sub-region is calculated using 1982 and 1972 production and crop budget data (Chang and Chen, 1995). An upper and lower bound of 2.0 and −2.0 are set, respectively, for elasticities beyond this range. In addition to changes in the input usage coefficients, the profit margin of each crop budget appearing in the objective function is also adjusted according to the percentage change in yield.

Using these projected yield changes and adjustments in input usage and profit margins, the economic implications of each of the 11 climate change scenarios are evaluated using the TASM outlined in Section 3. The percentage changes in consumers' and producers' welfare from the 1984 baseline are used to represent the welfare effect of the climate change. These changes are reported in Table 6. Our welfare results suggest that the climate impacts on welfare are mostly positive except for the first three scenarios where no temperature increase is assumed. This optimistic result can be attributable largely to the flexibility in TASM that allows farmers to change their crop mixes and land use pattern for adaptation.

Table 7 illustrates the changes in land use pattern in each climate change scenario. The total crop acreage decreases about 1–6% in the warming up scenarios.

Table 6
Changes in welfare from 1994 TASM base

Scenario	Percentage change (%)		
	Consumer welfare (%)	Producer welfare (%)	Total welfare (%)
1	1.88	−0.06	1.80
2	2.18	−2.39	2.15
3	2.76	−3.26	2.20
4	2.25	16.09	4.45
5	2.55	16.09	4.51
6	2.55	16.02	4.55
7	2.54	15.87	4.58
8	1.23	37.30	5.77
9	1.24	36.73	5.82
10	1.23	36.70	5.84
11	1.25	31.56	5.86

Given the very limited availability of arable land in Taiwan, farmers can generate more welfare from intensified land usage. In addition, from the percentage component results as shown in Table 7, there exists significant structural change, with planting acreage declining for cereal crops. On the other hand, the percentages on vegetables, pulse, and special crops increase. Therefore, given the possibility of adaptations, a climate change has the potential to encourage more production of vegetables and speciality crops. The shifts from traditional crops to higher value-added crops also contribute to the relatively large expansions on producers' welfare.

In the latter eight scenarios climate change seems to have a similar relative magnitude and pattern of impacts under both 1.5 and 2.5 °C temperature increase scenarios. In both sets of scenarios, producers' welfare gains are much more dramatic than consumers' in percentage terms. The results also indicate that the two climate variables have different implications for consumers and producers. Temperature increases have potential to bring more benefits than precipitation increases do. However, for consumers, the benefits are not monotonic. A moderate warming up is likely to be welfare-enhancing for consumers while a harsh temperature rise may result in their welfare losses. Producers are better off from a more dramatic rise, but too much rainfall tends to reduce producers' welfare.

The overall societal welfare implications of a warming up are similar to those reported in Adams et al. (1999). Both studies show that a moderate warming

Table 7
Impact of climate change on crop acreage

	BASE	1	2	3	4	5	6	7	8	9	10	11
Harvest acreage (1000 ha)												
Cereal	536	431	430	430	407	407	407	406	333	329	328	328
Pulse	46	59	60	60	57	57	57	57	64	65	65	66
Root	12	33	33	33	31	31	31	31	29	29	29	29
Special	85	96	95	94	103	103	103	102	114	114	114	114
Vegetables	118	196	196	196	197	197	197	197	200	200	200	199
Fruits	209	189	189	189	200	200	200	200	209	209	209	208
Total	1006	1004	1003	1003	994	994	993	992	950	946	945	943
Percentage in total (%)												
Cereal	53	43	43	43	41	41	41	41	35	35	35	35
Pulse	5	6	6	6	6	6	6	6	7	7	7	7
Root	1	3	3	3	3	3	3	3	3	3	3	3
Special	8	10	9	9	10	10	10	10	12	12	12	12
Vegetables	12	20	20	20	20	20	20	20	21	21	21	21
Fruits	21	19	19	19	20	20	20	20	22	22	22	22
Total	100	100	100	100	100	100	100	100	100	100	100	100
Percentage change from base (%)												
Cereal		−20	−20	−20	−24	−24	−24	−24	−38	−39	−39	−39
Pulse		29	30	31	23	23	24	24	39	40	41	43
Root		167	168	168	147	147	147	147	136	136	136	136
Special		13	12	12	21	21	21	21	35	35	35	35
Vegetables		66	66	66	66	66	66	66	69	69	69	68
Fruits		−10	−9	−9	−4	−4	−4	−4	0	0	0	0
Total		0	0	0	−1	−1	−1	−1	−6	−6	−6	−6

up benefits society as a whole, but benefits fall as temperature rises beyond a 1.5 °C change. However, the implications of more precipitation are different. More precipitation appears to be beneficial for producers in the US, but not necessarily so for those in Taiwan.

The results on producers are also very similar to the recent findings in Mendelsohn et al. (1999) in which the Ricardian approach is used to evaluate the relationship between net farm values and climate change. In the earlier one by Mendelsohn et al. (1996) they find that aggregate farm value in the U.S. with a temperate climate pattern is hill-shaped with a maximum of 63°F. Thus, they predict that only a small increase in temperature raises farm values so that countries in temperate and polar regions benefit while countries in subtropical and tropical areas will suffer losses. However, in their 1999 study climate variations are added into their regression model and the new results show that temperature increases are strictly beneficial to farm values in the US.

In our study climate variations are also added into our yield response estimates. Similar monotonic effects on producers' welfare are found. The possible explanation is that climate change may induce changes in crop mixes and land use pattern, along with the realignments in market prices. Still, great caution should be taken when applying these response functions to a climate change outside the range of data used here.

5. Concluding remarks

This paper basically researches the impact of climate change on the agricultural activities in the semi-tropical area using Taiwan as an example. The methodology involves a two-step procedure. First, pooling data on crop yields and climate and other non-climate-related variables are used to estimate yield response equations. The yield equations are used to simulate the physical impacts of alternative climate change scenarios on per hectare yields. This approach addresses farmer's adjustments to environmental conditions and thus provides relatively more realistic estimates of the magnitude of climate impacts than do traditional agronomic crop weather models.

Our empirical results on 60 crops in Taiwan show that, in general, the two climate variables (temperature and precipitation) have a significant and non-monotonic impact on crop yields. Climate variations also have significant implications on many crop yields, similar to those found in the US. Therefore, incorporating climate variations should be important in studying climate impacts on agriculture in subtropical and tropical regions. The impact of other tropical climatic anomalies, such as cyclones, El Niño-southern-oscillation and hurricanes, are also very critical to the well-being in these regions and should be explored in the future. In addition, since seasonal difference are found when examining the impact of climate on crop yields, future research would benefit with the availability of data on the time intervals when crops enter into their various growth stages as well as the growth-stage-related climate data.

In our second step the predicted yield changes are incorporated into a model of the Taiwanese agricultural sector where prices are endogenously determined and farmer's adaptations are allowed by varying crop mixes, land use pattern and input uses in response to price and yield changes. The welfare implications of various climate change scenarios are examined. The comparison result suggests that climate change impacts on welfare are mostly positive. The impacts on producers are much more significant than they are on consumers, with the two climate variables found to also have quite different implications for consumers and producers. A temperature rise is not stressful to Taiwan's farmers, and may even be beneficial when adaptation is taken into account. However, the upward shift in rainfall intensity could be devastating to farmers' welfare.

The impact of climate change on agriculture is a very complicated issue. Many analysts predict that developing countries in tropical and semi-tropical regions are the most vulnerable to global warming. This paper presents a preliminary evaluation on Taiwan's relatively modernized agricultural sector. Unfortunately, because the flexibility in land use, the ability of farmers to adapt and the existence of adaptation possibilities vary, our results may not be applicable to other neighboring Asian economies directly. This leads to a number of potential research directions such as comparing alternative adaptation strategies available in tropical and semitropical regions.

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