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Climate change, sea level rise and rice: global market implications

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Abstract Climate change will influence yields while sea level rise can inundate producing lands. The research reported investigates the individual and simultaneous effects of these factors on production, trade and consumption of rice the world's number one food crop. A global rice trade model is utilized to do this. The results indicate that the combination of yield and sea level effects causes a significant reduction in production and an increase in rice prices which may have important policy implications for food security. Global rice production is reduced by 1.60% to 2.73% while global rice price increases by 7.14% to 12.77%. Sea level rise is particularly a risk factor in Bangladesh, Japan, Taiwan, Egypt, Myanmar and Vietnam. In the face of such developments, adaptation may well be desirable and thus an investigation is done over adaptation options of increased technical progress or trade liberalization with the results showing that both can mitigate such damages.

1 Introduction

Sea level rise (SLR) due to global warming is a long-term, serious threat to portions of society. The rate of sea level rise has been accelerating with the 100 year average being 1.8 mm per year and the 1993–2003 periods showing an average of 3.1 mm per

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year (Douglas 1997; Church and White 2006; Bindoff et al. 2007). Some predict yet larger rates for the future. For instance,

- Raper and Braithwaite (2006) project annual sea level rise from melting mountain glaciers and icecaps will be 0.046 and 0.051 m by 2100.
- Meier et al. (2007) estimate an additional 0.1 to 0.25 m sea level rise by 2100 due to glaciers and ice caps melting alone.
- The IPCC (2007) fourth assessment report projects 0.18 to 0.59 m sea level rise without consideration of ice flow by 2100.
- Rahmstorf (2007) projects a cumulative sea-level rise of 0.5 to 1.4 m by 2100.
- Dasgupta et al. (2009) projects 1 to 3 m but also suggests as much as 5 m is possible if the unexpected rapid breakup of the Greenland and West Antarctic ice sheet occurs.
- Hansen (2007) suggests up to a 5 m rise is possible and in Hansen and Sato (2011) argues that a nonlinear, rapid rise is likely later in the century.

Sea level rise would affect coastal areas in a variety of ways, including flooding, potential loss of life, damage to property, coastal erosion, changes in surface and ground water quality, decreased agricultural and aquaculture production through land inundation, and damages to transportation infrastructure. Darwin and Tol (2001) estimated the direct economic damage of sea level rise but did not focus much on agricultural implications. However, a literature review did not reveal studies that focused on sea level rise implications for global food markets in general or rice in particular.

Agriculture and the global food market are vulnerable. Figure 1 displays the percentages of agricultural lands that would be inundated under various levels of

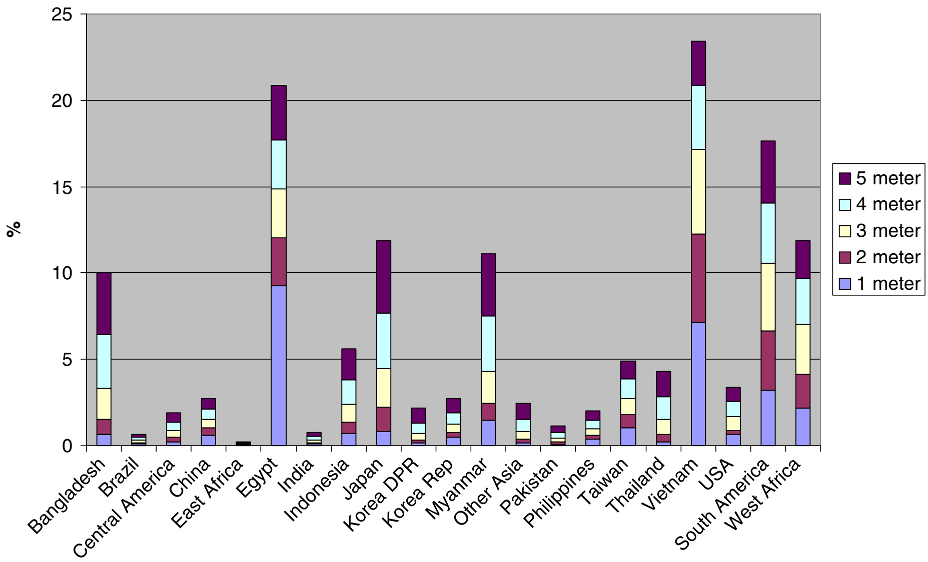

Fig. 1 The percentage impacts of sea level rise on agricultural land

sea level rise in Southeast Asia, East Asia, South Asia, and the Southeast U.S (Dasgupta et al. 2009). Significant rice acreage occurs in these areas thus sea level rise constitutes a threat to rice. This is of concern since rice is a major staple crop for half of the world's population. On the other hand rice production is responsible for about 13% of global methane emissions where mainly is in Asia and methane is an active greenhouse gas with emissions likely to increase as population expands. Therefore, while rice area is also significantly affected by climate change, a reduction in planted area would contribute to a reduction in future climate change (Note there is no attempt to estimate the magnitude of the climate change reduction in this study). This study estimates the economic impacts of sea level rise in terms of rice production and resultant consequences in a global rice market.

Climate change will also influence rice production through temperature and precipitation plus the associated level of CO2 yield enhancement. Therefore, this analysis will simultaneously and individually consider yield and sea level rise effects. This paper will examine these issues focusing on the implications for rice production, global trade, prices and welfare. To do this, the study employs a global rice market model that represents production/consumption in 26 major rice production/consumption countries/regions (Table 1) and trade in between. These regions produce/consume over 95% of world rice.

Table 1 Definitions of regions

Region	Countries contained
Australia	Australia
Bangladesh	Bangladesh
Brazil	Brazil
Central Africa	Central Africa
Central America	Costa Rica, Cuba, Dominica, Mexico, Panama
China	China
East Africa	Eastern Africa
Egypt	Egypt
Europe	Italy, Portugal, Spain, other Europe
Former USSR	Former USSR
India	India
Indonesia	Indonesia
Japan	Japan
Korea REP	Korea REP
Korea DRP	Korea DRP
Myanmar	Myanmar
Other Asia	Afghanistan, Cambodia, Iran, Iraq, Laos, Malaysia, Nepal, Sri Lanka, Turkey
Pakistan	Pakistan
Philippines	Philippines
South Africa	Southern Africa
South America	Argentina, Colombia, Ecuador, Guyana, Peru, Surinam, Uruguay, Venezuela
Taiwan	Taiwan
Thailand	Thailand
USA	USA
Vietnam	Vietnam
West Africa	Western Africa

2 Sea level rise, crop yield effects, climate change and rice

To estimate the effects of sea level rise on rice production, the sea level rise scenarios from Dasgupta et al. (2009) are employed wherein the rise ranges from 1 to 5 m. Dasgupta et al. (2009) developed estimates of agricultural acreage effects combining geographic information system and coastal terrain modeling. Estimations of the global agricultural area vulnerable to sea level range from 0.65% to 23.43% depending on the extent of sea level rise as shown in Fig. 1. To estimate rice planted acreage affects, the ratio of rice acreage divided by total cropland based on FAO (2007) data is applied to the land loss scenarios. The consequent effects of sea level rise on rice acreage are shown in columns 2 to 6 of Table 2.

Climate change plus the underlying drivers also has implications for yields due to altered temperature, precipitation and carbon dioxide. To simultaneously consider climate change implications for rice production, the yield sensitivity data from Lobell et al. (2008) and Iglesias and Rosenzweig (2010) are used. Lobell et al. provided the probability distribution of estimated crop yield sensitivity across random draws based on 20 GCM models and SRES scenarios. Their median, 5th, and 95th percentile projected impacts for the 2030 case are shown in the first three columns of Table 3. The data sets for 2080 climate change on rice yields from Iglesias and Rosenzweig (2010) are based on output of HadCM3 model with GHG concentrations from the Special Report on Emissions Scenarios (hereafter SRES) to simulate dynamic process crop growth models at 127 sites in the principal crop-growing regions. The

Table 2 Loss of cropland as sea level rises based on Dasgupta et al. and FAO data

	Sea level rise scenario				
	1 m	2 m	3 m	4 m	5 m
Regions	% of rice cropland lost to inundation				
Bangladesh	0.54	1.25	2.77	5.33	8.34
Brazil	–	–	–	–	–
Central America	–	–	–	–	–
Central Africa	–	–	–	–	–
China	0.03	0.05	0.07	0.1	0.13
Egypt	1.72	2.23	2.76	3.29	3.87
India	0.02	0.04	0.08	0.13	0.18
Indonesia	0.18	0.34	0.6	0.96	1.41
Japan	0.3	0.82	1.62	2.76	4.28
Korea DRP	0.03	0.06	0.14	0.26	0.43
Myanmar	0.85	1.41	2.49	4.35	6.44
Other Asia	0	0	0.01	0.02	0.03
Pakistan	0.01	0.02	0.04	0.08	0.11
Philippines	0.12	0.19	0.32	0.48	0.66
South America	0.03	0.06	0.09	0.12	0.16
Taiwan	0.33	0.57	0.85	1.2	1.53
Thailand	0.12	0.35	0.84	1.57	2.36
USA	0.001	0.003	0.003	0.003	0.003
Vietnam	5.53	9.5	13.28	16.15	18.15
West Africa	0.02	0.03	0.05	0.07	0.09

The numbers in sea level rise scenarios represent the percentage loss in rice producing acreages which were calculated using the ratio of rice acreage divided by agricultural acreage times the numbers of percentage change due to sea level rises on agricultural acreage

Table 3 The effects of climate change on rice yield

	2030 from Lobell et al.			2080 from Iglesias and Rosenzweig						
	95%	Median	5%	A1F	A2a	A2b	A2c	B1a	B2a	B2b
Regions	% rice yield change									
Bangladesh	−0.69	−1.99	−4.41	6.76	7.58	8.31	4.57	−1.49	1.67	−1.53
Brazil	−1.24	−4.5	−10.35	10.06	6.51	6.52	10.47	−7.43	−2.50	−3.32
Central America	1.23	−1.9	−6.52	−3.57	0.32	−3.25	0.74	−8.24	−3.68	−5.94
Central Africa	1.23	−1.9	−6.52	−15.23	−7.65	−6.74	−6.41	−8.55	−7.83	−8.00
China	1.37	−0.44	−3.15	7.12	8.71	8.91	7.55	−0.63	3.83	4.29
Egypt	0.92	−4.92	−12.7	−21.10	−10.00	−7.05	−8.10	−3.65	−5.79	−11.27
India	−0.69	−1.99	−4.41	−3.44	−2.07	−1.08	−3.11	−7.86	−5.64	−3.26
Indonesia	1.7	−3.4	−10.27	−0.50	4.78	3.02	2.76	−2.29	2.00	1.51
Japan	1.7	−3.4	−10.27	−4.95	3.50	−1.38	3.57	−0.89	3.77	3.60
Korea DRP	1.7	−3.4	−10.27	−4.95	3.50	−1.38	3.57	−0.89	3.77	3.60
Myanmar	1.7	−3.4	−10.27	6.76	7.58	8.31	4.57	−1.49	1.67	−1.53
Other Asia	−0.69	−1.99	−4.41	−6.22	0.10	0.54	0.50	−3.25	−1.70	−3.35
Pakistan	1.7	−3.4	−10.27	−8.05	−3.27	−3.63	−3.92	−8.92	−5.69	−9.66
Philippines	1.7	−3.4	−10.27	−0.50	4.78	3.02	2.76	−2.29	2.00	1.51
South America	−1.07	−3.45	−7.35	−2.13	2.97	2.94	0.20	−4.92	−1.18	−1.15
Taiwan	1.7	−3.4	−10.27	7.12	8.71	8.91	7.55	−0.63	3.83	4.29
Thailand	1.7	−3.4	−10.27	−9.32	0.53	−1.17	−2.26	−0.42	1.17	2.23
USA	1.23	−1.9	−6.52	1.00	2.13	1.00	1.81	−3.14	1.68	−2.23
Vietnam	1.7	−3.4	−10.27	0.90	5.54	3.47	4.07	−1.19	2.72	3.16
West Africa	0.75	−1.91	−5.91	−12.73	−5.15	−4.24	−3.91	−6.05	−5.33	−5.50

crop yield assessments contain consistent crop simulation methodology and climate change scenarios, weighting of model site results by regional and national, and irrigated and rainfed production, and modeling of physiological CO2 effects on crop yields across four SRES scenarios (A1Fl, A2, B1, and B2). The 2080 rice yield changes under A1F1, A2, B1, and B2 are selected and the effects on rice yield percentage change are shown in the last seven columns in Table 3.

3 A global rice trade market model

To examine the market effects of sea level rise and crop yield effects, a global rice price, production and trade model is employed. This is a mathematical-programming-based spatial equilibrium (SE) model based on Samuelson (1952) and Takayama and Judge (1971). This model extends a deterministic model (Chen et al. 2006) that has been used in a number of agricultural trade studies. The extension involves the inclusion of stochastic climate and yields following Chen and McCarl (2000), and Chen et al. (2008). A two-step decision is embedded in the model where the first step decides how much acreage to plant given uncertain climate and crop yield conditions. Subsequently, harvest levels, prices and quantities traded are determined for each state of nature given realized yields.

The model is outlined in the following equations with subscript s representing the state of nature from climate conditions and i and i' representing the trading regions:

$$\begin{aligned} Max \quad CSPS = \sum_s \rho(s) \times \Bigg[\sum_i \Bigg(\int f_i\left(QD_{is}\right) dQD_{is} \\ - \int g_i\left(\left(QS_i + Y_{is}\right)^* \left(1 + Yieldper_i\right)\right) dQS_i \Bigg) \\ - \sum_i \sum_{i'} t_{i,i'} TRE_{i,i',s} + \sum_i stoc_i \left(STOA_{is}\right) \\ - \sum_i \sum_{i'} tar_{i'} - exs_{i'} \Bigg) TRE_{i,i',s} - \sum_i prs_i QS_i \Bigg] \end{aligned} \tag{1}$$

s.t.

$$\begin{aligned} + \sum_{i'} \left(TRE_{i,i',s} - TRE_{i',i,s}\right) - \left(QS_i + Y_{is}\right)^* \left(1 + Yieldper_i\right) \\ - STOW_{is} + STOA'_{is} + QD_{is} \leq 0 \quad \forall\, i, s \end{aligned} \tag{2}$$

$$\sum_s \rho\left(s\right) * \left[STOA_{is} - STO\mathrm{W}_{is}\right] = 0 \quad \forall\, i \tag{3}$$

where

Variables	Definitions	Units
ρ(s)	is the probability of state of nature s	Proportion
$t_{ii'}$	is the transportation cost from region i to region i'	US$/metric ton
$tar_{i'}$	is the import tariff imposed by region i'	US$/metric ton
prs_i	is the domestic subsidy in region i	US$/metric ton
exs_i	is the export subsidy employed by region i	US$/metric ton
$stoc_i$	is the storage cost in region i	US$/metric ton
Y_{is}	is the proportional rice production uncertainty due to climate in region i under state of nature s	Metric ton
$Yieldper_i$	is the rice production percentage change due to sea level rise or climate change in region i	%
QD_{is}	is the domestic demand in region i under state of nature s	Metric ton
QS_i	is the domestic supply in region i	Metric ton
$f_i(QD_{is})$	is the inverse demand function in region i	US$ given QD
$g_i(QS_i + Y_{is})$	is the inverse supply function in region i	US$ given QS
$TRE_{i,i',s}$	is the quantity traded between region i and region i' under state of nature s	Metric ton
$STOA_{is}$	is the addition to storage in region i under state of nature s	Metric ton
$STOW_{is}$	is the withdrawal from storage in region i under state of nature s	Metric ton

The model in Eqs. 1, 2 and 3 maximizes total expected consumer's plus producer's surplus subject to market equilibrium and stock clearing conditions in each region. The first line in Eq. 1 is the probability-weighted area under the demand curve minus the area under the supply curve, while the second line is the transportation cost and storage cost. The third line represents government policy interventions in the rice market including a domestic price subsidy (prs), an import tariff (tar), and an export subsidy (exs).

Equation 2 is the supply and demand balance for a country under each state of nature. Equation 2 states that the total supply in each region includes imports ($\mathrm{TRE}_{\mathrm{i',i}}$), domestic supply (QS) adjusted for rice production state of nature (Y), storage withdrawals (STOW) and the variations from climate change and sea level rise on rice production (Yieldper). In turn this supply should be greater than or equal to total demand which includes domestic demand (QD), exports ($\mathrm{TRE}_{\mathrm{i,I'}}$) and storage additions (STOA). Equation 3 is a long-run equilibrium constraint for storage activities which ensures average storage withdrawals equals to average storage additions.

There are two important properties in this model. First, rice production in each region is uncertain. To represent this uncertainty, the stochastic rice production levels were included. Specifically Song and Carter (1996)'s approach is used. Non-climate-related factors are used as explanatory variables with the residuals representing the unknown climate effects. Equation 4 models total rice production as being influenced by planted acreage and time (a proxy for technological progress) as follows:

$$TQ_i = \alpha + \beta_1 AR_i + \beta_2 AR_i^2 + \beta_3 Year + \varepsilon_i \tag{4}$$

where subscript i represents rice production regions, TQ is the annual total rice production, AR the planted acreage, Year a time trend proxy technological advances over time, ε the error term, and α, β_1, β_2, β_3 the parameters to be estimated. The planted acreage is used as a composite management variable including the presence of government policies.

In Equation 4, the residuals give year by year deviations from average production. A positive residual signals the presence of an above-average observation and vice versa. Therefore, these residuals represent the uncertainty of rice production which could be interpreted as states of nature. The results of the estimation over (FAO 2007) data from 1961–2005 are shown in Table 4. Most of the estimated parameters are significant with high R-squares.

Since rice production is affected by annual climate and this is reflective of uncertainty, the residual estimates from Eq. 4 will be used to define the state of nature data in Eqs. 1 and 2 as the term Y_{is}. This Y_{is} term shifts the domestic supply curve, and, thus, domestic demand, trade, storage, and prices are all affected and become state-of-nature dependent.

Trade prices are endogenously determined in the model. The first order Kuhn–Tucker conditions on the transport variables are:

$$\mu_i - \lambda_{i'} - t_{i,i'} - prs_i - tar_{i'} + exs_i = 0, \tag{5}$$

where μ and λ are the state-of-nature-dependent equilibrium prices from Eq. 2 in the importing and exporting countries, respectively, and are interpretable as import and export prices. Equation 5 implies that transportation cost (t), and policy interventions (*prs*, *tar and exs*) play a role in forming the price wedges between importing and

Table 4 Rice production estimation results

Region	Estimated parameters			Adjusted R-square
	AR	AR^2	Year	
Australia	34.36 (0.22)	0.376 (4.70)	6,714.9 (3.96)	0.95
Bangladesh	−7,496.5 (−4.81)	0.038 (4.82)	509,607.7 (14.5)	0.94
Brazil	162.85 (1.16)	−0.0009 (−0.65)	145,444.2 (12.4)	0.79
Central America	228.06 (0.602)	0.0066 (0.14)	15,384.4 (11.93)	0.80
Central Africa	83.8 (5.07)	−0.002 (−1.26)	3,354.7 (3.401)	0.96
China	7,730.9 (8.03)	−0.011 (−7.59)	2,901,360 (31.5)	0.96
East Africa	−166.9 (−1.98)	0.005 (1.91)	59,418.8 (6.82)	0.94
Egypt	−1,196.09 (−3.79)	0.226 (7.01)	2,737,455 (8.12)	0.97
Europe	186.3 (0.48)	0.014 (0.38)	24,257.5 (5.49)	0.94
Former USSR	344.3 (7.19)	0.006 (1.05)	2,620.3 (2.17)	0.98
India	−3,136.9 (−3.84)	0.004 (4.42)	1,249,136 (7.33)	0.96
Indonesia	1,045.7 (3.54)	−0.003 (−2.03)	495,961.6 (3.59)	0.98
Japan	1,775.7 (4.25)	−0.0203 (−3.08)	146,720.7 (2.77)	0.85
Korea REP	2,619.9 (0.55)	−0.06 (−0.31)	94,996.1 (9.08)	0.72
Myanmar	−1,175.2 (−2.91)	0.012 (3.51)	286,753.7 (15.34)	0.96
Other Asia	−263.9 (−1.27)	0.012 (2.43)	77,888.8 (14.46)	0.98
Pakistan	100.7 (0.73)	0.007 (2.00)	23,025.2 (1.66)	0.96
Philippines	−1,340.8 (−1.84)	0.021 (2.11)	194,191.7 (20.31)	0.96
South America	443.8 (1.06)	0.0003 (0.039)	212,906.4 (3.12)	0.94
South Africa	814.2 (0.16)	0.095 (0.11)	1,422.7 (1.67)	0.63
Thailand	−1,045.4 (−5.25)	0.007 (5.67)	280,543 (9.76)	0.96
USA	−349.5 (−1.49)	0.034 (3.27)	106,769 (15.27)	0.97
Vietnam	2,704.6 (−5.78)	0.025 (7.64)	366,316 (5.21)	0.97
West Africa	242.9 (6.70)	−0.0011 (−2.69)	14,171.1 (1.16)	0.99

The numbers in the parentheses are *t*-values

exporting countries and determining the import volume in each country. If there is no policy intervention, i.e., *prs*=*tar*=0, then Eq. 5 may be simplified as $\mu_i - \lambda_{i'} - t_{i,i'} = 0$. Such a condition characterizes a perfectly competitive market as shown in Takayama and Judge (1971).

4 Trade model specification and calibration

The above model is set up for data reflective of the 2005 international rice market.[1] The model determines bilateral trade flows as well as quantities and prices of supply and demand in each region. The main data source is FAO statistics (2007). All quantities are converted into milled rice. Demand and supply elasticities are based on Cramer et al. (1993). The storage cost is assumed to be the supply price times an assumed annual interest rate of 5%. Finally, transportation cost and policy parameters including import tariffs, export subsidies and production subsidies are

[1]Rice is assumed as a homogeneous product in this study, but there may be different impacts in variety sensitive rice markets such aromatic, glutinous, Japonica or Indica varieties because climate change and sea level rise may affect one rice variety more than another. We do appreciate reviewer's helpful comment on this footnote.

obtained from Chen and McCarl (2000) and the Global Trade Analysis Project (GTAP) database (1998).

Model calibration is an important step in preparing the model for policy simulations. The three policy intervention parameters in the objective function will be used as adjustment tools to allow the model solutions to be consistent with the observed data. For instance, if the quantity consumed is higher but production is lower than the observed data in an importing country, the import tariff parameter will be adjusted downward to reduce consumption but increase production simultaneously. When the model solutions for all trading countries are close to the observed data, the prices will also be very close to the observed data.

The basic idea behind this adjustment process is the theory of strategic trade policy. Assuming that the transportation cost and storage cost remain constant, any change in government's intervention policies could change the deviations of the equilibrium prices between importing and exporting countries and result in different solutions for production, consumption, and trade. Given that government policy is very difficult to measure, policy parameters are used for fine-tune calibration by matching the model solutions and the observed data in 2005. The comparisons between model solutions and observed data of demand/supply quantities and prices of each trading region are listed in Table 5. Because the percentage deviations are mostly below 8%, the comparisons indicate that the model has been verified and is now suitable for depicting the international rice market.

Finally, some properties and inherent limitations of this global rice trade model merit discussion. This empirical model only considers the rice market and thus omits effects translated through production and consumption shifts in other commodities. Secondly, the empirical model is a static model which does not consider the dynamic effects of storage activity. Finally, crop mix adjustment is precluded since only rice production is considered. Therefore, when land availability is reduced due to sea level rise the model omits the possibility that other crops may be pushed out on non inundated area with rice production increased.[2]

5 Scenario design

A base plus four sets of scenarios were used to simulate the economic impacts of climate change induced sea level rise and crop yield alteration along a limited set of adaptation efforts.

- BASE: This scenario does not have sea level rise or crop yield effects.
- Sea Level Rise: These scenarios subject the model to the lost acreage implications of sea level rise varying from levels of 1 to 5 m. The assumed percentage changes in rice production are given in Tale 2 columns 2–6. These percentages change are used for the parameter *Yieldper* in Eqs. 1 and 2.
- Crop Yield Effects: The crop yield effects of climate change on rice production are shown in Table 3. Three sub-cases are simulated the "worst case " with yields at the lowest 5% of the distribution from 2030 climate change scenarios, the "median" case, and "best case" with yields at the upper 95% part of the distribution.

[2]We appreciate the reviewer's helpful suggestion on this model limitations section.

Table 5 Observed and model generated quantities and prices by region

Regions	Demand quantities (metric tons)			Supply quantities (metric tons)			Prices (US$/metric ton)		
	Observed	Model	% Dev	Observed	Model	% Dev	Observed	Model	% Dev
Bangladesh	32,250,605	30,929,247	−4.1	31,836,494	30,921,266	−2.87	195.58	210.95	7.86
Brazil	10,725,182	10,317,651	−3.8	10,554,290	10,316,911	−2.25	298.64	292.94	−1.91
Central Africa	1,011,852	968,646	−4.27	450,865	465,546	3.26	247.62	239.39	−3.32
Central America	1,229,661	1,131,185	−8.01	898,773	952,158	5.94	265.99	280.18	5.33
China	145,076,400	145,915,800	0.58	145,599,300	145,909,900	0.21	262.82	248.09	−5.61
East Africa	4,769,571	4,654,162	−2.42	6,705,782	6,833,589	1.91	166.44	178.51	7.25
Egypt	4,564,570	4,679,677	2.52	4,900,240	4,679,677	−4.5	282.5	263.17	−6.65
Europe	3,141,596	3,037,279	−3.32	2,675,118	2,508,961	−6.21	1,214.51	1,309.16	7.79
Former USSR	794,294	734,590	−7.52	459,668	455,063	−1	185.24	198.33	7.07
India	105,672,700	102,168,400	−3.32	110,096,000	108,557,300	−1.4	207.18	210.89	1.79
Indonesia	43,024,103	43,194,824	0.4	43,187,674	43,135,875	−0.12	323.43	319.19	−1.31
Japan	9,611,317	9,737,269	1.31	9,073,600	9,737,269	7.31	3,218.97	2,931.98	−8.92
Korea DRP	2,843,448	2,856,115	0.45	2,065,600	2,241,582	8.52	2,002.18	2,170.01	8.38
Korea Rep	5,119,225	5,086,704	−0.64	5,148,000	5,086,704	−1.19	2,034.55	2,122.85	4.34
Myanmar	20,150,812	20,863,262	3.54	20,291,200	20,864,124	2.82	7,289.77	7,791.05	6.88
Other Asia	12,928,006	12,830,940	−0.75	7,681,474	7,590,104	−1.19	509.7	550.66	8.04
Pakistan	3,993,489	3,805,603	4.94	6,656,640	6,313,595	−5.15	290.81	309.18	6.32
Philippines	11,869,766	11,811,518	−0.49	11,682,404	11,787,378	0.9	321.93	327.26	1.65
South Africa	742,277	781,082	5.23	–	–	–	536.05	509.76	−4.9
South America	22,100,560	23,945,402	8.35	21,795,162	20,344,529	−6.66	332.37	308.01	−7.33
Taiwan	1,220,337	1,218,913	−0.12	1,087,256	1,027,617	−5.49	1,207.8	1,214.87	0.59
Thailand	18,088,898	17,314,698	−4.28	24,233,496	25,557,527	5.46	241.29	261.58	8.41
USA	6,153,710	6,289,883	2.21	8,100,000	8,264,274	2.03	254.65	268.88	5.59
Vietnam	27,584,764	27,922,279	1.22	28,632,640	27,958,842	−2.35	260.7	240.4	−7.79
West Africa	9,267,011	8,038,550	−2.47	–	–	–	708.87	761.27	7.39

The rice yield effects due to 2080 climate change are also simulated here. These yield percentage changes are also implemented through the parameter *Yieldper* in Eqs. 1 and 2.

- Simultaneous Sea Level Rise and Crop Yield Effects: Both the effects of sea level rise and crop yield effects on rice production are simultaneously being considered with their effects multiplied.
- Simulating Export Policy Restriction: Some major exporting countries such as India and Vietnam implemented either export bans or taxes on rice exports during the 2008 and 2009 food price crisis. These export policy restrictions with sea level rise and crop yield effects will be simultaneously simulated.
- Adaptation Strategies: Two possible adaptation strategies including rice yield technology improvement and trade liberalization through tariff reduction are simulated in order to mitigate the damage from sea level rise and crop yield effects. In particular the simultaneous Sea Level Rise and Crop Yield Effects cases are run with rice yield improvements and tariff reductions to see if either can offset the climate change induced losses.

The major economic outcomes for model solutions of each scenario are reported below and focus on the level of production, trade, prices and welfare.

6 Results

Table 6 contains results on production, trade, prices and welfare under the alternative sea level rise and crop yield scenarios.

6.1 Sea level rise only results

First examining just sea level rise under no yield effect, global rice production is decreased by 1.1 million metric tons (MMT or 0.22%) under a 1 m rise and 5.85 MMT (or −1.16%) under 5 m. Global rice trade increases by 3.91% to 18.7%. Price levels increase from 0.90% to 5.13%. Total welfare relative to the BASE scenario is reduced by US$1.45 billion under a 1 m rise and US$10.59 billion under 5 m. The country by country impacts of sea level rise are shown in Fig. 2 where the most significant impacts are located in Bangladesh, Japan, Taiwan, Myanmar, Vietnam, and Egypt. Under the 6 m case imports rise by 292% for Bangladesh, 41% for Japan, and 3% for Taiwan. Myanmar, Vietnam, and Egypt go from being exporters to importers. Those who suffer production reduction import more or export less. However, some exporting regions such as the U.S. and East Africa export more to meet the world market.

6.2 Crop yield effect only

The impacts of crop yield effects in the absence of sea level rise are summarized in the third column of Table 6. The most favorable yield effect scenario (95%) for the 2030 cases results in a positive impact on global production and trade volume, increasing global welfare by US$ 3 billion. The median case and the least favorable (5%) yield effects reduce global rice production by 1.01% and 3.10%, respectively. In turn, global rice prices increase by 4.68% and 15.97%. Global welfare is reduced

Table 6 Economic impacts of climate change on international rice markets

	Scenarios	Sea level rise in meters					
	Economic items	BASE	1	2	3	4	5
No yield effect	Total production (1,000 mt)	504,476	−0.22%	−0.40%	−0.63%	−0.89%	−1.16%
	Total trade (1,000 mt)	22,416	3.91%	7.29%	10.83%	14.52%	18.67%
	World price ($/mt)	361.43	0.90%	1.67%	2.67%	3.88%	5.13%
	Total social welfare ($ billion)	2,309	−1.45	−2.51	−4.33	−7.25	−10.59
2030							
95% Yield Effect	Total production (1,000 mt)	0.39%	0.16%	−0.01%	−0.01%	−0.50%	−0.76%
	Total trade (1,000 mt)	1.68%	4.34%	7.78%	7.78%	15.19%	19.23%
	World price ($/mt)	−2.24%	−1.35%	−0.59%	−0.59%	1.54%	2.72%
	Total social welfare ($ billion)	2.99	1.56	0.52	−1.26	−4.14	−7.45
Median Yield Effect	Total production (1,000 mt)	−1.01%	−1.23%	−1.40%	−1.62%	−1.88%	−2.13%
	Total trade (1,000 mt)	0.69%	5.83%	9.11%	12.63%	16.50%	20.83%
	World price ($/mt)	4.68%	5.60%	6.39%	7.41%	8.62%	9.89%
	Total social welfare ($ billion)	−6.91	−8.41	−9.51	−11.39	−14.38	−17.77
5% Yield Effect	Total production (1,000 mt)	−3.10%	−3.29%	−3.45%	−3.66%	−3.92%	−4.17%
	Total trade (1,000 mt)	0.53%	9.58%	12.70%	16.14%	20.00%	24.45%
	World price ($/mt)	15.97%	17.06%	17.90%	19.03%	20.44%	21.91%
	Total social welfare ($ billion)	−22.55	−23.72	−24.85	−26.77	−29.78	−33.17
2080							
A1F	Total production (1,000 mt)	0.52%	0.30%	0.12%	−0.12%	−0.41%	−0.71%
	Total trade (1,000 mt)	−5.98%	−4.10%	−1.83%	1.20%	3.59%	5.71%
	World price ($/mt)	−1.88%	−0.81%	−0.02%	0.95%	2.12%	3.38%
	Total social welfare ($ billion)	6.55	5.15	4.11	2.37	−0.38	−3.58
A2a	Total production (1,000 mt)	1.96%	1.72%	1.54%	1.30%	1.00%	0.71%
	Total trade (1,000 mt)	−7.12%	−6.31%	−4.37%	−1.23%	1.31%	3.60%
	World price ($/mt)	−9.52%	−8.51%	−7.75%	−6.78%	−5.64%	−4.41%
	Total social welfare ($ billion)	12.20	10.83	9.84	8.15	5.45	2.32
A2b	Total production (1,000 mt)	1.91%	1.67%	1.49%	1.25%	0.96%	0.65%
	Total trade (1,000 mt)	−5.65%	−4.23%	−1.52%	1.63%	4.10%	6.40%
	World price ($/mt)	−8.28%	−7.29%	−6.53%	−5.58%	−4.47%	−3.31%
	Total social welfare ($ billion)	11.74	10.36	9.37	7.69	5.02	1.91
A2c	Total production (1,000 mt)	1.28%	1.05%	0.87%	0.63%	0.35%	0.06%
	Total trade (1,000 mt)	−7.30%	−6.87%	−4.80%	−1.59%	1.19%	3.72%
	World price ($/mt)	−7.02%	−6.06%	−5.26%	−4.27%	−3.09%	−1.81%
	Total social welfare ($ billion)	8.03	6.62	5.59	3.84	1.04	−2.22

Table 6 (continued)

	Scenarios	Sea level rise in meters					
	Economic items	BASE	1	2	3	4	5
B1a	Total production (1,000 mt)	−1.60%	−1.81%	−1.98%	−2.20%	−2.47%	−2.73%
	Total trade (1,000 mt)	−6.86%	−6.16%	−3.40%	−0.16%	3.08%	6.88%
	World price ($/mt)	7.14%	8.12%	8.94%	10.01%	11.35%	12.77%
	Total social welfare ($ billion)	−5.39	−6.92	−8.04	−9.94	−12.94	−16.38
B2a	Total production (1,000 mt)	0.11%	−0.11%	−0.29%	−0.52%	−0.79%	−1.07%
	Total trade (1,000 mt)	−7.26%	−7.22%	−5.09%	−1.85%	1.07%	4.23%
	World price ($/mt)	−2.16%	−1.23%	−0.43%	0.57%	1.79%	3.12%
	Total social welfare ($ billion)	2.81	1.36	0.29	−1.52	−4.42	−7.77
B2b	Total production (1,000 mt)	0.16%	−0.06%	−0.24%	−0.47%	−0.74%	−1.00%
	Total trade (1,000 mt)	−3.61%	−2.52%	−0.10%	3.57%	7.41%	11.60%
	World price ($/mt)	−3.02%	−2.01%	−1.19%	−0.13%	1.12%	2.43%
	Total social welfare ($ billion)	−0.65	−2.13	−3.22	−5.08	−8.05	−11.43

Numbers in BASE and No Yield Effect scenario give levels while other numbers give changes with respect to this BASE scenario. Results for all but except Total Social Welfare gives the percentage change while the numbers for Total Social are the difference in billon US$

by US$ 6.9 billion and US$ 22.6 billion. The country by country impacts of 2030 yield effects are shown in Fig. 3 where the most affected areas are in Indonesia, Korea, Philippines, Brazil, India, and Pakistan. Furthermore, the economic impacts due to 2080 crop yield effects for most of scenarios except B1a scenario are positive. as The CO2 effects considered in Iglesias and Rosenzweig (2010), cause positive yield implications as shown in the last seven columns in Table 3 (note while not reported here we also ran the in Rosenzweig and Iglesias (2001) scenarios where CO2 was ignored and found negative results there suggesting the importance of modeling including CO2 effects). In turn, global rice production increases, rice prices decreases and welfare increases. However, if the worst scenario B1a is taken into consideration, global rice production is reduced with an increasing rice price and decreasing social welfare.

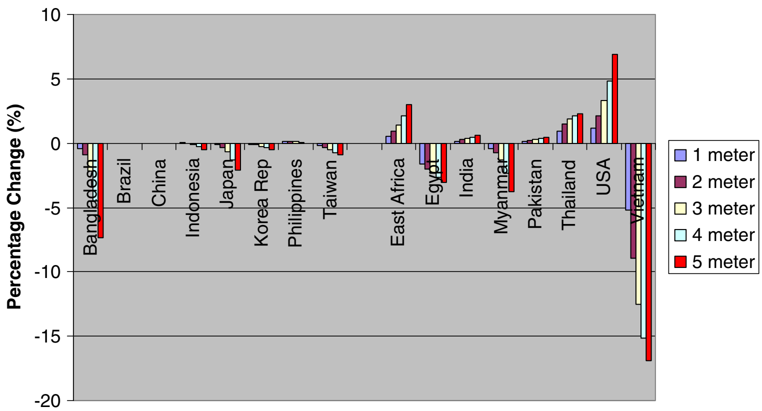

Fig. 2 Rice production percentage change due to sea level rise for each individual country/region

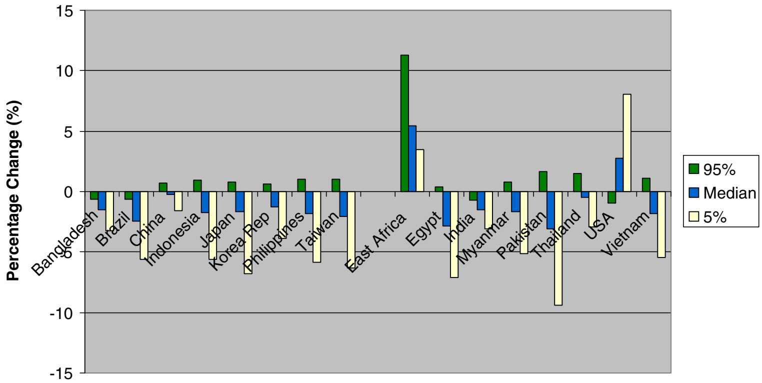

Fig. 3 Rice production percentage change due to 2030 climate change for each individual country/region

6.3 Simultaneous crop yield and sea level

Since climate change and sea level rise involve common drivers, both the effects of seal level rise and crop yield effects on rice production will likely happen simultaneously. The consequent results are shown in Table 6. Taking the worst 2030 crop yield case (i.e. 5%) with a 1 m sea level rise, global production is reduced by 16.6 MMT (3.29% reduction) with a 17.06% rise in the global price and a US$ 23.7 billion welfare loss. Under the 5 m sea level rise and the worst yield case, global rice production will be reduced by 21.0 MMT (4.17% reduction) which is the magnitude of the current global rice trade amount. The average rice price increases by 21.91% which may create food-insecurity in some of developing countries. Figure 4 shows

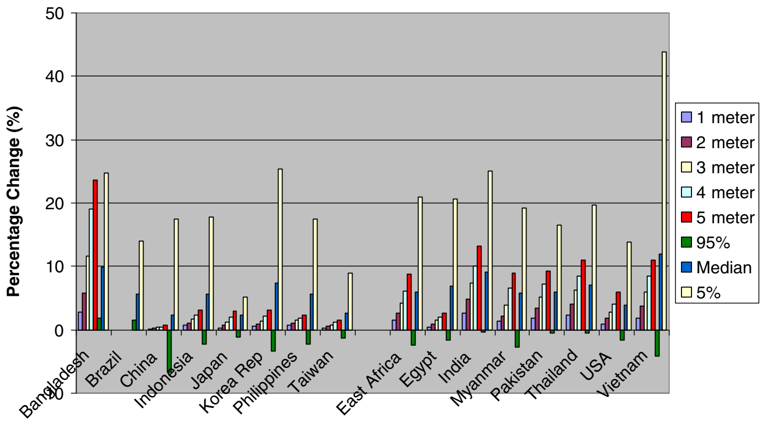

Fig. 4 Rice price percentage change due to sea level rise and 2030 climate change for each individual country/region

that rice prices could be increased by 10% to 40% and depends on the effects of sea level rise and crop yield effects on rice production in each region with Bangladesh, Japan, Taiwan, Myanmar, and Egypt suffer from both effects. Such price increases may cause food insecurity.

When combining the sea level rise and 2080 crop yield effects, the economic impacts are mixed and depend on the SRES scenario (i.e. A1, A2, or B1, B2). Finally, comparing the sea level and crop yield effects, the crop yield effects at 2030 cases are larger since they are more pervasive but reverse when the 2080 with CO2 climate change scenarios are considered.

6.4 Export restriction policy

During the 2008 and 2009 food price crisis, some exporting countries a limited or taxed rice exports (For instance, India had an export ban and Vietnam an export tax. Therefore, scenarios were run with export taxes and limits plus climate change/sea level rise. Empirical results for a simultaneous 10% export tax in India, Thailand, Vietnam, and Pakistan plus the 95% climate change yield effect in 2030 and alternative sea level rises are shown in the second row of Table 7. Export ban cases again in these four countries are in the bottom row of Table 7. The results show that world rice price will be increase and total trade amount decreases under either policy reaction with the export ban causing larger welfare losses.

Table 7 Economic impacts of climate change with export restriction policies on international rice markets

	Scenarios	Sea level rise in meters					
	Economic items	BASE	1	2	3	4	5
No export restriction	Total production (1,000 mt)	504,476	−3.29%	−3.45%	−3.66%	−3.92%	−4.17%
	Total trade (1,000 mt)	22,416	9.58%	12.70%	16.14%	20.00%	24.45%
	World price ($/mt)	361.43	17.06%	17.90%	19.03%	20.44%	21.91%
	Total social welfare ($ billion)	2,309	−23.72	−24.85	−26.77	−29.78	−33.17
Export tax	Total production (1,000 mt)	504,476	−3.47%	−3.63%	−3.84%	−4.10%	−4.35%
	Total trade (1,000 mt)	22,416	8.09%	11.19%	14.68%	18.46%	22.87%
	World price ($/mt)	361.43	18.05%	18.91%	20.07%	21.52%	23.02%
	Total social welfare ($ billion)	2,309	−24.25	−25.39	−27.32	−30.34	−33.73
Export Ban	Total production (1,000 mt)	504,476	−3.15%	−3.31%	−3.53%	−3.79%	−4.05%
	Total trade (1,000 mt)	22,416	−35.52%	−34.65%	−33.15%	−31.35%	−29.50%
	World price ($/mt)	361.43	22.15%	23.40%	25.01%	27.00%	29.24%
	Total social welfare ($ billion)	2,309	−27.46	−28.75	−30.88	−34.12	−37.78

Numbers in BASE and No Yield Effect scenario give levels while other numbers give changes with respect to this BASE scenario. Results for all but except Total Social Welfare gives the percentage change while the numbers for Total Social are the difference in billon US$

Table 8 Amount of adaptation needed to overcome sea level and crop yield effects in rice yields and trade barrier relaxation

Scenarios	Sea level rise in meters					
	BASE	1	2	3	4	5
No yield effect		(1%) [14%]	(2%) [18%]	(2%) [22%]	(4%) [28%]	(5%) [33%]
2030 lower 5% yield effect	(10%) [45%]	(10%) [46%]	(11%) [46%]	(12%) [48%]	(13%) [49%]	(15%) [51%]
2080 B1a	(3%) [27%]	(3%) [30%]	(4%) [32%]	(5%) [35%]	(6%) [38%]	(7%) [41%]

The numbers in parentheses represent the percentage change that rice yields must increase to reduce the welfare implications of the scenario to zero while the numbers in brackets represent the amount the trade barriers must be cut (i.e. trade liberalization) to mitigate the damages

6.5 Considering adaptation

As damages from the sea level rise and crop yield effects by climate change then adaptations such as new rice varieties tolerant to higher temperature or added salt water intrusion, plus expansions to new lands, and freer trade could arise. Here the effects of larger rice yields and trade barrier relaxations are simulated. In particularly, the model is used to independently solve for

- the percentage change that rice yields must increase without production cost increasing to reduce the welfare implications of the scenario to zero
- the amount that average import tariffs for all importers must be cut (i.e. trade liberalization) to reduce the welfare implications of the scenario to zero

The results of this exercise appear in Table 8. They show that a 1% rice yield improvement for all rice trading countries or a 14% import tariff reduction for all importing countries totally compensates for the effects of 1 m sea level rise. They also show that under larger sea level rises, that larger rice yield improvements or trade barrier reductions are necessary to achieve to compensate for the climate change/sea level induced losses. In particular a 15% rice yield improvement or a 51% reduction in average import tariffs is needed to compensate for a 5 m sea level rise under the lower 5% tail in yield effects in 2030. When the 2080 crop yield effects with a 5 m sea level rise are considered, a 7% rice yield improvement or a 41% reduction in average import tariffs is needed. Such evaluation indicates that the sea level and crop yield effects can be overcome by yield enhancement or trade liberalization but that substantial degrees are needed under the harsher scenarios. This means a more interconnected or productive rice economy will be needed as climate change progresses. The productivity part of this implies adaptation may require increased research and development spending on rice variety climate tolerance (as argued more generally in McCarl (2007)).

7 Concluding comments

This study investigates the economic impacts of sea level rise and crop yield effects due to climate change on rice production, supply, welfare and trade.

Several major empirical findings arise.

- Rice production is sensitive to sea level rise resulting in annual welfare losses ranging up to US$10.59 billion. The more significantly negative impacts fall in Bangladesh, Japan, Taiwan, Myanmar, Egypt, and Vietnam.
- Climate change damages are in part offset by an increase in rice trade with the sensitive countries increasing imports or decreasing exports and those relatively immune increasing exports. Under extreme sea level cases three countries, Myanmar, Vietnam, and Egypt go from being exporters to importers
- The economic sensitivity to climate change induced crop yield effects at 2030 cases are larger than those of sea level rise due to pervasiveness and stimulate as large as a US$22.5 billion welfare loss.
- Simultaneous sea level rise and crop yield effects at 2030 cases exhibit the largest economic sensitivities. Rice production is reduced by 16.6 MMT to 21.0 MMT which causes 17.06% to 21.91% rises in rice prices and welfare losses of US$23.7 to US$33.1 billion. However, such damages in global rice market are reduced under the 2080 cases since consideration of the CO2 effects results in positive effects on rice yields.
- The climate change induced damages can be offset by adaptations in the form of enhanced crop yield improvements and trade liberalization in the form of lower barriers.
- The reduction in rice area would partially offset a degree of future climate change due to the rice–methane link and the accompanying climate forcing properties of methane.

The results provide several policy implications.

- Sea level rise does put rice area at risk particularly in Bangladesh, Japan, Taiwan, Egypt, Myanmar and Vietnam. Rice is their major staple food and such developments may result in food security crises. Adaptation and freer trade are certainly desirable for those regions.
- Rice production globally is vulnerable to the yield effects of climate change along with sea level rise. There is need to develop rice varieties that tolerate the changed climate and salt water intrusion. Globally adaptation will likely require increased expenditures on rice related research and development.
- Climate change will increase pressure for trade liberalization as an adaptive mechanism.

Finally, the empirical results from this study have limitations as they are based on a partial equilibrium model. More comprehensive equilibrium or general equilibrium frameworks would perhaps better illuminate the effects arising through of other commodities and income changes with accompanying changes in policy implications.

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