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Hurricanes and Possible Intensity Increases: Effects on and Reactions from U.S. Agriculture

Chi-Chung Chen and Bruce McCarl

Hurricanes have caused substantial damage in parts of the U.S. Damages are increasing, perhaps as part of a natural cycle or perhaps in part related to global warming. This paper examines the economic damages that hurricanes cause to U.S. agriculture, estimates the increased damage from an increase in hurricane frequency/intensity, and examines the way that sectoral reactions reduce damages. The simulation results show that hurricanes and associated adjustments cause widespread damage and redistribute agricultural welfare. We find that crop mix shifts of vulnerable crops from stricken to nonstricken regions significantly mitigate hurricane damages.

Key Words: crop mix, hurricane intensity, stochastic agricultural sector model

JEL Classifications: Q24, Q54, R14

Recent hurricanes have caused substantial damage in the U.S. and Mexico, as well as Central and South America. In 2005, Hurricane Katrina resulted in property damage of $81.2 billion while Hurricane Andrew in 1992 caused about $44.9 billion in property damage (Burton and Hicks; Pielke and Landsea; USDA). The major categories of damage have included structural damage, destroyed equipment, and interrupted business. However, hurricanes also affect environmental conditions, species distribution, forests, crops, and wetlands. There is substantial debate as to whether hurricanes are strengthening either because of natural cycles or climate change (Webster et al.). This raises the issue of what would be the cost if the frequency and/or intensity of hurricanes were to strengthen, regardless of the causal factors. This paper examines this issue by investigating the economic consequences for agriculture of the incidence of hurricanes and their possible strengthening.

The economic damage caused by hurricanes has been examined by several studies. Hallstrom and Smith used a hedonic approach to estimate property value damage under Hurricane Andrew and found that property values were reduced by 19%. Bin and Polasky estimated the flood hazard effects of Hurricane Floyd on property values, while Pinelli et al. estimated the damage induced by hurricane force winds on residential structures. Regional and local economic impact studies were performed by both West and Lenze and Burrus et al.

While the local and regional agricultural economic impacts of hurricanes have been examined (Guidry; Herndon et al.), in specific cases, the broad agricultural sector economic impacts of hurricanes have not received detailed research attention and the national implications

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have largely been overlooked. For example, hurricane-induced damage to Louisiana rice production may result in increases in the price of rice and result in positive benefits to rice farmers elsewhere. Furthermore, a long-term increase in hurricane frequency may alter changes in crop mix and bring about a possible shifting of production spatially.

Some studies (Paarlberg, Seitzinger, and Lee; Pendell et al.) estimate economic damage of infectious diseases or disasters on a regional level while Paarlberg, Lee, and Seitzinger and Brown et al. estimate its effects on a national level. This study estimates the economic impacts of hurricanes on the U.S. agricultural sector as well as their possible strengthening, while also examining both their regional and national implications. The impacts of hurricanes on crop yield are estimated using econometric models and then the estimation results are incorporated into a stochastic agricultural sector model to evaluate their economic impact on the agricultural sector. Subsequently, the intensity and frequency of hurricanes are simulated to examine the implications of such shifts for the U.S. agricultural sector. Simultaneously, the types of reactions that would make the sector more resilient to hurricanes are examined.

Hurricanes and Crop Yields

In this study, we estimate the impact of hurricanes on crop yields using regressions that follow numerous other climate-related studies (Becker; Chen and Chang; Chen and McCarl; Chmielewski and Potts; Naylor et al.; Tiongco and Dawe). Based on the historical observation of the mainland U.S. hurricane strikes from 1851 to 2004 by state and hurricane category, the major affected states are Florida, Texas, Louisiana, Mississippi, and North and South Carolina. Where available agricultural data from the stricken and nonstricken counties in these states are used in estimating the crop yield impacts of hurricanes, otherwise state level data sets are applied. The impacts of hurricanes also depend on intensity. The Saffir-Simpson hurricane intensity scale for the Atlantic and Northeast Pacific basins is applied here to reflect intensity.

The effects of hurricanes on the average crop yields and their variances are estimated using the Just and Pope stochastic production function specification approach. The explanatory variables, both in the average and variability equations, include crop planted acreage, time trend, and the intensity of hurricane. Planted acreage is included in this equation to reflect the relationship between crop yield and planted acreage which might be decreased as acreage expands as the lesser productive cropland is added or less timely practices used. The estimated crop yield equation we use is shown as Equation (1):

$$\begin{aligned} Y &= f(Acre, Time, Hurcat; \beta) \\ &\quad + h(Acre, Time, Hurcat; \alpha)\varepsilon \end{aligned} \tag{1}$$

where Y is crop yield:

$f(.)$ is an average crop production function,
$h(.)$ is the variance component telling how the yield variability depends on the acreage and hurricane incidence data,
$Acre$ is the acreage of the crop planted,
$Time$ is a time-trend variable to pick up technical change,
$Hurcat$ is the average hurricane intensity level using the Saffir-Simpson scale,
β represents the parameters in the average crop production equation and
α represents the parameters in the yield variability equation, and ε is an error term.

Data are used for yields of barley, corn, cotton, wheat, grapefruit, oranges, potatoes, rice, sorghum, soybeans, sugarcane, and tomatoes as they occur across the states of Florida, Louisiana, Texas, Mississippi, North Carolina, and South Carolina. These data cover the years 1951–2004 and include both county and state level data. In particular county data are used for the strike counties for the following cases: corn, cotton, and sugarcane in Florida; soybeans, rice, and sugarcane in Louisiana; corn, cotton, soybean, wheat, sorghum, and rice in Texas; corn, cotton, soybean, wheat, and oats in North Carolina; and corn, soybean, and oats in South Carolina. The other crop cases used state level data due to a lack of data availability. Crop yield and acreage data are obtained from

USDA Agricultural Statistics while NOAA was the source of the hurricane data.

The crop yield function in Equation (1) is assumed to be a Cobb-Douglas function and therefore the estimation parameters are elasticities. To estimate the function in the face of heteroskedasticity, a maximum likelihood estimation (MLE) approach is used following Chen and Chang, Chen, McCarl, and Schimmelpfennig, and Saha et al. The likelihood function is given in Equation (2):

$$
\begin{aligned}
L(\alpha,\beta) &= -\frac{1}{2}\Big[n * \text{In}(2\pi) \\
&\quad + \sum_{t=1}^{n} \text{In}(h(Acre, Time, Hurcat, \alpha)) \\
&\quad + \sum_{t=1}^{n} \frac{(y_t - f(Acre, Time, Hurcat, \beta))^2}{h(Acre, Time, Hurcat, \alpha)}\Big] \\
&= -\frac{1}{2}\Big[n * \text{In}(2\pi) \\
&\quad + \sum_{t=1}^{n} \text{In}(\alpha_0 + \alpha_1 Acre + \alpha_2 Time + \alpha_3 Hurcat) \\
&\quad + \sum_{t=1}^{n} \frac{(y_t - \beta_0 + \beta_1 Acre + \beta_2 Time + \beta_3 Hurcat)}{\alpha_0 + \alpha_1 Acre + \alpha_2 Time + \alpha_3 Hurcat}\Big]
\end{aligned}
\tag{2}
$$

where t is the time period extending from 1951 to 2004.

The estimation results using county level data in hurricane strike areas are presented in Table 1, while the crop yield variances are shown in Table 2. The estimated outcomes for the time trend effects for most crops in many states are positive, which indicates that the production technology for crop yields has improved. However, the impacts of hurricanes on crop yields in different states exhibit different signs. Table 1 indicates that hurricanes have damaged the crop yields for grapefruit, cotton, potato, and sugarcane in Florida; corn, cotton, sorghum, wheat, and sugarcane in Louisiana; corn, cotton, soybean, and rice in Mississippi; corn, cotton, soybeans, wheat, sorghum, oat, barley, potatoes, and tomatoes in North Carolina; and corn, cotton, soybean, rice, oats, potatoes, and tomatoes in Texas. Therefore, for 34 of the 43 state crop estimations, the effects of hurricane category on crop yields were significant and negative at the 10% level. These estimation results are consistent with the USDA's incident analysis estimates of hurricane damage for specific storms. For example, the 2005 USDA's report on the effects of Katrina estimated losses of 10% of the unharvested corn in Louisiana and Mississippi and 3.96% and 4.62% cotton losses in Louisiana and Mississippi, respectively.

The estimations of crop yield variability are shown in Table 2. It shows that 22 crop state combinations out of 40 have positive and significant sign on crop yield variance due to the hurricane category, while 17 out of 40 have negative and significant sign. The major reason that both positive and negative signs on yield variances are possible is due to the rainfall level as hurricanes strike. The estimated parameters for the hurricane categories in Tables 1 and 2 could be expressed as the effect of a percentage change in hurricane intensity on the average crop yields and yield variances since yield functions are estimated using a Cobb-Douglas function. For example, the 3.39% loss in Louisiana cotton in Table 1 indicates that the average cotton yield will be decreased by 3.39% as the average hurricane intensity increased by one unit from 1951 to 2004.

The impacts of hurricane on average state level crop yields are shown in Table 3. The numbers in the first row of Table 3 represent the impact of hurricane on the strike areas while the numbers of the second row are from counties that did not receive direct strikes. The numbers in the last row of Table 3 are the average effects from all areas where county level data sets were used. When county level data were not available, then state level estimations are applied. We find that the reduction in the average state level crop yields due to hurricanes range from 0.20 to 12.90%, as shown in Table 3. We also find that the crop yield variances are significantly affected by hurricane intensity and the magnitudes of the yield variances due to the hurricanes are higher than the impacts on average crop yields as shown in Table 2. These estimations imply that hurricanes not only damage crop yield but also raise crop production risk.

Economic Modeling of Hurricanes

To estimate the economic impacts of hurricane incidence in the U.S. agricultural sector, the percentage changes in crop yields in Table 3 are incorporated into an economic model. The

Table 1. Estimation Results for Average Crop Yield Functions

	Intercept	Area	Time	Hurricane Category
Florida				
Corn	−39.204**	0.081**	0.0215**	0.0117**
	(0.231)	(0.0012)	(0.0001)	(0.0007)
Cotton	−6.080**	0.064**	0.0059**	−0.0298**
	(0.524)	(0.0031)	(0.0002)	(0.0022)
Sugarcane	−1.169**	−0.0012**	0.0023**	−0.0131**
	(0.212)	(0.0010)	(0.0001)	(0.0009)
Potato	−27.315**	−0.717**	0.0177**	−0.0059**
	(0.482)	(0.0180)	(0.0002)	(0.0016)
Orange	−18.975**	−0.117**	0.0128**	−0.0020
	(4.486)	(0.0607)	(0.0024)	(0.0061)
Grapefruit	11.789**	−0.371**	−0.0019**	−0.0076**
	(2.057)	(0.0290)	(0.0010)	(0.0026)
Louisiana				
Corn	−70.84**	−0.042**	0.0379**	−0.0095**
	(0.450)	(0.0043)	(0.0002)	(0.0021)
Cotton	−16.26**	−0.166**	0.012**	−0.0339**
	(0.355)	(0.013)	(0.0002)	(0.0031)
Soybean	−2.940**	-0.0034**	0.0031**	0.0007
	(0.330)	(0.0012)	(0.0001)	(0.0010)
Wheat	−27.56**	0.032**	0.0155**	−0.0558**
	(0.565)	(0.0045)	(0.0003)	(0.0037)
Sorghum	−34.14**	0.098**	0.019**	−0.0191*
	(0.504)	(0.0029)	(0.0003)	(0.0016)
Rice	−15.71**	0.0369**	0.0118**	0.0111**
	(0.115)	(0.001)	(0.0001)	(0.0009)
Sugarcane	−11.781**	0.0038**	0.0075**	−0.055**
	(0.155)	(0.001)	(0.0001)	(0.0006)
Texas				
Corn	−22.976**	0.094**	0.0134**	−0.113**
	(0.499)	(0.002)	(0.0002)	(0.0027)
Cotton	−28.547**	0.026**	0.0173**	−0.0528**
	(0.156)	(0.0007)	(0.0001)	(0.0009)
Soybean	−9.874**	0.0152**	0.0064**	−0.0350**
	(0.186)	(0.0008)	(0.0004)	(0.0008)
Wheat	−18.831**	0.049**	0.0108**	0.0137**
	(0.853)	(0.0049)	(0.0004)	(0.0037)
Sorghum	−6.741**	−0.018**	0.0055**	0.0199**
	(0.114)	(0.001)	(0.0001)	(0.0004)
Rice	−7.672**	−0.055**	0.0084**	−0.0199**
	(0.119)	(0.0007)	(0.0001)	(0.0006)
Oats	−56.867**	0.266**	0.0297**	−0.0115*
	(0.901)	(0.0081)	(0.0004)	(0.0021)
Potato	−1.318**	−0.186**	0.0032**	−0.0238**
	(0.595)	(0.0226)	(0.0003)	(0.0052)
Tomato	−76.045**	0.284	0.0409**	0.0969
	(31.671)	(0.308)	(0.0158)	(0.0968)

Table 1. Continued.

	Intercept	Area	Time	Hurricane Category
Mississippi				
Corn	−65.693**	0.0299**	0.0351**	−0.020**
	(0.398)	(0.0037)	(0.0002)	(0.0100)
Cotton	−15.258**	−0.138**	0.011**	−0.032**
	(0.929)	(0.0309)	(0.0004)	(0.0056)
Soybean	−14.18**	0.029**	0.0086**	−0.061**
	(0.703)	(0.0088)	(0.0003)	(0.0066)
Wheat	−24.305**	−0.0484**	0.0141**	0.0015**
	(0.693)	(0.0046)	(0.0003)	(0.0021)
Sorghum	−44.72**	0.0726**	0.0243**	0.0122**
	(0.315)	(0.0019)	(0.0002)	(0.0033)
Rice	−35.27**	−0.087**	0.019**	−0.0042**
	(0.464)	(0.0049)	(0.0002)	(0.0027)
North Carolina				
Corn	−32.943**	0.0575**	0.0185**	−0.0634**
	(0.036)	(0.0004)	(0.0002)	(0.0003)
Cotton	−27.882**	0.0304**	0.0171**	−0.0036**
	(0.208)	(0.0009)	(0.0001)	(0.0010)
Soybean	−13.89**	0.048**	0.0084**	−0.0393**
	(0.055)	(0.0005)	(0.0002)	(0.0003)
Wheat	−22.09**	0.0471**	0.0128**	−0.0374**
	(0.083)	(0.0003)	(0.00004)	(0.0003)
Sorghum	−21.616**	0.0808**	0.0126**	−0.0273**
	(1.063)	(0.0097)	(0.0005)	(0.0043)
Barley	−26.21**	-0.0054**	0.0152**	−0.028**
	(0.487)	(0.0089)	(0.0002)	(0.0032)
Oats	−15.353**	0.0642**	0.0096**	−0.0184**
	(0.580)	(0.0021)	(0.0003)	(0.0019)
Potato	−18.582*	−0.047**	0.0119**	−0.0023**
	(0.459)	(0.0143)	(0.0002)	(0.0013)
Tomato	−11.38**	0.0514**	0.0089**	−0.0077**
	(0.854)	(0.0248)	(0.0004)	(0.0038)
South Carolina				
Corn	−45.514**	0.069**	0.0246**	−0.113**
	(0.335)	(0.0023)	(0.0002)	(0.0030)
Cotton	−14.180**	−0.145**	0.0138**	−0.0237**
	(1.125)	(0.009)	(0.0005)	(0.0012)
Soybean	−4.728**	0.0115**	0.0038**	−0.0133**
	(0.272)	(0.0012)	(0.0001)	(0.0015)
Wheat	−12.593**	0.113**	0.0075**	−0.048**
	(0.556)	(0.0078)	(0.0003)	(0.0010)
Sorghum	−29.152**	0.113**	0.0163**	−0.0517**
	(0.751)	(0.0085)	(0.0004)	(0.0082)
Oats	−16.74**	0.065**	0.0101**	0.0157**
	(0.607)	(0.0056)	(0.0029)	(0.0029)

Note: The numbers in the parentheses are the standard deviations. * Represents significance at the 10% level, while ** represents significance at the 5% level.

Table 2. Estimation of Crop Yield Variability Functions

Florida	Intercept	Area	Time	Hurricane Category
Corn	−3.124**	0.709**	−0.191**	−0.0057**
	(0.706)	(0.0071)	(0.0047)	(0.0006)
Cotton	−50.001**	−0.088**	0.121**	0.0239**
	(3.874)	(0.0212)	(0.0127)	(0.0020)
Sugarcane	−5.649**	0.0824**	0.316**	0.0048**
	(0.255)	(0.0219)	(0.0258)	(0.0022)
Potato	1333.31**	4.049**	−0.0767**	−0.198**
	(11.499)	(0.372)	(0.0060)	(0.0016)
Orange	46.836	−1.164	−0.022	0.258**
	(72.63)	(1.093)	(0.039)	(0.0912)
Grapefruit	240.84**	−5.928**	−0.109**	−0.093**
	(28.67)	(0.777)	(0.014)	(0.057)
Louisiana				
Corn	−38.78**	−0.146**	0.0182**	−0.195**
	(4.010)	(0.0322)	(0.0020)	(0.0322)
Cotton	−46.91**	−0.273	0.0225**	0.120**
	(4.753)	(0.205)	(0.0026)	(0.0392)
Soybean	−63.444**	-0.222**	−0.232**	−0.031**
	(2.111)	(0.0110)	(0.0122)	(0.0010)
Wheat	−32.86**	0.009	0.0147**	0.291**
	(5.541)	(0.036)	(0.0028)	(0.0225)
Sorghum	−56.38**	−0.321**	0.0268**	−0.042
	(6.734)	(0.0378)	(0.0034)	(0.0289)
Rice	0.710**	−0.483**	0.147**	−0.018**
	(0.142)	(0.0133)	(0.0129)	(0.0008)
Sugarcane	−1.787**	−0.209**	−0.516**	−0.007**
	(0.117)	(0.012)	(0.0125)	(0.0011)
Texas				
Corn	3.519**	−0.717**	0.106**	−0.014**
	(0.114)	(0.0140)	(0.0195)	(0.0013)
Cotton	0.111**	−0.244**	0.0406**	0.0033**
	(0.034)	(0.0036)	(0.0042)	(0.0004)
Soybean	−4.230**	0.066**	−0.179**	0.0004**
	(1.203)	(0.0050)	(0.0063)	(0.0006)
Wheat	−39.398**	−0.249**	−0.0016**	0.019**
	(3.283)	(0.023)	(0.015)	(0.0016)
Sorghum	−0.731**	−0.245**	−0.218**	0.0259**
	(0.049)	(0.0044)	(0.0033)	(0.0003)
Rice	−3.349**	−0.099**	0.135**	0.0200**
	(0.081)	(0.0071)	(0.0055)	(0.0006)
Oats	−76.539**	0.811**	0.0344**	−0.274**
	(8.015)	(0.0819)	(0.0038)	(0.0262)
Potato	−48.959**	4.427**	0.0232**	0.506**
	(9.165)	(0.341)	(0.0046)	(0.0528)
Tomato	7.066	−0.183	−0.0033	−0.0791
	(24.61)	(0.239)	(0.0123)	(0.075)

Table 2. Continued.

Florida	Intercept	Area	Time	Hurricane Category
Mississippi				
Corn	48.513**	0.0415	−0.0268**	0.707**
	(5.465)	(0.0466)	(0.0026)	(0.0462)
Cotton	−21.62**	1.193**	0.0049	0.082*
	(7.714)	(0.298)	(0.0032)	(0.038)
Soybean	−14.198**	−1.166**	0.0233**	0.366**
	(5.468)	(0.0681)	(0.0029)	(0.0371)
Wheat	−12.051**	0.548**	0.0029	−0.410**
	(6.618)	(0.0522)	(0.0034)	(0.0435)
Sorghum	111.16**	−0.479**	−0.0574**	0.360**
	(5.721)	(0.0381)	(0.0029)	(0.0359)
Rice	57.701**	−0.259**	−0.031**	0.207**
	(16.01)	(0.149)	(0.0084)	(0.0363)
North Carolina				
Corn	0.0097	−0.237**	0.107**	−0.024**
	(0.021)	(0.0021)	(0.0013)	(0.0001)
Cotton	56.059**	-0.0335**	−0.302**	−0.029**
	(1.151)	(0.0062)	(0.0075)	(0.0006)
Soybean	1.406**	−0.537*	0.351**	0.0018**
	(0.052)	(0.0051)	(0.0031)	(0.0003)
Wheat	−2.928**	−0.138**	0.114**	0.029**
	(0.208)	(0.0026)	(0.0028)	(0.0003)
Sorghum	31.673**	-0.0514**	−0.0176**	−0.128**
	(9.508)	(0.0915)	(0.0046)	(0.0384)
Barley	−100.09**	1.183**	0.0462**	0.175**
	(8.258)	(0.125)	(0.0039)	(0.0402)
Oats	−2.215**	−0.255**	−0.222**	−0.0021**
	(0.142)	(0.0209)	(0.0199)	(0.0029)
Potato	−123.95**	0.870	0.0588**	−1.116**
	(13.45)	(0.801)	(0.0070)	(0.0749)
Tomato	−168.53**	−1.627**	0.0829**	0.153**
	(12.11)	(0.287)	(0.0060)	(0.0425)
South Carolina				
Corn	−1.336**	−0.174**	0.268**	0.019**
	(0.114)	(0.0113)	(0.0107)	(0.0007)
Cotton	−51.935**	−1.215**	0.0281**	−1.741**
	(6.701)	(0.089)	(0.0032)	(0.0735)
Soybean	−2.430**	−0.176**	−0.0909**	0.0073**
	(0.136)	(0.0128)	(0.0165)	(0.0015)
Wheat	−3.795**	0.145**	−0.0003	0.406**
	(5.015)	(0.0701)	(0.0025)	(0.0420)
Sorghum	−41.34**	−0.081**	0.0194**	0.126**
	(5.799)	(0.0681)	(0.0029)	(0.0391)
Oats	−2.871**	−0.022**	−0.245**	−0.0090**
	(0.327)	(0.0469)	(0.0509)	(0.0027)

Note: The numbers in the parentheses are the standard deviations. * Represents significance at the 10% level, while ** represents significance at the 5% level.

Table 3. Percentage Change in Average Crop Yield due to Hurricanes

Results for Hurricane Strike Areas using County Data

	Florida	Louisiana	Texas	Mississippi	North Carolina	South Carolina
Corn	1.17		−1.13		−6.34	−11.30
Cotton	−2.98		−5.28		−0.36	
Wheat			1.37		−3.74	
Sorghum			1.99			
Rice		1.11	−1.99			
Oats					−1.84	1.57
Soybean			−3.50		−3.93	−1.33
Sugarcane	−1.31	−5.50				

Results for Nonstrike Areas using County Data

	Florida	Louisiana	Texas	Mississippi	North Carolina	South Carolina
Corn	0.88		0.48		−7.91	−13.05
Cotton	−1.87		−5.86		−0.43	
Wheat			1.65		−3.55	
Sorghum			−1.24			
Rice		0.61	−2.31			
Oats					−2.39	1.93
Soybean			−2.64		−1.46	1.15
Sugarcane	−0.37	−4.87				

Average Effects of Hurricanes at the State Level

	Florida	Louisiana	Texas	Mississippi	North Carolina	South Carolina
Corn	0.93	−0.95	−0.09	−2.00	−6.47	−12.90
Cotton	−2.25	−3.39	−5.81	−3.20	−0.42	−2.37
Wheat		−5.58	1.64	0.15	−3.59	−4.80
Sorghum		−1.91	−0.31	1.22	−2.73	−5.17
Barley					−2.80	
Rice		0.69	−2.21	-0.42		
Oats			−1.15		−2.35	1.86
Potato	−0.59		−2.38		−0.23	
Soybean			−2.69	−6.10	−1.97	0.49
Sugarcane	−0.85	−5.06				
Orange	−0.20					
Grapefruit	−0.76					
Tomato					−0.77	

estimated functions are then subsequently used to estimate the hurricane damage due to the increase in hurricane intensity.

A stochastic agricultural sector model is constructed and employed in this study. The model depicts world trade in eight commodities in conjunction with a detailed U.S. agricultural sector model. Specifically, the model links the Agricultural Sector Model (ASM) developed by McCarl and associates (Baumes; Chang et al.; Chen and McCarl) with a set of spatial equilibrium (SE) world trade models as explained in Chen and McCarl. The basic model is a price endogenous mathematical program reviewed by McCarl and Spreen, and Norton and Schiefer. The model used has been modified into a stochastic mathematical program with recourse by Chen and McCarl (see also Cocks; Dantzig; Lambert et al.; McCarl and Parandvash) and has been modified to reflect hurricane uncertainty. Below, we provide details on the features related to hurricane uncertainty, market structure, risk behavior, trade activity, and storage, and then follow this with an algebraic overview.

Hurricane Uncertainty

Agricultural crop yields fluctuate from year to year depending on the hurricane incidence and other factors. Yield uncertainty is included in the model following Lambert et al. by employing a stochastic programming with recourse approach. In the first stage of the model, decisions are made on crop acreage before yield outcomes are known. Therefore, land allocation and input usage in the first stage do not depend on the state of nature. However, in the second stage, decisions on harvesting, consumption, and livestock feed rations and trades are all set with knowledge of yield outcomes and resulting prices. Thus, consumption and prices depend on the stochastic outcome, but acreage mix is set based on expectations.

The hurricane case is formulated in this two-stage decision process structure. In the first stage, the crop acreages in the coastline states are decided before the hurricane season. However, the final crop yields and market production/price levels depend on whether hurricanes occur or not and are revealed in the second stage. To calculate crop yield distributions (or states of nature) due to the impacts of hurricanes on crop yield, the residuals for each year from 1951 to 2004 are computed based on the estimation of MLE. Therefore, there are 54 states of nature, each of which is assumed to be equally likely, which means that the probability for each state of nature is 1/54. These residuals are added to the 2005 yields for each crop, and used to develop a stationary multivariate yield distribution. Such a method is based on the efforts in Thaysen's study as used in Chen and McCarl.

Perfectly Competitive Markets

Agricultural markets are assumed to be perfectly competitive. Total social welfare is maximized using a price endogenous model as discussed in McCarl and Spreen, but with an expected value maximization variant referred to in Lambert et al. Both of these variants yield first-order conditions that simulate a perfectly competitive economy as explained in the above-referenced papers, but the stochastic model implies that a producer equates average expected marginal revenue with marginal cost in setting decisions.

Risk Response

Decision makers are assumed to be risk neutral where producers maximize their net expected profit given a production technology and prices, while consumers minimize the expected cost of their food purchases. The markets are cleared for each state of nature.

Regional, National, and International Modeling

To estimate the regional and national economic impacts of hurricanes on the U.S. agricultural sector, the model should depict the national and regional production activities and create the regional, national, and international markets for crops. The empirical model depicts these commodity markets in two basic ways. First, the major traded commodities of hard red spring wheat (HRSW), hard red winter wheat (HRWW), soft red winter wheat (SOFT), durum wheat (DURW), corn, soybeans, sorghum, and rice are incorporated using a spatial equilibrium modeling approach following Takayama and Judge that embodies constant elasticity demand and supply functions (based on SWOPSIM, see Roningen) in 23 world regions and 10 U.S. domestic regions, as discussed in Chen and McCarl. To accommodate this, we adjust the ASM national market structure to a regional structure that reflects the relative advantage of certain U.S. regions to ship to certain trade regions. That is, we divide the U.S. into 10 marketing regions, each of which could ship each of the commodities identified above to the foreign regions. These models are then blended in with the regional production and processing/livestock feeding structure of ASM that depicts U.S. consumption in the 10 regions. For the other commodities, we use aggregate U.S. border excess supply and demand functions (i.e., for sugar, cotton, beef, and other items).

Data on the foreign regional quantity, price, and supply/demand elasticities are obtained from three sources: Fellin and Fuller, USDA Agricultural Statistics, and the USDA SWOPSIM model (Roningen). Transport costs are specified using either trade costs adapted from Fellin and Fuller's international grain trade studies or computations of the differences between importing and exporting prices, which are also factors in price wedges caused by imperfect competition and other trade distortions.

Storage

Storage activity can smooth out price variations. We include a storage variable in the model and allow goods to be placed into storage at 7% of the commodity price. In addition, across the uncertain yield states of nature, average storage additions equal average withdrawals.

Model Formulation

Overall, the model framework is summarized by the following equations. The model's objective function is

$$
\begin{aligned}
Max\colon & -\sum_{j,k,z} C_{jkz}X_{jkz} - \sum_{k}\int \beta(L_k)dL_k \\
& - \sum_{k,r}\int \alpha(R_{rk})dR_{rk} \\
& + \sum_{s} PR_s {}^{*}[\sum_{i\in LN}\sum_{k} P_i^{LN} DQ_{iks} \\
& + \sum_{i}\int \varphi(Q_{is})dQ_{is} \\
& + \sum_{i,c}\int ED(FQD_{ics})dFQD_{ics} \\
& - \sum_{i,c} ES(FQS_{ics})dFQS_{ics} \\
& - \sum_{i,c,k} USFCST_{ikc} {}^{*} USFTRD_{icks} \\
& - \sum_{i,c,c1} FFCST_{icc1} {}^{*} FTRD_{icc1s} \\
& - \sum_{i,k,k1} USCST_{ikk1} {}^{*} USTRAN_{ikk1s} \\
& - \sum_{i,k} PDIF_{ik} {}^{*} TN_{iks} \\
& - \sum_{i} stor_i {}^{*} QSTORW_{is}]
\end{aligned} \tag{3}
$$

where

i indexes commodities,

j indexes production processes,

k, k_1 indexes US regions,

c, c_1 indexes the rest of the world's regions,

r indexes resources,

s indexes uncertain yield states of nature (SON),

z indexes farm program participation options (none, full),

C_{jkz} is the cost of the jth production process per acre in U.S. region k under farm program participation option z,

X_{jkz} is the acreage of the jth production process in U.S. region k under farm program participation option z,

$\beta(L_k)$ is the inverse U.S. land supply function in region k,

L_k is the land supply for U.S. region k,

$\alpha(R_{rk})$ is the inverse U.S. factor supply function for resource r in region k,

R_{rk} is the resource supply for U.S. region k of resource r,

PR_s is the probability of state of nature s,

P_i^{LN} is the market loan rate for commodity i,

DQ_{iks} is the quantity received of marketing loan payment for commodity i in U.S. region k under SON s,

$\varphi(Q_{is})$ is the inverse of the U.S. demand function for commodity i,

Q_{is} is U.S. domestic consumption (not including intermediate product consumption) of the ith product under SON s,

$ED(FQD_{ics})$ is the inverse excess demand function for commodity i in importing ROW region c,

FQD_{ics} is the excess demand quantity in ROW region c for commodity i under SON s,

$ES(FQS_{ics})$ is the inverse excess supply function for commodity i in exporting ROW region c,

FQS_{ics} is the excess supply quantity in ROW region c for commodity i under SON s,

$USFCST_{ikc}$ is the transportation cost from U.S. region k to ROW region c for commodity i,

$USFTRD_{icks}$ is the trade between ROW region c and U.S. region k of commodity i under SON s,

$FFCST_{icc1}$ is the transportation cost from ROW regions c and $c1$ for commodity i,

$FTRD_{icc1s}$ is the trade between ROW regions c and $c1$ of commodity i under SON s,

$USCST_{ikk1}$ is the transportation cost between U.S. regions $k1$ and k for commodity i,

$USTRAN_{ikk1s}$ is the quantity shipped between U.S. regions $k1$ and k of commodity i under SON s,

$PDIF_{ik}$ is the price difference between U.S. region k and U.S. national market for commodity i,

TN_{iks} is the transfer to the U.S. national balance of commodity i from U.S. region k for SON s,

$stor_i$ is the storage cost in the U.S. for commodity i and

$QSTORW_{is}$ is the quantity withdrawn from the storage of commodity i under SON s.

The objective function blends the spatial equilibrium and price endogenous models. In particular, the first three lines include terms typically used in the conventional sector model with probabilistically weighted terms giving the area under the demand equations ($\int \varphi(Q_{is})dQ_{is}$) for commodity i minus the area under the regional U.S. factor supply curves for perfectly elastic production costs associated with production process $j(C_{ijk}X_{ijk})$ and quantity dependent prices for land and factor r summed across all k regions ($\int \beta(L_k)dL_k$ and $\int \alpha(R_{rk})dR_{rk}$).

The next four lines are those typically in a spatial equilibrium model with line four giving the area under the ROW excess demand curves minus the area under the excess supply curve for commodity i in ROW region c. Line five sums up the transportation costs between the U.S. and foreign regions involved with trade (*USFTRD*). Line six sums up the transportation costs among foreign regions for the goods traded (*FTRD*). Line seven sums up the transportation costs between the U.S. regions for interregional shipments (*USTRAN*). Line eight blends the U.S. national demand representation in the Agriculture Sector Model (ASM; Chang et al.) model from which we draw data from the regional U.S. markets needed for this model by introducing goods movements from the U.S. regions to the national demand at historic price differences. The last line gives the cost of storage.

The model is stochastic in that all terms and variables except for acreage allocation and factor use activities are SON dependent. This assumes that production and factor use are set before the yield uncertainty is resolved but that demand and trade are set afterward. The third line in this objective function introduces the yield SON probabilities. This renders the objective function as being the maximization of expected welfare at the equilibrium point.

The regional balance constraint for goods depicted with a spatial equilibrium trade model (f, where f is a subset of i) in the U.S. is

$$\begin{aligned} & -\sum_j Y_{fjks} * (1 + Hurper_{ik}) * X_{jk} - DQ_{fks} \\ & - \sum_c USFRTD_{fcks} - \sum_{k1} USTRAN_{fk1ks} \\ & + \sum_c USFTRD_{fkcs} + \sum_{k1} USTRAN_{fkk1s} \\ & + TN_{fks} \le 0, \quad \forall f,k,s. \end{aligned} \tag{4}$$

where Y_{fjks} is the per acre yield above under the SON s and this parameter is the average yield plus the residuals for the SON.

$Hurper_{ik}$ is the crop yield percentage change due to the hurricane (i.e., the numbers in the upper rows of Table 3).

DQ_{fks} is the regional farm program production quantity that receives the marketing loan payment.

Equation (4) portrays the supply and demand balance for the U.S. regions. The first item depicts regional nonfarm program production in the U.S. The second term represents the farm program production. The other items in Equation (4) are variables for the shipments among U.S. regions (*USTRAN*), between U.S. regions and foreign countries (*USFTRD*), and between regions and the national U.S. market (*TN*).

The national balance constraint for traded farm program goods is

$$Q_{fs} - \sum_k TN_{fks} \le 0, \quad \forall f, s, \tag{5}$$

where aggregate demand (Q) is balanced with the quantities (TN) from the regions (k) by farm program commodity (f) and SON (s).

The balance constraint for the proportion of farm program commodities eligible for regional deficiency and marketing loan payments is

$$(6) \qquad DQ_{fks} - \sum_{j} Y^{LN}_{fjks} * X_{jk} \le 0, \quad \forall f, k, s,$$

where Y^{LN}_{fjks} is the smaller of the actual yield under this SON and the yield that can be put under a marketing loan. Therefore, the farmers receive market prices on all production and LDP payments.

The national balance constraint for nonfarm program goods in the U.S. is

$$(7) \qquad \begin{aligned} & Q_{is} - \sum_{k,j,i\in h} Y_{hjks} * (1 + Hurper_{ik}) * X_{jk} - TN_{is} \\ & + \sum_{c,i\in h} [USFTRD_{hcs} - USFTRD_{hcs}] \\ & + [QSTORA_{is} - QSTORW_{is}] \le 0 \quad \forall i,s. \end{aligned}$$

where $QSTORA_{is}$ is the quantity added to the storage of commodity i under SON s.

The land constraint for region k in the U.S. is

$$(8) \qquad \sum_{j} X_{jk} \le L_{k}, \quad \forall k,$$

The other resource constraint for region k in the U.S. is

$$(9) \qquad \sum_{j} f_{rjk} * X_{jk} \le R_{rk}, \quad \forall r,k.$$

Collectively, Equations (5) to (7) balance demand and supply in regional and national markets under any deficiency or marketing loan payments. Equation (5) is a regional balance for goods with regional trade being accounted for after farm program payments. Equation (6) is the regional production balance for deficiency payments and marketing loan payments. Equation (7) is the U.S. national supply and demand balance constraint for all goods including those not traded at a regional level and nonfarm program goods. Equations (8) and (9) depict land and other resource constraints for region k in the U.S.

The balance constraint for traded goods in country c is

$$(10) \qquad \begin{aligned} & + FQD_{ics} + \sum_{k} USFTRD_{icks} \\ & + \sum_{c1} FTRD_{icc1s} \\ & - FQS_{ics} - \sum_{k} USFTRD_{ikcs} \\ & - \sum_{c1} FTRD_{ic1cs} \le 0 \quad \forall i,c,s, \end{aligned}$$

where foreign region demand (*FQD*), exports to the U.S. (*USFTRD*) and exports to the rest of the world (*FTRD*) are balanced off against foreign region supply (*FQS*), imports from the U.S. (*USFTRD*), and imports from the rest of the world (*FTRD*).

Finally, we have the storage balance

$$(11) \qquad \sum_{s} PR_{s} * [QSTORA_{is} - QSTORW_{is}] = 0 \quad \forall I,$$

where the probability weighted net additions and withdrawals storage are equal and where net additions are bounded by the maximum observed quantity.

Empirical Results

To estimate the economic impacts of hurricanes on the U.S. agricultural sector, the hurricane impacts on crop yields by state level in Table 3 are incorporated into the above stochastic agricultural sector model. The numbers in the bottom rows of Table 3 represent the percentage change in average crop yields due to hurricane incidence. These numbers are multiplied by the crop yield for each state of nature [i.e., $Y_{iks} * (1 + hurper_{ik})$], which is shown in Equation (7). Analyses are performed under current hurricane intensity and increased intensity with frequency change.

Current Hurricane Intensity

The national and regional agricultural economic impacts of hurricanes on commodity prices, production, and social welfare are listed in Tables 4–7. Three major empirical findings arise in relation to the current level of hurricane damage. First, we find that hurricanes and the reaction they stimulate in terms of acreage shifts and other production realignments have commodity specific impacts on national crop prices and production, which can be positive or negative as shown in Table 4. Negative national production effects are found for corn, soybeans, wheat, rice, oat, oranges, potatoes, and tomatoes, with positive effects on prices. Positive national production effects are found for cotton, sorghum, barley, grapefruit, and sugarcane, with generally negative effects on prices. We find that the magnitudes of the impacts on the national production and prices of such hurricanes

Table 4. National Economic Impacts of Hurricanes in the U.S. Agricultural Sector

	Price			Production		
	W/O Hurricane	With Hurricane	Percentage Change	W/O Hurricane	With Hurricane	Percentage Change
Corn (bu)	2.08	2.10	0.96	9,312,017	9,247,257	−0.69
Cotton (bale)	259.02	255.55	−1.34	16,111	16,285	1.08
Soybeans (bu)	5.81	5.88	1.20	2,113,707	2,101,240	−0.59
Sorghum (cwt)	1.91	1.91	0.00	830,713	836,259	0.67
Wheat (bu)	3.29	3.29	0.00	2,613,560	2611,615	−0.07
Rice (Cwt)	6.42	6.73	4.83	172,977	171,081	−1.09
Barley (bu)	2.09	2.14	2.39	400,572	406,084	1.50
Oats (bu)	1.39	1.51	8.63	315,564	312,012	−1.12
Orange (box)	5.13	5.13	0.00	53,435	53,392	−0.08
Grapefruit (box)	4.41	3.99	−9.52	29,639	30,996	4.58
Potato (Cwt)	6.25	6.33	1.28	401,019	399,452	−0.39
Tomato (25 lb box)	9.32	9.33	0.11	148,794	147,154	−1.10
Sugarcane (1000 lbs)	195.65	198.05	1.22	2,892	3,060	5.81

and associated adjustments for most crops are below 5%, except in the cases of oat and grapefruit prices.

The second finding is that acreage farmed and acreage of select crops shifts from stricken to nonstricken regions. Table 5 shows regional crop acreage shifts particularly out of the U.S. Gulf coast and the southern Atlantic coastal regions, with the opposite impacts being found outside these areas. (Note that the upper rows in Table 5 represent crop acreages for each region while the lower rows are the percentage changes in regional crop acreage relative to a no hurricane case.) For example, hurricane incidence and accompanying adjustments have a negative impact on cotton, soybean, wheat, rice, barley, oat, orange, potato, and tomato acreages in the Southern Plains region (Texas), while there are acreage increases for barley, oats, potatoes, and tomatoes in the Pacific region. The regional production impacts are higher in the stricken states than those of the national production impacts, with the responses in the rest of the country providing a more robust "hardened" agricultural sector.

The third finding is that welfare also shifted from stricken to nonstricken regions. Table 6 shows the effects on consumer's and producer's surplus and national welfare. Therein the hurricane stricken regions such as Appalachia, the Delta States, and the Southeast exhibit welfare losses while gains appear elsewhere in the Northeast, Lake States, Northern Plains, and Mountains. Nationally and agricultural sector-wide hurricanes and accompanying adjustments cause damage (Table 7) with average annual consumers' surplus losses of about $490 million and producers' gains of about $260 million along with foreign surplus losses of $20 million all in year 2004 dollars. Thus, total social welfare decreases by $250 million.

Effects of Increased Hurricane Intensity with Frequency Change

Many earth scientists argue that hurricanes have recently become more intense and that the length of the storm season is increasing. Webster et al. found that between 1975 and 1989 about 8–25% of the hurricanes fell into categories 4 and 5 but that more recently this had increased from 25% to 41%. Emanuel obtained similar findings. Blake et al. found that the probability of at least one major (category 3, 4, 5) hurricane landfall increased from 52% over the last century to 73% more recently. Some have argued that climate change is behind this, while others have argued that it is part of a natural cycle. Nevertheless, it would be interesting to examine the possible magnitude of the economic impacts if the occurrence probability of a hurricane and its strength were to shift.

Table 5. Average Crop Acreage Change with and without Hurricane in the 10 USDA Regions

Crop Planted Acreage without Hurricane by 1000 Acres

	Corn	Cotton	Soybeans	Sorghum	Wheat	Rice
Northeast	2,196	—	469	7	539	—
Lake states	11,828	—	5,054	—	4,454	—
Cornbelt	36,700	320	24,583	954	4,419	78
Northplain	12,296	—	7,915	5,725	24,898	—
Appalachia	3,224	721	4,357	119	1,649	—
Southeast	2,019	1158	2,191	76	489	—
Deltastate	168	1927	8,647	380	2,108	1,956
Southplain	1,629	4652	745	3,955	9,805	383
Mountain	837	607	—	582	9,148	—
Pacific	266	1,213	—	23	3,735	410

	Barley	Oats	Orange	Grapefruit	Potato	Tomato
Northeast	209	469	—	—	283	15
Lake states	704	1,669	—	—	161	3
Cornbelt	—	1,869	—	—	27	4
Northplain	2,238	1,167	—	—	181	—
Appalachia	104	58	—	—	32	9
Southeast	14	104	40	45	46	58
Deltastate	—	16	—	—	1	2
Southplain	32	117	6	13	17	3
Mountain	1,903	201	8	4	60,051	—
Pacific	890	117	125	13	1,215	40

Percentage Reduction in Acreage with Hurricane

	Corn	Cotton	Soybeans	Sorghum	Wheat	Rice
Northeast	0.00	—	0.00	0.00	0.00	—
Lake states	4.78	—	8.42	—	−4.14	—
Cornbelt	−2.39	–18.03	5.31	−3.13	−3.53	−12.85
Northplain	−0.03	—	−0.03	−23.94	−0.03	—
Appalachia	0.00	0.00	−0.03	0.00	0.00	—
Southeast	−7.11	−8.05	4.27	2.25	6.41	—
Deltastate	134.55	41.03	−20.08	27.00	8.30	0.83
Southplain	3.37	−6.84	−3.04	5.85	–0.91	−3.58
Mountain	6.47	–0.23	—	−3.16	2.03	—
Pacific	−2.00	−4.64	—	−19.85	−0.26	−2.83

	Barley	Oats	Orange	Grapefruit	Potato	Tomato
Northeast	0.00	0.15	—	—	0.00	0.20
Lake states	2.96	−10.83	—	—	−1.84	−7.85
Cornbelt	—	0.62	—	—	0.55	−3.31
Northplain	−0.03	−0.03	—	—	−0.02	—
Appalachia	0.00	0.22	—	—	0.00	0.00
Southeast	−10.99	3.11	–3.00	4.11	1.51	−2.25
Deltastate	—	168.11	—	—	−73.45	−36.54
Southplain	–29.80	−0.95	–3.63	21.23	−10.26	−2.75
Mountain	2.27	−21.89	42.60	3.05	–1.42	—
Pacific	3.36	6.83	–0.20	−0.69	2.50	2.35

Note: — means no data available.

Table 6. The Impacts of Hurricanes on Regional Welfare in US$ Million

	Without Hurricane			With Hurricane		
	CS	PS	Total Welfare	CS	PS	Total Welfare
Northeast	38,108	1,532	39,640	38,285	1,548	39,832
				(0.46)	(1.00)	(0.48)
Lake states	182,128	5,717	187,844	188,583	5,988	194,571
				(3.54)	(4.74)	(3.58)
Cornbelt	550,188	18,528	568,716	546,606	18,522	565,128
				(−0.65)	(−0.03)	(−0.63)
Northplain	245,846	8,211	254,058	246,721	8,295	255,016
				(0.36)	(1.02)	(0.38)
Appalachia	52,014	1,143	53,157	50,670	1,109	51,779
				(−2.58)	(−3.04)	(−2.59)
Southeast	47,922	1,366	49,288	46,279	1,322	47,601
				(−3.43)	(−3.22)	(−3.42)
Deltastate	33,747	996	34,743	30,348	864	31,212
				(−10.07)	(−13.23)	(−10.16)
Southplain	70,219	2,130	72,349	73,862	2,275	76,137
				(5.19)	(6.81)	(5.24)
Mountain	49,098	1,531	50,629	49,351	1,582	50,933
				(0.51)	(3.35)	(0.60)
Pacific	48,673	1,855	50,528	46,904	1,800	48,704
				(−3.63)	(−2.96)	(−3.61)

Notes: The numbers in the parentheses represent the percentage change. CS means the consumer's surplus while PS represents producer's surplus. Total welfare is the summation of the consumer's and producer's surplus.

To simulate the economic impacts of increasing hurricane intensity, we evaluate our crop yield estimations under increases in average hurricane intensity. The data in Table 3 give the percentage change in crop yields under the average hurricane category during the period from 1951 to 2004. We recomputed these assuming that average hurricane intensity in all years increases by one category, which results in our functional form having twice the Table 3 damages. We also simulate an increase in the hurricane intensity of two categories. In turn, the results for welfare are shown in the upper rows of Table 8.

Table 8 shows that the losses to the consumers, foreign trade parties, and total welfare increase as the hurricane intensity increases. However, the producer's surplus moves in the opposite direction. For instance, the loss of consumer's surplus due to the current hurricane intensity is $490 million but the loss increases to $1042 million with a one-unit increase in hurricane intensity and a $1361 loss with a two-unit increase. At the same time, the producer's surplus in the stricken regions falls by $210 million to $410 million, which reveals a redistribution of agricultural income as the sector adjusts to become more significant with respect to hurricane damage.

An increase in hurricane frequency is also simulated. To do this, the probability distribution is shifted. The original probability distribution based on each state of nature (i.e., from 1951 to 2004) is an equal distribution that was 1/54 for each state of nature. Webster et al. have found that the occurrence probabilities of categories 4 and 5 hurricanes have increased, and therefore the probability of years where those occurred increases while for the other years the probabilities decrease. That is, for 1957, 1969, and 1992 the probability increases from 1/54 to 2/57 while the probability for other states of nature is reduced from 1/54 to 1/57 to ensure that the probabilities still sum to one.

The resultant welfare impacts under the base incidence and the increased intensities with frequency change are shown in the bottom row of Table 8. These results show that under

Table 7. The Impact of Hurricanes on Aggregate Welfare in the U.S. Agricultural Sector in US$ Million

Welfare Items	W/O Hurricane	With Hurricane
CS	1,178,791	1,178,301 (−490)
PS in strike regions	3,505	3,325 (−210)
PS outside strike regions	34,604	35,074 (470)
Total PS	38,109	38,369 (260)
Foreign Trade Surplus	250,195	250,175 (−20)
Total Welfare	1,467,095	1,466,833 (−250)
U.S. Government Payments	11,255	11,330 (75)
Total Net Welfare	1455,840	1,455,531 (−325)

Notes: The numbers in parentheses are the absolute change.Total P.S. is the summation of P.S. in the hurricane stricken regions and outside the stricken regions. Foreign Trade Surplus is the trade surplus while Total Welfare is the summation of CS, Total PS, and Foreign Trade Surplus. U.S. Government Payments include the government expenditure from implementing U.S. farm programs and Total Net Welfare is the Total Welfare less U.S. Government Payments.

increased intensity and subsequent sector adaptation, consumers and the foreign trade interests incur larger welfare losses, while producers make largest gains outside the stricken areas and smaller losses within the hurricane stricken areas. This welfare change pattern is amplified when the frequency changes. For instance, when the hurricane category is increased by two but the frequency is not changed, then consumers' surplus falls by $1,361 million, and producers' surplus increases by $786 million, and as frequency changes these measures increase to $1,483 and $1,093 million. These numbers in Table 8 could be interpreted as the correct damages when people do not know that the regime has changed to reflect a more severe hurricane pattern.[1]

A More Robust Sector Through Crop Mix Adjustment

In the face of changes in hurricane frequency, the model adjusts acreage distribution to mitigate vulnerability. We examine the nature and consequences of such decisions in this section. To do so, three alternative scenarios are run, namely, the historic hurricane incidence, one Saffir-Simpson unit higher hurricane category incidence without crop mix adjustment using the crop mixes from the current hurricane incidence case, and one Saffir-Simpson unit higher hurricane category incidence with crop mix adjustment. The results are shown in Table 9. It is shown that the crop mix adjustment has a significant mitigation effect on the hurricanes. For instance, the loss in terms of consumer's surplus is reduced from $1999 million to $552 million, while the loss in terms of total social welfare is reduced from $791 million to $141 million. Such welfare differences with and without adjustments are the gains from being correctly informed about the true likelihood of hurricanes, which is referred as value of information. Empirically, crop mix in the stricken regions adjusts due to the effects of hurricane, while crop mix in the nonhurricane-stricken regions adjust due to the effect of national price change, and these changes are shown in Table 10.

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[1] We thank a reviewer for suggesting this explanation.

Table 8. The Welfare Impact of Hurricanes by Increasing Hurricane Intensity in the U.S. Agricultural Sector in US$ Million

		With Hurricane		
		Category Increased		
Welfare Items	W/O Hurricane	Current Hurricane Incidence	Increased by 1 Category	Increased by 2 Categories
CS	1,178,791	−490	−1,042	−1,361
PS in stricken regions	3,505	−210	−294	−410
PS outside stricken regions	34604	470	986	1,196
Total PS	38,109	260	692	786
Foreign Trade Surplus	250,195	−20	−41	−141
Total Welfare	1,467,095	−250	−391	−716
U.S. Government Payments	11,255	75	33	14
Total Net Welfare	1,455,840	−325	−424	−730
		Frequency Change with Category Increased		
	W/O Hurricane	Current Hurricane Incidence	Increased by 1 Category	Increased by 2 Categories
CS	1,178,791	−609	−1,104	−1,483
PS in stricken regions	3,505	−168	−269	−384
PS outside stricken regions	34,604	692	1,167	1,477
Total PS	38,109	524	898	1,093
Foreign Trade Surplus	250,195	−53	−165	−213
Total Welfare	1,467,095	−138	−371	−603
U.S. Government Payments	11,255	−28	−54	−45
Total Net Welfare	1,455,840	−110	−317	−558

Note: The numbers with hurricanes are the differences with respect to there being no hurricane.

Conclusions

Some scientists suggest the frequency and intensity of hurricanes has increased in the last decade. We estimated the economic impacts of such a development and associated sectoral adjustments on both local and national U.S. agriculture. We used an econometric approach

Table 9. The Mitigation Effects by Cropping Patterns on Aggregate Welfare in the U.S. Agricultural Sector in US$ Million

		Increased by 1 Category	
Welfare Items	Current Hurricane Incidence	No Crop Mix Adjustment	Crop Mix Adjustment
CS	1,178,301	−1,999	−552
PS in stricken regions	3,325	23	−114
PS outside stricken regions	35,074	1,815	546
Total PS	38,369	1,838	432
Foreign Trade Surplus	250,175	−630	−21
Total Welfare	1,466,833	−791	−141
U.S. Government Payments	11,330	−280	−42
Total Net Welfare	1,455,531	−511	−99

Table 10. Crop Mix Adjustment under the Change of Frequency and Intensity of Hurricanes in the 10 USDA Regions

Percentage Change with Hurricane	Corn (%)	Cotton (%)	Soybeans (%)	Sorghum (%)	Wheat (%)	Rice (%)
Northeast	0.46	—	0.46	0.43	0.46	—
Lake states	−1.96	—	−3.37	—	1.85	—
Cornbelt	0.33	3.97	0.85	3.79	1.19	7.51
Northplain	16.56	—	16.56	16.36	16.60	—
Appalachia	9.95	9.92	9.92	9.96	10.03	—
Southeast	−4.12	−5.42	3.05	0.71	2.46	—
Deltastate	3.23	0.70	−0.52	2.57	−1.86	0.62
Southplain	−12.06	−5.58	−42.00	9.14	11.04	−15.43
Mountain	0.00	0.44	—	0.43	0.25	—
Pacific	4.55	5.79	—	−31.22	−1.85	3.46

Percentage Change with Hurricane	Barley (%)	Oats (%)	Orange (%)	Grapefruit (%)	Potato (%)	Tomato (%)
Northeast	0.46	0.46	—	—	0.46	0.46
Lake states	−1.23	5.45	—	—	0.80	3.47
Cornbelt	—	−7.95	—	—	−5.44	−0.49
Northplain	12.60	16.53	—	—	16.56	—
Appalachia	9.61	9.91	—	—	9.92	9.87
Southeast	−6.78	1.20	−2.06	1.91	0.57	−1.54
Deltastate	—	−2.32	—	—	0.00	−0.76
Southplain	128.24	10.19	62.46	−18.14	7.43	1.57
Mountain	0.12	−1.75	2.57	−0.25	−0.39	—
Pacific	−3.73	−7.62	2.23	5.58	9.46	0.99

Note: The numbers under the table are regional crop acreage percentage changes with respect to the change of frequency and intensity of hurricanes. — means no data available.

to estimate yield effects and find that coastal state crop yields are reduced from 0.20% to 12.90% dependent on crop and location. In turn, we incorporated the yield effects into a stochastic U.S. agricultural sector model to look at economic costs and sectoral land use adjustments. The results show that while hurricanes and associated adjustments negatively affect regional production in the strike zone, national adjustments can compensate with a redistribution of welfare and acreage outside of the strike areas. Namely, changes in cropping patterns make the sector more resilient to hurricane risk by reducing the near coastal acreage of vulnerable crops such as cotton, soybeans, and rice. Running the model with and without such adjustments shows this action reduces sector-wide damage by $650 million.

We also examine crop damage resulting from an increase in hurricane intensity, finding that losses increase by $391 million when intensity rises by one Saffir-Simpson category and by a further $716 million when it goes up by two categories.

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