Climate Change, Agriculture, and Water Quality in the U.S. Chesapeake Bay Region[*]

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1. Introduction

Research on the impacts of climate change and variability on agriculture has been largely concerned with implications for the supply and cost of food and for producer incomes. Societal interest in agriculture is, however, much broader than these issues. Rural and urban populations in developed countries often value agricultural land as open space and as a source of countryside amenities. Agricultural land is also an important habitat for remaining wildlife species in developed countries. These values are reflected in public programs in many countries to protect farmland from development and preserve particular types of agricultural landscapes. Agriculture is also a source of negative environmental externalities in both developed and developing countries. Conversion of forest and wetlands to agricultural production is a major cause of deforestation and species loss in developing countries. In both developed and developing countries, nutrients, pesticides, pathogens, salts, and eroded soils are leading causes of water quality problems. In addition, agriculture is potentially a sink for greenhouse gases.

Changes in environmental externalities from agriculture due to climate change may be more important from a public policy perspective than impacts on agricultural production, food prices, or farm incomes. Farmers—as well as seed companies, fertilizer distributors, and other firms that sell products and services to farmers—will have strong financial incentives to adapt to climate change by minimizing negative impacts on production and exploiting positive impacts.

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No one has any similar, direct financial stake in minimizing any negative environmental externalities from climate change or exploiting any positive externalities. It will be up to governments in each country to decide what environmental externalities are important enough to warrant action and what kinds of actions need to be taken to address these issues.

Several studies in recent years have been directed at the effects of climate change on the negative environmental externalities from agricultural production, including runoff (e.g., Chiew et al., 1995; van Katwijk et al., 1993), leaching (e.g., Follett 1995), and erosion (e.g., Favis-Mortlock and Savabi 1996; Phillips et al., 1993; Williams et al., 1996). These studies excel at modeling the biological and physical relationships and processes underlying runoff, leaching, and erosion. However, they do not consider economic responses by farmers to climate change. Instead, they implicitly assume that farmers will continue to produce the same crops and livestock on the same land using the same management practices.

Changes in temperature, precipitation, and atmospheric carbon dioxide (CO_2) levels that affect the profitability of agricultural enterprises could lead to changes in the amounts and locations of cropland and pasture land, the types of crops and livestock produced, and management practices for individual crops and livestock. These economic responses could give rise to "indirect" impacts of climate change on runoff, leaching, and erosion that could in principle augment, diminish, or even reverse the "direct" impacts assuming no economic responses on the part of farmers.

The objective of this paper is to analyze the potential impacts of climate change on agriculture and water quality in the U.S. Chesapeake Bay Region, taking into account economic responses by farmers to climate change. To accomplish this objective we construct a simulation model of maize production in six watersheds within the Chesapeake Bay Region with economic and watershed modules linking climate to productivity, production decisions by maize farmers, and nonpoint pollution loadings. Maize is an important crop to study because of its importance to the region's agriculture and because it is a major source of nutrient pollution. Maize is the most nitrogen-intensive of all major crops currently grown within the region. Livestock farms within the region also often dispose of manure on maize land.

2. The Chesapeake Bay Region

The Chesapeake Bay Region is a good case for study. The 165,000 square kilometer Chesapeake Bay watershed is the largest estuary in the United States (Chesapeake Bay Program, 1999). The watershed includes parts of the states of New York, Pennsylvania, West Virginia, Delaware, Maryland, and Virginia, as well as the entire District of Columbia. Over 15 million people currently live in the Chesapeake Bay watershed.

The Chesapeake Bay is one of the most valuable natural resources in the United States. It is a major source of seafood, particularly highly valued blue crab and striped bass. It is also a major recreational area, with boating, camping, crabbing, fishing, hunting, and swimming all very popular and economically important activities. The Chesapeake Bay and its surrounding watersheds provide a summer or winter home for many birds, including tundra swans, Canada geese, bald eagles, ospreys, and a wide variety of ducks. In total, the Bay region is home to more than 3,000 species of plants and animals (Chesapeake Bay Program, 1999).

Human activity within the Chesapeake Bay watershed during the last three centuries has had serious impacts on this ecologically rich area. Soil erosion and nutrient runoff from crop and livestock production have played major roles in the decline of the Chesapeake Bay. The Chesapeake Bay Program (1997) estimates that agriculture currently accounts for about 39% of nitrogen loadings and about 49% of phosphorus loadings in the Chesapeake Bay. This makes agriculture the single largest contributor to nutrient pollution in the Chesapeake Bay. Other contributors include point sources such as wastewater, forests, urban areas, and atmospheric deposition.

The locations of the six watersheds analyzed here—Clearfield Creek, Conodoquinet Creek, Juniata/Raystown River, Pequea Creek, Pine Creek, and Spring Creek—within the Chesapeake Bay region are shown in Figure 1. Statistics on land cover/use for the watersheds are provided in Table 1, while statistics on nitrogen loadings are provided in Table 2. The watersheds are diverse in terms of the percentage of land devoted to agriculture as a whole and to maize. However, they are similar in that agriculture accounts for the vast majority of nonpoint nitrogen loadings. Maize alone accounts for more than half of total nonpoint nitrogen loadings in every single watershed. On average across the six watersheds, maize accounts for more than two-thirds (69%) of total nonpoint loadings.

3. Economic-Watershed Model

The simulation model of maize production in the Chesapeake Bay Region has economic and watershed modules linking climate to productivity, production decisions by maize farmers, and nonpoint pollution loadings. The economic module predicts the choices that farmers make with respect to the amount of land devoted to maize and the usage of fertilizer and other inputs into maize production. Precipitation, temperature, and atmospheric CO_2 levels affect the uptake of nutrients and the productivity of land used in maize production. The economic module is based on previous economic models we constructed to examine nonpoint agricultural pollution (Abler and Shortle, 1995, 1996, 1997; Shortle and Abler, 1997).

The expected cost function for maize is a two-level CES exhibiting constant returns to scale at each level. At the upper level, maize is produced from a composite mechanical input and a composite biological input. Mechanical inputs provide the power needed for tasks such as planting, weeding, and harvesting, while biological inputs provide nutrients and a growth environment. The lower levels generate the composite inputs. The mechanical input is produced from capital and labor, while the biological input is produced from land and nutrients. The two-level CES production function is parsimonious in parameters and may represent a reasonable approximation at an aggregate level to agricultural production processes (Hayami and Ruttan, 1985).

The expected cost function for maize (C^e) can be written as

$$C^e = \left[a \left(\frac{p_M}{M} \right)^{1-s} + (1-a) \left(\frac{1}{A^e} \right) p_B{}^{1-s} \right]^{1/(1-s)} Y^e, \tag{1}$$

where a is a distributive share parameter, s is an elasticity of substitution, p_M is the shadow price of the composite mechanical input, M is the level of mechanical productivity (which increases over time due to technical change), p_B is the shadow price of the biological input (a composite of fertilizer and land), A^e is the expected level of climate productivity, and Y^e is planned output. The shadow price of the biological input is:

$$p_B = \left[b \left(\frac{p_N}{B_N} \right)^{1-b} + (1-b) \left(\frac{p_L}{B_L} \right)^{1-b} \right]^{1/(1-b)}, \tag{2}$$

where b is a distributive share parameter, b is an elasticity of substitution, p_N is the price of nitrogen fertilizer, B_N is the level of fertilizer productivity (which increases over time due to technical change), p_L is the price of land, and B_L is the level of land productivity (which also increases over time due to technical change).

We assume that the shadow price of the composite mechanical input (p_M), which is determined the prices of capital and labor, is exogenous. This is a reasonable assumption given that maize accounts for a negligible fraction of the Chesapeake Bay region's total demand for capital and labor. For similar reasons, we assume that the price of nitrogen fertilizer (p_N) and input productivity levels are exogenous. We also assume that the output price (p) is exogenous, which is reasonable because maize production within the region is a negligible fraction of U.S. and global maize production.

Maize output market equilibrium requires that the exogenous output price (p) equal expected marginal cost, which is equal to average cost because there are constant returns to scale:

$$p = \partial C^e / \partial Y^e = C^e / Y^e \ . \tag{3}$$

Because the output price is exogenous and all input prices are exogenous except the price of land, equation (3) can be used to obtain a solution for p_L.

The supply of land to maize production (L^s) is:

$$L^s = g_0 p_L^g \ , \tag{4}$$

where g_0 is a constant scaling factor and g is the elasticity of land supply. Land market equilibrium requires land supply equal land demand. Given the solution obtained above for p_L, the land supply equation (4) gives a solution for the amount of land in maize.

The derived demands for land (L) and nitrogen (N) are:

$$L = \partial C^e / \partial p_L \ , \tag{5}$$

$$N = \partial C^e / \partial p_N \ . \tag{6}$$

Given the solutions obtained above for p_L and L^d, the land demand equation (5) gives a solution for planned output (Y^e). These solutions can then be inserted into the nitrogen demand equation (6) to find the amount of nitrogen applied to maize.

The climate productivity equation (A^*) is assumed to be constant-elasticity:

$$A^* = f_0 (CO_2)^f \prod_i \left(\overline{Z_i}\right)^{a_i} \prod_i \left(Z_i / \overline{Z_i}\right)^{e_i} \prod_i \left(\overline{T_i}\right)^{m_i} \prod_i \left(T_i / \overline{T_i}\right)^{d_i} , \tag{7}$$

where f_0 is a constant scaling factor, CO_2 is the level of atmospheric carbon dioxide (known in advance to both farmers and policy makers), $\overline{Z_i}$ is the mean level of precipitation in time period i (i = 1 for April-June, 2 for July-September, 3 for October-January, and 4 for February-March), Z_i is the actual realized level of precipitation in time period i, $\overline{T_i}$ is the mean temperature in time period i, and T_i is the actual realized temperature in time period i. The parameters f, a_i, e_i, m_i, and d_i are all elasticities.

With this formulation, changes in climatic means have different effects on productivity than deviations from climatic means. This is intuitively reasonable because farmers, public- and private-sector agricultural R&D organizations, and others in the food and agricultural system can, given time, adjust to changes in climatic means in a way that they cannot adjust to short-term climatic shocks.

We scale climate productivity so that it lies between zero and one. Given this, it can also be interpreted as uptake of nitrogen by maize crops. To ensure that it lies between zero and one regardless of the realized values of the climatic variables, we use a climatic productivity variable (A) bounded between 0.01 and 0.99:

$$A = \begin{cases} 0.01, \ A^* < 0.01 \\ A^*, \ 0.01 \le A^* \le 0.99 \\ 0.99, \ A^* > 0.99 \end{cases} . \tag{8}$$

As it turns out, however, A^* almost always lies between 0.01 and 0.99 in the simulation results we report below. The expected level of climate productivity (A^e), which is used in the expected cost function (1), is simply the expected value of A^*, subject to the same upper and lower bounds as in equation (8).

Using the farmer decisions predicted by the economic module outlined above, the watershed module predicts nitrogen loadings from maize production within each of the six watersheds we examine here. The environmental module is based on the Generalized Watershed Loading Functions (GWLF) model (Haith et al., 1992). GWLF uses precipitation and temperature data, combined with data on land use, topography, and soil types, to estimate water runoff and pollutant concentrations flowing into streams from several types of land use, including maize. GWLF predicts both nitrogen and phosphorous loadings. However, we found that phosphorous loadings from maize production were very highly correlated with nitrogen loadings from maize production in each watershed. Thus, we focus here on nitrogen loadings.

Nitrogen concentration in runoff (R_i), measured in mass per unit volume of water, in time period time period i , i = 1, 2, or 3, is modeled as

$$R_i = \frac{q_i (1 - A) N}{Z_i}, \tag{9}$$

where q_i is a constant scaling factor. This formulation presumes that nitrogen fertilizer is applied in time periods 1 and 2 and runs off/leaches in time periods 1, 2, and 3 (April-June, July-September, and October-January, respectively). Total nitrogen loadings from maize production (G) are modeled as

$$G = j\ L \sum_{i=1}^{3} R_i Z_i^2\ , \tag{10}$$

where j is another constant scaling factor.

Values for the model's economic parameters and initial values for economic variables in the model are based on prior reviews of the literature by us (Abler and Shortle, 1995, 1996, 1997) and on state-, county-, and watershed-level data on farm production, land use, nutrient applications, and usage of other inputs. For the parameters in the climate productivity equation (7), we ran time-series regressions for maize yields in the state of Pennsylvania and cross-sectional regressions across U.S. states on maize yields. The results are not reported here for sake of conserving space. We also relied on regression results in Teigen and Thomas (1995) and on maize simulation modeling results in Izaurralde et al. (1999). Values for the model's watershed/water quality parameters were based on the GWLF model, which was calibrated to field conditions in the six watersheds by Chang et al. (2000).

4. Climate/Baseline Scenarios

We consider three climate scenarios in the model. The first is present-day climate (temperature and precipitation averages for the 1965-1994 period), which serves to establish a reference point. The second climate scenario is based on projections from the Hadley climate model for the 2025-2034 period. The Hadley model suggests increases in average daily minimum and maximum temperatures and increases in average annual precipitation (Yarnal 2000). The third climate scenario is based on projections from the Canadian Climate Centre (CCC) model for the 2025-2034 period. The CCC model suggests a much warmer and drier climate than the Hadley model (Yarnal 2000).

In the simulation model, the weather is random in the sense that farmers do not know what temperature and precipitation during the growing season will turn out to be. They must therefore make planting and production decisions on the basis of expected temperature and precipitation patterns (see equation (1)). However, farmers in the model are aware of climate change in the sense that they know how average temperature and precipitation patterns are evolving over time in their area. Because the weather is random in the model, the climate scenarios involve changes in the means and variances of the model's temperature and precipitation variables. These variables are assumed to be lognormally distributed.

We also consider two future baseline scenarios in the model. These scenarios describe what might happen to maize production in the Chesapeake Bay region between now and the 2025-2034 period independent of climate change. Shortle et al. (1999) discuss procedures to use in constructing future baseline scenarios. These procedures do not attempt to predict the future, which is essentially impossible. Instead, they focus on developing scenarios that establish probable upper and lower bounds on economic and environmental impacts. In this way, while one cannot pinpoint the exact magnitude of an impact, one can say that the impact is likely to lie within a certain interval.

With an eye toward establishing probable upper and lower bounds on changes in nitrogen loadings from maize production in the Chesapeake Bay region between now and the 2025-2034 period, we consider two future baseline scenarios. These two scenarios—a continuation of the status quo (SQ) and an "environmentally friendly," smaller agriculture (EFS)—are described in general terms in Table 3. The EFS scenario is motivated by a number of developments likely to occur in Chesapeake Bay region agriculture, including rapid improvements in biotechnology, widespread adoption of precision agriculture (which uses remote-sensing and information technologies in order to achieve very precise control over agricultural input applications), continued declines in real prices of farm commodities, continued conversion of agricultural land to urban uses, and more stringent environmental regulations facing agriculture, which would work to increase nitrogen costs to farmers (Abler and Shortle, 2000). Biotechnology and precision agriculture could both significantly increase agricultural productivity, as well as decrease the sensitivity of the region's agriculture to climatic variations (Abler and Shortle, 2000).

Table 4 provides details on differences in the model's parameters between the SQ and EFS scenarios. Levels of mechanical productivity (M) and fertilizer productivity (B_N) are 60% greater in the EFS scenario than in the SQ scenario, while the level of land productivity (B_L) is 80% greater. Leaving aside changes in weather and atmospheric CO_2 levels, the level of climate productivity (f_0) is 20% greater in the EFS scenario than in the SQ scenario. The share of fertilizer in the biological production function (b) in the EFS scenario is only one-half of its share in the SQ scenario, reflecting a shift toward more "environmentally friendly" production techniques. The output price (p) in the EFS scenario is about two-thirds of its value in the SQ scenario, reflecting continued declines in global real agricultural commodity prices. The fertilizer price (p_N) is 20% greater in the EFS scenario than in the SQ scenario, reflecting the impacts of stricter environmental regulations on nitrogen costs to farmers. Several elasticities in the climate productivity equation (7) are lower in absolute value in the EFS scenario than in the SQ scenario, reflecting a decrease in climate sensitivity on the part of the region's agriculture. The intercept in the land supply equation (g_0) is 40% less in the EFS scenario than in the SQ scenario, reflecting continued conversion of agricultural land to urban uses.

The EFS scenario is much more probable than any scenario approximating a continuation of the status quo, but both scenarios are needed to establish probable bounds on climate change impacts. The EFS scenario establishes a lower bound on any increase in nitrogen loadings due to climate change because biotechnology and precision agriculture help minimize loadings from any given level of agricultural production. In addition, stricter environmental regulations in the EFS scenario lead farmers to adopt less nitrogen-intensive maize production practices. None of these things occur in the SQ scenario, and so the SQ scenario establishes an upper bound on increases in nitrogen loadings due to climate change.

With three climate scenarios and two future baseline scenarios, there are a total of six ($3\times2 = 6$) scenario combinations to be analyzed. Because the weather is random, we analyzed each combination using a Monte Carlo experiment in which we took 100,000 random samples of the model's temperature and precipitation variables. Each of these random samples can be considered an alternative possible growing season within a particular climate scenario. The results below represent means and standard deviations over the 100,000 random samples.

5. Simulation Model Results

Results from the simulation model for total nitrogen loadings from maize production for each watershed and for the six watersheds as a whole are presented in Table 5. Results for nitrogen loadings per hectare are presented in Table 6, again for each watershed and for the six watersheds as a whole. Results for other variables in the model for the six watersheds as a whole are presented in Table 7.

The results for the SQ baseline scenario suggest that climate change could lead to significant increases in nitrogen loadings from maize production, both in total and on a per hectare basis. For the six watersheds as a whole, mean nitrogen loadings are more than 1500 metric tons higher in the Hadley climate scenario than with the present-day climate, an increase of about one-third (33%). In the CCC climate model scenario, mean nitrogen loadings for the six watersheds as a whole are nearly one thousand metric tons higher than with the present-day climate, an increase of about one-fifth (19%). On a per hectare basis, mean loadings for all six watersheds as a whole are more than one-fifth (23%) greater in the Hadley climate scenario than under the present-day climate. In the CCC climate scenario, mean loadings per hectare are about one-tenth (11%) greater than under the present-day climate.

The results for the EFS baseline scenario, on the other hand, suggest that climate change would lead to far more modest increases in nitrogen loadings from maize production. For the six watersheds as a whole, mean nitrogen loadings are about 200 metric tons higher in the Hadley climate model scenario than with the present-day climate, an increase of about one-fifth (19%). In the CCC climate model scenario, mean nitrogen loadings for the six watersheds as a whole are only about 90 metric tons higher than with the present-day climate, an increase of only about 9%. On a per hectare basis, mean loadings for all six watersheds as a whole are about one-eighth (13%) greater in the Hadley climate scenario than under the present-day climate. In the CCC climate scenario, mean loadings per hectare are only about 3% greater than under the present-day climate.

The results for the SQ and EFS baseline scenarios differ significantly in magnitude in part because the EFS scenario starts from a much lower level than the SQ scenario. Under the present-day climate, mean total loadings for the six watersheds as a whole are only about 1000 metric tons in the EFS scenario, compared to over 4700 metric tons in the SQ scenario. There are many forces at work that cause nitrogen applications and environmental impacts to be much lower in the EFS scenario than in the SQ scenario. As noted above, biotechnology and precision agriculture help minimize loadings from any given level of agricultural production. In addition, stricter environmental regulations in the EFS scenario lead farmers to adopt less nitrogen-intensive maize production practices. The results for the SQ and EFS scenarios also differ because agriculture is less climate-sensitive in the EFS scenario than in the SQ scenario.

Both the SQ and EFS baseline scenarios are in agreement, however, regarding the direction of change in nitrogen loadings from maize production. In both scenarios, climate change leads to increases in loadings. In percentage terms, the mean increase in total loadings for the six watersheds as a whole ranges from 9% (EFS scenario/CCC climate model) to 33% (SQ scenario/Hadley climate model). The mean increase in loadings per hectare for the six watersheds as a whole ranges from 3% (EFS scenario/CCC climate model) to 23% (SQ scenario/Hadley climate model).

The reason why loadings increase is that climate change makes maize production in the six watersheds more economically attractive, largely because of carbon dioxide accumulation. Elevated levels of atmospheric CO_2 can lead to an increase in photosynthesis and thus crop yields, a phenomenon known as the CO_2 fertilization effect. Elevated levels of CO_2 can also lead to a decrease in transpiration (evaporation from plant foliage), which reduces water stress during periods with little or no rainfall (Rosenzweig and Hillel, 1998). As maize production becomes economically more attractive, farmers devote more land to maize and increase their use of inputs per hectare in order to raise yields. In the SQ baseline scenario, land use increases by about 7% in both the Hadley and CCC climate scenarios, while nitrogen applications per hectare increase by more than 20% (see Table 7). In the EFS baseline scenario, land use increases by more than

10% in the Hadley and CCC climate scenarios, while nitrogen applications per hectare increase by more than 15%.

Elevated levels of CO_2 in and of themselves—forgetting for the moment about economic responses by farmers— increase the uptake of nitrogen by crops, leaving less nitrogen to run off into surface waters or leach into groundwater. However, economic responses by farmers to elevated levels of CO_2 overwhelm this "direct" impact, leading to greater nitrogen fertilizer usage and thus greater nitrogen loadings. In the Hadley climate model scenarios, nitrogen loadings also increase because mean precipitation during the growing season increases, washing more nutrients into streams, rivers, and groundwater. In the CCC climate model scenarios, on the other hand, mean precipitation during the growing season falls. Nevertheless, because of the way that farmers respond to elevated levels of CO_2, nitrogen loadings from maize production still increase in the CCC climate model scenarios.

6. Conclusions

Four main conclusions emerge from our results. First, economic responses by farmers to climate change do matter, in the sense that they have major impacts on environmental externalities due to climate change. As our results indicate, assuming that farmers do not respond to changes in temperature, precipitation, and particularly atmospheric CO_2 levels could lead to mistaken conclusions about the magnitudes and even the directions of environmental impacts.

Second, environmental impacts are highly dependent on the climate and future baseline scenarios used. Our simulation results indicate that changes in nitrogen loadings from maize production in the Chesapeake Bay region differ significantly depending on whether we use projections from the Hadley climate model or the Canadian Climate Centre (CCC) model. Our results also indicate that changes in nitrogen loadings differ significantly depending on whether we use our status quo (SQ) baseline scenario or our environmentally friendly, smaller agriculture (EFS) baseline scenario.

Third, environmental impacts are also highly dependent on the ability of maize to productively use higher atmospheric levels of carbon dioxide (CO_2). In and of itself, a higher level of CO_2 increases nitrogen uptake by maize plants, leaving less nitrogen to run off into surface waters or leach into groundwater. However, higher levels of CO_2 also make maize production in the Bay region economically more attractive. As maize production becomes more attractive, farmers devote more land to maize and increase their nitrogen applications per hectare in order to raise yields. As they do these things, nitrogen loadings increase.

Finally, additional research is needed on extreme weather events. Current climate models do not adequately represent extreme weather events such as floods or heavy downpours, which can wash large amounts of fertilizers, pesticides, and animal manure into surface waters. For this reason, we did not incorporate extreme weather events into our model. However, changes in extreme events could easily overwhelm the environmental effects of changes in average levels of precipitation or temperature as well as the effects of changing atmospheric CO_2 levels. Current trends for the Chesapeake Bay region suggest a change toward fewer extreme temperatures but more frequent severe thunderstorms and severe winter coastal storms (Yarnal, 2000). Whether these trends will continue is unclear.

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Table 1. Land Cover/Use in the Six Study Watersheds

Watershed	Land Area (1000 Hectares)			Percentage of Total Land Area	
	Total	All Agriculture	Maize	All Agriculture	Maize
Clearfield Creek	97	14	3	14%	3%
Conodoquinet	130	81	10	62%	7%
Juniata/ Raystown	185	62	16	34%	9%
Pequea Creek	40	28	3	71%	9%
Pine Creek	254	27	11	11%	4%
Spring Creek	18	9	5	49%	31%
All Six Watersheds	724	220	49	30%	7%

Note: Figures for the six watersheds may not add to the column totals shown in the last row or divide into the percentages in the right-most two columns because of rounding.

Table 2. Nonpoint Nitrogen Loadings in the Six Study Watersheds

Watershed	Nonpoint Inorganic Nitrogen Loadings (1000 Metric Tons)			Percentage of Total Nonpoint Nitrogen Loadings	
	Total	All Agriculture	Maize	All Agriculture	Maize
Clearfield Creek	0.93	0.84	0.66	90%	71%
Conodoquinet	2.31	2.28	1.32	98%	57%
Juniata/ Raystown	1.98	1.93	1.66	98%	84%
Pequea Creek	0.61	0.60	0.43	99%	70%
Pine Creek	0.74	0.60	0.44	81%	60%
Spring Creek	0.32	0.32	0.27	98%	83%
All Six Watersheds	6.89	6.57	4.78	95%	69%

Note: Figures for the six watersheds may not add to the column totals shown in the last row or divide into the percentages in the right-most two columns because of rounding.

Table 3. Baseline Agricultural Scenarios for the 2035-2034 Period

Scenario	Scenario Description
"Environmentally Friendly," Smaller Agriculture (EFS)	• Significant decrease in number of commercial maize farms in Chesapeake Bay region • Substantial increase in agricultural productivity due to biotechnology and precision agriculture • Major increase in maize production per farm and maize yields on remaining commercial farms • Significant decrease in agriculture's sensitivity to climate variability due to biotechnology and precision agriculture • Continued conversion of agricultural land to urban uses, with some abandonment of unprofitable agricultural land • Significant decrease in commercial fertilizer and pesticide usage due to biotechnology • Less runoff and leaching of agricultural nutrients and pesticides due to precision agriculture • Stricter environmental regulations facing agriculture
Status Quo (SQ)	Agriculture as it exists today in the Chesapeake Bay region

Table 4. Model Parameters: SQ versus EFS Scenarios

Model Parameter	Value in Status Quo (SQ) Scenario	Value in Environmentally Friendly, Smaller Agriculture (EFS) Scenario
Productivity Parameters		
Mechanical productivity (M)	1	1.6
Fertilizer productivity (B_N)	1	1.6
Land productivity (B_L)	1	1.8
Intercept in climate productivity equation (f_0)	0.5	0.6
Factor Proportions		
Fertilizer share in biological production function (b)	0.4	0.2
Output and Input Prices		
Output price (p)	1	0.65
Fertilizer price (p_N)	1	1.2
Climate Sensitivity Parameters		
Elasticity wrt deviation of precipitation from mean, period 1 (e_1)	0.2	0.1
Elasticity wrt deviation of precipitation from mean, period 2 (e_2)	0.3	0.2
Elasticity wrt mean temperature, period 2 (m_2)	-0.1	-0.05
Elasticity wrt deviation of temperature from mean, period 2 (d_2)	-2.5	-2
Land Supply		
Intercept in land supply equation (g_0)	0.15	0.09

Table 5. Nitrogen Loadings from Maize Production under Alternative Scenarios (1000 Metric Tons)

Watershed	Mean (Standard Deviation)					
	Status Quo (SQ)			Environmentally Friendly, Smaller Agriculture (EFS)		
	Present-Day Climate	Hadley Climate Model	CCC Climate Model	Present-Day Climate	Hadley Climate Model	CCC Climate Model
Clearfield Creek	0.65 (0.09)	0.87 (0.12)	0.78 (0.11)	0.14 (0.02)	0.17 (0.03)	0.15 (0.02)
Conodoquinet	1.30 (0.23)	1.74 (0.31)	1.56 (0.28)	0.29 (0.06)	0.34 (0.07)	0.31 (0.06)
Juniata/ Raystown	1.63 (0.30)	2.18 (0.40)	1.95 (0.36)	0.36 (0.07)	0.43 (0.09)	0.39 (0.08)
Pequea Creek	0.42 (0.08)	0.56 (0.11)	0.50 (0.09)	0.09 (0.02)	0.11 (0.02)	0.10 (0.02)
Pine Creek	0.44 (0.08)	0.58 (0.11)	0.52 (0.10)	0.10 (0.02)	0.11 (0.02)	0.10 (0.02)
Spring Creek	0.26 (0.05)	0.35 (0.07)	0.31 (0.06)	0.06 (0.01)	0.07 (0.01)	0.06 (0.01)
All Six Watersheds	4.71 (0.41)	6.28 (0.55)	5.62 (0.49)	1.03 (0.10)	1.23 (0.12)	1.12 (0.11)

Note: The figures shown for each scenario are means and standard deviations (in parentheses) across 100,000 random samples. Figures for the six watersheds may not add to the column totals shown in the last row because of rounding. Means for the status quo/ current climate scenario do not agree exactly with the figures in Table 2 (which are the population means) because the figures here are sample means.

Table 6. Nitrogen Loadings per Hectare from Maize Production under Alternative Scenarios (Kilograms per Hectare)

Watershed	Mean (Standard Deviation)					
	Status Quo (SQ)			Environmentally Friendly, Smaller Agriculture (EFS)		
	Present-Day Climate	Hadley Climate Model	CCC Climate Model	Present-Day Climate	Hadley Climate Model	CCC Climate Model
Clearfield Creek	202 (28)	248 (35)	225 (32)	65 (10)	72 (12)	66 (11)
Conodoquinet	136 (24)	167 (30)	151 (27)	44 (9)	49 (10)	45 (9)
Juniata/ Raystown	102 (19)	125 (23)	113 (21)	33 (7)	36 (8)	33 (7)
Pequea Creek	122 (22)	150 (28)	136 (25)	39 (8)	44 (9)	40 (8)
Pine Creek	40 (8)	49 (9)	44 (8)	13 (3)	14 (3)	13 (3)
Spring Creek	48 (9)	59 (11)	54 (10)	15 (3)	17 (4)	16 (3)
All Six Watersheds	97 (8)	119 (10)	108 (9)	31 (3)	35 (3)	32 (3)

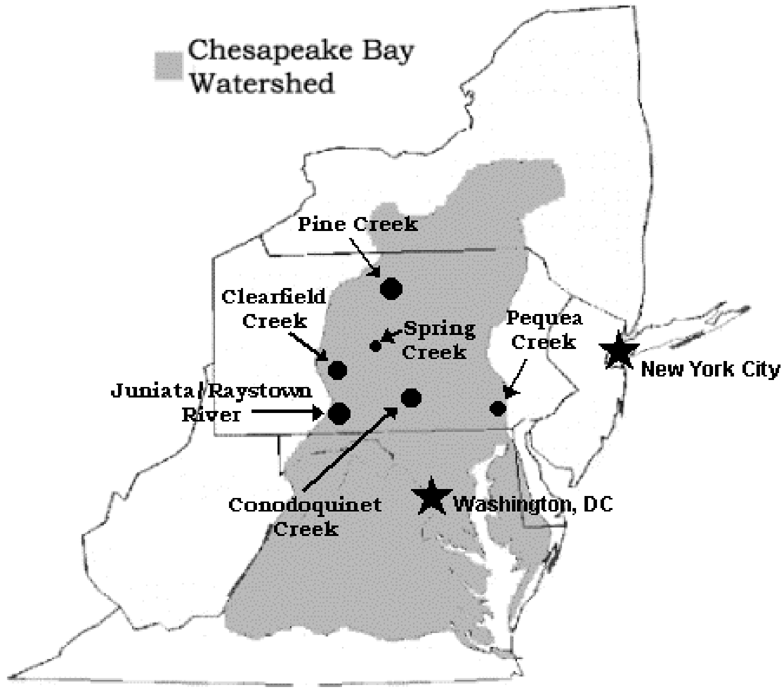
Note: The figures shown for each scenario are means and standard deviations (in parentheses) across 100,000 random samples.

Table 7. Results for Other Variables for All Six Watersheds as a Whole under Alternative Scenarios

Variable	Mean (Standard Deviation)					
	Status Quo (SQ)			Environmentally Friendly, Smaller Agriculture (EFS)		
	Present-Day Climate	Hadley Climate Model	CCC Climate Model	Present-Day Climate	Hadley Climate Model	CCC Climate Model
Production (thousands of metric tons)	293 (4)	388 (6)	368 (6)	334 (3)	410 (4)	397 (4)
Land Use* (thousands of hectares)	55 (0)	59 (0)	59 (0)	37 (0)	40 (0)	39 (0)
Maize Yield (kilograms per hectare)	5.4 (0.1)	6.5 (0.1)	6.3 (0.1)	9.0 (0.1)	10.3 (0.1)	10.1 (0.1)
Land Rent* (index, initially≡1)	1 (0)	1.19 (0)	1.15 (0)	1.30 (0)	1.48 (0)	1.45 (0)
Nitrogen Applications* (kilograms per hectare)	175 (0)	217 (0)	210 (0)	70 (0)	83 (0)	81 (0)
Time 1 Runoff Concentration (mg/liter)	12.0 (2.4)	12.4 (2.6)	13.7 (3.8)	3.8 (0.7)	3.6 (0.7)	4.0 (0.8)
Time 2 Runoff Concentration (mg/liter)	3.0 (0.6)	3.1 (0.6)	3.4 (0.7)	1.0 (0.2)	0.9 (0.2)	1.0 (0.2)
Time 3 Runoff Concentration (mg/liter)	3.0 (0.6)	3.1 (0.5)	3.4 (0.5)	1.0 (0.1)	0.9 (0.1)	1.0 (0.2)

Note: The figures shown for each scenario are means and standard deviations (in parentheses) for all six watersheds as a whole across 100,000 random samples. The variables marked with an asterisk (*) are nonstochastic because they are derived from decisions by farmers that are taken on the basis of expected temperature and precipitation.

Figure 1. Chesapeake Bay Region and Study Watersheds



Sources: Chesapeake Bay Program (1997) and Chang et al. (2000).

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