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Climate change and agriculture in the Mid-Atlantic Region

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ABSTRACT: Agriculture in the Mid-Atlantic Region, like agriculture worldwide, has an intrinsic relationship with climate. This article considers how climate change might affect future Mid-Atlantic agriculture. Our assessment differs from prior work in 2 important ways. First, prior assessments have for the most part examined the impacts of future climate change on present-day agriculture, neglecting the fact that agriculture is likely to change dramatically in the coming century independent of climate change. Second, previous assessments have focused almost exclusively on the impacts of climate change on agricultural production. Societal interest in agriculture, however, is much broader than production because agriculture is a source of both rural amenities and negative environmental impacts. Our assessment suggests that Mid-Atlantic crop and livestock production will probably not change significantly in either direction. There might be changes in the environmental impacts of agricultural production and land use, but we currently lack evidence on the magnitudes and even directions of these changes. Given that agriculture currently has significant negative impacts on water quality in many areas, including the Chesapeake Bay, this should be a high priority for research. In addition, research is needed to understand climate impacts on agriculture's contributions to wildlife habitat, rural landscape amenities and carbon sequestration.

KEY WORDS: Climate change · Agriculture · Mid-Atlantic · Environment · Adaptation

1. INTRODUCTION

Agriculture in the Mid-Atlantic Region (MAR), like agriculture worldwide, has an intrinsic relationship with climate. Increasing atmospheric concentrations of carbon dioxide and other greenhouse gases along with climate change in the MAR could lead to potentially significant changes in crop and livestock production. The objective of this article is to consider how climate change might affect future Mid-Atlantic agriculture, including impacts on Mid-Atlantic agriculture due to the effects of climate change on other regions and countries.

Several assessments and reviews of the potential impacts of climate change on US and world agriculture have been conducted in recent years (Darwin et al. 1995, IPCC 1996, Schimmelpfennig et al. 1996, Adams et al. 1998, 1999a, Rosenzweig & Hillel 1998, Lewandrowski & Schimmelpfennig 1999). Our assessment differs from prior work in 2 important ways. First, the previous assessments have for the most part examined the impacts of future climate change on present-day agriculture, neglecting the fact that agriculture is likely to change dramatically in the coming century independent of climate change. As discussed below, failing to consider potential changes in agriculture independent of climate change could give rise to misleading conclusions about climate change impacts. Some studies, such as Adams et al. (1999b), have considered hypothetical future baseline scenarios. However, the future baseline considered in Adams et al. (1999b) involved a simple extrapolation of past trends for some variables (e.g., yields, consumption, imports) and an assumption that past relationships between crop yields and other variables (e.g., use of crop inputs such as fertilizer, livestock feed use) would continue to hold in the future. At a regional level, we believe it is

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possible to do better using forward-looking baseline scenarios that take into account probable future developments within the region.

Second, previous assessments have focused almost exclusively on the impacts of climate change on agricultural production. Societal interest in agriculture, however, is much broader than production. As discussed below, agriculture is a source of rural amenities as well as negative environmental impacts, and it is important to also consider how these impacts might change as a result of climate change.

2. PRESENT-DAY MID-ATLANTIC AGRICULTURE

Compared to many other parts of the US, Mid-Atlantic agriculture is characterized by smaller farms and a wider range of crops and livestock products. Average farm size in the Mid-Atlantic is about 180 acres (~73 ha), compared with over 500 acres (~203 ha) for the rest of the US (US Department of Agriculture, National Agricultural Statistics Service 1999). However, poultry and hog operations within the region tend to be as large on average as those in other parts of the country. Average poultry sales per poultry farm and average hog sales per hog farm are about the same in the Mid-Atlantic as in the rest of the US (US Department of Agriculture, National Agricultural Statistics Service 1999).

The single largest source of cash receipts in most of Pennsylvania, upstate New York, and much of Maryland is dairy production. Mushrooms, other vegetables, and nursery products are important in New Jersey, parts of Maryland, and parts of eastern Pennsylvania. Chicken and eggs tend to dominate in the Delmarva Peninsula and in parts of Virginia and southern Pennsylvania. Significant production of apples, peaches, and other tree fruits occurs in certain areas of Maryland, New Jersey, Pennsylvania, and West Virginia. In western Virginia and West Virginia, cattle raising is the most important agricultural activity. Tobacco production tends to predominate in southern Virginia and northern North Carolina.

Due to historically adequate supplies of rainfall in most years, crop production in the MAR is overwhelmingly rainfed rather than irrigated. Less than 3% of crop acreage in the Mid-Atlantic is irrigated, compared with about 13% in the rest of the US (US Department of Agriculture, National Agricultural Statistics Service 1999).

Agriculture accounts for about one-fourth of total land area in the MAR. Hay and pastureland are the predominant uses of agricultural land, accounting for nearly three-fourths of total agricultural land in the MAR. The remainder, about one-fourth, is accounted for by cropland. Livestock and livestock products account for about 65% of total agricultural sales in the region, with the remaining 35% accounted for by crops. However, the relative economic importance of crops is larger as measured by the total value of production, which includes not only sales but also products consumed on the farm and not sold. Crops account for about three-fourths of the total value of agricultural production in the MAR, with livestock and livestock products accounting for about one-fourth. Including both full-time and part-time farmers, agriculture accounts for about 4% of the total labor force in the MAR. This proportion drops to less than 2% if one includes only those workers whose principal economic activity is farming.

Agriculture's importance in the MAR extends well beyond its role as a source of food, income, and employment. Agriculture is the second largest land use after forests and the dominant land use in some areas. Its presence defines many rural landscapes. Rural and urban populations within and outside the region value the region's agricultural and rural land as open space and as a source of countryside amenities. Fishing, boating, hunting, sightseeing, and other recreational activities are important in rural areas throughout the Mid-Atlantic. Agricultural land is an important habitat for some wildlife species within the region. Open space and countryside amenity values are reflected in public programs to protect farmland from development and preserve agricultural landscapes in all 8 states within the region (American Farmland Trust 1997). Programs in place within the region include agricultural protection zoning, differential property assessment, and conservation easements.

Agriculture in the Mid-Atlantic is also a source of negative environmental impacts, particularly water pollution from nutrients, eroded soils, and pesticides. Of 2105 watersheds (defined at the 8-digit hydrologic unit code level) in the 48 contiguous states, watersheds in southern New York, northern Pennsylvania, southeastern Pennsylvania, western Maryland, and western Virginia rank in the top 10% in terms of manure nitrogen runoff, manure nitrogen leaching, manure nitrogen loadings from confined livestock operations, and soil loss due to water erosion (Kellogg et al. 1997). Watersheds in southeastern Pennsylvania and along the southern Virginia/northern North Carolina coasts also rank in the top 10% in terms of nitrogen loadings from commercial fertilizer applications (Kellogg et al. 1997). Watersheds in the tobacco-growing areas of southern Virginia and northern North Carolina rank near the top as measured by potential threats to human drinking water supplies, fish, and other aquatic life from pesticide leaching and runoff (Kellogg et al. 1999).

Environmental impacts of agricultural production in the Mid-Atlantic are of concern for many reasons, but perhaps the most important is because of their impact on the Chesapeake Bay. The Chesapeake Bay is one of the nation's most valuable natural resources. It is a major source of seafood, particularly highly valued blue crab, menhaden, 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.

Human activity within the Chesapeake Bay watershed during the last 3 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 (e.g., wastewater), forests, urban areas, and atmospheric deposition.

3. IMPACT DOMAINS TO BE EXAMINED

The consensus of recent assessments and reviews of the potential impacts of climate change on US and world agriculture (Darwin et al. 1995, IPCC 1996, Schimmelpfennig et al. 1996, Adams et al. 1998, 1999a,b, Rosenzweig & Hillel 1998, Lewandrowski & Schimmelpfennig 1999) is that global climate change will probably not threaten global food supplies. Changes in global agricultural production of most agricultural commodities are likely to be small, although agricultural production could change significantly in some areas of the world. Agricultural commodity markets in the MAR are very well integrated into national and global agricultural commodity markets. Even if agricultural production in the region fell significantly, food demand within the region could be satisfied by imports from other regions and countries.

For these reasons, barring a global food supply catastrophe, climate change impacts on consumers of agricultural products within the MAR are likely to be minimal. We therefore exclude consumer impacts from the impact domains that we examine here. We instead focus on agricultural production within the region and on the environmental impacts of agricultural production. The scope of potential agricultural environmental impacts includes air and water quality, carbon sequestration, wildlife habitat, and landscape amenities. Among these impacts, we focus on water quality because it is the most pressing environmental concern associated with agriculture in the MAR.

4. FUTURE AGRICULTURAL BASELINE SCENARIOS

Mid-Atlantic agriculture, like US agriculture as a whole, has changed radically during the last century. With the notable exception of the Amish, tractors and other farm machinery have virtually eliminated the use of draft animals and have made it possible for a single farmer to cultivate tracts of land orders of magnitude larger than a century ago. The introduction of synthetic organic pesticides in the 1940s revolutionized the control of weeds and insects. Similarly, there has been tremendous growth in the use of manufactured fertilizers and hybrid seeds. Farmers have become highly specialized in the livestock products and crops they produce, and they have become much more dependent on purchased inputs. Crops that were virtually unheard of 100 yr ago, such as soybeans, are of major importance today. As agricultural productivity has risen, and as real (inflation-adjusted) prices of farm commodities have fallen, substantial acreage in the MAR has been taken out of agriculture and either returned to forest or converted to urban uses.

There are few reasons to expect this rapid pace of change to slow down during the coming century. The basic science of biotechnology is progressing very rapidly, and already tens of millions of crop acres in the US have been planted with genetically modified organisms (GMOs). Plant biotechnology has the potential to yield crops with significantly greater resistance to a whole host of pests, greater resilience during periods of temperature and precipitation extremes, and even cereal varieties that fix atmospheric nitrogen in the same manner as legumes (Huttner 1996, Plucknett & Winkelmann 1996). Work is also underway to engineer pest vectors into beneficial insects as part of integrated pest management (IPM) strategies. However, GMOs with tolerance to specific herbicides are also being developed and released, and concerns have been raised that these may promote herbicide usage (Rifkin 1998).

Animal biotechnology has the potential to yield livestock that process feed more efficiently, leading to reduced feeding requirements and fewer nutrients in animal wastes. Feed may also be genetically modified so as to reduce nutrients in livestock wastes. Genetically engineered vaccines and drugs could significantly reduce livestock mortality and increase yields.

Another development already underway is precision agriculture, which uses remote-sensing, computer, and information technologies in order to achieve very precise control over agricultural input applications (chemicals, fertilizers, seeds, etc.). Precision agriculture has the potential to significantly increase agricultural productivity by giving farmers much greater control over microclimates and within-field variations in soil conditions, nutrients, and pest populations (National Research Council 1997). This may be accompanied by significant improvements in computer-based expert systems to aid farmers with production decision-making (Plucknett & Winkelmann 1996). The environment could also benefit insofar as precision agriculture permits fertilizers and pesticides to be applied more precisely where they are needed at the times of the year when they are needed.

Future improvements in computer technology and in modeling smaller scale climatic processes such as thunderstorms can be expected to lead to improved weather forecasts (Tribbia 1997). Improved forecasts may lead farmers to make better choices about what crops to plant, when to plant and harvest, when to protect temperature-sensitive crops such as tree fruits, when to fertilize, and other farm management decisions (Johnson & Holt 1997, Mjelde et al. 1998). This can be expected to increase agricultural productivity.

At the same time, economic conditions facing agriculture in the MAR can be expected to continue changing for many other reasons, including changes in global agricultural commodity prices and continuing regional pressures to convert agricultural land to urban uses. Analyses by the International Food Policy Research Institute (Islam 1995), the US Department of Agriculture, Interagency Agricultural Projections Committee (1999), and Crosson & Anderson (1992) suggest that real prices for major agricultural commodities such as wheat, corn, other grains, soybeans, dairy products, beef, pork, chicken, and eggs are all likely to decline in coming decades, perhaps significantly. Others, such as Tweeten (1998) and Brown (1996), suggest that real prices of agricultural commodities could increase over the next few decades. However, as Johnson (1998) emphasizes, projections of rising agricultural prices have consistently been wrong in the past.

Future increases in population in the MAR may lead to additional conversion of farmland to residential and commercial uses. Future increases in per capita income could manifest themselves in larger homes and lot sizes, and thus more residential land use, a tendency evident over the last 30 to 40 yr. Studies of land use confirm that population and per capita income are important determinants of the conversion of farmland and forestland to urban uses (Hardie & Parks 1997, Bradshaw & Muller 1998). Probable futures for the spatial pattern of development within the MAR are more difficult to assess than an overall tendency toward urbanization. One possible future involves a 'fill in' of areas between existing major urban centers, such as the area between Baltimore and Washington, DC (Bockstael & Bell 1998).

For these reasons, it is probable that there will be significantly fewer commercial crop and livestock farms within the region in the future than there are today, and that a lot of the agricultural production will shift to other regions and countries. It is also probable that production per farm on the remaining farms within the MAR will be significantly higher than it is today, at least on commercial farms where agriculture is the farm operator's principal occupation. There may be growth in 'weekend', 'hobby', and other noncommercial farms within the region. However, such farms account for only a small fraction of total agricultural output. Noncommercial farms (defined as those with less than \$50 000 in sales) accounted for only 8% of total farm sales in the MAR in 1997 (US Department of Agriculture, National Agricultural Statistics Service 1999).

The MAR and national US climate change assessments focus on 2 future time periods, the 'near' future (signified by the year 2030) and the 'deep' future (signified by the year 2100). Our focus here is limited to the year 2030. For the year 2100, the uncertainties are so overwhelming that it is very difficult to think about baseline agricultural scenarios. To illustrate this point, it would have been exceedingly difficult if not impossible for someone in 1900 to foresee the dramatic changes that would occur in MAR agriculture during the 20th century. It is probable that MAR agriculture in 2100 will bear only a faint resemblance to the region's agriculture today, but it is not possible to say with any confidence what the major changes between now and then might be.

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 the impact domains of interest, analogous to confidence intervals on impacts. With an eye toward establishing probable upper and lower bounds on potential climate change impacts on MAR agriculture in the year 2030, we consider 2 baseline scenarios. These 2 scenarios, a continuation of the status quo (SQ) and a smaller, more 'environmentally friendly' agriculture (SEF), are detailed in Table 1. The SEF 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.

Table 1. Baseline agricultural scenarios for the MAR in the year 2030

Scenario	Scenario details
Smaller, more ‘environmentally friendly’ agriculture (SEF)	• Significant decrease in number of commercial farms in region • Substantial increase in agricultural productivity due to biotechnology and precision agriculture • Major increase in agricultural production per farm on the remaining farms • Significant decrease in agriculture’s sensitivity to climate variability due to biotechnology, precision agriculture, and improved climate forecasts • Some conversion of agricultural land to urban uses, with conversion slowed by farmland protection programs • Some reforestation of existing, economically marginal agricultural lands • 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, especially intensive livestock operations
Status quo (SQ)	• Agriculture as it exists today in the MAR

Table 2. Upper and lower bounds established by the 2 agricultural baseline scenarios. SQ = Status quo scenario; SEF = Smaller, more ‘environmentally friendly’ scenario

	Negative impacts on production	Positive impacts on production	Negative environmental impacts	Positive environmental impacts
Upper bound	SQ	SEF	SQ	SQ
Lower bound	SEF	SQ	SEF	SEF

The upper and lower bound established by each scenario are listed in Table 2. The SQ scenario establishes an upper bound on negative climate change impacts on production simply because agriculture is much larger in the SQ scenario than in the SEF scenario. The SEF scenario establishes an upper bound on positive climate change impacts on production because, even though agriculture is smaller than in the SQ scenario, it is much better equipped to take advantage of positive climate developments. The SQ scenario establishes upper bounds on positive and negative environmental impacts because agriculture in this scenario is larger than in the SEF scenario. In addition, biotechnology and precision agriculture in the SEF scenario that are unavailable in the SQ scenario help minimize negative environmental impacts from any given level of agricultural production.

Using the SQ scenario alone (i.e., imposing future climate change on present-day agriculture) instead of using both scenarios could be misleading. The SQ scenario represents an extreme future, not a probable or likely future. Using the SQ scenario alone would lead to overestimation of negative impacts of climate change on production as well as overestimation of positive and negative environmental impacts. It would also lead to underestimation of positive impacts on production.

5. CLIMATE CHANGE AND MAR AGRICULTURE

This section assesses potential climate impacts on agricultural production in the MAR and on environmental impacts of agricultural production in the year 2030. For the year 2100, the same overwhelming uncertainties that make it impossible to construct baseline scenarios also make it impossible for us to assess potential climate change impacts on agricultural production or agriculture’s environmental impacts.

5.1. Impacts on agricultural production

Carbon dioxide (CO_2) accumulation and climate change within the MAR may have a number of direct and indirect effects on the region’s agriculture (Adams et al. 1999a). Elevated levels of CO_2 may lead to an increase in photosynthesis and thus crop yields, a phenomenon known as the CO_2 fertilization effect. CO_2 is an indispensable component in the process of photosynthesis. The balance of evidence to date suggests that higher atmospheric concentrations of CO_2, holding constant other climatic factors affecting crop yields, could lead to significant increases in yields (Rosenzweig & Hillel 1998). Elevated levels of CO_2 may also lead to a decrease in transpiration (evaporation from plant foliage), which would reduce water stress during periods with little or no rainfall (Rosenzweig & Hillel 1998).

Climate projections for the MAR differ significantly according to the climate model used. Projections using the Hadley and GENESIS models suggest increases in average daily minimum and maximum temperatures for most of the MAR and increases in average annual precipitation (Polsky et al. 2000, in this issue). However, projections using the Canadian Climate Centre (CCC) model suggest a much warmer and drier climate than the Hadley or GENESIS models (Polsky et al. 2000).

Table 3 presents estimates from Izaurralde et al. (1999) of percentage changes in crop yields due to CO_2 fertilization effects and climate change (using Hadley climate model results) for unirrigated corn, soybeans, and unirrigated alfalfa in 3 regions of the US, the Northeast, Appalachian, and Corn Belt regions. The Northeast and Appalachian regions overlap the MAR, while the Corn Belt is shown because estimates for alfalfa are not available from Izaurralde et al. (1999) for the Northeast or Appalachian regions. The estimates suggest that CO_2 fertilization impacts on yields may be significant, while impacts of climate change on yields may be mixed. Other analyses (e.g., Rosenzweig et al. 1993) also suggest that CO_2 fertilization impacts on yields may be large, including impacts on crops important to the MAR such as soybeans and tobacco.

Beyond these direct effects, climate change may have indirect effects on MAR agriculture (Schimmelpfennig et al. 1996, Adams et al. 1999a). Climate change in other regions and countries may affect agricultural production in those areas. As national and global agricultural commodity markets adjust to these changes in production, commodity prices facing MAR farmers could change. Climate change may also have impacts on nonagricultural sectors of the MAR economy or economies of other regions and countries. These changes, which we refer to as economy-wide effects, might manifest themselves as changes in prices of purchased inputs used by MAR farmers, in competing demands for land within the region, or alternative employment opportunities available to MAR farmers.

Table 4 presents estimates from Tsigas et al. (1997) of the impacts of climate change on prices of agricultural commodities and inputs into agricultural production, both with and without CO_2 fertilization effects. In general, many impacts on prices are large without CO_2 fertilization effects, but price changes become small to moderate once these impacts are taken into account. Other economic analyses (e.g., Reilly et al. 1994, Dar-

Table 3. Percentage changes in regional crop yields as estimated by Izaurralde et al. (1999). *Change statistically significant at the 10% level

Crop	50% increase in CO_2 (365 to 560 ppm)			Change from 1961–90 climate to 2025–34 climate		
	Northeast	Appalachian	Corn Belt	Northeast	Appalachian	Corn Belt
Unirrigated corn	10.5*	11.1*	9.0*	14.3*	–1.7	5.6*
Soybeans	18.6*	18.5*	17.0*	4.6	–7.0	–7.4*
Unirrigated alfalfa	–	–	19.2*	–	–	14.4*

Table 4. Percentage changes in US agricultural commodity and input prices as estimated by Tsigas et al. (1997)

Commodity or input	With CO_2 fertilization effect	Without CO_2 fertilization effect
Commodity		
Wheat	1.6	33.0
Other grains	19.9	31.5
Non-grain crops	–13.4	27.5
Livestock	3.9	12.0
Input into production		
Land	–1.3	61.0
Labor	0.1	0.3
Capital	0.1	0.5

win 1995) also find that changes in agricultural commodity prices are likely to be moderate.

Evidence of the potential impacts of climate change on weeds and on crop and livestock pests and diseases is much more limited. CO_2 fertilization effects may increase growth of many weed species (Rosenzweig & Hillel 1998). Warming can be expected to lead to a northern expansion of tropical and other warm-season weeds, plant parasitic nematodes, and insects, presenting MAR agriculture with a different set of pest challenges than it faces today (Main 1999). In the case of the European corn borer, warming can be expected to lead to an increase in the number of generations completed each year and an increase in the average population level (Calvin 1999). However, MAR agriculture is more diverse in terms of growing conditions and the types of crops and livestock produced than agriculture in many other parts of the US or other countries, which should render it less vulnerable to devastating macro-scale disease or pest epidemics (Main 1999).

In general, livestock production tends to be less climate-sensitive than crop production. For outdoor livestock production, heat waves can lead to increased livestock mortality, lower livestock yields, and lower reproductive capacity (Klinedinst et al. 1993). However, increases in summer temperatures projected for the region (Polsky et al. 2000) will probably not be large enough to be a major detriment to livestock production. Furthermore, much livestock production in the MAR, especially poultry production, occurs indoors under controlled climatic conditions. Producers in these settings have several low-cost options for adapting to higher temperatures, including fans and improved ventilation. Climate change can also affect livestock production through changes in the quality and availability of forage, or through changes in prices of purchased feeds. However, because of CO_2 fertilization effects, forage yields could increase (Izaurralde et al. 1999). Estimates of changes in agricultural prices discussed above suggest that changes in prices of purchased feeds are likely to be modest.

The studies cited above all impose future climate change on present-day agriculture, which is tantamount to using our SQ future baseline scenario. In order to impose bounds on the potential climate change impacts, it is also necessary to consider the SEF future baseline scenario. In the SEF scenario, a number of factors operate to place a lower bound on any negative impacts on agricultural production. First, plant biotechnology leads to crops that have significantly greater pest resistance and greater resilience during periods of temperature and precipitation extremes. Biotechnology also leads to the engineering of pest vectors into beneficial insects as part of IPM strategies. Second, precision agriculture gives farmers much greater control over microclimates and within-field variations in soil conditions, nutrients, and pest populations. Third, improved forecasts permit farmers to make better choices about what crops to plant, when to plant and harvest, when to protect temperature-sensitive crops such as tree fruits, when to fertilize, and other farm management decisions. Finally, the number of commercial farms and agricultural land used in the MAR is significantly smaller in the SEF scenario than in the SQ scenario.

5.2. Agriculture's environmental impacts

The potential effects of climate change on the environmental impacts of agricultural production in the MAR are very difficult to assess. In part this is because we are unsure about how climate might change within the region (Polsky et al. 2000). Projections of changes in streamflow in the MAR vary significantly from one climate model to another because of differences between models in precipitation and temperature projections (Neff et al. 2000, in this issue). Furthermore, 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. Extreme precipitation events have increased significantly in the MAR in the 20th century (Polsky et al. 2000). Whether climate change will lead to an additional increase in the frequency or severity of extreme events is unclear.

Environmental impacts are also difficult to assess because of a lack of research on climate change, agriculture, and the environment. Only a small number of studies have been directed at impacts of climate change on agricultural runoff (Izaurralde et al. 1999), leaching on agricultural soils (Follett 1995), and soil erosion (Phillips et al. 1993, Favis-Mortlock & Savabi 1996, Williams et al. 1996).

To the extent that elevated atmospheric CO_2 levels lead to increased photosynthesis and reduced transpiration, nutrient leaching and runoff from crop production could decline because higher-yielding plants tend to take up more nutrients, leaving fewer nutrients to run off or leach. On the other hand, to the extent that precipitation in the MAR increased, more excess nutrients from crop production could be washed into surface waters or groundwater before plants are able to take them up. An increase in precipitation might also wash more pesticides and animal manure into surface waters or groundwater, and might wash more eroded soils into surface waters. Estimates shown in Table 5 of changes in runoff per hectare of unirrigated corn in the

Table 5. Percentage changes in runoff per hectare of unirrigated corn as estimated by Izaurralde et al. (1999)

Scenario	Northeast	Appalachian
50% increase in CO_2 (365 to 560 ppm)	0.9	1.7
Change from 1961–90 climate to 2025–34 climate	–4.3	–16.6

Northeast and Appalachian regions (which overlap the MAR) from Izaurralde et al. (1999) using the Hadley climate model suggest that increasing atmospheric concentrations of CO_2 might have minimal impacts on runoff, while changes in climate might reduce runoff.

An additional factor limiting our ability to assess environmental impacts is that studies to date have not been designed to consider economic responses by farmers to climate change. Instead, they have implicitly assumed that farmers would continue to produce the same crops and livestock on the same land using the same management practices with the same technologies available to them today. If climate change led to an increase in soil erosion, farmers would have an incentive to take additional steps to counteract erosion in order to preserve the productivity of their own soils. These steps might involve planting less erodible crops, changing management practices for existing crops, or even removing some highly erodible cropland from production. Similarly, if climate change led to an increase in runoff or leaching of crop nutrients or pesticides, farmers would have an incentive to take counteractive measures. From a farmer's perspective, nutrients or pesticides that do not reach their target represent lost income. However, farmers would only take counteractive measures to the extent that they themselves expected to benefit in some way. They might or might not take all counteractive measures that would be desirable from the point of view of society as a whole.

Whether changes in nutrient leaching and runoff, pesticide leaching and runoff, and soil erosion will be large or small depends in part on what agriculture in the MAR will be like in the future. In the SEF scenario, where agriculture is significantly smaller than it is today, there may be fewer nutrients and pesticides to leach or run off simply because there is less agriculture. In addition, biotechnology and precision agriculture in the SEF scenario lead to livestock wastes with lower nutrient contents and more 'environmentally friendly' crop and tree fruit farms that use significantly fewer commercial fertilizers and pesticides. Alternatively, under the SQ scenario, where agriculture does not shrink significantly and does not become more environmentally friendly, water quality impacts could be significant.

6. CONCLUSIONS

In their review of the literature on climate change and US agriculture, Lewandrowski & Schimmelpfennig (1999) conclude that costly adaptation strategies are not warranted on the basis of available evidence. Our assessment for the MAR leads to the same conclusion. The impacts of climate change on MAR crop and livestock production will probably not be large one way or the other.

Many adaptations to exploit opportunities created by climate change and minimize climate-related risks will occur more or less autonomously as farmers and agribusinesses react to experiences with climate change and evolving climate expectations. Agriculture is an industry already very familiar with continual, rapid, and often tumultuous change. Farmers have a wide array of options at their disposal for minimizing negative impacts on production and exploiting positive impacts. For crops these options include changes in crop acreages, the types or varieties of crops grown, planting and harvesting dates, crop rotations, tillage practices, fertilization practices, and pest management practices. For livestock these options include changes in herd sizes, livestock types or breeds, feeding rations, and heating and cooling systems.

Nevertheless, there are actions that can be taken to facilitate adaptation. Our assessment of agriculture's adaptive abilities hinges in part on the development and adoption of new technologies, particularly biotechnology, precision agriculture, and improved climate forecasting. Farmers will need to have the education and skills to understand and exploit these technologies. Public- and private-sector agricultural and meteorological research organizations will need employees with the scientific skills to develop these new technologies. This poses a challenge for educational institutions within the MAR, particularly the region's land-grant institutions. Public- and private-sector agricultural research organizations may also need to devote additional resources to climate change adaptation, such as breeding for CO_2 responsiveness in crops and for greater tolerance to climatic stress in crops and livestock. These additional resources could potentially come at the expense of resources devoted to advancing agricultural technology in other ways.

The vast majority of research to date on climate change and agriculture has focused on agricultural production impacts. Very little work has been done on how climate change might affect the environmental impacts of agricultural production and land use. Given the magnitudes of water quality effects in many areas, including the Chesapeake Bay, this should be a high priority for research. In addition, research is needed to understand climate impacts on agriculture's contributions to wildlife habitat, rural landscape amenities and carbon sequestration.

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