Pesticide externalities from the US agricultural sector – The impact of internalization, reduced pesticide application rates, and climate change

Nikolinka G. Koleva [a,b,*] *, Uwe A. Schneider* [a] *and Bruce A. McCarl* [c]

[a] *Research unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg, Germany*
[b] *International Max-Planck Research School for Maritime Affairs, Hamburg, Germany*
[c] *Department of Agricultural Economics, Texas A&M University, College Station, TX 77843-2124, USA*
[*] *Corresponding author:*
Research unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science, Bundesstrasse 55, 20146 Hamburg, Germany,
nikolinka.genova@zmaw.de

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Abstract

Pesticides used in agricultural production affect environmental quality and human health. These external costs can amplify due to climate change because pest pressure and optimal pesticide application rates vary with weather and climate conditions. This study uses mathematical programming to examine alternative assumptions about regulations of external costs from pesticide applications in US agriculture. We use two climate projections given by the Canadian and Hadley climate models. The impacts of the internalization of the pesticide externality and climate change are assessed both independently and jointly. We find that, without external cost regulation, climate change benefits from increased agricultural production in the US may be more than offset by increased environmental costs. The internalization of the pesticide externalities increase farmers' production costs but increase farmers' income because of price adjustments and associated welfare shifts from consumers to producers. Our results also show that full internalizations of external pesticide costs substantially reduces preferred pesticide applications rates for corn and soybeans as climate change.

Key words: climate change impacts, pesticide externalities, farm management adaptation, agricultural sector model, welfare maximization, environmental policy analysis, mathematical programming, United States.

Introduction

Climate change is already widely considered a reality (IPCC, 2007). An extensive literature has emerged on the interdependencies between climate and agriculture. Earlier studies have focused primarily on the vulnerability of the agricultural sector to changes in climate and weather variability (Rosenzweig and Hillel 1995, Reilly et al. 1996, Fischer 1993, Strzepek and Smith 1995, Adams et al. 1990, Mendelsohn et al. 1994, Darwin et al. 1995). There is general agreement that the degree of vulnerability depends on many local environmental and management factors (IPCC 2007). Changes in temperature, precipitation, and CO2 will alter local land and water managements and in turn affect agricultural production and agricultural sector welfare.

A series of studies measure the economic consequences of various climate change impacts on the agricultural sector. Adams et al. (1990) combine global circulation, biologic, and agricultural economic models to analyze the economic implications of climate change on US agricultural production. They find increasing crop prices due to reduced yields and increased crop water requirements due to changes in precipitation and temperature regimes. They conclude that under relatively adverse cases of climate change, domestic and foreign consumers' surplus will moderately decrease while the US producers' surplus will increase with the same amount. In a later study, Adams et al. (1993) investigate the effects of climatic conditions on farmers’ input and output choices. Accounting for carbon dioxide fertilization effects and commodity trade impacts, they estimate net gains in agricultural surplus between 9 and 10.8 billion dollars. The 2001 US National Assessment finds similar results (Reilly et al. 2001). Darwin et al. (1995) make a similar investigation on the issue and find climate change impacts on US agriculture to range between 4.8 and 5.8 billion dollars. Reilly et al.

(1994, 1996) approximate global welfare changes in the agricultural sector (without adaptation) between and find estimates that range from losses of 61.2 billion dollars and gains of 0.1 billion dollars. This is in contrast to losses of 37 billion dollars and gains of 70 billion dollars with appropriate adaptations in place.

A few studies provide have addressed the actual vulnerability of agriculture to variability related factors such as the increased frequency of extreme events including droughts and floods, changes in precipitation and temperature variance. Using a dynamic crop model, Rosenzweig et al. (2002) simulate the effect of heavy precipitation on crop growth and plant damage from excess soil moisture. They estimate damages from changes in weather variability on US corn production to equal approximately 3 billion dollars per year. Lobel and Asner (2003) find a 17 percent decrease in corn and soybean yields in the US for each degree increase in growing season temperature, indicating a higher observed sensitivity of agriculture to temperature than studies had predicted previously.

As climate and atmospheric carbon dioxide concentration shift, the outbreak of and induced plant damage from agricultural pests may increase. Studies on carbon dioxide concentration changes suggest positive yield and plant growth effects not only for agricultural crops but also for weeds due to increased water use efficiency and photosynthesis (Darwin 2001, Hulme 1996, Rosenzweig and Hillel 1995). Several studies have examined the interaction between pests and climate change (Patterson et al. 1999, Porter et al. 1991, Gutierrez et al. 2008) concluding that pest activity especially of insects will increase and lead to higher crop losses. Chen et al. (2003) estimate the cost implications of a potential increase in pest invasion and find that climate change will increase the treatment cost for major crops. The same authors went further in their analysis to examine the US wide costs showing increased pesticide treatment costs reduced welfare by 100 million dollars. However, this estimate does not account for the external costs of pesticide use.

During the last tree decades, agricultural pesticides have been increasingly recognized for their adverse effects on the environment and human health. There are numerous studies on these external costs. Pimentel (2004) estimates the external cost of pesticide applications at recommended dose rates to equal approximately 9 billion each year comprising 1.1 billion dollars of human health impacts, 2.0 billion dollars groundwater contamination, and 6.3 billion dollars of other environmental losses. In a similar study, Tegtmeier and Duffy (2004) calculate the external cost in the US agricultural sector between 5.7 and 16.9 billion dollars. Pretty et al. (2001) employ a relatively comprehensive dataset and compute annual external costs of pesticide applications in UK, Germany and the US. They find the total cost in the US at about 35 billion dollars. While most existing studies investigate current external cost, Koleva and Schneider (2009) provide external cost changes from changes in US pesticide applications due to climate change. They couple the pesticide environmental accounting tool (Leach et al. 2008) with statistically estimated adjustments in US pesticide applications to climate change (Koleva et al. 2009) and calculate external cost increases of up to 25 dollars per hectare until 2100. However, this estimate neglects possible agricultural adaptations regarding crop and management choice.

This study analyzes a hypothetical regulation of the pesticide externality in the US under current climate conditions and for different projections of climate change. Two major questions will be addressed both of which are relevant to researchers, policymakers, and the general public. First, we want to quantify the net impacts of pesticide regulations on the US agricultural sector including likely consequences for agricultural producers, consumers, and the environment. Second, we want to estimate if and how these impacts differ under projected changes in weather and climate. We hope that the answers to these questions will provide more insight into the ongoing debate about the scope, degree, and justification of environmental policies. To simultaneously portray the diverse spectrum of agricultural production options, feedback from national and international commodity markets, climate change impacts, and external effects of pesticides, we integrate the results from Koleva et al. (2009), Koleva and Schneider (2009), and Knutson et al. (1999) in the Agricultural Sector and Mitigation of Greenhouse Gas (ASMGHG) model (Schneider et al. 2007).

The paper proceeds as follows. Section 2 describes the data and basic structure of the ASMGHG model. The monetary estimates of agricultural surplus, market shifts, and land use changes associated with climate change are analyzed in section 3. Finally, section 4 concludes.

Data and Methods

The basic methodology of this study involves five major components. First, we use the estimates from Koleva et al. (2009) on the effects climate change has on pesticide use. Second, we use the estimates from Pretty et al. (2001) on how pesticide use causes external costs. Third, we use estimates of the effects of climate change on yields, and water use that are derived from Alig et al. (2002). Fourth, we use results from Knutson et al. (1999) to depict the impact of reduced pesticide application rates on crop yields and costs. Fifth, we integrate all of these into an agricultural sector model to estimate the welfare costs and influence of considering pest related differences. Each of these steps is reviewed in more detail below.

Pesticide intensities and climate change

To estimate the effects of weather and climate on conventional pesticide application rates, Koleva et al. (2009) investigate crop and chemical class specific panel data across 14 years and 30 US states. They regress pesticide application rates on marginal revenue, total crop area, and climate and weather variables related to temperature and precipitation (Appendix 1). The authors then combine the regression coefficients with downscaled climate projections developed at the Canadian Centre for Climate and the Hadley Centre in the United Kingdom based on the IPCC's A2 scenario (IPCC data distribution center, 2006). Their study explicitly considers three time periods: 2033, 2066 and 2099. For each time period, a 33-year average over the relevant weather and climate variables is used to estimate changes in pesticide application rates.

Figure 1 shows the projected pesticide application rates under the Canadian and Hadley climate change models for US costal states. The relative change is computed as weighted average over all crops and pesticide classes. In most of the states pesticide applications might increase up to 20 percent.

< Figure 1 here>

Figure 2 shows projections of pesticide use by chemical classes. The relative change is computed as weighted average over US states and crops. The illustration shows that while most pesticide application rates increase under climate change, a few others are likely to decrease.

<Figure 2 here>

Projections of pesticide application rates by crop type classes are given in Figure 3. The relative change is computed as weighted average over US states and pesticide classes. While pesticides applied to fruits and vegetables increase two to three times compared to the base period, cereals and beans remain the most pesticide intensive crops.

<Figure 3 here>

External costs of pesticides

The external cost calculations for pesticide applications in the US are based on Koleva and Schneider (2009). These authors update the cost component estimates by Pretty et al. (2001) and integrate them with the Pesticide Environmental Accounting (PEA) tool developed by Leach and Mumford (2008). Koleva and Schneider (2009) use the year 2000 as base period and project external costs of individual pesticides to three future dates including 2033, 2067 and 2100. For the base period, their cost estimates use observed data on individual pesticide applications from NASS (2009). The impact of climate change on external costs is based on the above described projections of pesticide applications by Koleva et al. (2009). The external cost estimates from Koleva and Schneider (2009) are illustrated below.

Figure 4 shows increases in external cost for all major pesticide classes, however, these increases occur at different rates. The highest change takes place in the insecticide category with external costs per kilogram active ingredient and treated hectare increasing from $30.6 in 2000 to $48.8 in 2100. External costs from fungicide and herbicide applications change less and incur average increases of $7.25 and $3.23, respectively. The total external costs over all pesticide classes increase from $43.09 in 2000 to $71.64 in 2100.

< Figure 4 here>

Figure 5, shows the external cost of pesticides for different crop types under current climate conditions and two climate projections for 2100. Results indicate increases in total external costs for all crop types. The highest absolute change until 2100 occurs in insecticides applied to berries, fruiting vegetables, pome and stone fruits.

< Figure 5 here>

Crop impacts of climate change

Reilly et al. (2003) examine the impacts on US agriculture of transient climate change as simulated by 2 global general circulation models focusing on the decades of the 2030s and 2090s. They use site-specific crop models to project biophysical impacts and linked economic models to simulate commodity trade and market effects. Crop modeling studies are conducted at 45 national sites for wheat, maize, soybean, potato, citrus, tomato, sorghum, rice, and hay, both under dryland and irrigated conditions. Impacts on barley, oats, sugar cane, sugar beet, and cotton are extrapolated. The biophysical impacts on yields and water requirements are passed from the crop models to an economic model. Expert knowledge is used to project additional adjustments with respect to crop management costs, The final results of this national assessment indicate substantial regional differences. Particularly, under the Canadian scenario, the authors find agricultural production to increase between 40 and 80 percent in the Corn Belt and the Lake States but to decrease by as much as 60 percent in the Southeast. For the Hadley scenario, all regions show increased crop production with a more than 100 percent increase in the Lake States. The Canadian model based scenario leads to a much warmer and much drier climate, particularly in the 2030 period, thus projecting less positive effects on overall crop production and more negative effects in the Southern and Plains areas of the US. For this study, we use the climate, region, and crop specific data on yields, irrigation water requirements, and production costs from Reilly et al. (2003).

Pest management

We also introduce alternative pest management options: conventional pesticide application rates, 50 percent reduction of overall pesticide rates, and pesticide free crop management. The data on associated cost and yield changes are based on Hall et al. (1994) and Knutson et al. (1999). Both studies investigate empirically the potential effect of reduction or elimination of various pesticides in US agriculture and find that the broader the group of pesticides eliminated, the greater are the yield impacts. Their results also show that fruits and vegetables are more adversely affected by a broad-based reduction in pesticides than are field crops. Note that the 50 percent reduction scenario does not refer to a 50 percent reduction of all individual pesticides applied to a specific crop but rather an elimination of one or several individual pesticides which account for approximately 50 percent of the total application of active ingredients. Additionally, the authors observe that alternative pest control options to compensate the lack of chemicals are hardly sensible because the percentage increase in alternative treatment cost is generally larger than the percentage increase in revenue from avoided yield losses.

Integrating agricultural sector model

The above described impact estimates of climate on the pesticide externality did not depict possible agricultural adaptation regarding crop acreage, livestock numbers, and management intensity. To include these impacts, we use the model ASMGHG (Schneider et al). Here we briefly describe the general mathematical structure of ASMGHG model and specific modifications for the purpose of this study. A more detailed technical description is given in the Appendix 1 and is also available in Schneider et al. (2007).

ASMGHG is designed to emulate US agricultural decision making along with the impacts of agricultural decisions on agricultural production factors, international agricultural commodity markets, and the environment. The model has been used for the analysis of technological developments and policy scenarios including environmental, agricultural, and energy regulations. ASMGHG is an extended version of Agricultural sector model of McCarl and associates (McCarl et al. 1980; Chang et al. 1992). Schneider (2000) modified and expanded ASM to include a comprehensive GHG emission accounting module along with emission mitigation possibilities. ASMGHG portrays the following key components: natural and human resource endowments, agricultural production factor markets, agricultural technologies (Table 1), primary and processed commodity markets, and agricultural policies. The model depicts representative crop and livestock enterprises in 63 aggregated US production regions. International markets and trade relationships are portrayed through 27 international regions for 8 major crops and through one rest-of-the-world region for 32 other commodities including various crop, livestock and processed products. A brief summary of ASMGHG's spatial resolution is contained in Table 2.

The objective function of the model maximizes total agricultural economic surplus subject to a set of constraining equations, which include resource limits, supply and demand balances, trade balances, policy restrictions, and crop mix constraints. The economic surplus equals the sum of consumers' surplus, producers' surplus, and governmental net payments to the agricultural sector minus the total cost of production, transportation, and processing. Based on economic theory, the optimal variable levels can be interpreted as equilibrium levels for agricultural activities after adjustment to given economic, political, and technological conditions. The shadow prices on supply demand balance equations identify market clearing prices.

ASMGHG is setup as mathematical programming model and contains more than 20,000 individual variables and more than 5000 individual equations. All agricultural production activities are specified as endogenous variables. The equations are indexed and listed in Appendix 1. Model solutions provide projection on land use and commodity production within the 63 US regions, commodity production in the rest of the world, international trade, crop and livestock commodity prices, processed commodity prices, agricultural commodity consumption, producer income effects consumer welfare effects, and various environmental impacts.

To do this study we integrate pest costs and yield changes under the SRES based A2 climate change scenario following the procedures used in the US National assessment. When we add the external costs we run the model with and without the externality internalized.

Results

The objective of this study is to find out how pesticide externalities are affected by climate change and by the internalization of the pesticide externality that would hold farmers accountable for the environmental damages of pesticides. Furthermore, we want to analyze the role of alternative pest management regimes. To accomplish these objectives, we consider a total of 28 scenarios which result from combinations of four time steps (2000, 2030, 2060, 2090), two climate projections (Canadian and Hadley), and four the internalization of the pesticide externalities (internalization of external environmental costs at 0, 50, 100, 200 percent). We use different internalization rates to address the uncertainty of the estimated external costs. For each scenario, we solve a scenario specific version of the ASMGHG model.

3.1. Agricultural market and welfare impacts

Table 3 summarizes the individual and combined effects of climate change and the degree of internalization of the pesticide externality on agricultural market and welfare indicators. Climate and pesticide policy impacts affect agricultural markets in opposite directions. Especially under the Hadley climate change projection, we find substantial increases in US crop production. While production increases continuously under the Hadley projection until 2100, the Canadian climate projection ceases to increase production after 2030. A 50 percent internalization of external environmental costs of pesticides more than offsets the positive impacts of climate change. If stronger regulations of external costs are used, i.e. 100 or 200 percent, the negative impacts on production amplify. Agricultural crop prices and exports mirror the impacts on crop production. Climate change alone decreases prices and increases pesticide use. Note, however, that we kept the international crop supply functions constant. If crop production outside the US decreased substantially due to climate change, the downward pressure on crop prices from increases US crop production could have been mitigated. The combination of climate change and pesticide policy projections yields more complex price effects because the external costs are sensitive to climate change affects. Under the Canadian climate projection, a full (100 percent) internalization of external costs decreases US production by 20 percent and this almost doubles crop prices in the last simulation period.

Agricultural welfare impacts are displayed in the last four columns of Table 3. In absence of pesticide externality internalization, total agricultural sector surplus monotonically increases for both climate projections. These changes are increasingly higher for the Hadley projection, and in the last period with a projected increase of 19 billion dollars about twice as high as the 9.6 billion dollar increase under the Canadian projection. With the combined impact of climate change and the assumed pesticide policies, total agricultural sector surplus decreases. The decreases are the consequence of increasing market prices and reduced supply. It is important to note that the combined impacts do not equal the sum of individual impacts. For example, the Canadian projection for 2060 increases total agricultural surplus by 8.77 billion US dollars. On the other hand, the 50 and 100 percent externality regulation scenarios decrease total agricultural surplus by 25.51 and 37.85 billion US dollars, respectively. However, the combined effect of climate change and the internalization of the pesticide externality decrease total surplus by 22.86 and 38.83 billion US dollars for the 50 and 100 percent internalization scenarios, respectively. The non-additionality of climate change and the internalization of the pesticide externality impacts arises for two reasons. First, downward sloped demand and upward sloped supply cause non-linear responses with non-constant rates of welfare changes. Second, climate change affects pesticide applications and thus the magnitude of external costs from agricultural pesticides. The increased benefits under climate change from positive supply shifts are partially or completely offset by the increased external costs from the additional use of pesticides.

Table 3 also reveals the distribution of agricultural surplus between US producers, US consumers, and foreign countries. The direction of changes in consumers' surplus reflects price changes. The more prices increase, the higher are losses to US consumers. The impact on producers is more diverse because price and supply impacts work in opposite directions. Particular, supply increases lead to higher sales at lower prices and vice versa. Our simulation results show that the supply enhancing impact of climate change projections do not benefit producers. A 50 percent internalization of pesticide externalities worsens producer surplus. However, if the external costs are fully internalized, producers gain because the beneficial producer surplus effects of increased prices outpace the negative effects of reduced supply. Under a 200 percent internalization, this effect becomes much stronger. Foreign countries' surplus aggregates foreign producer and consumer surplus changes. The net effects are moderately positive for climate change in absence of US pesticide policies and, with few exceptions, moderately negative under the combined impact of climate change and pesticide policies. Again, it is important to note that we did not have adequate data to shift the crop supply functions in foreign countries.

Details on pesticide externality impacts in US agriculture in response to the internalization of the pesticide externality and climate change are displayed in Table 4. In absence of internalization, climate change leads to relatively minor changes in US total agricultural revenue (TAR) but substantial increases in total environmental and human health costs (TEHH) this was not introduced above. Particularly, the latter costs increase relative to total US agricultural revenue from about one third in 2000 to about one half in 2090. While, the total environmental and human health costs increase continuously under the Hadley projection, they cease to increase after 2030 for the Canadian climate projection. An internalization of the external costs of pesticides increases moderately total US agricultural revenues but decrease substantially the total environmental and human health costs. The increase in total revenue implies that supply reductions are more than compensated for by associated price changes. At a 100 percent internalization rate, agricultural revenues change by no more than 11 percent but pesticide externalities decrease by 80 percent and more across all climate scenarios. If stronger or weaker regulations of external costs are used, the magnitude of effects changes accordingly.

3.2. Pesticide Application Intensities

Climate change and pesticide externality internalization affect agricultural decisions in multiple ways. Farmers may grow different crops, use different rotations, and change the intensity of management related to irrigation, tillage, fertilization, and pesticide use. These adjustments are represented in ASMGHG to the degree specified in Table 2. The simulated combined effects of climate projections and internalization on pest management strategy are provided in Table 5.

The first table section shows the change in total crop area summed over all pesticide application intensities. Total area decreases both in response to climate change and regulations of external costs from pesticides. Note, however, that the impacts of the two drivers do not add up. For example, a full internalization of external pesticide cost under climate 2000 conditions would reduce the cropped area by almost 14 percent. Equivalently, climate 2060 projections without internalization of external cost would reduce cropping areas by 13 to 14 percent for both climate models. The combined impact of climate change and pesticide impact internalization on cropping is only slightly stronger than the individual effects and amounts to 14 and 16 percent reduction, for the Canadian and Hadley projection, respectively.

The following table sections show the area allocated to different pesticide application intensities. In absence of pesticide externality internalization, agricultural producers fare best with conventional pesticide intensities under all climate projections. As the regulation of external costs increases, the planted area fully treated with pesticides decreases and reduced or zero pesticide application intensities become more frequent. Particularly, if 50 percent of the external environmental costs of pesticides are internalized (columns 3 and 4 of Table 5), the land share under conventional pesticide application intensity decreases by about 35 percent and goes to reduced and zero application intensities. For stronger regulations of external costs, the land shares under conventional application rates decrease further and the area with zero pesticide application rates reaches about one third of the entire crop area.

Our simulation results indicate that, climate change coupled with internalization of the externality mostly decreases conventional and reduced pesticide application intensity, but increases the share of pesticide-free crop management. The changes in area shares of different pesticide application intensities due to climate are relatively small and do not exceed 10 percent across the entire simulation period. The simulation results from Table 5, represent weighted averages over major crop groups. To show the influence of climate change and full external pesticide cost internalization on individual crop categories, Figures 6-9 display the total and pest management specific areas allocated to all major crops. To keep the graphical display manageable, the results from both climate change models are averaged.

Figure 6 shows for major crop categories the combined impact of climate change and full external cost internalization on total area relative to the base area in 2000 without internalization of the pesticide externality. We find changes in areas for all crop groups however, these changes differ substantially between crops. Cotton is the only crop which increases - by 9 percent - compared to the base area. The highest decrease in area occurs for citrus fruits and tomatoes with some reductions above 50 percent. In most cases, the internalization of the pesticide externality effect dominates the climate change effect, i.e. area change for the year 2000 is higher than additional, climate changed based adjustments at subsequent dates. For cereals and sugar crops, we find monotonous decreases until 2100. All other crop groups show a mixed response to climate changes involving both increases and decreases in total area relative to previous date. The area changes due to climate change remain below 5 percent except for citrus fruits and tomatoes.

Figures 7 to 9 display the combined impact of climate change and full external cost internalization on area shares for alternative pesticide intensity options. We find that conventional pesticide rates dominate reduced rate strategies for all crops except for corn and soybeans. Almost no pesticide rate reductions are observed for cereals and potatoes, however, there is a substantial reduction in conventional pest management averaging about one third of the total area across the different climate scenarios. Sugar crops, fodder crops, and tomatoes show no or relatively little change in pesticide intensities. Climate change projections affect the preferred pesticide intensities for corn and soybeans and lead to monotonously increasing shares of pesticide free management at the expense of the area under reduced pesticide applications. Citrus fruit shows high potential importance of pesticide free management only under current climate conditions. For all other crop groups, climate change has relatively little impact on non-conventional pesticide control strategies.

Conclusions

This study examines alternative assumptions about regulations of external costs from pesticide applications in US agriculture under different climate conditions. The impacts of the internalization of the pesticide externality and climate change are assessed both independently and jointly. Without external cost regulation, climate change benefits from increased agricultural production in the US may be more than offset by increased environmental costs. While the internalization of the pesticide externalities may increase farmers' production costs, they are likely to increase farm income because of price adjustments and associated welfare shifts from consumers to producers. Our study also illustrates that full consideration of pesticides' external costs motivate farmers to substantially reduce pesticide applications for corn and soybeans and considerably for cereals and potatoes. While the additional impact of climate change on preferred pesticide intensities is marginal for most crops, it is substantial for corn and soybeans.

Our results have important research and policy implications. First, this analysis quantifies the tradeoff between agricultural market surplus and external pesticide costs under different climate conditions. Our estimated benefits from internalization may be contrasted with policy transaction costs, to judge whether externality regulation is desirable. The examined pesticide policy could be interpreted as a pesticide tax, where the tax level corresponds to the environmental and human health damage. Such a policy is different from most existing regulations, which only prohibit pesticides but impose no charge on admitted ones. Second, if climate change leads to higher pesticide applications, the socially optimal response to climate change moves away from adaptation towards mitigation. Third, our results could affect agricultural research programs because the expected social returns to research on alternative pest control strategies depend also on the expected external cost change. Fourth, our study can help to improve the mathematical representation of agricultural externalities in integrated assessment models. These models are increasingly used for the design and justification of climate and other environmental policies.

Several important limitations and uncertainties to this research should be noted. First, the findings presented here reflect agricultural management options for which data were available to us. Alternative pesticide management options are limited to three levels of application rates. In reality, farmers could adopt any application rate and could consider many other pest control adaptations which are not considered here. Second, the data for pesticide treatment costs, yield impacts, irrigation water requirements, and external costs involve regression analyses and mathematical simulation models. Thus, the certainty of the estimates presented here depends on the quality of these models and the certainty of all associated input data. Third, not monetarized in this analysis were costs or benefits from reduced levels of other agricultural externalities, and costs or benefits of changed income distribution in the agricultural sector. Fourth, we operate with 32 crops mainly grains and not many fruits and vegetables which have higher contribution to the external cost of pesticide use. Fifth, the reductions in external costs due to regulation may be overstated because of leakage of pesticide intensive crops to other countries. Finally, all simulated results are derived from the optimal solution of the mathematical program and as such constitute point estimates without probability distribution.

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Table 1 Scope of agricultural management alternatives in ASMGHG

Management parameter	Available options
Crop choice	Cotton, Corn, Soybeans, Winter wheat, Durum wheat, Hard red winter wheat, Hard red and other spring wheat, Sorghum, Rice, Barley, Oats, Silage, Hay, Sugar Cane, Sugar Beets, Potatoes, Tomatoes, Oranges, Grapefruit Switchgrass, Willow, Hybrid poplar
Irrigation	No irrigation Full irrigation
Tillage	Conventional tillage (<15% plant cover) Reduced tillage (15-30% plant cover) Zero tillage (>30% plant cover)
Fertilization	Observed nitrogen fertilizer rates Nitrogen fertilizer reduction corresponding to 15% stress Nitrogen fertilizer reduction corresponding to 30% stress
Pesticide application	Conventional (Average current rate) Reduced (50% of current rate) Minimum (No pesticide application)
Animal production	Dairy, cow-calf, feedlot beef cattle, heifer calves, steer calves, heifer yearlings, steer yearlings, feeder pigs, pig finishing, hog farrowing, sheep, turkeys, broilers, egg layers, and horses
Feed mixing	1158 specific processes based on 329 general processes differentiated by 10 US regions
Livestock production	Four different intensities (feedlot beef), two different intensities (hog operations), liquid manure treatment option (dairy and hog operations), BST treatment option (dairy)

Table 2 Spatial Scope of ASMGHG

Region Set	Region Set Elements	Associated Features
Non-US world regions	Canada, East Mexico, West Mexico, Caribbean, Argentina, Brazil, Eastern South America, Western South America, Scandinavia, European Islands, Northern Central Europe, Southwest Europe, France, East Mediterranean, Eastern Europe, Adriatic, former Soviet Union, Red Sea, Persian Gulf, North Africa, West Africa, South Africa, East Africa, Sudan, West Asia, China, Pakistan, India, Bangladesh, Myanmar, Korea, South East Asia, South Korea, Japan, Taiwan, Thailand, Vietnam, Philippines, Indonesia, Australia	Excess demand and supply function parameter for 8 major crop commodities; transportation cost data; Computation of trade equilibrium
US	US	Demand function parameters for crop, livestock, and processed commodities
US macro regions	Northeast, Lake States, Corn belt, Northern Plains, Appalachia, Southeast, Delta States, Southern Plains, Mountain States, Pacific States	Feed mixing and other process data; labor endowment data;
US minor regions	Alabama, Arizona, Arkansas, N-California, S-California, Colorado, Connecticut, Delaware, Florida, Georgia, Idaho, N-Illinois, S-Illinois, N-Indiana, S-Indiana, W-Iowa, Central Iowa, NE-Iowa, S-Iowa, Kansas, Kentucky, Louisiana, Maine, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, Montana, Nebraska, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Carolina, North Dakota, NW-Ohio, S-Ohio, NE-Ohio, Oklahoma, Oregon, Pennsylvania, Rhode island, South Carolina, South Dakota, Tennessee, TX-High Plains, TX-Rolling Plains, TX-Central Blackland, TX-East, TX-Edwards Plateau, TX-Coastal Belt, TX-South, TX Transpecos, Utah, Vermont, Virginia, Washington, West Virginia, Wisconsin, Wyoming	Crop and livestock production data and activities, land type and water resource data
US Land types	Agricultural Land: Land with wetness limitation, Low erodible land (Erodibility Index (EI) < 8), Medium erodible land (8 < EI < 20), Highly erodible land (EI < 20), Pasture, Forest	Land endowments; Cost, yield, and emission data adjustment

Table 3 **Economic surplus and market effects in US agriculture in response to pesticide policy and climate change**

Internalization of External Pesticide Impacts	Climate Projection[1]	*US Agricultural market impacts (Fisher Index)*				*Change in agricultural surplus (Billion $)*				
		Production	Prices	Exports	Imports	US Producers	US Consumers	Foreign Producers	Foreign Consumers	Total Surplus[2]
None	2000	100.0	100.0	100.0	100.0	0.00	0.00	0.00	0.00	0.00
	2030 H	111.0	80.2	130.8	79.5	-2.42	9.40	-0.99	3.88	9.86
	2030 C	106.0	87.2	118.0	91.9	-1.48	5.52	-0.39	3.33	6.98
	2060 H	117.0	73.4	154.5	79.1	-4.17	12.81	-1.68	7.12	14.08
	2060 C	107.0	87.0	120.5	96.6	-0.73	4.31	-0.15	4.12	7.55
	2090 H	125.0	69.3	191.6	75.3	-2.09	13.82	-1.87	8.38	18.24
	2090 C	106.0	92.0	124.5	112.4	2.87	0.22	-0.08	5.14	8.15
50%	2000	84.9	131.8	53.7	132.8	-3.05	-18.64	3.23	-5.52	-23.97
	2030 H	90.1	119.6	70.5	104	-4.58	-12.39	2.09	-2.50	-17.37
	2030 C	90.0	125.5	69.7	110.3	-3.36	-15.96	2.77	-3.58	-20.12
	2060 H	93.8	116.6	85.9	114.6	-2.89	-12.38	1.60	-0.49	-14.15
	2060 C	87.8	133.3	69.0	114.7	-1.03	-20.82	3.01	-3.29	-22.13
	2090 H	98.3	109.9	103.4	114.3	-2.79	-9.83	0.92	1.57	-10.14
	2090 C	87.3	138.9	72.0	127.6	0.66	-24.57	3.13	-2.68	-23.46
100%	2000	77.1	170.2	34.6	168.3	6.51	-38.39	5.61	-8.53	-34.80
	2030 H	81.1	165.9	50.9	147.7	9.77	-37.63	4.88	-6.29	-29.26
	2030 C	80.2	172.9	47.6	141.0	9.57	-39.95	5.69	-7.97	-32.68
	2060 H	83.4	163.2	59.3	149.4	11.87	-37.27	4.38	-4.66	-25.67
	2060 C	78.7	193.4	48.7	163.4	17.30	-51.34	6.25	-7.95	-35.74
	2090 H	85.4	154.2	66.5	129.5	10.45	-32.10	3.00	-2.64	-21.29
	2090 C	78.3	211.6	51.9	167.8	23.10	-61.12	6.40	-7.29	-38.91
200%	2000	70.2	242.1	21.0	230.7	29.68	-74.03	9.47	-12.97	-47.85
	2030 H	72.8	246.5	31.0	177.0	34.28	-74.03	7.37	-10.65	-43.02
	2030 C	72.2	256.3	28.6	174.8	33.21	-76.82	8.33	-12.41	-47.69
	2060 H	74.6	246.4	40.5	173.8	38.92	-75.16	6.95	-9.57	-38.86
	2060 C	71.0	285.6	28.7	182.7	43.17	-91.51	8.83	-12.50	-52.01
	2090 H	76.2	240.0	46.5	166.4	40.94	-73.04	6.00	-7.53	-33.63
	2090 C	70.0	353.3	35.2	212.7	68.37	-124.46	10.87	-13.06	-58.28

[1] H=Hadley Climate Model, C=Canadian Climate Model
[2] Includes internalized external environmental and human health effects

Table 4 **Pesticide externality impacts in US agriculture in response to pesticide policy and climate change**

Internalization rate of external pesticide impacts	Climate Projection	Average internalized pesticide costs ($/kg/ha)	Total Environmental and Human Health Costs in US (TEHH)	Total Internalized Costs in the US	Total Agricultural Revenues in the US (TAR)	Absolute Change in TEHH	Absolute Change in TAR	TAR Levels Relative to Base	TEHH Levels Relative to Base
			- - - - - - - - in Billion US dollars - - - - - - - -					- - - in % - - -	
None	2000	0.00	125.2	0.00	357.1	0.0	0.0	100.0	100.0
	2030 H	0.00	150.8	0.00	351.6	25.6	-5.5	98.5	120.5
	2030 C	0.00	161.0	0.00	353.5	35.8	-3.6	99.0	128.6
	2060 H	0.00	172.0	0.00	350.8	46.9	-6.3	98.2	137.4
	2060 C	0.00	175.4	0.00	356.3	50.2	-0.8	99.8	140.1
	2090 H	0.00	186.4	0.00	349.7	61.2	-7.4	97.9	148.9
	2090 C	0.00	178.3	0.00	359.1	53.1	2.0	100.6	142.5
50%	2000	21.50	27.5	13.7	367.7	-97.7	10.6	103.0	21.9
	2030 H	25.09	31.5	15.8	364.9	-93.6	7.8	102.2	25.2
	2030 C	25.87	34.1	17.0	366.4	-91.1	9.3	102.6	27.2
	2060 H	31.19	31.5	15.8	364.7	-93.7	7.6	102.1	25.2
	2060 C	32.37	34.8	17.4	368.0	-90.3	10.9	103.1	27.8
	2090 H	33.98	31.1	15.5	364.2	-94.1	7.1	102.0	24.8
	2090 C	35.44	39.4	19.7	371.3	-85.8	14.2	104.0	31.4
100%	2000	42.99	18.1	18.1	380.3	-107.1	23.2	106.5	14.5
	2030 H	50.19	18.2	18.2	378.8	-107.0	21.7	106.1	14.5
	2030 C	51.73	19.3	19.3	378.2	-105.9	21.1	105.9	15.4
	2060 H	62.38	17.9	17.9	378.9	-107.3	21.8	106.1	14.3
	2060 C	64.74	20.1	20.1	386.7	-105.0	29.6	108.3	16.1
	2090 H	67.96	17.1	17.1	375.0	-108.0	17.9	105.0	13.7
	2090 C	70.88	24.4	24.4	397.0	-100.8	39.9	111.2	19.5
200%	2000	85.98	10.5	21.1	401.4	-114.6	44.3	112.4	8.4
	2030 H	100.37	10.8	21.6	400.1	-114.4	43.0	112.0	8.6
	2030 C	103.46	12.3	24.5	402.0	-112.9	44.9	112.6	9.8
	2060 H	124.75	10.1	20.2	402.1	-115.1	45.0	112.6	8.1
	2060 C	129.49	13.2	26.4	413.0	-112.0	55.9	115.7	10.6
	2090 H	135.92	9.4	18.9	401.5	-115.7	44.4	112.4	7.5
	2090 C	141.75	15.1	30.2	438.6	-110.1	81.5	122.8	12.1

Table 5 **Effect of climate projections and the internalization of the pesticide externalities on pesticide application rates**

Pesticide Application Rate	Climate Projection	Internalization Rate of External Environmental Costs of Agricultural Pesticides							
		None (Base)		50 Percent		100 Percent		200 Percent	
		in million acres (in percent relative to base)							
All Pesticide Management	2000 (Base)	330	(100.0)	299	(90.5)	280	(84.7)	275	(83.5)
	Hadley 2030	321	(97.2)	274	(83.0)	270	(81.9)	262	(79.5)
	Canada 2030	308	(93.3)	284	(86.0)	280	(84.7)	269	(81.6)
	Hadley 2060	318	(96.2)	284	(86.0)	273	(82.7)	263	(79.6)
	Canada 2060	303	(91.9)	284	(85.9)	279	(84.6)	267	(80.8)
	Hadley 2090	313	(94.9)	286	(86.7)	267	(80.8)	254	(77.1)
	Canada 2090	296	(89.8)	275	(83.2)	273	(82.8)	265	(80.4)
		in million acres (share of total acreage)							
Conventional (100 Percent)	2000 (Base)	330	(100.0)	194	(58.7)	165	(50.1)	156	(47.1)
	Hadley 2030	321	(100.0)	172	(52.1)	154	(46.8)	145	(43.8)
	Canada 2030	308	(100.0)	183	(55.4)	167	(50.5)	154	(46.8)
	Hadley 2060	318	(100.0)	172	(52.0)	149	(45.1)	143	(43.2)
	Canada 2060	303	(100.0)	180	(54.3)	162	(49.2)	152	(45.9)
	Hadley 2090	313	(100.0)	171	(51.9)	150	(45.3)	138	(41.7)
	Canada 2090	296	(100.0)	168	(50.8)	158	(48.0)	151	(45.8)
Reduced (50 Percent)	2000 (Base)	0	(0.0)	73	(22.1)	60	(18.2)	28	(8.4)
	Hadley 2030	0	(0.0)	64	(19.4)	56	(17.0)	29	(8.8)
	Canada 2030	0	(0.0)	64	(19.4)	48	(14.5)	32	(9.6)
	Hadley 2060	0	(0.0)	70	(21.3)	44	(13.4)	21	(6.4)
	Canada 2060	0	(0.0)	56	(17.0)	45	(13.8)	26	(8.0)
	Hadley 2090	0	(0.0)	65	(19.6)	35	(10.7)	17	(5.1)
	Canada 2090	0	(0.0)	60	(18.2)	42	(12.8)	20	(6.1)
Minimum (0 Percent)	2000 (Base)	0	(0.0)	32	(9.7)	54	(16.4)	92	(27.9)
	Hadley 2030	0	(0.0)	38	(11.5)	60	(18.2)	89	(26.9)
	Canada 2030	0	(0.0)	37	(11.1)	65	(19.7)	83	(25.2)
	Hadley 2060	0	(0.0)	42	(12.7)	80	(24.2)	99	(30.0)
	Canada 2060	0	(0.0)	48	(14.7)	71	(21.6)	89	(26.9)
	Hadley 2090	0	(0.0)	50	(15.2)	82	(24.8)	100	(30.2)
	Canada 2090	0	(0.0)	47	(14.2)	73	(22.0)	94	(28.5)

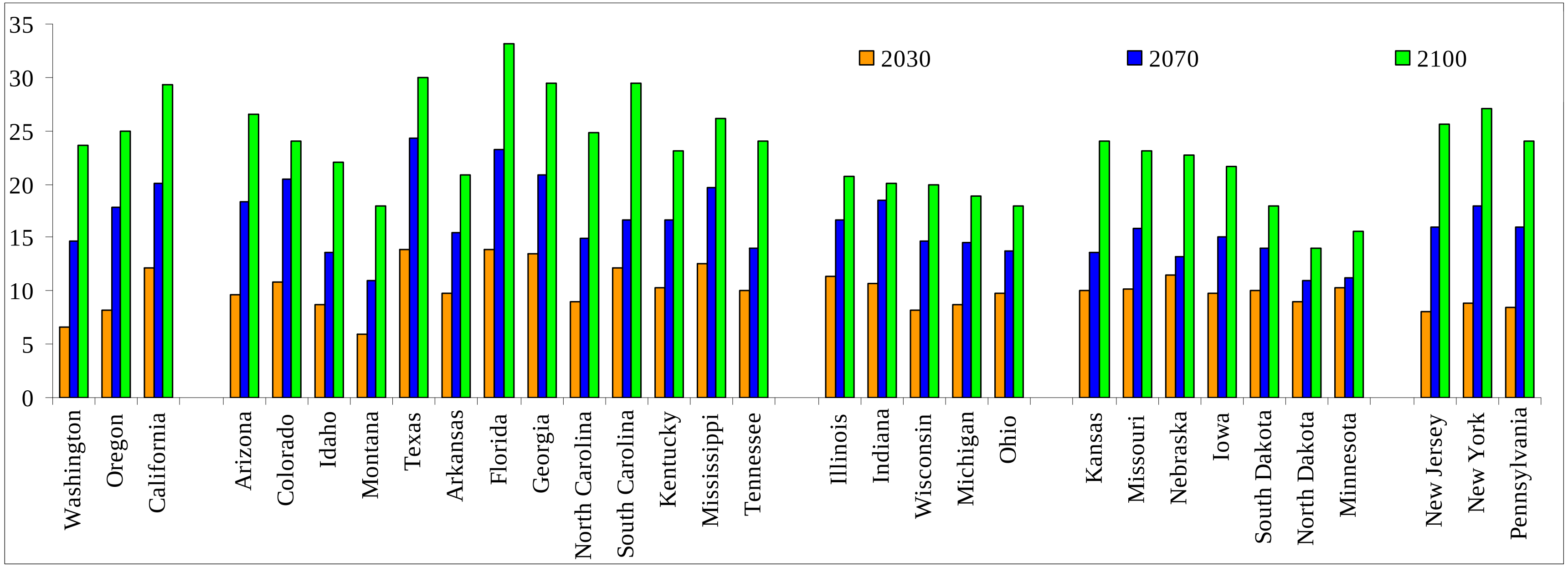

Figure 1 Climate change scenario results: Impacts on pesticide application rates by region in geographical order [in percent]

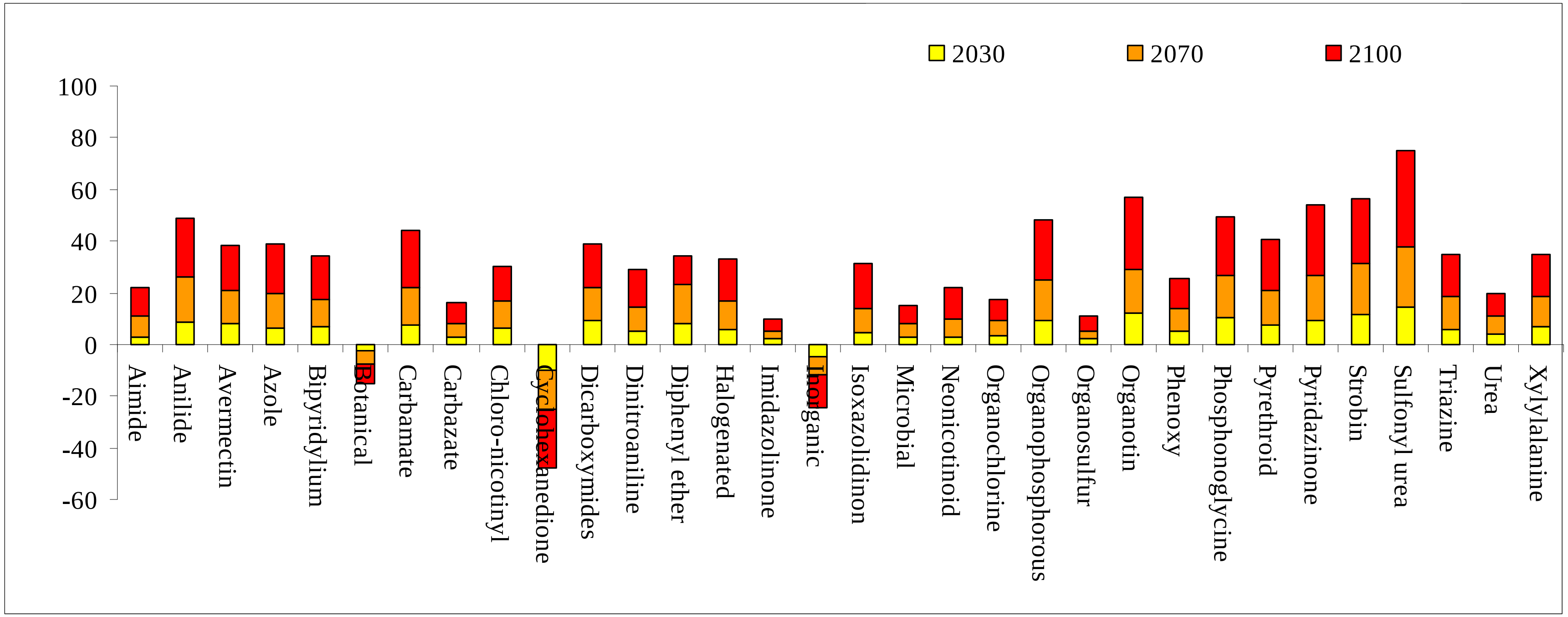

Figure 2 **Climate change scenario results: Impacts on pesticide application rates by chemical class [in percent]**

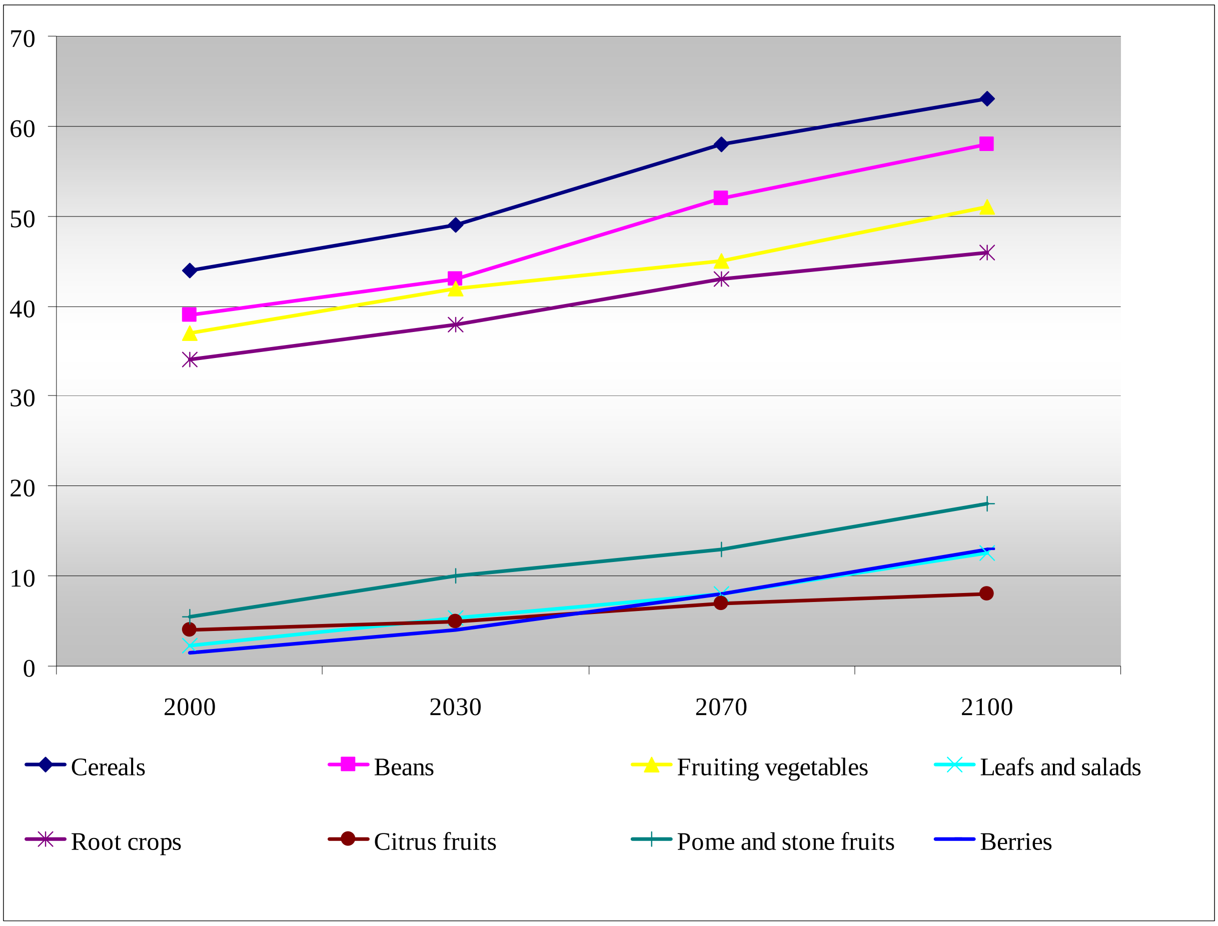

Figure 3 **Climate change scenario results: Impacts on pesticide application by crop type [in percent]**

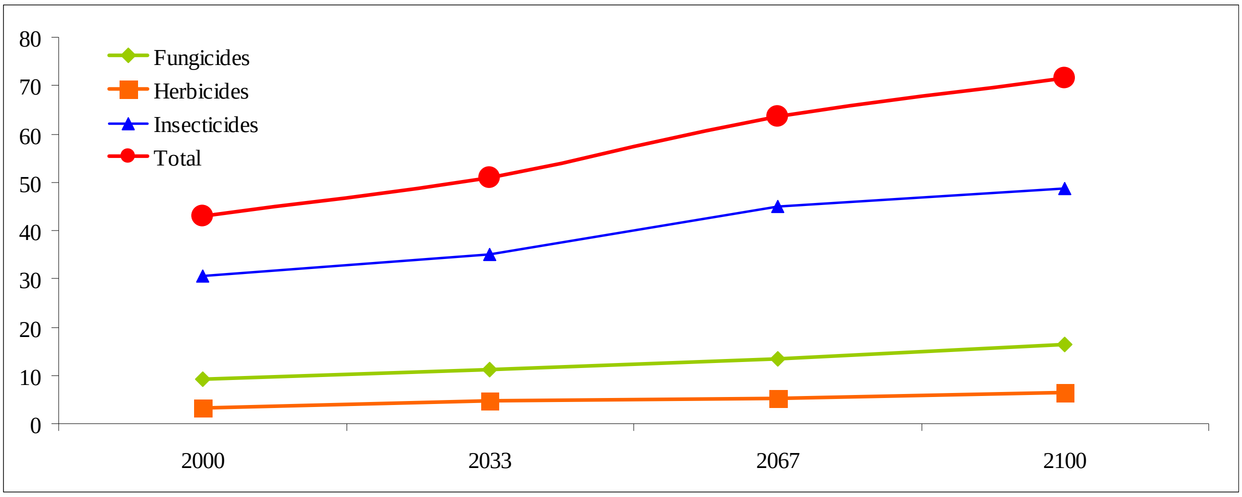

Figure 4 **Aggregated external cost of pesticides in the US [$2007/kg/ha] by pesticide class (based on Koleva and Schneider 2009)**

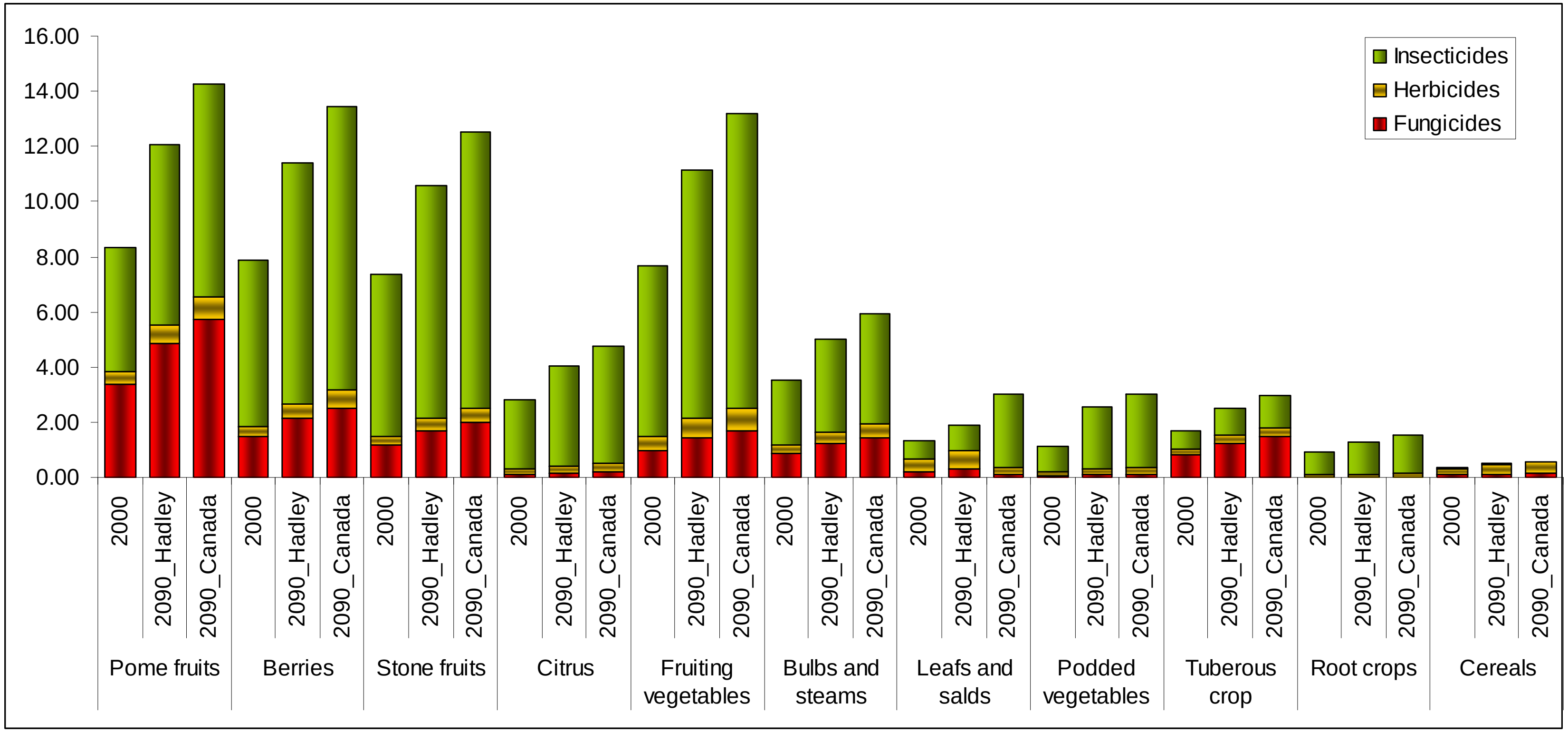

Figure 5 **Pesticide external costs [$2007/kg/ha] for current application rates and for adjusted rates to the Hadley and Canadian climate projection in 2090 (based on Koleva and Schneider 2009)**

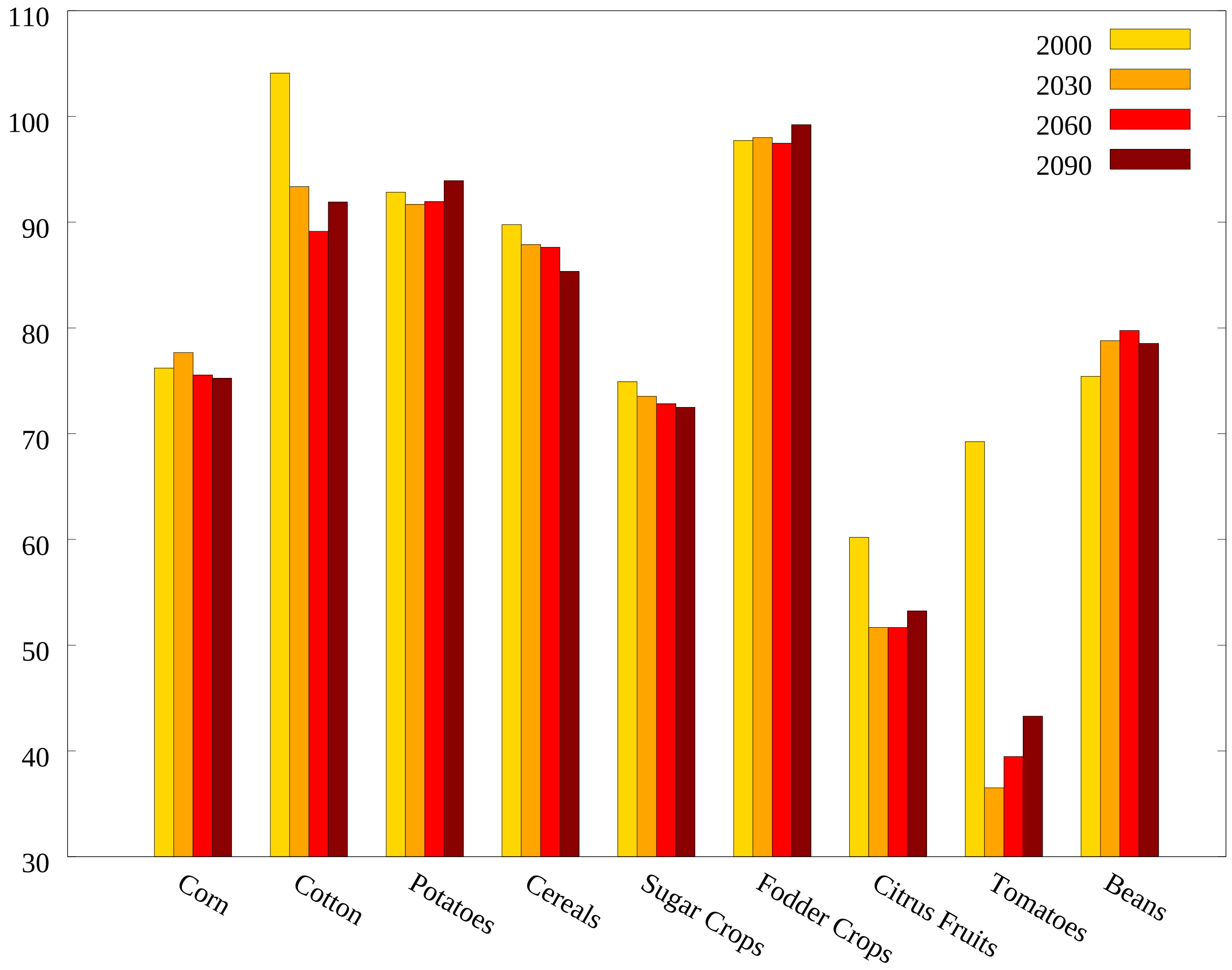

Figure 6 **Effect of projected climate change and 100% internalization of external environmental cost of pesticides on total crop area (in percent) relative to no internalization and year 2000**

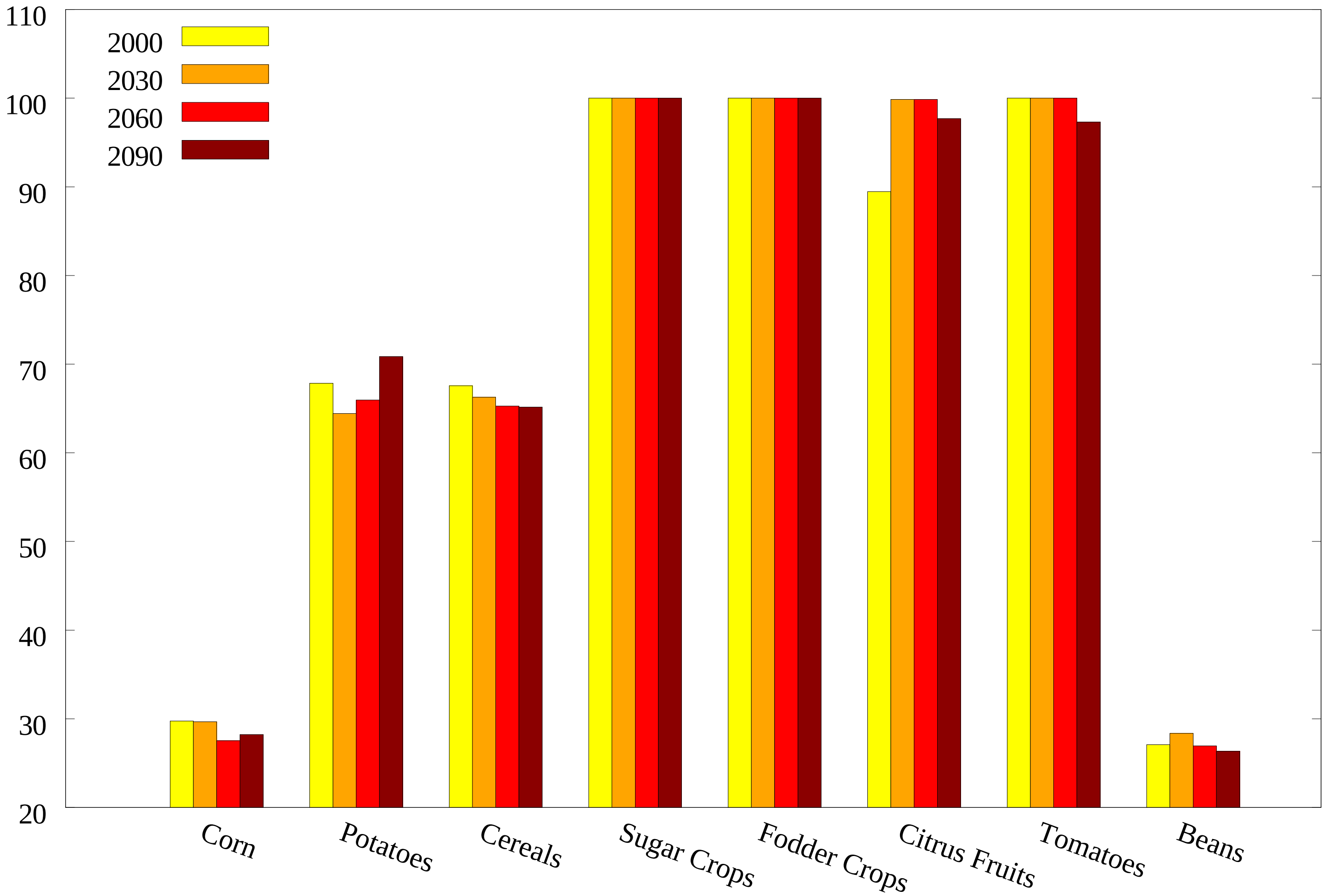

Figure 7 **Effect of projected climate change and 100% internalization of external environmental cost of pesticides on area share (in percent) under conventional pesticide management by crop group**

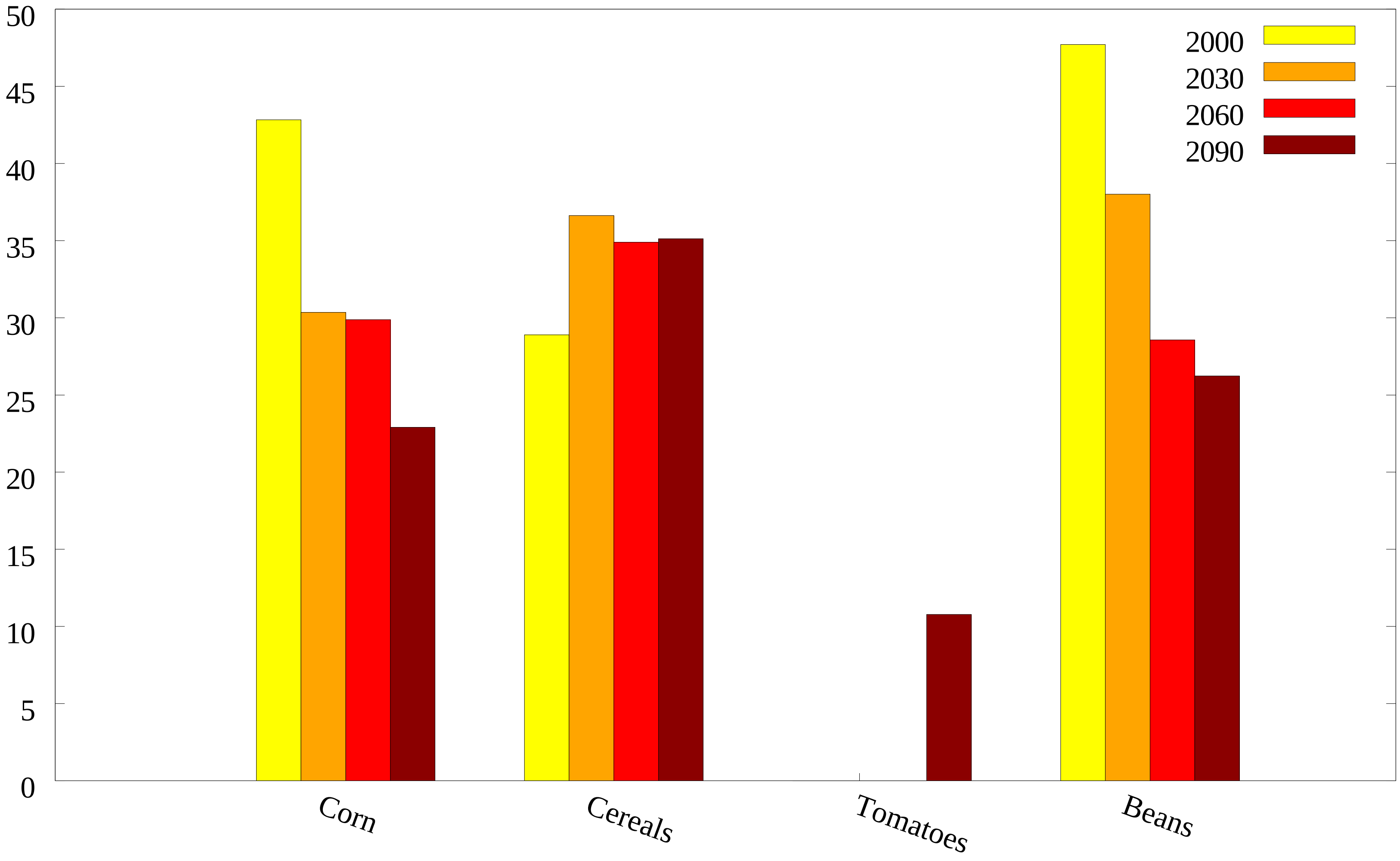

Figure 8 **Effect of projected climate change and 100% internalization of external environmental cost of pesticides on area share (in percent) under reduced pesticide management by crop group**

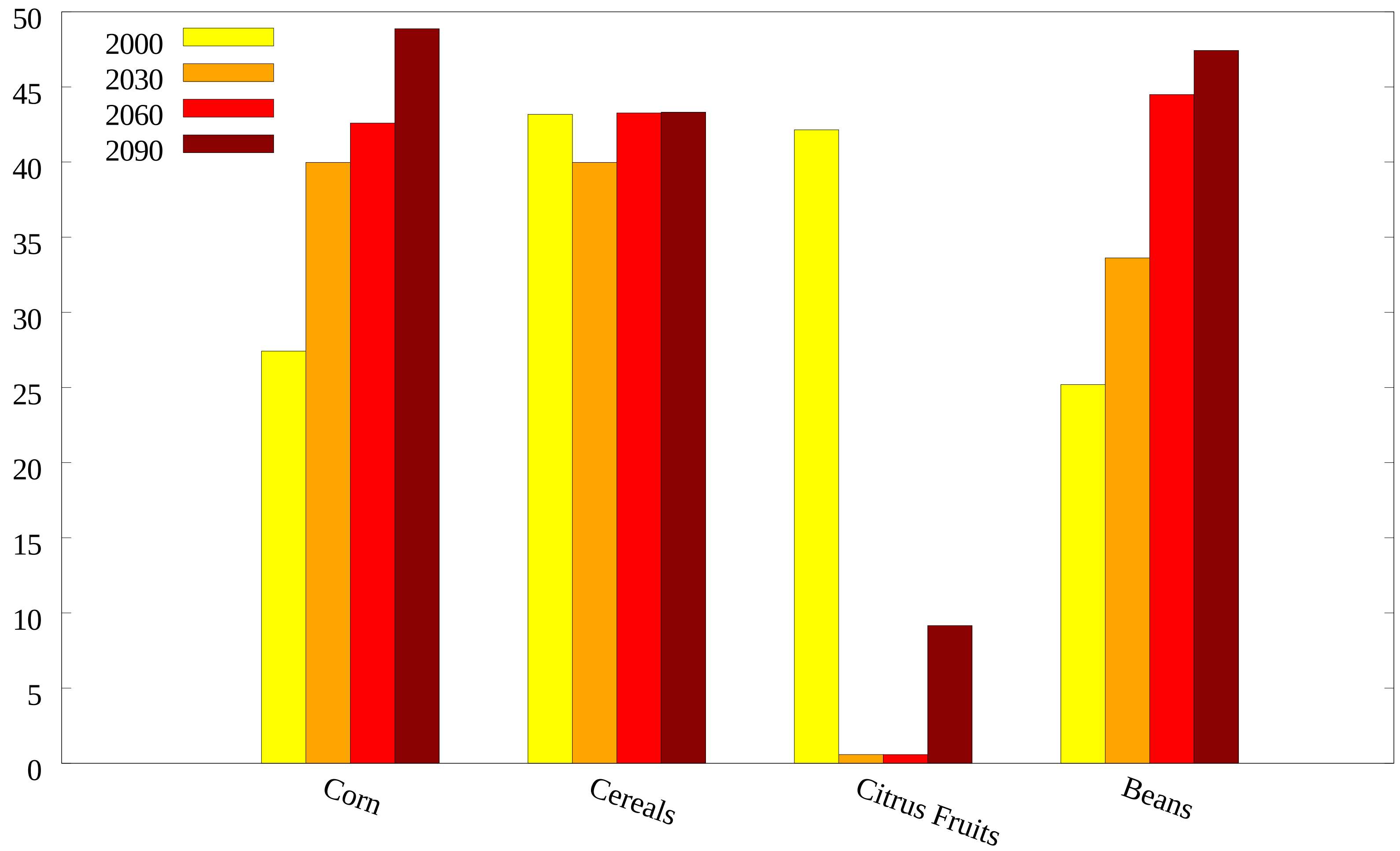

Figure 9 **Effect of projected climate change and 100% internalization of external environmental cost of pesticides on area share (in percent) under pesticide free management by crop group**

Appendix 1

Mathematical Structure of ASMGHG

ASMGHG is setup as mathematical programming model and contains more than 20, 000 individual variables and more than 5, 000 individual equations. These equations and variables are not entered individually but as indexed blocks. All agricultural production activities are specified as endogenous variables and denoted here by capital letters. In particular, the variable block CROP denotes crop management variables, LUTR = land use transformation, LIVE = livestock raising, PROC = processing, and INPS = production factor (input) supply variables. Additional variable blocks reflect the dissemination of agricultural products with DOMD = U.S. domestic demand, TRAD = U.S. interregional and international trade, FRXS = foreign region excess supply, FRXD = foreign region excess demand, EMIT = Emissions, and SEQU = Emission reduction or sequestration variables. WELF denotes total agricultural welfare from both U.S. and foreign agricultural markets.

Demand and supply functions are denoted in italic small letters. Equations, variables, variable coefficients, and right hand sight variables may have subscripts indicating indices with index c denoting the set of crops, f = production factors with exogenous prices (subset of index w), g = greenhouse gas accounts, h = processing alternatives, i = livestock management alternatives, j = crop management alternatives, k = animal production type, l = land transformation alternatives, m = international region (subset of index r), n = natural or human resource types (subset of index w), r = all regions, s = soil classes (subset of index n), t = years, u = U.S. region (subset of index r), w = all production factors, and y = primary and processed agricultural commodities.

Equation block (1) shows the set of commodity supply and demand balance equations employed in ASMGHG. Note that equation block (1) is indexed over U.S. regions and commodities. Thus, the total number of individual equations equals the product of 63 U.S. regions times the 54 primary agricultural commodities.

(1) $$\begin{gathered}-\sum_{c,s,j}\left(a^{CROP}_{u,c,s,j,y}\cdot CROP_{u,c,s,j}\right)-\sum_{k,i}\left(a^{LIVE}_{u,k,i,y}\cdot LIVE_{u,k,i}\right)-\sum_{r}TRAD_{r,u,y}\\ +DOMD_{u,y}+\sum_{h}\left(a^{PROC}_{u,h,y}\cdot PROC_{u,h}\right)+\sum_{r}TRAD_{u,r,y}\le 0\end{gathered}$$ **for all u and y**

The structure of equation block (1) allows for production of multiple products and for multi level processing, where outputs of the first process become inputs to the next process. All activities in (1) can vary on a regional basis.

Supply and demand relationships are also specified for agricultural production factors linking agricultural activities to production factor markets. As shown in equation block (2), total use of production factors by cropping (CROP), livestock (LIVE), land use change (LUTR), and processing (PROC) activities must be matched by total supply of these factors (INPS) in each region.

(2) $$\begin{gathered}INPS_{u,w}-\sum_{c,s,j}a^{CROP}_{u,c,s,j,w}\cdot CROP_{u,c,s,j}-\sum_{l}a^{LUTR}_{u,l,w}\cdot LUTR_{u,l}\\ -\sum_{k,i}a^{LIVE}_{u,k,i,w}\cdot LIVE_{u,k,i}-\sum_{h}a^{PROC}_{u,h,w}\cdot PROC_{u,h}\le 0\end{gathered}$$ **for all u and w**

The mathematical representation of natural resource constraints in ASMGHG is straightforward and displayed in equation block (3). These equations simply force the total use of natural or human resources to be at or below given regional resource endowments $b_{u,n}$. Note that the natural and human resource index n is a subset of the production factor index w. Thus, all $INPS_{u,n}$ resource supplies also fall into constraint set (2). The number of individual equations in (3) is given by the product of 63 U.S. regions times the number of relevant natural resources per region.

(3) $\mathrm{INPS}_{u,n} \le b_{u,n}$ **for all u and n**

In ASMGHG, trade activities by international region of destination or origin are balanced through trade equations as shown in equation blocks (4) and (5). The equations in block (4) force a foreign region's excess demand for an agricultural commodity ($\mathrm{FRXD}_{m,y}$) to not exceed the sum of all import activities into that particular region from other international regions ($\mathrm{TRAD}_{\tilde{m},m,y}$) and from the U.S. ($\mathrm{TRAD}_{u,m,y}$). Similarly, the equations in block (5) force the sum of all commodity exports from a certain international region into other international regions ($\mathrm{TRAD}_{m,\tilde{m},y}$) and the U.S. ($\mathrm{TRAD}_{m,u,y}$) to not exceed the region's excess supply activity ($\mathrm{FRXS}_{m,y}$).

(4) $$-\sum_{u}\mathrm{TRAD}_{m,u,y} - \sum_{\tilde{m}}\mathrm{TRAD}_{m,\tilde{m},y} + \mathrm{FRXD}_{m,y} \le 0 \qquad \textbf{for all m and y}$$

(5) $$\sum_{u}\mathrm{TRAD}_{u.m,y} + \sum_{\tilde{m}}\mathrm{TRAD}_{\tilde{m},m,y} - \mathrm{FRXS}_{m,y} \le 0 \qquad \textbf{for all m and y}$$

The number of individual equations in blocks (4) and (5) equals the product of the number of traded commodities times the number of international regions per commodity.

Based on decomposition and economic duality theory (McCarl 1982, Onal and McCarl 1991), it is assumed that observed historical crop mixes represent rational choices subject to weekly farm resource constraints, crop rotation considerations, perceived risk, and a variety of natural conditions[equation (6)].

(6) $$-\sum_{t}\left(h^{CMIX}_{u,c,t} \cdot \mathrm{CMIX}_{u,t}\right) + \sum_{s,j}\mathrm{CROP}_{u,c,s,j} = 0 \quad \text{for all u and c}$$

The utilization of (6) has several important implications. First, many diverse constraints faced by agricultural producers are implicitly integrated. Second, crop choice constraints impose an implicit cost for deviating from historical crop rotations. Note that the sum of the CMIX variables over time is not forced to add to unity. Therefore, only relative crop shares are restricted, allowing the total crop acreage to expand or contract. Third, crop choice constraints prevent extreme specialization by adding a substantial number of constraints in each region and mimicking what has occurred in those regions. Fourth, crop choice constraints are a consistent way of representing a large entity of small farms by one aggregate system (Dantzig and Wolfe 1961, Onal and McCarl 1989).

Crop mix constraints are not applied to crops, which under certain policy scenarios are expected to expand far beyond the upper bound of historical relative shares. In ASMGHG, the biofuel crops of switchgrass, poplar and willow fall into this category.

The mix of livestock production is constraint in a similar way as crop production [equation (7)].

(7) $$-\sum_{t}\left(h^{LMIX}_{u,y,t} \cdot LMIX_{u,t}\right) + \sum_{k,i}\left(a^{LIVE}_{u,k,i,y} \cdot LIVE_{u,k,i}\right) = 0 \quad \textbf{for all u and y}$$

Agricultural land owners do not only have a choice between different crops and different crop management strategies, they can also abandon traditional crop production altogether in favor of establishing pasture or forest. In ASMGHG, land use conversions are portrayed by a set of endogenous variables LUTR. As shown in (8), certain land conversion can be restricted to a maximum transfer $d_{u,l}$, whose magnitude was determined by GIS data on land suitability. If $d_{u,l} = 0$, then constraint (8) is not enforced. In such a case, land use transformations would only be constraint through constraint set (3).

(8) $$LUTR_{u,l} \le d_{u,l}\Big|_{d_{u,l}\ge 0} \quad \textbf{for all u and l}$$

The assessment of environmental impacts from agricultural production as well as political opportunities to mitigate negative impacts is a major application area for ASMGHG. To facilitate this task, ASMGHG includes environmental impact accounting equations as shown in (9) and (10). A detailed description of environmental impact categories and their data sources is available in Schneider (2000).

(9) $$\begin{aligned}\mathrm{EMIT}_{u,g} = &\sum_{c,s,j}\left(a^{CROP}_{u,c,s,j,g}\cdot \mathrm{CROP}_{u,c,s,j}\right)\Big|_{a^{LAND}_{u,c,s,j,g}>0}\\ &+\sum_{l}\left(a^{LUTR}_{u,l,g}\cdot \mathrm{LUTR}_{u,l}\right)\Big|_{a^{LUTR}_{u,l,g}>0}\\ &+\sum_{k,i}\left(a^{LIVE}_{u,k,i,g}\cdot \mathrm{LIVE}_{u,k,i}\right)\Big|_{a^{LIVE}_{u,k,i,g}>0}\\ &+\sum_{h}\left(a^{PROC}_{u,h,g}\cdot \mathrm{PROC}_{u,h}\right)\Big|_{a^{PROC}_{u,h,g}>0}\end{aligned}$$ **for all u and g**

(10) $$\begin{aligned}\mathrm{SEQU}_{u,g} = &\sum_{c,s,j}\left(a^{CROP}_{u,c,s,j,g}\cdot \mathrm{CROP}_{u,c,s,j}\right)\Big|_{a^{LAND}_{u,c,s,j,g}<0}\\ &+\sum_{l}\left(a^{LUTR}_{u,l,g}\cdot \mathrm{LUTR}_{u,l}\right)\Big|_{a^{LUTR}_{u,l,g}<0}\\ &+\sum_{k,i}\left(a^{LIVE}_{u,k,i,g}\cdot \mathrm{LIVE}_{u,k,i}\right)\Big|_{a^{LIVE}_{u,k,i,g}<0}\\ &+\sum_{h}\left(a^{PROC}_{u,h,g}\cdot \mathrm{PROC}_{u,h}\right)\Big|_{a^{PROC}_{u,h,g}<0}\end{aligned}$$ **for all u and g**

All equations described so far have defined the convex feasibility region for the set of agricultural activities. The purpose of this single equation is to determine the optimal level of all endogenous variables within the convex feasibility region. In ASMGHG a price-endogenous, welfare based objective function is used as proposed by McCarl and Spreen (1980) This equation is shown equation 11The left hand side of equation11 contains the unrestricted total agricultural welfare variable (WELF), which is to be maximized. The right hand side of equation equation11 contains several major terms, which will be explained in more detail below.

$$
\begin{aligned}
\text{Max WELF} = &\sum_{u,y}\left[\int_{y} p_{u,y}^{DOMD}\left(\text{DOMD}_{u,y}\right)d(\cdot)\right] \\
&-\sum_{u,n}\left[\int_{n} p_{u,n}^{INPS}\left(\text{INPS}_{u,n}\right)d(\cdot)\right] \\
&+\sum_{m,y}\left[\int_{y} p_{m,y}^{FRXD}\left(\text{FRXD}_{m,y}\right)d(\cdot)\right] \\
&-\sum_{m,y}\left[\int_{y} p_{m,y}^{FRXS}\left(\text{FRXS}_{m,y}\right)d(\cdot)\right] \\
&-\sum_{u,f}\left(p_{u,f}^{INPS}\cdot \text{INPS}_{u,f}\right) \\
&-\sum_{r,\tilde{r},y}\left(p_{r,\tilde{r},y}^{TRAD}\cdot \text{TRAD}_{r,\tilde{r},y}\right)
\end{aligned}
$$

The first term $\sum_{u,y}\left[\int_{y} p_{u,y}^{DOMD}\left(\text{DOMD}_{u,y}\right)d(\cdot)\right]$ adds the sum of the areas underneath the inverse U.S. domestic demand curves over all crops, livestock products, and processed commodities.

The second right hand side term $-\sum_{u,n}\left[\int_{n} p_{u,n}^{INPS}\left(\text{INPS}_{u,n}\right)d(\cdot)\right]$ subtracts the areas underneath the endogenously priced input supply curves for hired labor, water, land, and animal grazing units.

The following two terms $+\sum_{m,y}\left[\int_{y} p_{m,y}^{FRXD}\left(\text{FRXD}_{m,y}\right)d(\cdot)\right]$ and $-\sum_{m,y}\left[\int_{y} p_{m,y}^{FRXS}\left(\text{FRXS}_{m,y}\right)d(\cdot)\right]$ account for the areas underneath the foreign inverse excess demand curves minus the areas underneath the foreign inverse excess supply curves. Together these two terms define the total trade based Marshallian consumer plus producer surplus economic of foreign regions.

Finally, the terms $-\sum_{u,f}\left(p_{u,f}^{INPS}\cdot INPS_{u,f}\right)$ and $\sum_{r,\tilde{r},y}\left(p_{r,\tilde{r},y}^{TRAD}\cdot TRAD_{r,\tilde{r},y}\right)$ subtract the costs of exogenously priced production inputs and the costs for domestic and international transportation, respectively.