Pests and Agricultural Production under Climate Change

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Abstract

Although the effect of climate change on agricultural pests has been studied by biologists, thus far, large-scale assessments of climate change and agriculture have not included the impact of pests. We develop a simple theoretical model of farmer-pest interaction under climate change and explore the potential impacts on land values.

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There are several current examples of damage caused by the sudden spread of agricultural pests and crop diseases. Within two years of its first detection in 1989, the glassy-winged sharpshooter and its associated crop diseases had destroyed the majority of grape vines in the Temecula Valley of southern California, causing many growers to close their operations. In addition to grower costs, the federal government and State of California have dedicated $36 million for research to address the spread of the diseases associated with the glassy-winged sharpshooter. More recently, hoof and mouth disease in the UK has resulted in the destruction of more than two million animals in a two and a half month period, incurring devastating costs to both farmers and government. Many biologists predict an increase in the frequency of such exotic pest invasions as global temperatures rise.

Economists are working to determine the potential effects of climate change and, more particularly, how adaptive behavior or government policies may help mitigate the negative effects associated with increasing temperature and carbon-dioxide (CO2) levels. Thus far, large-scale assessments of the economic effects of climate change have ignored the interaction of pests and climate established within the entomology and biology literature (Porter, Parry, and Carter; Harrington and Stork; IPCC 1996; Patterson et al.).[1] Most research indicates that insect pest activity, the second major cause of damage to crops, will increase under climate change, leading to greater risk of crop losses (Rosenzweig and Hillel; Gutierrez; Patterson et al.). Moreover, while the direct effects of climate change on crops are expected to occur gradually, allowing controlled adaptation (Mendelsohn, Nordhaus, and Shaw, 1994), changes in pest activity may occur quickly and dramatically. New pest invasions can cause significant damage within a very short period and may remain indefinitely. The rapid time frame within which farmers may have to respond to these changes could lead to explosive transition and adaptation costs. Given the potential size and scope of exotic pest damage, the inclusion of pest behavior is vital to any assessment of the damages associated with climate change.

Separate from the climate change literature, agricultural economists have developed theoretical and empirical approaches to model how pests and pest control affect farmer production decisions. This literature focuses on the econometric specification of models, estimating marginal productivity of pesticides, determining optimal pest control under uncertainty, and understanding the impacts of different policy regimes on such factors as farm worker health and the environment. Few studies have explicitly included pest population dynamics (Regev, Shalit, and Gutierrez; Sunding and Ziven; Saphores), and none have explicitly considered the response of pests to climate change.

In this paper we address the pest issues that must be understood before reasonable estimates of climate change impacts may be assessed. In the following we present the current understanding of how climate change is likely to affect pest migration and behavior, discuss the ability of farmers and policy-makers to mitigate these changes in pest behavior and the costs incurred in these efforts. We develop a model of farmer-pest interaction under climate change and use it to explore the likely impacts of climate change on pest damage and land values. Finally we review how existing assessments of the impacts of climate change may be improved by including the effects of pest activity.

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[1] An exception is the work by Chen and McCarl that relates climate change and pesticide costs. We discuss this study later.

Climate Change and Pest Activity

Agricultural systems are a complex balance of biological, agronomic and economic factors with agricultural producers closely managing crop-pest interactions. Climate change will fundamentally alter the underlying agro-ecosystems through elevated temperatures and CO_2 levels, leading to changes in pest activity and population levels (IPCC 1996). Higher temperatures will increase rates of development and the number of pests surviving the winter temperatures. Geographic distributions of crops, pests, and predators are expected to shift, with pests extending to higher latitudes. For example, the northern distribution of the pink bollworm, a pest known to feed on cotton, is limited by cold winter temperatures. It has been restricted from spreading to the San Joaquin Valley in California because heavy frosts are common in this area (Gutierrez). Climate change may enable this pest to invade the Valley. Pests may cause damage for longer periods within a year. Warmer temperatures in the spring and fall will enable certain pests to become active sooner in the season and persist longer.

In addition to these direct effects on pests, climate change will alter the seasonal patterns and chemistry of crop plants, indirectly affecting the pests that feed on the plants. For example, elevated CO_2 levels may change the nutritional content of some crops, increasing the feeding requirements for insect pests (U.S. EPA). Even if pest numbers do not change each pest may become more destructive and more intense infestations may occur (Patterson et al; Harrington and Stork; IPCC 1998).

Farmer and Public Response to Pests

Climate-induced changes in pest activity are likely to affect agricultural production in several ways. Increased pest populations will stress crop plants and increase the risk of crop loss (Gutierrez; Patterson et al.), reducing yield and/or quality of harvest. Moreover, as climate change progresses, the damages due to pests will compound and interact with plant stress due to the direct effects on crops of changes in temperature, precipitation, and carbon dioxide levels.

Farmers may respond to new pest activity by changing their pesticide use. Feder uses a simple expected utility framework to show that as variance of pest damage increases, threshold populations that trigger pesticide application decline (pesticide is applied more often) – and for infestation levels above the threshold, pesticide application increases. With increased pesticide use comes additional crop damage as well as associated environmental and health impacts. If new pests are resistant to current pesticides, farmers may choose to use new chemicals. Moreover, effective techniques to combat foreign pest species may not exist or may not be known. New chemical pesticides or newer strains of crops may be required. Ferdandez-Cornejo, Jans, and Smith note that the costs to research and develop a new chemical pesticide are high ($50 to $70 million) and may take many years to complete.

For some pests, pesticides may have only limited effectiveness and farmers may choose to reduce current production to avoid or eradicate pests. For example, in the Imperial Valley of California, where pest problems tend to occur during the last weeks of summer, a shorter growing season can help combat the effects of pests. Farmers can harvest early, reducing pest damage along with yield and input use (Carlson and Wetzstein).

Farmers may also respond to pests through changes in non-pesticide practices – irrigation, fertilizer use, or use of precision farming practices. Farmers may work with extension agents to adopt a multi-pronged approach of field inspections, specific practices, and biological controls often called Integrated Pest Management (IPM). In particular, IPM's focus on scouting, or monitoring pest populations to determine the optimal timing of farmer response, may make IPM particularly effective for dealing with climate-induced changes in pest activity. On the other hand, IPM's reliance on a delicate balance of biological controls and known pests may make it more susceptible to collapse under climate change. Farmers, local consultants and extension agents may not recognize exotic species, or have the pest specific knowledge necessary to prevent damage due to a recently invading pest.

In extreme cases, farmers may choose to switch crops entirely, or destroy current crops or livestock. Destruction of infected livestock is the primary defense strategy against spread of hoof and mouth disease. Throughout California, grape growers have worked to slow the spread of Pierce's disease primarily by removing and replacing vines in infected areas at great cost to the grower.

Costs of Response

Input use changes, cropping changes and, in extreme cases, destruction of crops and livestock come at a cost. Farmers may face lost revenues from pest and pesticide damage to crops, higher pest control and input costs, and costs of obtaining new human capital (first–hand experience with a particular crop or pest) as well as physical capital from switching crops. As noted by Quiggin and Horowitz, these costs of adjustment may be significant. Incorrect beliefs concerning climate change trends, in addition to high fixed costs of adaptation, may slow farmer investment in pest mitigation strategies.

Governments traditionally play a significant role in managing exotic pests and crop disease outbreaks. All levels of government – federal, state and local - have a role in preventing and responding to new pests and increased pest activity. The USDA is responsible for setting import standards, inspection and funding new research. State-level departments of agriculture develop and enforce state-specific standards for inspection and pest eradication. Extension agents from state universities work with local farmers and farmer associations to develop regional as well as farm specific response strategies. When exotic pests invade, resources must be spent to train local extension agents, and later farmers, about strategies to combat the new pest. As was the case with the glassy-winged sharp shooter, and the Mediterranean fruit fly in California, significant amounts of money may be spent by both state and federal governments to prevent widespread damage.

General Framework

It is important that any model of farmer welfare under climate change include the possible effects of altered pest behavior. We frame the problem for a decision-maker in a particular region facing uncertainty in pest damage.[3] Suppose the decision-maker's problem may be represented as follows:

$$\max_{\{x_i, y_i\}_{i=1}^{\infty}} \left\{ \sum_{t=1}^{\infty} \frac{1}{(1+r)^t} E_0 \left[\left(w + R(x_t, y_t) \right) - c(D_t, x_t, y_t) \right] \right\},$$

where x_t is a vector of mitigation behaviors (e.g., pesticide use) chosen in period t, y_t is a vector of target level yields for various crops, T represents climate variables, B mitigation actions taken by outside actors (e.g., government or neighboring farmers), w represents wealth, r is the interest

[3] Although we focus here on agriculture, the model can represent the impact of pests on any managed environment (e.g., forests, fisheries, or urban landscapes.)

rate, R represents revenue, and c are production costs incurred. Crop damage in year t, given by D_t, is a random variable with density function given by $f_t\left(D_t \mid D_{t-1}, x_t, y_t, T, B\right)$. Hence, current decisions will affect the distribution of damages in future periods. The operator E_t denotes the expectation with respect to the random variables D_i with $i > t$ given the value D_t. Given knowledge of damage in the current period, the decision-maker considers all possible damage in the future.

Adaptation to climate change may take the form of a new crop choice (reflected in y_t), or in the levels of mitigation behavior chosen (reflected in x_t). Government policies (reflected in B) may promote or prevent pest damage. Irresponsible trade policies may increase the chances of foreign pest invasions, causing greater costs to farmers. Subsidizing farmer training through extension may lower the costs to farmers from pest damage. It is likely (particularly in the cases of exotic species and climate change) that farmers misperceive the correlation between today's actions and tomorrow's pest damage. A myopic farmer (one who ignored future costs of this period's actions) would likely under-invest in mitigation activity or adaptive strategies (Just). Further, if mitigation has positive external effects on neighboring farmers, investment in mitigation may be sub-optimal from a social welfare standpoint even if the farmer has perfectly rational expectations.

Farmer welfare may be represented by the change in land values (Mendelsohn, Nordhaus and Shaw 1994). It is common to assume that agricultural land-values are equivalent to the net present discounted value of the stream of maximized profits from agricultural production. In this sense, the framework presented in this section can be thought of as a farm welfare model under climate change. It would be difficult to make use of this model in any context without first employing some set of simplifying assumptions. In the next section we provide a simple example of the relationship this model implies for land-values, climate change and exotic pest invasions.

A Simple Example

Let us consider a single pest with significant destructive capacity that has not yet entered the region of our analysis. In this case, there is a significant probability that no damage will be done by the pest in this period, some possibility of positive damage, and little probability of large damage.

Figure 1. Probability Density of Damage Following a Year with No Damage.

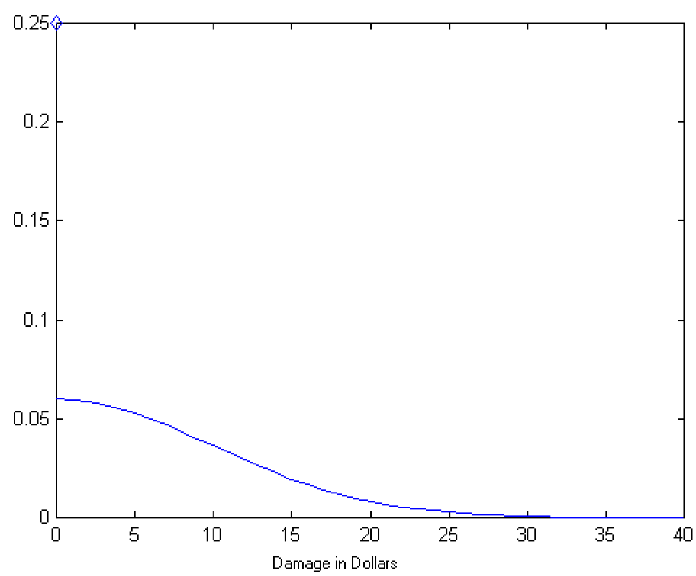

Figure 1 displays a possible probability density of damages from an exotic pest in a typical year. There is a mass point at zero, indicating that $0 damages occur with probability .25 (realistically this should be much higher) and positive but decreasing density for values larger than zero. We can suppose that the farmer employs subjective beliefs similarly to the true distribution of damages when he plants and makes production decisions for the coming year.

Let us examine a single crop. Of course, if the profitability of this crop falls low enough, a farmer is likely to switch crops to maintain the value of production. By examining a single crop we wish only to show that climate change may have significant impacts on cropping decisions. Hence, even if temperatures and rainfall remained nearly the same, CO2 levels may cause crop switching due to increased pest activity. Suppose that the farmer faces the following problem in time period *t*

$$\max_{y} E\left(py - C\left(D_t, y, T\right)\right).$$

Where *y* is the target yield (which implicitly defines input choice), prices, given by *p*, are exogenous, and costs are given by *C*. Costs depend on the farmer's choice of *y*, climate, *T*, and pest damage. Suppose that the damage from pest species, D_t has the following definition

$$D_t = \begin{cases} u_t & \text{if} \quad u_t > 0 \\ 0 & \text{if} \quad u_t \leq 0, \end{cases}$$

where u_t is a random variable with cumulative density $F\left(u_t \mid u_{t-1,}, T, B\right)$. This formulation simplifies the previous formulation by making the choice of y_t independent from one period to the next. Theoretically, the first order conditions from this optimization can be solved for the optimal level of production, $y^*\left(u_{t-1}, T, B\right)$.

We can further simplify this model by assuming u_t depends upon u_{t-1} in the following way

$$F\left(u_t \mid u_{t-1}, T, B\right) = \begin{cases} F_0\left(u_t \mid T, B\right) & \text{if} \quad u_{t-1} \leq 0 \\ F_1\left(u_t \mid T, B\right) & \text{if} \quad u_{t-1} > 0. \end{cases}$$

This assumption allows us to more easily examine future behavior of the farmer, as now there are two possible planned levels of production, $y_g^*\left(T, B\right)$ following a year with no damage, and

$y_b^*(T,B)$ following a year with some positive level of damage. This means also that, following a year with no damage, we may represent the farmer's expected profits as $p_g^*(T,B)$, and, following a year with positive damage from pest invasions, we may denote expected profits $p_b^*(T,B)$. Two years following a good year the expected profit is given by $E_t(p_{t+2}) = F_0(0)p_g^* + (1-F_0(0))p_b^*$.

Let us assume that $F_0(0\,|\,T,B) = (1-\bar{h})$, and $F_1(0\,|\,T,B) = (1-\underline{h})$, where $\bar{h}$ is the probability of damage this period given there was no damage last period and $\underline{h}$ is the probability of damage this period given there was damage last period. Suppose that a_t and b_t are the probability of no damage and damage respectively in period *t* evaluated at period zero. Then in period $t+1$ the probability of no damage is $a_t(1-\bar{h}) + b_t(1-\underline{h})$ and the probability of damage is $a_t\bar{h} + b_t\underline{h}$. We can write this as a linear difference equation in vector notation as

$$v_{t+1} = \begin{bmatrix} 1-\bar{h} & 1-\underline{h} \\ \bar{h} & \underline{h} \end{bmatrix} v_t = Av_t,$$

where $v_t = \begin{bmatrix} a_t \\ b_t \end{bmatrix}$. The net present discounted value of profits is thus given by

$$NPV = \sum_{t=1}^{\infty} \frac{1}{(1+r)^t} \begin{bmatrix} p_g^* & p_b^* \end{bmatrix} A^t v_0.$$

Using the Putzer Algorithm (Elaydi) it is possible to rewrite A^t as

$$A^t = \begin{bmatrix} 1-\bar{h}\sum_{i=0}^{t-1}\left(\underline{h}-\bar{h}\right)^{t-1-i} & \left(1-\underline{h}\right)\sum_{i=0}^{t-1}\left(\underline{h}-\bar{h}\right)^{t-1-i} \\ \bar{h}\sum_{i=0}^{t-1}\left(\underline{h}-\bar{h}\right)^{t-1-i} & 1+\left(\underline{h}-1\right)\sum_{i=0}^{t-1}\left(\underline{h}-\bar{h}\right)^{t-1-i} \end{bmatrix}.$$

If the pest species is not present in the region in period zero (i.e., it is exotic), then the probability of damage in period 0 is 1, or $v_0 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$, and if the species is already present by the time of calculation, then $v_0 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$. Thus we can solve for the difference in capitalized land value if invasion has not yet occurred, NPV_g, and if the pest is already present, NPV_b. By simple substitution, we find

$$NPV_g = \sum_{t=1}^{\infty} \left\{ \frac{p_g^* - \left(p_g^* - p_b^*\right)\left[\bar{h} \sum_{i=1}^{t-1} \left(\underline{h} - \bar{h}\right)^{t-1-i}\right]}{\left(1+r\right)^t} \right\}.$$

and

$$NPV_b = \sum_{t=1}^{\infty} \left\{ \frac{p_b^* + \left(p_g^* - p_b^*\right)\left[\left(1-\underline{h}\right) \sum_{i=1}^{t-1} \left(\underline{h} - \bar{h}\right)^{t-1-i}\right]}{\left(1+r\right)^t} \right\},$$

The difference in capitalized land values for farms that have the pest in the initial period and those that do not is given by

$$NPV_g - NPV_b = \sum_{t=1}^{\infty} \left\{ \frac{\left(p_g^* - p_b^*\right)\left[1 + \left(\underline{h} - \bar{h} - 1\right) \sum_{i=1}^{t-1} \left(\underline{h} - \bar{h}\right)^{t-i-1}\right]}{\left(1+r\right)^t} \right\}.$$

Comparative Statics

First, let us suppose that T represents CO2 levels, and examine the effects of elevated CO2 on land values, and disparity in farm income due to agricultural pests. The following derivatives are informative

(1.1)

$$\frac{\partial NPV_g}{\partial T}=\sum_{t=1}^{\infty}\left\{\frac{p^*_{gT}-\left(p^*_{gT}-p^*_{bT}\right)\left[\bar{h}\sum_{i=1}^{t-1}\left(\underline{h}-\bar{h}\right)^{t-1-i}\right]-\left(p^*_{g}-p^*_{b}\right)\left[\bar{h}_T\sum_{i=1}^{t-1}\left(\underline{h}-\bar{h}\right)^{t-1-i}+\left(\underline{h}_T-\bar{h}_T\right)\bar{h}\sum_{i=1}^{t-1}\left(t-1-i\right)\left(\underline{h}-\bar{h}\right)^{t-2-i}\right]}{\left(1+r\right)^t}\right\},$$

(1.2)

$$\frac{\partial NPV_b}{\partial T}=\sum_{t=1}^{\infty}\left\{\frac{p^*_{bT}+\left(p^*_{gT}-p^*_{bT}\right)\left[\left(1-\underline{h}\right)\sum_{i=1}^{t-1}\left(\underline{h}-\bar{h}\right)^{t-1-i}\right]+\left(p^*_{g}-p^*_{b}\right)\left[\left(\underline{h}_T-\bar{h}_T\right)\left(1-\underline{h}\right)\sum_{i=1}^{t-1}\left(t-1-i\right)\left(\underline{h}-\bar{h}\right)^{t-2-i}-\underline{h}_T\sum_{i=1}^{t-1}\left(\underline{h}-\bar{h}\right)^{t-1-i}\right]}{\left(1+r\right)^t}\right\},$$

and,

(1.3)

$$\frac{\partial\left(NPV_g-NPV_b\right)}{\partial T}=$$

$$\sum_{t=1}^{\infty}\left\{\frac{\left(p^*_{gT}-p^*_{bT}\right)\left[1+\left(\underline{h}-\bar{h}-1\right)\sum_{i=1}^{t-1}\left(\underline{h}-\bar{h}\right)^{t-1-i}\right]+\left(p^*_{g}-p^*_{b}\right)\left[\left(\underline{h}_T-\bar{h}_T\right)\sum_{i=1}^{t-1}\left(\underline{h}-\bar{h}\right)^{t-1-i}+\left(\underline{h}_T-\bar{h}_T\right)\left(\underline{h}-\bar{h}-1\right)\sum_{i=1}^{t-1}\left(t-1-i\right)\left(\underline{h}-\bar{h}\right)^{t-2-i}\right]}{\left(1+r\right)^t}\right\}.$$

The derivative in (1.1) will be negative if $p^*_{gT}<0$, $p^*_{bT}<p^*_{gT},$ $\bar{h}_T>0,$ and $\bar{h}_T<\underline{h}_T$. The conditions on profit require that CO2 levels lower profits in both states, but have a larger effect on profits in the bad state. The conditions on probabilities require that CO2 levels increase the probability of invasion and decreases the probability of eliminating a pest that has invaded. Note that these are sufficient conditions.

The derivative in (1.2) will be negative if $p^*_{bT} < 0$, $p^*_{gT} < p^*_{bT,}$ $\underline{h}_T > 0$, and $\bar{h}_T > \underline{h}_T$. These conditions require the same signs on all parameters as in the previous paragraph, however the relationships between good and bad state parameters are switched. If an increase in CO2 implies profit decreases faster in the good state than in the bad, and the probability of invasion increases faster than the probability of a pest remaining, then the land value of an infested farm will decrease.

The derivative in (1.3) will be positive if $p^*_{gT} > p^*_{bT}$, and $\bar{h}_T < \underline{h}_T$. This condition on profits indicates that CO2 decreases profits of infested farms faster than that of un-infested farms. The condition on probabilities is that the probability of continued infestation increases faster than the probability of a new infestation. Another way to describe this condition is in terms of the informational content of an infestation. If infestations are rare and unlikely to be eradicated, then knowing the current state of the land reveals more information about future profitability. The current research in biology suggests that these relationships will hold under climate change, suggesting one effect of climate change is greater disparity between infested farms and un-infested farms. This increases the potential damage of an exotic pest introduction.

Numerical Examples

Since climate is likely to affect $\bar{h}$ and $\underline{h}$, it may be illustrative to consider how changes in these parameters may affect welfare Table 1 gives values for the difference, $NPV_g - NPV_b$, assuming r = .05, $p^*_g - p^*_b = 100$, and allowing $\bar{h}$ and $\underline{h}$ to take on various values in relevant ranges.

Table 1. Changes in Welfare at the Time of Invasion

$\bar{h}$	$\underline{h} = 0.5$	$\underline{h} = 0.6$	$\underline{h} = 0.7$	$\underline{h} = 0.8$	$\underline{h} = 0.9$	$\underline{h} = 1.0$
0.0	$191	$233	$300	$420	$700	$2100
.1	$162	$191	$233	$300	$420	$700
.2	$140	$162	$191	$233	$300	$420
.3	$124	$140	$162	$191	$233	$300
.4	$111	$124	$140	$162	$191	$233
0.5	$100	$111	$124	$140	$162	$191

As the probability of moving from a state with no damage (no pest) to a state with damage goes down ($\bar{h}$ decreases – the pest is less likely to invade), and as the probability of damages continuing into the next period goes up ($\underline{h}$ increases – the pest is more persistent) then the difference in damages between farms with and without the pest in the initial period increases. It is reasonable that most regions currently would have an $\bar{h}$ of less than .1 for pests that are potentially extremely damaging. And for many invading species of insects, $\underline{h}$ (a measure of how permanent an invasion is likely to be) may be very high if the pests are unlikely to leave or are not easily eliminated with pesticides or other treatment methods.

Let us now assume that when a new pest is introduced, profit in current period is reduced by X percent, $X = \left(p_g^* - p_b^*\right) / p_g^*$. It is now possible to express the decrease in land-value from a pest invasion as a percentage of land value before the pest is introduced. Table 2 displays this loss as a percentage of X for various values of $\bar{h}$ and $\underline{h}$. Note that these numbers are independent of profit levels. A pest that is extremely unlikely to invade and is highly persistent may cause a shift in land values close to 100% of the instantaneous change in profitability *X* (given that farmer is continues to farm the same crop). The impact would not be so great if the farmer now finds it profitable to plant a different crop that is resistant to the new pest.

Table 2. Changes in Welfare at Time of Invasion (as a Percentage of *X*).

$\bar{h}$	$\underline{h} = 0.5$	$\underline{h} = 0.6$	$\underline{h} = 0.7$	$\underline{h} = 0.8$	$\underline{h} = 0.9$	$\underline{h} = 1.0$
0.0	9.08%	11.12%	14.28%	20.00%	33.32%	100.00%
0.1	8.00%	9.52%	11.76%	15.4%	22.24%	40.00%
0.2	7.16%	8.32%	10.00%	12.52%	16.68%	25.00%
0.3	6.44%	7.40%	8.68%	10.52%	13.32%	18.20%
0.4	5.88%	6.68%	7.68%	9.08%	11.12%	14.28%
0.5	5.40%	6.08%	6.88%	8.00%	9.52%	11.76%

Improving Estimates of Climate Change

Recent large-scale assessments conclude that adaptation may significantly mitigate the potential costs of climate change for agriculture (U.S. National Assessment; Mendelsohn, Nordhaus, and Shaw; Mendelsohn and Neumann; IPCC 1996) and may even result in benefits for the agricultural sector. These assessments ignore several factors including pests; Adams, Hurd, and Reilly state that including such factors could change the conclusions of these assessments.

There are two prominent methods of predicting the effects of climate change on agriculture: the Ricardian and production function approaches. Within this section we critique the way these methods handle (or ignore) agricultural pests and suggest extensions that may provide more accurate predictions. This critique is motivated by the scientific evidence linking climate change and pests. Incorporating pest factors in the effects of pest damage may have a significant impact on damage estimates.

The Ricardian Method

Mendelsohn, Nordhaus, and Shaw (1994) estimate the impact of climate change on U.S. farmers using what they have termed the "Ricardian" approach. This approach assumes a relationship between land-values and ability to profit from land use. Given that each land-owner maximizes profit from land-use activities, the value of the land should be the net present discounted value of the stream of profits from this land. They project the value of land under hypothetical climate conditions using a hedonic pricing system estimated using current climate, land characteristic and land value data. In other words land value at some future date may be represented as

$$LV = f(T) + e,$$

Where LV is land value, T is some vector of climate and land characteristic variables and e is an error term.

As previously discussed, a critique of this model is that it ignores the dynamic effects of climate change (Quiggin and Horowitz). In other words, a farmer may maintain land value by switching crops, but there are costs to switching crops that are not capitalized in land values. Mendelsohn, Nordhaus, and Shaw (1999) suggest that these effects may be negligible as climate change is likely to occur over such a long period of time. If new equipment is bought when older equipment would have to be replaced anyway, then costs of switching crops may be small. As we discussed, however, pest populations may respond rapidly and dramatically to climate change, requiring quick and significant response and adaptation.

If all pest behavior and migration were deterministically controlled by temperature alone, then the Ricardian method, as it has been used to date, would be adequate for predicting land values (except for adjustment costs). The indirect effect of $CO2$ on pests and plants, however, is ignored in these studies. Further, pest migration and introduction is not easily predictable. Some exotic species will thrive in areas they have never before lived. Others, who may face less evolutionary pressure in their current region, may remain even when climate has changed in a significant way. In other words there is a degree of uncertainty in predicting the pest population in a certain location even if $CO2$ levels are taken into account.

Let us consider two regions, A and B. Suppose we believe that 100 years from now region A will face climate factors, *T*, identical to those now extant in region B. If we wished to use the Ricardian method to estimate land values in A under climate change, we would simply use equation 1 and estimate

$$LV_{100}\left(A\right)=LV_{0}\left(B\right)=f\left(T_{B}\right).$$

However, this ignores the effects of pest migration. There may be some exotic pests that could thrive in the climate of region B but that are not living there currently. These pests may already exist in region A, or it may be that they will be introduced to region A in the next 100 years. In truth there may be many pests that fit this description. From our dynamic example we know that the existence of such a pest would bias our land value estimates, possibly severely (i.e., if we do not know if we in a state that is best represented by NPV_b or NPV_g).

It may be possible to eliminate this problem by incorporating some proxy for the response of pest populations to climate and then use some algorithm to find the expected land value of A given possible pest and climate scenarios. For instance, we could propose the model

$$ELV = E\left(f\left(\mathbf{T},\mathbf{P}\right) + e \right),$$

where **P** is a random vector of pest populations within the region, where **P** has joint density given by $g\left(\mathbf{P} \mid \mathbf{T},\mathbf{Y}\right)$, where **Y** is a vector of factors such as trading partners and current pest populations in adjoining regions.

In an effort to consider the effect of pests, Chen and McCarl use a Ricardian-type approach to assess the relationship between rainfall and growing season temperature variations and pesticide use/costs using data at the state level. The authors find that climate change alters the average and variability of pesticide treatment costs, though the impacts are not very significant, and their tests have very little power. This approach is not adequate for characterizing the impacts of climate change and pests. The climate variables included do not necessarily represent critical thresholds for year-to-year population levels such as winter temperatures. The study in no way considers pest population dynamics, spatial dynamics nor any kind of response other than pesticide use. The study is also severely limited by aggregation - aggregate pesticide costs by state do not allow local or sub-regional effects to be evaluated. Climate/pest/crop interactions can only be meaningfully considered when examined on a geoclimactic-region basis.

The Production Function Approach

The production function approach to estimating the effects of climate change uses the farmer's profit maximization problem along with crop models to impute the damage due to climate change. Typically the farmer is assumed to have a vector production function, and must solve the problem

$$\max_{\mathbf{x}} \mathbf{pf}\left(\mathbf{T},\mathbf{x}\right)-C\left(\mathbf{x}\right),$$

where **f** is a vector of outputs, **p** is a vector of prices, and **x** is a vector of inputs. Given a specification of the production function, it is possible to estimate parameters and examine the effects of a change in **T** on the profit to the farmer.

Mendelsohn, Nordhaus and Shaw (1994) criticize this method as requiring too much data in estimation. Essentially, the modeler must plan for every crop contingent in order to get accurate estimates. Without allowing the farmer to fully adjust, the estimates will be biased upwards. Pests may again be viewed as a missing variable within these models. By modifying the production function to include a vector of pest populations, as in the previous section, and using models of pest migration, it may be possible to improve estimates. However, doing so would increase the burden Mendelsohn, Nordhaus, and Shaw have drawn attention to. Certainly there are many more pests that may be relevant than possible crops. Research should be narrowly focused on the subset of pests that are most important for the particular crop or region studied.

The Costs of Transition and the Role of Government

Climate change assessments should include not only farmer investment in adaptation, but also the cost of government programs that might help educate and mitigate damage. Possibly chief among these costs will be the costs to government of moving and creating human capital. The recent example of the glassy-winged sharpshooter may be illustrative. The glassy-winged sharpshooter is indigenous to the southeastern U.S., a region with a climate considered favorable for grape vineyards (Purcell 1997). In fact, many entomologists believe the glassy-winged sharpshooter to be the only reason grape production is unprofitable in the southeastern U.S. (Purcell 1997). Because no grapes are grown in this region, there was very little reason to study the behavior of this pest. In 1989 the glassy-winged sharpshooter was discovered in southern California, and began to destroy many of the southern vineyards. Currently the insect has migrated as far north as Napa and Sonoma counties, and the state and federal governments are struggling to find any viable method of controlling damage.

Beyond public research efforts, there have been problems in communicating the seriousness of the problem to vineyard owners. Because growers have never experienced destruction of the magnitude caused by the glassy-winged sharpshooter, they display a certain degree of disbelief when extension agents prescribe preventative treatments (Purcell 2000). Resistance by growers has slowed research efforts considerably.

Concluding Remarks

Of necessity, any estimates of climate change impacts will be flawed. The processes that govern climates, species and producer decisions are too complex to be perfectly captured in any model. However, there are certainly some areas in which we may improve existing estimates.

We suggest that, while difficult to model, pest activity and migration should be represented in the current estimates of the impacts of climate change on agriculture. Few people living in agricultural states would call the impact of unexpected pests on local economies negligible. These effects may be even more devastating in developing countries where governments can do little to mitigate pest damage. We find that ignoring the effects of climate change on pests may be severely biasing our perception of the impacts of climate change on farmers. For this reason, greater effort should be made by policymakers and researchers to obtain the necessary data to assess the risks of increased pest activity.

Although science currently allows only very crude predictions of pest behavior, including these predictions would improve estimates. Several programs such as CLIMEX (Sutherst) are able to use changes in critical thresholds to make some probability assessments of pest migration within a region. It would be reasonable to link these models into Ricardian anlayses of the impacts of climate change.

International trade is also known as a source of pest migration. This form of migration is less predictable, in that it introduces trade agreements and trade barriers as factors that shift the effects of climate change. For example, some insects brought to U.S. ports aboard Brazilian ships may not be harmful to crops currently grown in regions near the port. Climate change may cause farmers to switch crops, possibly making trade with Brazilians more (or even less) risky. This suggests trade scenarios may also be necessary to predicting land values. Of course this would also require adjusting for climate changes among trading partners that might affect pest populations abroad. These are contingencies that would be difficult to incorporate in any meaningful way. However, the increased possibility of exotic pest invasion from climate change and increased international trade should be remembered when interpreting any estimates of the impacts of climate change.

Even if climate change is a net benefit to agriculture, preparation for and anticipation of potentially damaging pests may have significant benefits for farmers. In this way, it may be that large-scale assessment of damages from climate change may miss the mark. Perhaps we should focus more effort on anticipating the effects of climate change that may be mitigated through public policy and education. This requires more small-scale efforts to assess how microclimates may be affected rather than large general studies that provide little or no information on plausible policy.

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