Modeling Path Dependence in Agricultural Adaptation to Climate Variability and Change

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Path dependence of farmers' technical choices for managing climate risk combined with farmers' difficulties in discerning climate change from natural variability might hamper adaptation to climate change. We examine the effects of climate variability and change on corn yields in the Southeast United States using a regional climate model nested within a global climate model (GCM) simulation of the equilibrium atmospheric CO_2 concentration of 540 ppm. In addition to a climate scenario with normal variance, we modify the GCM outputs to simulate a scenario with a highly variable climate. We find that climate variability poses a serious challenge to the abilities of farmers and their supporting institutions to adapt. Consistently lower corn yields, especially in the scenario with a highly variable climate, illustrate that farmers' abilities to make informed choices about their cropping decisions can be constrained by their inabilities to exit from their current technological regimes or path dependence. We also incorporate farmers' responses to climate change using three adaptation scenarios: no adaptation, "perfect knowledge," and a scenario that mimics diffusion of knowledge across the landscape. Regardless of adaptation scenario and variance structure, the most common result is a decline in corn production to the point where yield reductions of 1 percent to 20 percent occur across 60 percent to 80 percent of the region. The advantage of the perfect knowledge adaptation scenario declines through time compared to the diffusion-process adaptation scenario. We posit that the cost of path dependence to farmers, in the form of yield reductions, is likely unavoidable because the inherent variability of the climate system will result in adaptation choices that will be suboptimal for some years. *Key Words: adaptation, agriculture, climate change and variability, path dependence, Southeast United States.*

农民技术选择在管理气候风险上的路径依赖，和农民区别气候变化和作物自然变异的困难，妨碍了他们对气候变化的适应能力。我们用嵌套在全球气候模式（GCM）中的区域气候模式，来模拟大气中二氧化碳 540ppm 浓度平衡，研究气候变化的影响和美国东南部的玉米产量变化。除了正常变异的气候情况，我们修改了全球气候模式的输出来模拟一个极为多变的气候情景。我们发现，气候变化对农民的能力和他们赖以适应的辅助机构构成了严重挑战。特别是在高度多变的气候情况下持续地降低玉米产量，说明了农民作出明智种植决定的能力，受制于他们无法从目前的技术体制或路径依赖选择中退出的境况。我们还使用三种适应方案：没有适应，"完美的知识"，以及全景观的知识传播模拟方案，来体现农民对气候变化的反应。无论是哪种适应方案和方差结构，最常见的结果是玉米产量在该地区百分之六十至百分之八十的地方下降百分之一到百分之二十。相比扩散过程中的适应方案，完美知识适应情况下的优势随着时间消退。我们断定农民路径依赖的成本，将以减产的形式不可避免，这是因为气候系统的内在变化会导致一些年份里退而求其次的适应选择。*关键词：适应，农业，气候变化和变异，路径依赖，美国东南部。*

La dependencia de la trayectoria en las opciones técnicas de los agricultores para el manejo del riesgo, combinada con sus dificultades para discernir el cambio climático de la variabilidad natural, podrían malograr la adaptación al cambio climático. Estudiamos los efectos de la variabilidad y el cambio climático sobre la producción de maiz en el Sudeste de los Estados Unidos, utilizando un modelo climático regional como parte de la simulación del equilibrio de la concentración de CO2 atmosférico de 540 ppm en un modelo climático global (GCM, sigla en inglés). Además de un escenario climático de varianza normal, modificamos los resultados generados por el GCM para simular un escenario con un clima altamente variable. Encontramos que la variabilidad climática plantea un reto serio a las habilidades para adaptarse en los agricultores y las instituciones que los apoyan. Rendimientos consistentemente más reducidos, en especial en el escenario de clima muy variable,

Annals of the Association of American Geographers, 100(4) 2010, pp. 894–907 © 2010 by Association of American Geographers
Initial submission, June 2009; revised submission, November 2009; final acceptance, January 2010
Published by Taylor & Francis, LLC.

indican que las habilidades de los agricultores para hacer elecciones informadas acerca de sus decisiones de siembra pueden verse afectadas por sus inabilidades para dejar de lado sus actuales regímenes tecnológicos o dependencia de la trayectoria. Incorporamos también las respuestas de los agricultores al cambio climático utilizando tres escenarios de adaptación: ninguna adaptación, "conocimiento perfecto" y un escenario que imita la difusión de conocimiento a través del paisaje. Sin consideración al escenario de adaptación y estructura de la varianza, el resultado más común es un declive en la producción de maiz, al punto que se presentan reducciones del 1 al 20 por ciento en un 60 al 80 por ciento de la región. La ventaja del escenario del conocimiento perfecto para la adaptación declina con el tiempo en comparación con el escenario del proceso de difusión. Planteamos que para los agricultores el costo de la dependencia de la trayectoria, manifiesto en la caida de la producción, es poco menos que inevitable debido a que la inherente variabilidad del sistema climático resultará en la elección de adptaciones que estarán por debajo del óptimo durante varios años. *Palabras clave: adaptación, agricultura, cambio y variabilidad climática, dependencia de la trayectoria, Sudeste de los Estados Unidos.*

Farmers and their supporting institutions must respond to a never-ending barrage of challenges, some localized and short term and some global and long term. In both cases, history shows that farmers and those institutions are remarkably successful in introducing measures to respond and adapt to myriad challenges, some environmental and some socioeconomic. Global agricultural capacity has grown apace with demand throughout the latter twentieth and early twenty-first centuries. However, in spite of this success, farmers everywhere in the world remain vulnerable to the vagaries of climate. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007) concludes that the Earth is committed to at least as much warming over the next ninety years as was experienced over the previous century, even if greenhouse gas concentrations are immediately curtailed to 2000 levels. This means that agricultural adaptation to climate change is both necessary and inevitable.

The ability of agricultural systems to adapt to climate change is unlikely to follow a smooth trajectory with time. One reason is due to the nature of climate change itself. Multiple climate model simulations show the potential for accelerating changes in climate with significant shifts in interannual variability (MacCracken et al. 2003; Stainforth et al. 2005). Although the average climatic conditions might be changing more or less monotonically, seasonal and interannual variability could be highly unstable, creating extreme climatic conditions. The impact of extreme climatic conditions on crop productivity will likely be far greater than effects associated with the average change in climatic conditions (Mearns, Rosenzweig, and Goldberg 1997). Another reason pertains to how accurately farmers and their supporting institutions will interpret signals of climate change and respond to them when they are embedded in a set of climate observations punctuated by a high degree of variability.

The ability of agricultural systems to adapt effectively might further worsen if those systems are path dependent on a suite of technologies that are rendered partially or totally ineffectual by the shift in climatic means and variability. The concept of path dependence or "lock-in"[1] is generally used in the analysis of adoption of competing innovations by end users, but in this article it is used to understand how path dependence might interact with climate variability to challenge the efficiency of agricultural adaptation in the future. In agriculture, path dependency occurs when a particular technological innovation becomes dominant and self-reinforcing, leading to a situation where it excludes competing and possibly superior alternatives. In the context of climate change, such rigidity implies an inability of farmers to respond appropriately to minimize losses or to take advantage of new climatic conditions. This need for appropriate and robust adaptation highlights the importance of a system that is flexible enough to make numerous informed midcourse adjustments to maintain optimal production as the climate changes. These corrections must be made in the absence of knowledge about how the climate is likely to evolve in the near future. Farmers must also establish the probability of being correct by introducing a set of adaptive choices available to them.

Does the interlocking nature of technological regimes interfere with smooth and efficient adaptive responses to climate change? In this study, we address this question through an assessment of the impacts of climate variability and change on corn (*Zea mays*) in the Southeastern United States. We use a coupled atmosphere–ocean global climate model, a regional climate model, and the Erosion Productivity Index Calculator (EPIC) agricultural production model (Williams, Jones, and Dyke 1984) to examine the impact that doubling of CO_2 emissions has on corn yields. We also investigate several possible scenarios of likely adaptive responses to changes in the climatic variability and mean in the context of path dependence as a regional process and a potential impediment to future agricultural production.

In the next section, we provide the theoretical premise of path dependency in the context of farmers' abilities to adapt smoothly to a changing climatic state. Also, we present the case that the existence of path dependency in agricultural systems is not only of theoretical importance; it has consequences for devising and implementing appropriate policies for adaptation to climate change. We discuss the study area and outline the methodology to test the concept of path dependency. We then present the results of the analysis. This is followed by a discussion of the prospect of regional agricultural adaptation to climate variability and change. In the final section, we summarize the overall findings in light of possible implications for agricultural systems to adapt to climate change and variability.

Theoretical Framework

Interest in path dependency emerged in the 1980s to counter neo-classical assumptions about the reversibility of economic decisions (Nelson and Winter 1982; Dosi 1984). It gained prominence after David's (1985) work on the economic history of technology and Arthur's (1989) work on nonlinear economic processes. The concept of path dependency was developed to describe how technologies and social systems could eventually become suboptimal solutions for new and emerging challenges due to norms associated with a particular technological regime and the sunk-in costs of investments in infrastructure for research and development (David 1985). This idea spawned interest in various fields, including geography, where it has been used to explain the fundamental features of the regional geography of economic activities. The most important characteristic of path dependency is its *nonergodicity*, a system's inability to detach itself from its past (Martin and Sunley 2006). In other words, a path-dependent system is one where the outcome evolves as a consequence of the system's own history (McGuire 2008).

Recent work on path dependency involves three overlapping ideas: path dependency as technological lock-in, as dynamic increasing returns, and as an institutional lag effect (Martin and Sunley 2006). Scholars trace the idea of path dependency as technological lock-in to David's work on adoption and the famous example of the continued dominance of the QWERTY keyboard since the 1880s, despite more efficient alternatives for keyboard arrangement. According to David (1985), lock-in exists due to "self-reinforcing" processes operating through three mechanisms: complementarities between components of technology and its uses, the economy of scale as associated with the incremental use of technology, and the inertia of sunk costs due to the difficulty of switching from prevailing to new technologies. Although reinforcing to each other, these mechanisms jointly create the conditions to privilege a set of options over new and more efficient alternatives, inhibiting the takeoff of superior technologies over the suboptimal ones, thereby generating the lock-in.

The second mechanism of path dependency, dynamic increasing returns to scale, was introduced by Arthur (1989) to illustrate that existing learning mechanisms reinforce the prevailing development paths due to shared comparative advantage. In addition, Arthur asserted that the development of technologies both influences and is influenced by the social, economic, and cultural setting in which it takes place. This leads to the idea that successful innovation and adoption of a new technology depend on the historical path of its development, including the characteristics of initial markets, the institutional and regulatory factors governing its introduction, and the expected outcomes by the users (Ruttan 1996; Kemp 2000; Berkhout 2002). Therefore, socioeconomic and institutional arrangements interact to guide technological innovations along the desired path guided by the trajectory of its development.

The third mechanism, institutional lag effects, was advanced by North (1990) and Setterfield (1993), with further elaboration by Ruttan (1996, 2005). They argued that institutional configuration is the most important factor to create lock-in and path dependency. That is, institutions and the economy coevolve in an interdependent way, in which seemingly discrete innovations are not only the products of the systems of technological innovation of which they are a part but also the products of a nested institutional arrangement that reinforces technological systems (Martin and Sunley 2006). According to Ruttan (1996, 2005), preexisting institutional and socioeconomic structures and the lag effects of activities undertaken in the past constitute the environment in which current activities occur. Scholars studying path dependency from the perspective of institutional lag effects stress that nascent institutional structures might not be the most efficient means to address new and emerging conditions such as climate change, and their evolving arrangement might be locked-in for a considerable period of time

(Liebowitz and Margolis 1995). Therefore, technological paths followed during one institutional structure can persist long after conditions have changed to a new state.

Although most literature on path dependence focuses on nonagricultural industries, lock-in also is observed in agricultural activities such as pest control strategies and breeding (Cowan and Gunby 1996; Wilson and Tisdell 2001; Vanloqueren and Baret 2008). In fact, we argue that the agricultural production system is a natural laboratory in which to examine potential path dependency. For instance, although recent years witnessed a higher level of awareness about the negative consequences of chemicals and pesticides and an increasing knowledge of alternative measures for crop protection, modern agriculture is still locked in to chemicals as the primary means of pest management (Cowan and Gunby 1996). Many farmers are not easily persuaded to switch to newer integrated pest management strategies due in part to uncertainty about their effectiveness, technological immaturity of the newer innovations, and the lack of coordination among various agencies that support them.

Plant breeding is another example where experience and knowledge from the past determine the trajectory of future research (McGuire 2008). For example, wheat varieties launched in the United States in the early 1990s rely on crop breeding research dating as far back as 1873 (Pardey and Beintema 2001). The accumulation of knowledge and the continuous interaction of all the drivers of innovation not only shape the current technological regime but also hinder the growth and development of new technological paradigms that are more applicable to the changing context in which the system operates (Håkansson, and Waluszewski 2002; McGuire 2008; Vanloqueren and Baret 2009). Likewise, if the existing system of agriculture is not flexible enough to make informed midcourse adjustments, it will have difficulty adapting to climate change.

We argue that path dependency is the cumulative outcome of technological trajectories adopted by farmers and promoted by extension services, agricultural policies, and agricultural research systems. Although technological choices in agriculture are rarely fixed, innovation and adoption of technologies often follow established pathways due to various factors. For example, in their discussion of pesticide lock-in, Vanloqueren and Baret (2009) have identified twelve factors that potentially can impede adoption of pesticide-resistant wheat cultivars in Wallonia (Belgium). These impeding factors exist at all levels, from farmers to input suppliers to national agricultural policies. The failure of pesticide-resistant wheat cultivars to become the mainstream cultivar of choice was not due to poor biological traits such as low yields or inferior bread quality but due to inhibiting lock-in processes that hindered the adoption by farmers of the more optimal configuration. Although new conditions such as tougher pesticide regulations, changing consumer preferences, and innovation of optimal technologies can break the lock-in, they also require a multidisciplinary effort at scales ranging from an individual farmer's field to the policy arena.

Method

This work is a continuation of an integrated assessment undertaken to explore the effects of global climate change and variability on agricultural production and economic welfare on a regional scale (see Mearns et al. [2003], for a complete discussion of the project). The study area is the Southeast United States (Figure 1). We employ the RegCM2 limited climate area model nested within the CSIRO Mark 2 GCM running an equilibrium experiment involving a near doubling of atmospheric CO_2 concentrations (330 ppm to 540 ppm). The RegCM2 domain consists of 414 grid cells over the Southeast United States at a resolution of 0.50 latitude by 0.50 longitude, whereas the GCM has a resolution of 50 latitude by 50 longitude. We note that given current emission trajectories, a doubling of CO_2 likely is the most optimistic scenario over the next 100 years. We chose to focus solely on corn production for the analysis because it is the most widely grown crop in the Southeast United States, is highly sensitive to meteorological stressors, and responds quickly to management changes.

Erosion Productivity Index Calculator

Due to the complexity of climate, soil, and crop systems, process-based computer simulation techniques are among the most practical approaches available to make assessments of climate change impacts on agriculture. We use the Erosion Productivity Index Calculator (EPIC; Williams, Jones, and Dyke 1984) model (currently known as Environmental Policy Integrated Climate) to estimate long-term climatic effects on corn yields. An attractive feature of EPIC is its ability to examine the effects of weather and agronomic practices on crop production and soil and water resources. The model integrates the major processes that occur in the

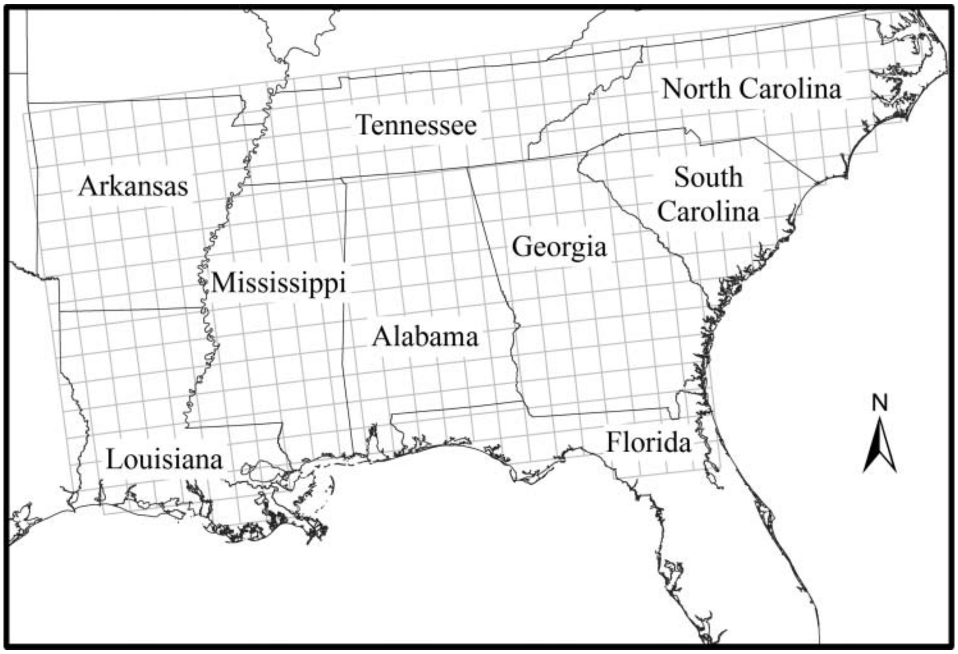

Figure 1. Southeast U.S. study area and RegCM2 grid.

soil, atmosphere, crop, and management systems. It runs on a daily time step at the scale of a single field. Input requirements include daily meteorological data, soil properties, and soil and crop management data. EPIC relies on radiation-use efficiency in calculating photosynthetic production of biomass and, as such, atmospheric CO_2 concentrations influence photosynthesis through this parameter (in the case of corn, we increase this rate by 10 percent for the doubled CO_2 scenario). The daily simulated potential biomass is adjusted to account for the level of stress from the input factors (e.g., water, temperature, nutrients [nitrogen and phosphorus], and soil aeration) in proportion to the magnitude of the most severe stress during that day. Stress days, which incorporate both stress duration and stress severity, are calculated during the growing season as the sum of (1 – daily stress factor). Thus, on a day when the stress factor is 0 (i.e., no growth), the model calculates one stress day. Similarly, if the stress factor is 1 (i.e., no stress) it calculates zero stress days. We assume that the number of stress days will go up with increased climate variability, causing negative consequences in the outcome of crop yields.

Adaptation Scenarios

We test the effects of technological lock-in in the context of highly variable climatic change using three adaptation scenarios: no adaptation, climatically optimized or clairvoyant adaptation, and adaptation based on the logistic model of technological substitution (we call this logistic adaptation). Typical adaptation actions that can be implemented in the EPIC crop model are changes in planting and harvest dates, changes in cultivar type, and, in extreme cases, irrigation and crop changes. Climatically optimized adaptation (the clairvoyant adaptation scenario) assumes that farmers make the correct adaptations in real time and in perfect timing with the climate change (Schneider, Easterling, and Mearns 2000). Although obviously not realistic, optimized adaptation is the most common approach used in modeling studies. The development of a model to represent logistic adaptation is described fully in Easterling, Chhetri, and Niu (2003). As shown in Figure 2, the model uses a logistic curve to represent varying rates of farmer adaptation to changing climate. In this scenario, a small fraction of farmers will change course and quickly adapt to a changing climate; the majority of farmers will take longer for various reasons, including technical lock-in or failure to realize that the climate has changed beyond the initial conditions; and a small fraction of farmers will wait many years to adjust production practices.

Because our model of logistic adaptation depicts changing behavior over many years, the analysis must include a time-evolving climate change scenario. The GCM output used to drive the RegCM output is from an equilibrium experiment and not a transient climate

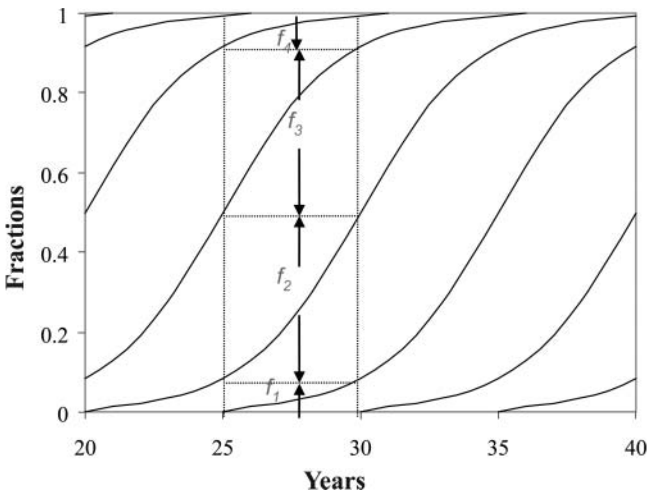

Figure 2. Logistic model depicting the time evolving fraction of farmers adapting to climate change: (f_1) cohort of early adopters who instantaneously recognize and adapt to a changing climate and climate variability, (f_2) cohort lagging on average five years behind f_1, (f_3) cohort lagging on average ten years behind early adopters, and (f_4) farmers lagging on average fifteen years behind the early adopters. Fractions f_2 and f_3 make up the largest fraction of farmers, and fractions f_1 and f_4 represent a minority of farmers.

change scenario. Therefore, we create a mock sixty-year scenario by dividing the difference between the RegCM doubled CO_2 climate and the baseline climate into twelve equal fractions representing five-year sampling intervals. We adjust the 1960 to 1995 baseline daily climate following the procedure of Mearns et al. (2003), using these twelve climate change segments for each EPIC climate parameter (i.e., temperature, precipitation, relative humidity, wind speed, and solar radiation). We aggregate these twelve climate segments into three twenty-year time series and assume that this represents the length of time required for adaptations to diffuse across the landscape under the logistic adaptation scenario (Easterling, Chhetri, and Niu 2003).

Altering Normal Climate

The first step is to create three possible annual variance outcomes given the monotonically changing climatic mean at each grid cell. Because the final outputs from the RegCM2 are monthly climatic means, it is necessary to develop estimates of daily meteorological data over many years to estimate a yearly variance structure. Using a stochastic weather generator we alter the variance associated with a parameter's monthly time series for each of the twelve climate segments used to simulate the corn yield outcomes. We follow the simple method suggested by Mearns (1995) in which the sample variance is inflated by a factor of 1.5 and 2.0 to simulate a more variable climate. Thus, the three possible variance outcomes are 100, 150, and 200 percent of the baseline climatic variance, adjusted for the twelve step changes in the climatic mean. Although there are more complicated methods for altering climate variability, Mearns, Rosenzweig, and Goldberg (1996, 1997) found the results were similar to their simpler method. The algorithm to modify the variance is as follows:

$$X't = \mu + \delta^{1/2}(Xt - \mu), \qquad (1)$$

where $X't$ is the new value of the climate variable in question, μ is the mean of the time series, δ is the ratio of the new to the old variance, and Xt is the original value of the climate variable.

For the three adaptation scenarios (clairvoyant, logistic, and no adaptation), we produce model output from EPIC representing thirty-six years for each of the twelve climate change segments at every grid cell, using the variance-altered climate and the daily meteorological data from the stochastic weather generator. We ignore the initial year of the simulation to allow for adequate model spin-up, resulting in thirty-five years of EPIC simulations for each of the twelve climate segments.

Modeling Changing Variability

Although the stochastic weather generator alters the climatic variability, the resulting variance structures still represent constant variance scenarios through time (i.e., variance inflation factors of 1.0, 1.5, or 2.0). We do not believe this is realistic. The interannual variability likely will change through time, with some years experiencing highly variable conditions and others remaining close to the baseline variability. This speaks to the potential for path dependence to penalize farmers who fail to adapt appropriately to unknown future climatic variability.

To model this uncertain variance structure, we represent the annual climatic variance in the EPIC model runs as a stochastic process. First, we add a possible variance deflation factor of 0.5 to allow for the possibility of periods of lower climatic variance. With these four variance factors, we determine the variance for any particular year in a thirty-five-year EPIC model run through random sampling from a Gaussian probability distribution. Most years will experience climatic variability similar to that for the thirty-five-year baseline climate, allowing for adjustments in the climatic mean. The probability of any of the thirty-five years of the EPIC run experiencing 1.5 or 2.0 times the baseline variance is much smaller. For example, the probability that a grid cell will experience similar or less variable conditions than the baseline climate is approximately 0.82, and the probability that it will experience two times the original variance is less than 0.05. Using the randomly sampled variance multipliers, we produce thirty-five years of EPIC model runs for each climate segment under each farmer adaptation scenario (clairvoyant, logistic, and no adaptation) and aggregate the final crop yield results over the three twenty-year periods.

Results

Yield Change Projections

For each scenario, we examine the percentage of the study area with yield changes greater than or less than 10 percent, 20 percent, or 30 percent of the baseline yields. For all scenario combinations (i.e., combinations of climate change, adaptation type, and climate variance structure), corn yields less than 10 percent but greater than 20 percent of the baseline yields are the most common throughout the study area (Figure 4). This is especially so by the end of experiment, where the model projections show yield declines of this magnitude for over a third of the study area for each adaptation and variance scenario. In addition, yield losses are much more common than yield gains, although the most extreme losses are rare.

Two-sample differences of means tests do not indicate significant differences between the mean yields for clairvoyant and logistic adaptation scenarios, regardless of the variance structure (Table 1). There are significant differences ($p < 0.05$) between the no adaptation scenario and the clairvoyant adaptation scenario for all years and variance structures. The results are similar for the logistic adaptation scenario, with the exception of the first twenty-year period, where the test does not indicate statistically significant differences between the scenarios. The largest difference between the clairvoyant and logistic adaptation scenarios is in the first twenty years of the climate change experiment, and this difference declines through time. However, the yield differences among the no adaptation scenario and the other two scenarios increase from less than 1.5 percent to over 6 percent from year twenty to year sixty. By the end of the experiment, of the six possible adaptation and variance combinations, the no adaptation–random variance scenario produced the lowest corn yields for 81 percent of the grid cells (Figure 3).

We omit the no adaptation scenario from the analysis and aggregate the model output according to the two variance and two adaptation treatments applied to simulated yields (Figure 5). Substantial yield losses are more common than yield gains, but large yield swings (either gains or losses) are uncommon. The primary within-scenario difference is in the percentage area projected

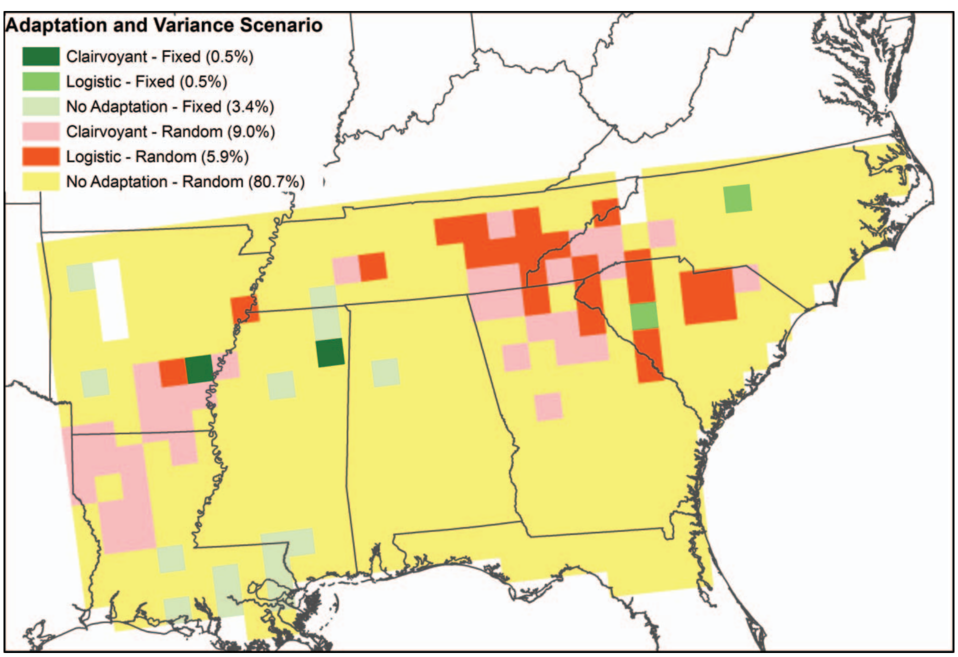

Figure 3. Spatial distribution of six adaption-variance scenarios according to the scenario with the lowest projected yields for each grid cell under the double CO_2 climate change experiment. The percentage of cells falling under each adaptation-variance scenario is displayed in parentheses in the legend.

Table 1. Comparison of grid-wise mean corn yield (mT Ha^{-1} and percent) between no adaptation, logistic adaptation, and clairvoyant adaptation under the fixed and random variance structures for the three twenty-year climate change periods

Climate/adaptation scenarios	Mean yield (mT Ha^{-1})	% Change in yield (from no adaptation scenario)	% Change in yield from logistic adaptation scenario
Year 20			
Fixed variance			
No adaptation	6.63		
Logistic adaptation	6.76	1.96	
Clairvoyant adaptation	6.87	3.60[a]	1.62
Random variance			
No adaptation	6.55		
Logistic adaptation	6.63	1.22	
Clairvoyant adaptation	6.72	2.60[a]	1.36
Year 40			
Fixed variance			
No adaptation	6.27		
Logistic adaptation	6.56	4.63[a]	
Clairvoyant adaptation	6.65	6.06[a]	1.37
Random variance			
No adaptation	6.16		
Logistic adaptation	6.42	4.22[a]	
Clairvoyant adaptation	6.51	5.68[a]	1.40
Year 60			
Fixed variance			
No adaptation	5.80		
Logistic adaptation	6.11	5.34[a]	
Clairvoyant adaptation	6.15	6.03[a]	0.65
Random variance			
No adaptation	5.71		
Logistic adaptation	6.01	5.25[a]	
Clairvoyant adaptation	6.04	5.78[a]	0.50

[a]Difference is statistically significant at $\alpha = .05$ level.

to experience modest increase in corn yields (Figure 5B). In this case, both the clairvoyant adaptation scenario and the fixed variance scenario projected higher corn yields than the alternative logistic or random variance scenarios.

Analysis of Variance (Two-Way)

We conduct a two-way analysis of variance (ANOVA) test on the corn yield projections to evaluate the relative impact of the two treatments (i.e., the adaptation scenario or the variance structure) on the mean corn yield for the three twenty-year climate change intervals (Table 2). There is evidence that the corn yield means for the different scenarios (adaptation or variance) are significantly different from each other ($p < 0.05$), with the possible exception of the variance scenario in the last twenty-year climate change period ($p = 0.10$). We fail to reject the null hypothesis of no interaction effect between adaptation choice and variance structure.

We reanalyze the model output using ANOVA but without the no adaptation scenario to remove outlier effects (Table 3). In this comparison, there still is no evidence for an interaction effect between the adaptation and variance scenarios. There are some critical differences among the main effects in this test compared to the previous test, however. For instance, only the first twenty-year period is close to showing significant differences among the means for the adaptation scenarios, whereas in all other periods, the p value does not warrant rejection of the null hypothesis of no difference among the means. The apparent convergence of crop yield means emerges as the simulation progresses through time. This suggests that, as long as some form of adaptation is occurring, farmers will perform better under the double CO_2 climate than if no adaptation occurs. At the same time, the perceived benefit of perfect

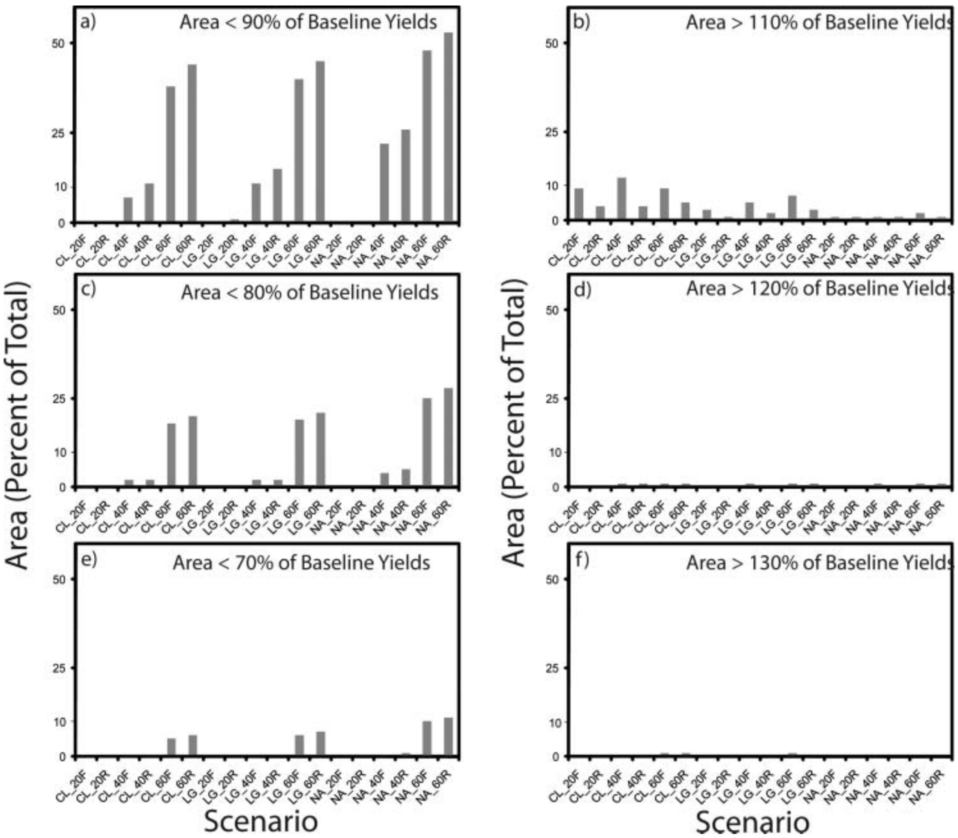

Figure 4. Grid-wise yield projection comparison for all adaptation scenarios. Bars represent percentage of total study area for a given scenario: (A) percentage area experiencing less than 90 percent of baseline yield amount for each grid cell, (B) percentage area experiencing 110 percent or more of baseline yields, (C) percentage area less than 80 percent of baseline, (D) percentage area greater than 120 percent of baseline, (E) percentage area less than 70 percent of baseline, and (F) percentage area greater than 130 percent of baseline. Scenarios are CL = clairvoyant adaptation; LG = logistic adaptation; NA = no adaptation; 20 = year twenty of climate change experiment; 40 = year forty; 60 = year sixty; F = fixed variance structure; R = random variance structure.

knowledge of the climate diminishes through time. In contrast, the ANOVA results for the variance scenarios are very similar to the results in Table 2. The tests show significant differences between the corn yield means for the random and fixed variance scenarios for the first forty years of the climate simulation. The difference between projected corn yields for the last twenty-year period is not significant at the 0.05 α level, but the pattern is similar to the previous two time periods.

Discussion

Investment in agricultural research and development has contributed substantially to meeting the global

Table 2. Analysis of variance results showing the main effects of the three adaptation scenarios and two variance structures on yield for the three twenty-year climate change periods

	Adaptation scenario clairvoyant, logistic, no adaptation ($N = 2{,}460$, $df = 2$)	Variance structure fixed, random ($N = 2{,}460$, $df = 1$)	Interaction effects ($N = 2{,}460$, $df = 2$)
Year 20			
μ	6.8, 6.7, 6.6	6.8, 6.6	—
F	5.9	5.72	0.17
p value	0.003	0.017	0.841
Year 40			
μ	6.6, 6.5, 6.2	6.5, 6.4	—
F	15.20	5.01	0.03
p value	0.000	0.025	0.969
Year 60			
μ	6.1, 6.1, 6.8	6.0, 5.9	—
F	12.07	2.73	0.01
p value	0.000	0.099	0.988

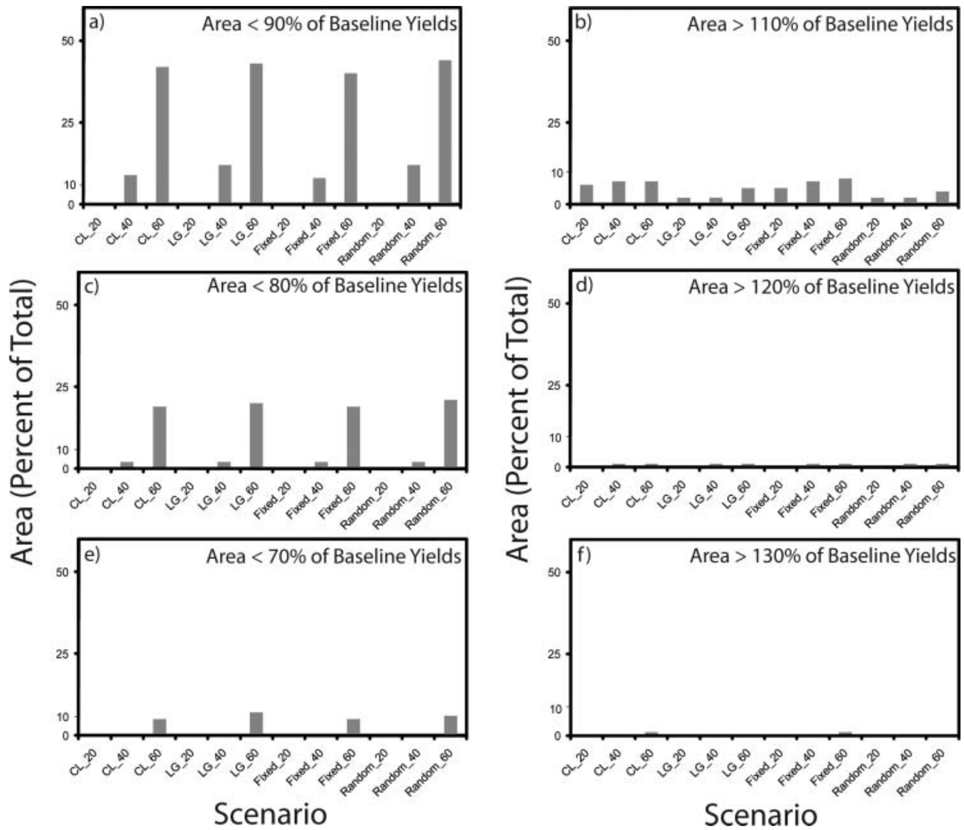

Figure 5. Same as Figure 4, except with aggregated variance (fixed variance or random variance) and adaptation (clairvoyant adaptation or logistic adaptation) climate change scenarios. Scenarios are CL = clairvoyant adaptation; LG = logistic adaptation; 20 = year twenty of climate change experiment; 40 = year forty; 60 = year sixty.

demand for food. This is achieved primarily through a strong focus on crop improvement, increased inputs of water and agrochemicals, and intense mechanization. Yet food security remains an unfulfilled dream for almost 800 million people (Food and Agriculture Organization of the United Nations 2005), and prospects for reducing this staggering figure appear grim as the world currently is consuming more than it is producing (von Braun 2007). In addition, the possible impact of climate variability and change in food production is raising the specter of a potentially perpetual food crisis in coming decades. The impact of increased climatic variability on crop yield could arise from several causes, including (1) increased sterility due to extreme temperature during anthesis (e.g., Wheeler et al. 2000); (2) moisture and heat stress during critical stages of crop growth and development (e.g., Easterling, Chhetri, and Niu 2003); and (3) reduction of input to agriculture

Table 3. Analysis of variance results showing the main effects of no adaptation scenarios and two variance structures on yield for the three twenty-year climate change periods

	Adaptation scenario clairvoyant, logistic (N = 1,640, df = 1)	Variance structure fixed, random (N = 1,640, df = 1)	Interaction effects (N = 1,640, df = 1)
Year 20			
μ	6.8, 6.7	6.8, 6.7	—
F	2.57	5.18	0.01
p value	0.109	0.023	0.925
Year 40			
μ	6.6, 6.5	6.6, 6.5	—
F	1.55	3.76	0.00
p value	0.213	0.053	0.958
Year 60			
μ	6.1, 6.1	6.1, 6.0	—
F	0.2	1.98	0.00
p value	0.652	0.159	0.993

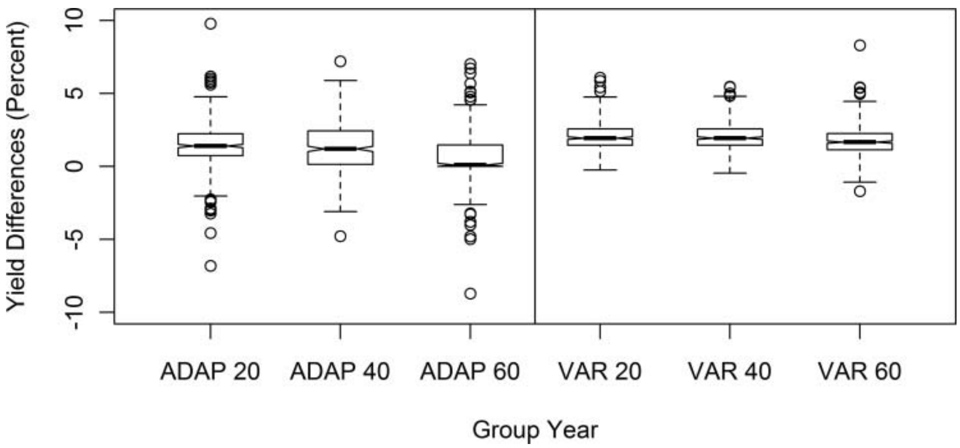

Figure 6. Box plot of grid-wise percentage differences in corn yields under each treatment for the three twenty-year time periods. The left panel shows the distribution of yield differences between the clairvoyant and logistic adaptation scenarios. The right panel shows the distribution of yield differences between the fixed and random variance scenarios. Positive values mean higher yields in the clairvoyant (left panel) and fixed variance (right panel) scenarios, respectively. The no adaptation scenario was removed from this portion of the analysis.

due to uncertainty associated with climate change (e.g., Antle et al. 2004). In the United States, the corn production losses due to extreme climatic conditions might double during the next thirty years, causing additional damages totaling an estimated $3 billion per year, which consequently will impact insurance and disaster relief programs (Rosenzweig et al. 2002). Addressing this challenge almost certainly will require a continuous flow of new technologies while adapting to emerging crop growing conditions brought about by climate variability and change.

The ability of society to make smooth transitions to new agricultural environments due to changing climatic conditions might worsen if farmers are locked in to a suite of rigid technological choices not suitable to the new climate. Although geographers have distinctly recognized the role that preexisting institutional and socioeconomic structures play in exerting influence on the evolution of technologies, no studies have yet explored the potential for technological lock-in to affect the efficiency of adaptation to climate change. In the case of agricultural adaptation, issues of scale take on added importance because lock-in will occur at regional scales. In our view, it is vitally important that geographers continue to research and explore the question of technological lock-in to avoid ambiguities brought about by the discussion in this topic. Following Martin and Sunley (2006), we believe that there is considerable value in applying the concept of path dependence in geographic inquiry. This emerging intellectual field can reveal its geographical foundation and implications, as exemplified by the centrality of regional lock-in to questions of agricultural adaptation to climate change.

Our results show that changes in temperature and precipitation affect both the mean and variance of corn yields. On average, corn yields increase as precipitation increases, but they decrease if temperature increases. Interestingly, the effect of increased precipitation variability is minimal compared to the effect of increased temperature variability. The results also indicate that, although the benefit from perfect knowledge of the climate decreases with time, the cost of a random variance structure in terms of yield reductions relative to the baseline remains nearly constant. The effects of the adaptation choice versus the variance structure differ in that the means of yields converge toward the same value for adaptation effects, but the difference among means remains nearly constant through time for the variance structure (Figure 6). Thus, the climate change scenario with a randomized variance structure consistently leads to lower yields compared to a fixed variance structure, regardless of the information available to the farmer. The consistently lower yields of the randomized variance scenario illustrate that farmers' abilities to make informed cropping decisions might be constrained by their inabilities to exit from their current system of strategies and technologies (i.e., they are locked in). The system's lock-in on "short shelf-life" sets of technologies will not maintain optimal production with a constantly changing variance structure.

Given the lower yield projections in the random variance structure, we posit that the cost of path dependence is a penalty for farmers who are subjected to a variance structure that is not consistent. Alternatively, this random variance structure shares similarity with regions currently experiencing large interannual variations in temperature and precipitation, such as the U.S. Great Plains. In these regions, boom and bust cycles of crop production are common and the risk of crop loss is higher compared to areas with a less variable climate. Thus, although the benefits of adaptation are clear, there is a cost of path dependence to farmers who lock in to a set of production choices that will likely be suboptimal for multiple years if the warming climate also is a more variable climate. Although society can make transitions to new technologies relatively quickly and efficiently, such as the transition from canals as a dominant mode of freight transportation to railways, the interlocking nature of technological regimes might discourage the deployment of efficient technologies needed by farmers. In the context of agricultural adaptation to climate change, such rigidity implies an inability of farmers to respond appropriately to minimize losses or to take advantage of new climatic conditions. This illustrates the importance of a system that is flexible enough to make numerous informed midcourse adjustments to maintain optimal production as the climate changes. These corrections must be made in the absence of knowledge about how the climate is likely to evolve in the near future and farmers must establish the probability of being correct by introducing a set of adaptive choices available to them.

The existing agricultural system is a result of decades of investment in research and development of agricultural technologies by the public and private sectors. The unprecedented growth of U.S. agricultural productivity over the past century is attributable to this investment, which includes such major developments as agricultural mechanization, chemical fertilizers and pesticides, genetic improvement in crops, and evolving agronomic practices. However, this system of investment in agricultural research has undergone significant changes in the last few decades due to developments in science, policy, and markets. Public investment, in real dollars, in U.S. agricultural research has declined steadily since the 1960s. As discussed earlier, the technological choices for farmers are not fixed, but innovation and adoption of technologies needed to address the challenges in the future are often guided by "self-reinforcing" mechanisms of complementarities, economies of scale, and the inertia of sunk costs. This is further complicated by the absence of perfect knowledge about the variability of climate over the timescales for which a set of adaptations must be effective.

Conclusion

The relative speed and efficiency with which farmers are able to change technologies and management practices in response to climate change will be an important determinant of adaptive success. It appears that farmers in the United States are susceptible to technological lock-in that forces them to stick with a particular suite of technologies, even when environmental or market conditions dictate technical change. Of particular interest here is the special case of lock-in of climate-related technology during a time of gradual climate change accompanied by different scenarios of change in interannual climate variability. We ask whether lock-in during a period of climate change accompanied by changes in interannual climate variability (i.e., change in frequency of extreme events) inhibits successful adaptation to avert crop yield loss.

To answer this question, we simulated future corn production in the Southeast United States in the context of a warming climate, using three adaptation scenarios (no adaptation, logistic adaptation, and clairvoyant or perfect knowledge adaptation) exposed to both a random and a fixed climatic variance structure. Logistic adaptation is a proxy for varying degrees of lock-in by farmers across a region. Clairvoyant adaptation is as if all farmers in a region are able to make technical changes in lock-step with climate change and variability. No adaptation is the control.

Across the study area, for all scenarios (i.e., combinations of climate change, adaptation type, and climate variance structure), the most common result is a moderate yield reduction (less than 10 percent decline from baseline yields), although the model output includes some areas with production declines of 30 percent or more. This decline is particularly pronounced by the end of the experiment. Corn yields decline in all adaptation scenarios and, by the end of the experiment, decrease 8 percent to 14 percent from the baseline yields with a fixed variance structure and decrease 10 percent to 15 percent with a random variance structure. We find consistently lower corn yields under a random variance structure compared to a fixed variance structure. Of the three adaptation scenarios tested, yield projections are consistently and significantly lower for the no adaptation scenario. No statistically significant differences are found between the clairvoyant and logistic adaptation scenarios, although the small differences that do occur (in the form of slightly higher yields for the clairvoyant scenario) decline through time. Although we conclude that farmers can ameliorate the effects of climate change by adjusting their crop growing decisions, there is a cost of path dependence to farmers who are locked in to a set of production choices that likely will be suboptimal for multiple years if the warming climate also is a more variable climate. The ability of agricultural systems to successfully transition to new crop-growing environments requires that farmers and their supporting institutions break their path dependency to rigid technological choices inappropriate for a nonstationary climate. This certainly requires a continuous flow of new technologies (or at a minimum, different technology) while adapting to emerging crop-growing conditions brought about by climate variability and change. This requires a multidisciplinary effort at scales ranging from an individual farmer's field to the policy arena to further increase resilience and reduce vulnerability to the changing climate.

Note

1. For the purposes of this study, we use the two terms *path dependency* and *lock-in* interchangeably.

Acknowledgments

This research was funded by the U.S. Environmental Protection Agency, NCERQA (Grant No. R824997–01-C), and the National Aeronautics and Space Administration, MTPE (Grant No. OA99073, W-19, 080). We thank the anonymous reviewers for the comments and encouragement. The views and conclusions contained in this article are those of the authors and should not be interpreted as representing the policies of the U.S. government.

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