

MEASURING CLIMATE IMPACTS WITH CROSS-SECTIONAL ANALYSIS

Introduction to the Special Issue in Climatic Change

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The collection of papers in this special issue of *Climatic Change* highlights the challenges and promise of using cross-sectional analysis to measure the climate sensitivity of the world's economic and nonmarket sectors. The papers all focus on the interaction between agriculture and climate. However, the problems that the techniques encounter and the successes of each paper are not limited to agriculture and illustrate the role of cross sectional analysis to illuminate the climate sensitivity of many economic and nonmarket sectors. In addition to agriculture, for example, cross sectional approaches have been used to measure the effect of climate on mortality (Mendelsohn and Shaw, 2003), energy demand (Morrison and Mendelsohn, 1999) and recreation (Mendelsohn and Markowski, 1999).

There is enormous public interest associated with measuring the impacts of climate change. The evidence that accumulating greenhouse gases will change our future climate has been growing for decades (Houghton et al., 1996, 2001). We are ever more aware how many aspects of our lives are tied to climate. Climate change may potentially have very large impacts across the planet (McCarthy et al., 2001). However, it is also becoming evident that reducing greenhouse gas emissions may require substantial sacrifices (Metz et al., 2001). Every country and all countries together needs to assess the magnitude of the impacts from climate change in order to determine what amount of abatement activity is justified.

Unfortunately, the impacts from climate change are difficult to measure. First, we have no direct experience with future new climates. The last time that the planet experienced warmth at this scale was before humans existed. Second, although there is evidence that warming has begun, it is at such a slow pace that it is dwarfed by the rapid changes of modern industrial times. We cannot observe how crops and people have changed over the last hundred years in which warming has occurred because technology and other developments have caused rapid changes that swamp the impact of the climate changes over the last century. Third, all the changes in the planet that greenhouse gases might cause are not known. Potential changes in the thermohaline circulation, West Antarctic Ice Sheet, and weather extremes loom ominously but are not well understood. Fourth, many changes to the global commons are hard to value. Changes in terrestrial and marine ecosystems, new health risks, and experiencing different weather patterns will

affect everyone's quality of life but what value to place on these changes remains elusive.

Despite these clear difficulties, the impact literature has made many strides forward understanding and quantifying climate impacts. Early studies put together comprehensive lists of the most serious impacts along with supporting evidence (Tirpak and Smith, 1990). Later studies began to quantify the magnitude of the impacts (Nordhaus, 1991, 1994; Cline, 1992; Tol, 1995; Fankhauser, 1995; Pearce, 1996). As quantification developed, the literature began to sort out which sectors were the greatest risks, such as agriculture, and which impacts were likely to be small or even beneficial (Mendelsohn et al., 2000, 2004; Tol, 2002a). The literature has also begun to discern when impacts will occur. The bulk of the literature simply makes before and after comparisons of climates in 1990 versus 2100. However, the literature is moving towards displaying a dynamic picture that explains how quickly impacts may occur and what the path might look like (Tol, 2002b). Finally, the literature is gradually doing a better job of discerning where impacts will likely fall (for example compare Pearce [1996] and McCarthy [2001]). All of these insights are critical in determining the path of abatement, the path of adaptation, and the need for compensation.

The literature has relied on two sets of methods or types of evidence to conduct climate impact assessments: experimental-simulations and cross-sectional analysis. The experimental-simulation approach begins with controlled experiments in laboratories and other controlled settings. In these experiments, we isolate the impact of climate change and changes in carbon dioxide on specific subjects, for example, plants. From these experiments, we extrapolate using simulation models to the real world around us and speculate what the experimental results imply for critical systems (agricultural, energy, or ecosystems) across the planet. The cross-sectional approach in contrast is a direct measurement of climate sensitivity that is made across locations. The critical system is observed in different climate zones and measurements are taken to see how the system responds to being in different climate settings.

Both approaches to measuring climate impacts have strengths and weaknesses. The experimental approach has the strength that it carefully controls for other variables while testing climate. This is a weakness of the cross sectional approach which must work hard not to be biased by omitted variables that are correlated with climate. The experimental approach can test scenarios that simply do not exist on the planet such as higher levels of carbon dioxide. The cross sectional approach has no way to measure carbon fertilization and must rely on the experimental approach for evidence. Another strength of the experimental approach is that it carefully explores mechanisms to understand precisely how climate affects plants. With the plants under a virtual microscope, scientists can discern exactly how each plant is reacting to climate. Understanding the mechanism is another weakness of the cross sectional approach which can readily measure outcomes but has more difficulty discerning what micro changes connect climate and observed results.

The cross sectional approach, however, is not without its own strengths. The cross sectional approach does an excellent job of capturing efficient adaptation because it measures precisely what people have decided to do to adjust to where they are. The experimental approach labors to capture adaptation because including adaptation directly in experiments ruins the controlled environment. Adaptation must be brought into the simulations by the expert builder and are done only as well as the expert can capture them. The cross sectional approach is also quite good at representing large landscapes since it is these very landscapes that are at the core of the technique. In contrast, the experimental approach struggles to extrapolate from limited laboratory examples to the world as a whole and can be misled by unrepresentative examples.

In net, the strength of each approach to measure impacts is the weakness of the other approach. The optimal strategy to understand climate impacts is consequently to employ both approaches. Since they depend on completely different assumptions, if the results can agree, then the researcher and policy maker can have confidence that the effects have been accurately captured. If there is a span of outcomes across the two approaches, this span reflects the uncertainty in our estimates. Of course, there are some phenomena that both methods struggle to capture. The dynamics describing how systems will actually adjust are difficult to measure. Any experiment that uses a realistic dynamic climate, will proceed at the same rate as the real world. The cross-sectional approach compares outcomes that have been reached after much trial and error. They are equilibrium comparisons, not dynamic studies. Both approaches consequently struggle to capture dynamic processes accurately.

This special issue focuses on measuring the effect of climate on agriculture. Partly this can be justified because agricultural impacts are the single biggest impact that has been quantified in the literature (McCarthy et al., 2001). Integrated assessments using both experimental-simulation and cross-sectional evidence suggest that the aggregate impacts in the agriculture sector dominate the quantified effects of climate change (Mendelsohn et al., 2000, 2004; Tol, 2002a). They explain both the largest overall impacts and also the distribution of impacts across countries (Mendelsohn et al., 2000, 2004).

Although both methods of measurement have been used for agriculture, this special issue focuses on using cross-sectional methods to measure agricultural impacts. We do not underestimate the many experimental-simulation studies; they have made important contributions to understanding how climate affects agriculture (see notably Adams et al., 1990, 1999; Rosenberg, 1993; Rosenzweig and Parry, 1994). Thus, although this special issue discusses only cross-sectional methods, we are not advocating that cross-sectional methods alone are sufficient. The future of impact assessment depends on the use of a balance of methodologies, not just cross-sectional studies.

This special issue on agriculture illustrates many issues that are generic to cross-sectional analysis. But, of course, there are some complexities that are particular to agriculture. For example, changes in temperature and precipitation clearly have a

direct effect on crops and grazing. However, climate also affects runoff and potential water supplies. Both experimental-simulation studies and cross-sectional studies have shown that changes in runoff due to climate change have important impacts on irrigated agricultural systems (Rosenberg, 1993; Hurd et al., 1999; Mendelsohn and Nordhaus, 1996; Mendelsohn and Dinar, 2003). The effects of runoff change must be included in any assessment of climate change. Another important issue to capture in agriculture is the direct impact of CO₂ on plants. A substantial body of experimental studies concludes that CO₂ fertilizes plants (Reilly et al., 1996). The yields of virtually all crops tested increase logarithmically with CO₂. The extent of the fertilization varies by crop. The yields of C₃ plants (the bulk of crops) increase at an average of 30% with a doubling of CO₂ but the yields of woody plants and C₄ plants (such as sorghum or sugar cane) increase much less (Reilly et al., 1996). The cross-sectional approach cannot measure CO₂ fertilization because all sites at one moment have the same CO₂ levels. The results of cross-sectional studies must consequently be adjusted for CO₂ fertilization.

The special issue includes many Ricardian studies, although some other cross-sectional analyses of individual crop yields and crop failure rates are also shown. The Ricardian approach measures how climate and other factors affect the net outcome of farms using either net revenue or land value (Mendelsohn, Nordhaus and Shaw, 1994). When the first Ricardian study was published, there was a great deal of concern about the theoretical approach and the empirical application. Through a series of comments and replies, several potential problems were raised and addressed. One issue was whether irrigation was properly taken into account (Cline, 1996). However, when percent-irrigated land is included in the model, there is no change in results (Mendelsohn and Nordhaus, 1996). More recently it has been shown that adding surface water, while important, also has little effect on the results (Mendelsohn and Dinar, 2003). Another concern was whether the cost of adaptation was measured (Quiggin and Horowitz, 1999). The Ricardian method is a long run model and does not capture short run adjustments to such phenomenon as yearly weather. However, the model measures the impact of climate on land value or net revenue, so that it captures not only effects on yields but also effects on long-run costs. Although these issues were addressed, many issues remain, especially concerning whether the methods can be applied globally.

The set of studies in this special issue highlight some of the problems that cross sectional studies have to overcome. Mendelsohn and Reinsborough tackle the question of whether it is necessary to study countries in each climate zone or whether one study in one country is adequate to capture effects elsewhere in the globe. Specifically, they ask whether a US study would predict what would happen in Canada and whether a Canadian study would reflect what would happen in the US. Each country represents an entire region: the US (temperate) and Canada (polar). The results reveal that the climate sensitivity of each climate region is different. The temperate zone cannot accurately predict what will happen in the polar zone and a study of the polar zone provides poor predictions of the temperate region.

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The study reveals that it will not be enough to do a careful cross-sectional study of the US. If we want to know what will happen in the rest of the world, we will have to study cross-sections in each region of the world.

Schlenker, Hanemann and Fisher examine the climate sensitivity of agriculture in California. Using data about individual farms, they ask what difference does climate and water make to farm value. They conclude that both water and heating-degree days (days above a critical temperature) are key variables for California crops. The study illustrates the merits of using individual farm data when it is available.

Kurukulasuriya and Ajwad also use micro level farm data in Sri Lanka to test the sensitivity of climate. They compare farm net revenues throughout the island to see what role climate plays. They find that warmer temperatures are harmful but that net revenues are very sensitive to the complex interplay of precipitation across the two monsoon seasons. Overall, Sri Lanka will be hurt only slightly from warming. The key to Sri Lanka's future, however, lies in what climate change does to the monsoon rains as some changes might even help them whereas others would be quite harmful. Another insight from this study is that armed conflict might limit the ability of a cross-sectional study to measure what is happening in some regions.

Mendelsohn analyses average crop failure rates across two decades in counties in the US. Climate, and specifically temperature, can explain a great deal of the variation in average failure rates. Although the failure of crops each year is a function of weather, counties with warmer average temperatures have much higher average failure rates. The study illustrates that warmer climates will cause catastrophic crop failure rates to climb. Countries must carefully consider whether they want to insure farmers in vulnerable counties against these risks or encourage farmers to adjust where they plant their crops in the future.

Mendelsohn, Basist, Williams, Kogan, and Kurukulasuriya tackle the difficult question of how best to measure climate: ground weather stations or satellites. Historically, weather stations do a much better job of measuring the climate in their vicinity. Weather stations, however, are dispersed across the landscape and remote activities such as farming may not have a nearby station. Climate must be interpolated across the landscape sometimes using sparse station data. In contrast, the satellites may have problems measuring phenomenon such as precipitation but they do a very good job of seeing the entire landscape. The study empirically compares climate measures from both sources and concludes that the satellite temperature measures do a slightly better job of measuring farm performance but interpolated ground weather station measurements do a better job of measuring precipitation effects. The results of this study indicate that both sources of climate data would be helpful for cross-sectional global studies.

Mendelsohn, Basist, Dinar, Kurukulasuriya, and Williams address another pressing question in the literature. How should climate be measured? Is farm performance dependent just on climate normals- the average weather over a long period of time- or is it necessary to measure climate variance (variations away from the climate normal) as well? The study reveals that climate normals and climate variance are

highly correlated. Either set of variables can explain a great deal of the variation in farm performance. However, when they are introduced together, the climate normals explain the bulk of the variation and the variance terms explain only a little more. The results imply that it would be attractive to include both climate normals and climate variance to the extent possible. Luckily, the satellite data should be able to support measures of both sets of climate variables. By capturing climate variance, the studies can begin to measure the importance of weather extremes.

Finally, Mendelsohn, Basist, Kurukulasuriya and Dinar explore the role of climate in rural income. A host of studies have revealed that climate affects agricultural performance. Since agriculture is a primary source of income in rural areas, it follows that these same variables should also explain variations in rural income. This is tested in the analysis and shown to be the case. The very same variables that explain how well farms are likely to do also explain why some rural districts and counties have higher income per capita than others. The results demonstrate the importance of climate to rural livelihood. The results also reveal that even if aggregate country-wide outcomes in agriculture are minimal, there may still be local effects from climate change that are quite severe. That is, the study reveals that local people in rural areas could be heavily impacted by climate change even in circumstances when the aggregate agricultural sector in the country does fine.

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