The Successive Nature of Development: How Natural Hazards Help Drive Landscape Transformation and Vice Versa*

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ABSTRACT

Development requires not only material transformation of local landscapes but adaptation to endemic natural hazards. Prior research has highlighted each of these dynamics but largely ignored their interaction. The present study helps to fill this gap by using county-level data on economic losses from natural hazards and data on local land development across the continental United States to examine how the two processes feedback successively in place over time. Results from panel regression and structural equation models provide evidence of such feedback and demonstrate how the political economy of place-making means that costly natural disasters do not impede development but rather successively contribute to it. Implications for theory, policy and future research are discussed.

The Successive Nature of Development:

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A fundamental way that societies act in and on nature is by transforming local landscapes to accommodate successively larger populations and their daily activities (Davis 1955). This transformation is the subject of ample sociological research. Classical urban ecology from the Chicago School, for example, emphasized how local zones that scholars observed were not just things but processes that ripple forth in successive fashion, interacting with what came before as they push into new areas (Park and Burgess 1925; Park 1936). More recently, political economists have highlighted how this successive development is not pre-ordained by market forces and transit costs. Instead, it emerges in societies and places that treat land as a commodity to be bought, sold, and developed for profit over time (Logan and Molotch 2007). Within such cultural milieus, landscapes beget opportunities, and opportunities beget interests that push for ongoing development.

Broadly, these are the social and political dynamics of place-making in the United States. Yet, rising concerns over global climate change remind us that there are environmental dynamics as well. The most obvious are those raised by urban and environmental historians who document how development has long required not just people and capital but also cultural and material transformation of local landscapes. In the process, waterways are straightened, dredged, reversed, leveed and dammed; hillsides are cleared, graded and removed; swamplands are pumped and filled; prairies are tilled and paved; and, ultimately, places are made and remade.

These actions produce landscapes that are neither strictly natural nor strictly social but mutually and iteratively both: what Cronon (1992) calls second nature; Harvey (XXXX) calls socionature; and, others call hybridity (cf: Brenner 2015).

Another environmental dynamic of local development that is now drawing more interest involves natural hazards. This type of socio-environmental interaction often leaps to our attention when spectacular disasters occur, such as Hurricane Katrina or Tropical Storm Sandy. Their devastation reminds us that nature also remains a powerful transformer of local landscapes, including especially those already developed. Rudel (2013) calls such disasters "focusing events" that have the potential to disrupt the status quo, galvanize social movements and promote widespread environmental awareness and action. Yet, just as large-scale transformation of local landscapes can obscure more gradual but no less consequential changes, so, too can dramatic catastrophes overshadow ongoing interactions with environmental hazards. Indeed in the United States, the Federal Emergency Management Agency declares a federal disaster an average of every six minutes, mostly for weather-related events. And, 95 percent of U.S. counties have reported at least a million dollars in property damage from natural hazards during the first decade of the 21st century alone (Schultz and Elliott 2013).

These facts underscore the point that where we build places includes not just land, water and other environmental resources that invite our large-scale transformation of them. They also include natural hazards that must be tirelessly negotiated. River valleys and delta plains, for instance, do not just offer fertile soils and easy passage for canals, railroads and highways; they also present perpetual flood risks. Sea coasts and wetlands do not just provide access to aquaculture, petroleum and inexpensive transport; they also offer regular exposure to hurricanes, tsunamis and erosion. Edges of tectonic plates not only make for great deep water ports and harbors; they also present chronic risks of earthquakes and volcanic eruptions. Flat expanses of arable land do not just afford access to large-scale agriculture and grazing; they also present regular risks of windstorms and tornadoes. The broad point is that local development occurs widely in the face of natural hazards endemic to where it occurs. And, because these hazards can never fully be quelled, they remain continual sources of input and interaction. An important question for social scientists is how this input and interaction plays out over time as local development continues to unfold.

To engage this question we review recent perspectives and develop one of our own that moves beyond extreme cases to conceptualize natural hazards as ubiquitous, ongoing and, in this sense, normal features of local landscapes. To test related hypotheses, we combine historical data on local economic losses from natural hazards with data on local land development and socio-demographic change for all counties in the continental United States. We then use panel regression models and simultaneous equations to examine the relationship between hazard-related damage and land development over time. Results indicate that far from being incidental or restrictive of local land development, costlier hazards promote even more local land development. Moreover, these two types of landscape transformation generally feedback to compound each other steadily over time, contributing to successive socio-environmental change.

LITERATURE REVIEW

The present study investigates a variant of the basic and enduring question of how society and nature entwine over time to make and remake place. At the center of this investigation is the relationship between development *of* and damage *from* local nature.

For purposes of the present study, development *of* local nature refers to the social transformation of landscapes in ways that involve not just changing their shape but, more specifically, what's on them. These processes include pouring foundations, paving lots, laying roads, erecting buildings, and otherwise covering the Earth with impervious surfaces that accumulate over time to comprise a society's built environment. This form of land-use intensification can be incremental, as implied by classical human ecology (Park 1925), or it can be abrupt, as documented in historical studies of rapidly urbanizing areas (Cronon 1992). In the contemporary United States, the net result is a resurfacing of roughly 880 square miles of land per year, most of it cropland (Clement and Podowski 2013).

By contrast, damage *from* local nature refers to economic losses to property attributable to natural processes that are globally linked but locally experienced. Mostly these processes are weather-related – including storms, floods, tornados, wildfires and the like – but they can also be terrestrially related – including quakes, mudslides and other geophysical shifts in local lands. Damage from such hazards presumes at least some development, or fixed capital, in place to experience negative impact. For purposes of the present study, such development represents the exposure element of local vulnerability. It refers not to the probability or incidence of hazardous conditions or events (McLeman and Smit 2006), but to the extent of built environment at risk of damage when such conditions or events occur, which is more frequent and costly than most Americans realize. Since 1960, annual economic losses from natural hazards have averaged roughly $13 billion (in constant 2015 dollars) – a total that brings recovery capital that often exceeds federal expenditures for all public housing operations, Section 8 subsidies, and housing for elderly and disabled, combined.

Investigating links between these two types of landscape transformation – development *of* and damage *from* local nature – means recognizing that the two are linked socially and politically, as well as geographically. Indeed, federal assistance for hazard recovery has been practiced in the United States from its founding, long before codification into law with the 1950 Disaster Relief Act. In 1803, Congress voted to waive duties and tariffs on imported goods in Portsmouth, New Hampshire to help residents recover from extensive local fires (Davies unpublished ms). In 1811 and 1812, Congress donated public lands to residents displaced by powerful quakes in New Madrid, Missouri. And in 1827, it allocated taxpayer funds to rebuild Alexandria, Virginia after fires ravaged the town. These early public interventions set precedents for massive government-aided recoveries following the 1906 San Francisco earthquake and great Mississippi floods of 1927 and 1937. They also paved the way for the emergence of a private insurance industry that now underwrites more than $64 trillion in property values across the United States – the equivalent of more than $200,000 per person.[1] As local development that drives these values not only continues but also faces increased risk of damage from future hazards, there is growing interest in how the two processes of local development and damage may be connected. A review of the literature suggests no consensus. Instead, it offers three perspectives. We review each below with two aims: to clarify underlying assumptions and to specify testable hypotheses.

Perspective 1: No Link between Local Damage and Development

As the number and cost of declared disasters began to rise after the Federal Disaster Act of 1950, scholars and policymakers became increasingly interested in whether natural hazards changed

[1] From http://www.insurancejournal.com/magazins/features/2013/06/17/295207.htm, accessed April 2, 2015.

places. Of particular concern were local population and housing trajectories, which if altered, would suggest that nature acted an unexpected driver of local and regional development trends. One of the first studies to tackle this question on a large scale was Wright and colleagues' (1979) monograph, *After the Cleanup*. Invoking few theoretical assumptions, the researchers assembled data on as many natural disasters as they could during the 1960s, using government declarations, local reports and newspaper coverage. They then coded counties as having experienced a natural disaster during the decade (or not), and included this indicator in regression models predicting changes in local population and housing stocks.

In hindsight, this research accomplished two things. Conceptually, it brought serious attention to the damage-development nexus. Instead of asking if disasters ignited panic or altruism or new forms of social organization, it asked if nature still influenced place-making in affluent societies such as the United States. The closest analog at the time was war, which was one reason why the federal government invested in the question and why researchers focused on extreme cases – ones that reached culturally accepted "disaster" levels. Second and more methodologically, the research established a change-score approach that helped to minimize omitted variable bias and emphasized not just change over time, but change that varied from what might otherwise be expecte, given other local dynamics and time invariant characteristics, such as location and types of hazards faced.

What the research found, even with its focus on extreme cases, was that natural hazards had no net effect on local population and housing trajectories – a finding confirmed by other studies using similar approaches around the same time (e.g., Cochrane 1975; Dacy and Kunreuteher 1969; Douty 1977; Friesma et al. 1977; Haas et al. 1977). The implication seemed to be that even in the face of significant damage, local development proceeded more or less apace. The reason, Wright et al. (1979) offered, is that even in extreme cases, damages still pales in comparison with total development already in (and about to be in) place. In other words, *development of* local landscapes had subsumed *damage from* local landscapes through a scaling up of assets and people in place. This cumulative development, it seems, was the new resilience. It was rooted not in decentralized accommodation to endemic local hazards (Oliver-Smith 1986), but in political and economic stakes that have grown high enough to negate any effect on local development. This line of research suggests the following baseline hypothesis:

> *Hypothesis 1: Local hazard damage has no effect on local land development, net of other factors.*

Perspective 2: Local Development Drives Damage, but Not Vice Versa

Just as nascent federal agencies and rising disaster costs spurred new research following the federal Disaster Act, growing concerns about climate change and disasters are now stimulating new studies on local hazard impacts from a wide range of fields. A major thrust of this work seeks to de-naturalize hazards by emphasizing how societal exposure to them is a product of "bottom-up development processes on hazardous landscapes, specifically demographic change and urbanization" (Preston 2013: 720). In other words, the local development that earlier researchers found to continue in the face of significant damage from natural hazards is now being credited as a primary driver of such impact, not hazards themselves. To clarify this point and demonstrate its future implications, researchers are engaging in more socio-environmental forecasting of short- and long-term hazard damage (Pielke et al., 2007; Hinkel et al., 2010; IPCC, 2012; Folke et al., 2002; Yohe and Tol, 2002; World Bank, 2010). Preston's (2013) recent study offers a useful example of this type of effort because, like earlier work, it uses counties across the continental United States to assess local interactions with a wide range of endemic hazards and because it reveals some of the assumptions now being made about the relationship between development of and damage from local landscapes.

In his study, Preston assumes that while the type and frequency of natural hazards may vary from region to region, their local incidence is not actually changing that rapidly relative to the other key component of exposure: development. Thus, researchers can use data on economic losses from natural hazards over, say, the last fifty years to develop a basic sense of locally hazardous conditions and events. Researchers can then use recent demographic trend data to develop a sense of how much new development will be in place to experience such hazards in the future. The result is a multiplier for forecasting how much local damage is likely to change, if hazardous conditions and events remain relatively similar but local development – in the form of population and aggregate income – continues its recent trajectory. What changes in these simulations, in other words, is not hazards endemic to local landscapes but what's on them, which is the primary driver of exposure.

What Preston finds from these forecasting efforts is that, on average, the real cost of property damage attributable to natural hazards is likely to increase somewhere between 180 and 390 percent by 2050, even if the intensity and frequency of local hazards remain the same as during the past half-century, which many scientists think is a conservative assumption (IPCC 2012). The high estimate assumes one-to-one correspondence used by prior work on hurricanes (Pielke 2007; Pielke et al. 2008), that is, damage and development will rise together at the same rate. The low estimate assumes that new building codes, better warning systems and other mitigation and planning efforts will cause projected losses to grower slower than the rate of local development, or exposure. Either way, it is development, not hazards, that is forecasted to be the real driver of future damage. And, this development is presumed to be "path dependent," that is, "due to the inertia of socioeconomic systems, demographic change and economic development." If there is a link between this path-dependent development and local hazard damage it is presumed to be incidental.

Broadly, this perspective is consistent with Hypothesis 1, in the sense that it sees no effect of local damage on local development, only the reverse. However, it does suggest that the two factors rise together, which suggests the following hypothesis.

> *Hypothesis 2: Local hazard damage has no effect on local land development, although the two do rise together, suggesting a positive correlation.*

Perspective 3: There Is a Feedback Relationship between Local Development & Damage

The above perspective maintains that, while damage may not affect development, development does affect damage because development determines exposure which determines damage. It also contends that, at the local level, such development is path dependent. Here, path dependence refers loosely to the idea that development generates conditions that incentivize future development along the same path, or trajectory, as before (Page 2006). Thus, history not only matters but feeds back on itself. In statistics, this dynamic is known as an auto-regressive process, and it is a reasonable assumption, especially for projections that use past trends to predict future ones. But, conceptually such assumptions lack analytical depth (Martin and Sunley 2006; Page 2006). They tell us that past development will continue, but not what drives it. And, they tell us that future development determines future damage, but not how the two interact over time. In this way, key relationships are invoked but not critically examined.

This observation is not to say that such efforts are misguided. To the contrary, they provide valuable illustration of the social side of seemingly "natural" hazards. Yet, in doing so, such efforts also downplay recent empirical and theoretical advances in sociology, which deserve deeper consideration. For example, recent research on major hurricanes shows that, contrary to earlier studies, such events now spur significant demographic and housing growth in affected areas (Pais and Elliott 2008). Research also shows that major hurricanes concentrate and intensify regional migration systems (Curtis, Fussell and DeWaard 2015), which tend to pull as well as push populations from affected regions (Elliott 2015). Extending beyond extreme cases and qualitative coding of local disasters, recent research has also shown a strong link between hazard damage in general and local housing and population growth at the county level, using the same types of data as Preston and others (Schultz and Elliott 2013).

This line of work suggests that prior empirical conclusions about the null effect of hazard damage on development may no longer hold. They also suggest that the causal arrow may run both ways. Not only does development determine exposure which determines damage, but damage feeds back to drive development through a political economy of recovery that privileges restoration and extension of property over community (Pais and Elliott 2008; Greenberg and Gotham 201X). This dynamic suggests a feedback not just of past development on future development but also of future damage on future development, as development *of* and damage *from* local landscapes continue to intersect in place, over time. This type of recursive interaction between natural and social systems has become the subject of recent theoretical efforts in sociology to rehabilitate and deploy a new, politically informed concept of ecological succession to better understand local place-making in an era of increasing environmental complexity.

A prominent example of this effort can be found in Rudel's (2009, 2014) recent work on landscape transformation, specifically, how it proceeds and how its environmental consequences spur counter-coalitions to form and press for new policies and regulations that feedback to influence local development. To make sense of these dynamics, Rudel (2014) reaches back to classical urban ecology to rehabilitate one of its core concepts: succession. Succession in Rudel's framework refers to the process by which land users gradually transform the local environment in ways that require them to adapt reflexively to changes they created before. In this way succeeding generations of locals must revisit and accommodate themselves to environmental changes wrought by their predecessors, setting in motion an endogenous force of local change. Recently, Elliott and Frickel have (2013, 2015) advanced a similar concept of succession to highlight the material transformation of urban environments through successive, or cumulative, land-based disposal of hazardous industrial wastes that take generations to bio-degrade. The common idea is that landscape development and damage are not strictly social or environmental, but mutually and iteratively both, as elements feedback on each other successively over time, in place.

In the present study, we extend these efforts as well as growing sociological attention to landscape transformation (Clement and Podowski 201X) to test whether such development and local hazard damage feedback on each other over time to successively increase one other. As described below, we use both panel fixed-effects models and simultaneous equation models to assess these dynamics empirically. The following hypotheses refer to each respectively:

Hypothesis 3a: Local hazard damage has a positive effect on local land development, and this effect increases over time.

Hypothesis 3b: Local hazard damage and local land development feedback on each other over time, such that each causes the other to increase in cumulatively interactive fashion.

DATA

All data are compiled and analyzed at the level of U.S. counties and county equivalents for those comprising the continental United States. In our study, we have three waves of data for the dependent and independent variables, allowing for fixed-effect and simultaneous equation estimation through time. For the dependent variable, the three waves were measured in 2001, 2006, and 2011; these are t_1, t_2, and t_3, respectively. For the independent variables, the three waves were measured in 2000, 2005, and 2010 (with the exception of percent voting Republican, as noted below), which we also label as t_1, t_2, and t_3, respectively. Independent variables are lagged by one year to establish temporal priority and to allow for some time for them to effect local land development.

Local Land Development

While prior studies have examined correlations between local economic losses from natural hazards and aggregate changes in population, housing and personal income (Wright et al. 1979; Schultz and Elliott 2013), we focus on changes in locally developed land, specifically the built environment, for a couple of reasons. First, investigation of the recursive relationship between development of and damage from local landscapes is fundamentally about settlement processes that fix capital, or property and infrastructure, in place. Second, such processes set the material conditions for other types of local growth. In these senses, changes in the built environment constitute a necessary but under-investigated dimension of development.

Data on the built environment come from the 2001, 2006 and 2011 National Land Cover Database (Fry et al. 2011). The NLCD is published by the Multi-Resolution Land Characterization consortium, which is a collaboration of the following federal agencies: the US Geological Survey, NASA, EPA, NOAA, US Forest Service, Bureau of Land Management, National Park Service, US Fish and Wildlife Service, US Army Corps of Engineers, and National Agricultural Statistical Service of the USDA. The NLCD data are based primarily on satellite images taken at a resolution of 30 $\times$ 30 square meters, identifying sixteen different types of land cover for the entire continental United States. Thus far, mostly landscape ecologists have been incorporating these data into research projects (e.g., Theobald 2010), with some urban and population ecologists also taking interest (Reibel and Agrawal 2007; York et al. 2011). The current study pays attention to the database's four categories of "developed land," all of which refer to the extent to which observed parcels are covered by impervious surface: developed open space (<20% covered); developed, low-intensity (20-49% covered); developed, medium-intensity (50-79% covered); developed, high-intensity (80-100% covered). Accounting of impervious surface includes not only buildings such as single-family housing, apartment complexes, commercial spaces, office buildings, and factories but also roads, and qualifying aspects of city parks, golf courses, utility easements, and the like.

With these data, we distinguish three types of change in locally developed land. The primary type, which we call simply *development*, is measured as change in the total new built environment (measured in square miles) during a given time period. This change includes new impervious surface area added to previously un-surfaced parcels as well as new impervious surface area added to previously but incompletely surfaced parcels. We refer to these two subprocesses as *extensification* and *intensification* of the built environment, respectively. Examining these two types of land-use change, in addition to total change, offers insight into how, as well as how much, land tends to come under development in the wake of losses from local natural hazards.

Local Hazard Damage

Data on local impacts from natural hazards come from the Spatial Hazard Events and Losses Database for the United States (SHELDUS), which is a government-funded database maintained by the Hazards and Vulnerability Research Institute (2012). This database collates local events and economic losses at the county level for eighteen types of environmental hazards, including wildfires, floods, severe storms, tornados and hurricanes. Data come principally from the National Climatic Data Center, the National Geophysical Data Center, and the Storm Prediction Center. They include information on more than 500,000 distinct events since 1960 that caused at least one death or $25,000 in estimated damages to property. From these data cumulative economic losses from (non-crop) property damage are computed for respective periods under investigation. This measure reflects estimates of direct economic loss associated with the physical impact of local hazards and does not include indirect disruption to commerce and production. Thus, it is a highly conservative measure of local hazard damage and best understood as a proxy for direct impact rather than as literal measures of total economic losses incurred, e.g., from displacement and disruption of services. All estimated losses are converted to constant 2011 dollars. Any spatial or temporal biases in reporting are assumed to be random or otherwise minimized by longitudinal analyses described below. Again, to allow time for observed hazard damage to begin to translate into changes in the local built environment, we lag these measures by one year relative to measures of local land development. For example, in models described below, we measure local hazard damage for 2000-05 to predict local land development for 2001-06.

Control Variables

Consistent with recent sociological research on local land use and environmental change (Clement et al. 2015; de Sherbinin et al. 2007), we incorporate an array of variables to control for local demographic, political, and economic forces. One control variable measures the total size of the local population, and another measures the number of people residing in Census-defined urban areas, i.e., settlements with at least 2,500 people living at a minimum density of 1,000 people per square mile. In addition, we control for percent of the population that is non-Hispanic white and percent of the population that is 65 years or older. We also incorporate measures that deal with various political forces that Rudel (2012) calls defensive environmentalism, including percent voting for a Republican presidential candidate,[2] percent of the population aged 25 years or older with a bachelor's degree, the number of residential building permits issued in a county, and the county's median household income. Lastly, to control for the size of the local economy, we integrate variables for total number of employed workers and total number of business establishments.

All of these variables are listed and described in Table 1. Figure 1 shows the geographic distributions of cumulative hazard damage and land development at the start of our analyses.

[2] As noted above, percent voting for Republican presidential candidate was measured in 2000, 2004, and 2008.

[TABLE 1 AND FIGURE 1 ABOUT HERE]

METHODS

We utilize two types of quantitative techniques to test our hypotheses: a spatial panel model with two-way fixed effects and, using structural equation modeling, a cross-lagged autoregressive panel model. Because all variables have been log transformed, the slope estimates from both of these techniques are interpreted as elasticities, representing the percent change in the dependent variable for every one-percent change in the predictor, holding the rest of the equation constant. In addition to addressing statistical concerns, such as heteroskedasticity, the log-transformation procedure yields standardized (i.e., comparable) slope estimates.

Spatial Panel Models

For the spatial panel models, land development is regressed on property damage (with a one-year lag) in a total of six models. The first three models examine the effect of property damage on change in total new surface area of developed land area as well as the subtypes of extensification and intensification. The next three models incorporate interactions between property damage and dummy variables for year to test whether or not the effect of property damage is changing over time. The slopes and standard errors in these six models are estimated using a spatial panel model with two-way fixed effects (Belotti et al. 2013; see also Lesage and Pace 2009). In this kind of model, not only can we can control for unit-specific and time-specific effects, thereby minimizing omitted variable bias (Allison 2009), we can also incorporate additional controls for spatial autocorrelation in the dependent variable, which would violate the assumption of independent observations (Anselin and Bera 1998). We employ a spatial autoregressive model, known as a SAR model, which includes a spatial lag of the dependent variable on the right hand side of the equation; for our study, this controls for spatial clustering in developed land area at the county-level.

With two-way fixed effects, the generic equation takes the following form:

$$y_{it} = \alpha + \rho W y_{it} + x_{itk}\beta_k + \varepsilon_{it}$$

The symbol α is the constant; y_{it} indicates the values of the dependent variable for the i^{th} case at time t; and, x_{itk} indicates the value of the k^{th} predictor for the i^{th} case at time t, with β_k representing the effect of the k^{th} predictor on the dependent variable. The spatial lag term ρ represents the weighted effect of the values of the dependent variable in neighboring units on the values of the dependent variable for the i^{th} case. This weighted effect ρ is based on the spatial weights matrix W. In our study, since we use county borders that did not change between 2001-2011, W is the same for all t; it is a row-standardized, first-order queen contiguity spatial weights matrix, where the weight equals "1" for any county that touches the i^{th} case and "0" otherwise. Thus, the spatial lag for the i^{th} county at time t is equal to the average area of developed land at time t for all of the counties that immediately border the i^{th} case. This estimation procedure was calculated in *Stata* using the command "xsmle" (Belotti et al. 2013).

Cross-Lagged, Autoregressive Panel Models

Next, using SEM, we test the reciprocal relationship between land development and property damage in a cross-lagged, autoregressive panel model (Selig and Little 2012). The general model we estimate is illustrated in Figure 2.

[INSERT FIGURE 2 ABOUT HERE]

For the sake of space, we do not display the control variables (discussed above) which are hypothesized to have direct effects on developed land area at each time interval. In this model, β_1 and β_2 are the auto-regressive parameters for the effect of property damage on itself over time; similarly, β_3 and β_4 are the auto-regressive parameters for developed land. The cross-lagged effects are represented by β_5, β_6 , β_7 ,and β_8; these slopes indicate the effect of one variable at time t_1 on another variable at time t_2. If the coefficients for β_5, β_6 , β_7 ,and β_8 are positive and statistically significant, it would provide evidence for a reciprocal relationship in which property damage and land development positively and successively feedback on each other over time.

RESULTS

Descriptive Analysis

Table 1 describes the variables in our study and reports means and estimates of variability. Respective change scores appear under columns labeled t_2- t_1 and t_3- t_2. Since all values have been logged, the latter can be interpreted as the percentage change between respective time points. For instance, during 2001-2006 the average area of impervious surface increased by approximately 4.8 percent. Then during 2006-11 – which included a deep economic recession – it increased by another 3.3 percent. The first rate of increase compounded by the second rate of increase results in an average gross increase of 8.3 percent in impervious surface during 2000-2011 ([Y*1.048]*1.033). If we exponentiate these values, we see that the average county increased its impervious surface from approximately 7.5 square miles in 2001 to 7.9 square miles in 2006 to 8.2 square miles in 2011.

Table 1 also indicates that new impervious surface on formerly undeveloped parcels – i.e., extensification – happened at a faster rate than additional surface on already developed parcels – i.e., intensification. Specifically, the average county added 0.44 square miles of impervious surface on undeveloped land ($e^{2.019+0.031+0.026}$ - $e^{2.019}$) compared with 0.34 square miles on land that had already been partially surfaced (=$e^{2.019+0.026+0.018}$ - $e^{2.019}$). With respect to property damage from natural hazards, the mean cumulative damage during 1960-2000 was roughly $32 million (in constant 2011 dollars). Over the next ten years, natural hazards caused an additional $15 million in damage, on average, for a mean cumulative damage of roughly $47 million during 1960-2010 (=$e^{17.278+0.225+0.157}$).

Figure 1 provides a geographic overview of initially observed damage from natural hazards and impervious surface coverage. Generally, patterns suggest a positive correlation between prior economic losses from hazards and current levels of development. In addition, the maps show how land development and property damage both tend to cluster along the coasts, which presents ongoing concern for scholars and policymakers alike.

Bivariate Analysis

Next, Figure 3 moves into formal bivariate assessment by displaying scatterplots of damage and development for the three waves of data. Results show that the bivariate correlation between developed land area and property damage has gradually increased over recent years, from R^2=0.276 during t_1 to R^2=0.281 during t_2 to R^2=0.303 during t_3. These results suggest that the link between property damage and land development is actually strengthening over time, as both cumulatively increase. To investigate this relationship net of other drivers of local land development, we turn to regression models in Table 2.

[INSERT FIGURE 3 ABOUT HERE]

Regression Analyses

Regression results in Table 2 come from spatial panel models estimated with two-way fixed effects, described above. Looking first at results in Model 1, we see that property damage has a significant impact on changes in total impervious surface, net of observed controls and unobserved time invariant factors, such as location, size and availability of local land for development. On average during 2001-2011, a one-percent increase in property damage from natural hazards resulted in a 0.007 percent increase in total impervious surface area. The implication is that observed bivariate relationships in Figure 3 are not spurious and that property damage from recent natural hazards drives rather than slows local development.

[INSERT TABLE 2 ABOUT HERE]

Results in Models 2 and 3 indicate that this relationship is positive and statistically significant for both types of development: intensification and extensification. That is, recent hazard damage contributes to the filling in of already surfaced parcels with more impervious surface, and it contributes to the filling out of such development onto previously unsurfaced parcels. The latter process is particularly strong, suggesting that hazard damage mostly tends to push development into new local areas. As it does, it increases the size of the built environment in place to interact with future hazards.

Next, Models 4-6 incorporate interactions between property damage and time-dummies to test whether the effect of property damage on land development has been increasing over time, net of other processes. Results confirm such increase, from a baseline rate of .04 to .06 to .10 over the observed time periods. To put this increase in context, we can take the average county's amount of total impervious surface in 2001, 7.5 square miles, and work it through the estimated equation in Model 4. For this simulation, we set all other variables equal to zero to determine the amount of new surface area attributable to hazard damage alone. We also assume a total damage of $10 million over each five-year span – a moderately high but not extreme level of impact. First, multiplying the log of this damage (ln($10m)=16.11) by .004, we get .064; which we then multiply by .006 to get .097; which we can then multiply by .01 to get .161. We then sum the three values to get a total value of .322 logged-square miles. If we exponeniate this value, we get 1.38 square miles of new, fully surfaced land area.

Now consider that most new development covers, or surfaces, only a portion of its respective parcel because of landscaping, easement and other features. Indeed, the latest statistics on new residential development in the United States indicate a median lot size of 9,664 square feet. They also indicate a median new structure size of 2,384 square feet. This ratio suggests that approximately 25% of newly developed land is actually surfaced. This compares with a ratio of 20% recently produced by academic researchers at Cornell. The implication is that the actual amount of land committed to new development is about 4 to 5 times the amount of new impervious surface observed. So, if we multiply this factor by the new surface area attributable to hazard damage simulated above, we get a value of 5.5 - 6.9 square miles of new hazard-related land development per county. If we then multiply this value by 3,079 counties and county equivalents, we get 16,934 to 21,245 square miles of newly developed land at the level of current cultural practices.

This is an impressive amount of development that can be attributed to hazard damage and recovery, net of other factors. Yet, even with the rigorous methods deployed, some may still contend that the relationship running from damage to development is incidental: Yes, development tends to happen in hazardous areas; and, yes, this development increases the amount and value of fixed property exposed to future hazards; but, this damage does not then feedback to spur additional development beyond what we would otherwise expect from recent development trajectories.

To test this matter further, we specified and estimated three structural equation models. As described above, each model predicts change in total impervious surface area while controlling for (a) correlation between initial amounts total impervious surface and four-decades of hazard damage and (b) all control variables present in the panel models during each period of change. Results appear in Figure 4. Before discussing the autoregressive and cross-lagged slope estimates, we first note that the various SEM fit indices (i.e., RMSEA, CFI, and SRMR) indicate that the three models (*a*, *b*, and *c*) fit the data relatively well.

Looking across the three models, we see strong auto-regressive tendencies for local land development *and* hazard damage, indicating that what happened before is a good predictor of what will happen next, all else equal. This is the path-dependent dimension of local landscape transformation, and it indicates a relatively stable trajectory for both development and damage over time. Given the strength of these auto-regression tendencies, any reciprocal, or cross-lagged, effect between the two variables is likely to be modest as a result of the reduced amount of variance to be explained. However, any evidence of such an effect is substantively important because it identifies a mechanism of interaction that modifies otherwise "set," or path dependent, trajectories.

Results in Model (c) offer such evidence. As we might expect, the strongest feedback, or cross-lag, is between changes in developed land and subsequent hazard damage, since the former determines relative exposure to the latter. Specifically, results indicate that for every 1% increase in impervious surface at the beginning of the observation period, there is a .47% increase in subsequent economic loss from natural hazards; and, for every 1% increase in new development thereafter, there is a .27% increase in subsequent economic loss. So, development does appear to drive hazard loss, above and beyond the auto-regressive tendencies of each. But, even after statistically controlling for these dynamics and other drivers of local development, results also indicate that hazard damage feeds back to increase new land development, beyond what we would expect from simple path dependence. Net of the historical correlation between development and damage, results indicate that a 1% increase in damage spurred a .04% increase in impervious surface during 2001-06. And, during 2006-11, it spurred to a .09% increase.

To illustrate, imagine two identical counties, each with 10 square miles of impervious surface in 2001, and each experiencing the same demographic, economic and political trends associated with the independent variables listed in Table 1 and controlled in Table 2. The only thing that differs is that one county experiences $1 million in hazard damage every 5 years, and the other experiences $1 billion. Now consider only the cross-lagged effects of damage on development in Model c. During 2001-06, the county experiencing $1 billion in damage would develop 0.4 square miles more impervious surface than the former (1000% more damage * .0004); and, during 2006-2011, it would develop 0.9 square miles more than the former. So, over the decade and all else equal, the county with the $2 billion in hazard damages would develop 1.3 square miles (or 13%) more new impervious surface area than the county with just $2 million in hazard damages. This is a significant increase. Moreover, as the feedback from damage to development continues to occur, it adds to path-dependent tendencies already in motion to scale up successively over time, further compounding both local development of and damage from local landscapes.

CONCLUSION

How societies adjust to climate change will depend on how they interact with local landscapes, including the natural hazards that come with them. Such hazards might result in catastrophes like Hurricane Katrina or Super Storm Sandy, but more commonly they will include smaller scale events that accrue over time to gradually change settlement areas where they occur. To improve understanding of this dynamic in the U.S. context – where land is a commodity that local coalitions seek to develop – the present study advanced a place-based approach. This approach grounds itself in the general concept of landscape transformation. It then subdivides this process into two basic types: One involves transformation of local landscapes through construction of the built environment; the other involves transformation – specifically, damage – of this modified landscape through natural hazards endemic to the area.

Empirical analyses of these two types of local society-nature interaction indicate that, in general, they are not only path dependent but mutually constitutive. That is, as social actors develop local landscapes, they ground fixed capital in place that, when damaged by natural hazards, generates significant economic losses. These losses in turn operate through existing policies and institutions to bring recovery capital that feeds further development. As these processes unfold over time, built environments and hazard losses feedback and scale up, each compounding the other in and across place over time. This dynamic has important theoretical, methodological, and policy implications for understanding and building a more sustainable future literally from the ground up.

Theoretical Implications

Theoretically, findings from the present study imply that, in the U.S. context at least, environmentally induced damage will not lead to local retreat. Instead, it will encourage building up and out into nearby areas. Thus, the dominant image becomes less one of displacement and more one of *re*-placement: the re-placement, or spread, of local development; and, in the process, the re-placement, or substitution, of formerly unbuilt environments with built ones. How local populations and institutions negotiate these dynamics will undoubtedly vary by economic, political and social resources at their disposal. Yet, one general theoretical point seems clear: Sociological understanding must continue to push beyond the notion that the environment is somehow "out there" waiting to strike or otherwise wear us down. Instead, we must develop theoretical frameworks that allow us to better understand and investigate how local society-nature interactions feedback to constitute one another, over and over again, in place.

Recent efforts to rehabilitate and extend classical theories of (ecological) succession offer one such framework. This work strives to inject environmental processes and political actors back into the Chicago School's early emphasis on local, place-based social change. Three points seem particularly relevant for ongoing work on development-hazard interactions. The first point is actually an axiom: that social and natural processes interact to constitute local landscapes, often slowly and in ways that go unrecognized by those involved. Second, this interaction is driven *and* hidden by residential changes that not only shift different subpopulations slowly around local areas but also, and in the process, reduce local memory of specific risks (e.g., how the immediate area might flood, or be prone to high winds, or falling trees, or wildfires, and so forth). Third, as these interactions and residential churning unfold gradually in local areas over time – often with help from powerful interests – they accumulate in ways that are often unplanned and difficult to reverse. As a result, socio-environmental changes in local landscapes become not only path dependent but successive, with each subsequent wave of change emerging through past interactions and spaces to shape the next.

This line of theorizing highlights how society and nature are not only indelibly connected but cumulatively co-emergent and ongoing. In this sense, there is no final fix; only suf-fix – or, modification through and of what came before, in interative fashion.

Methodological Implications

The findings and theoretical implications above suggest the need for ongoing place-based research that is explicitly historical and comparative in orientation. Such an approach will allow researchers to contextualize and analytically account for key process already in motion locally. This could be done qualitatively or quantitatively. It could also be designed to dig deeper into particular types of cases – e.g., areas experiencing particularly rapid or slow land development; or, areas experiencing different types of natural hazards; or, some combination of both that allows for better scoping of different scales and speeds of interaction between local development and damage.

Future research could also conduct deep case studies of key dynamics presumed but not directly demonstrated by the present study. Chief among them are questions about how much recovery capital tends to enter damaged areas, how quickly, from what sources, and to whom? For example, does it matter for local development whether more recovery funds arrive through private insurance claims than government assistance? Does it matter how much of these funds go to businesses versus residents, and what share of losses are actually covered? This line of research will not be easy, given the disaggregated nature of the evidence and concerns over confidentiality. But, it will be important, as will be investigating how local social inequalities and land-use policies work to moderate and mediate post-hazard development and recovery.

Policy Implications

Local development and damages are path dependent for a host of reasons. And, prevailing inequalities and institutional practices will make any attempts to modify the business-as-usual approach to their local interaction difficult. That said, policymaking should continue to include new design efforts and improved building codes that help reduce risk to life and property. It should also extend to engage longer term interactions between damage and development. These considerations could take many paths, but in closing we highlight one that we think is particularly important but have yet to address: the interaction of natural and human-made hazards.

A good deal of damage and economic loss can be triggered by natural hazards, but when these hazards compromise local infrastructure and release industrial pollutants on a large scale, the effects can become much more far-reaching in time and space. Although not initiated by a natural hazard the BP Horizon oil spill offers one cautionary example, as does industrial pollution released from above-ground storage tanks in and around New Orleans during Hurricane Katrina. As these cases illustrate, there exists a great deal of infrastructure and industrial hazards that are vulnerable to natural hazards, especially in and around port towns and cities of which there are many in the United States, as well as around the world. Thinking more about how to develop and implement policy that better addresses these types of nature-industry risks will become increasingly important, as will paying more attention to social inequalities that leave some groups more exposed to them than others. The Japanese case of nuclear release triggered by an earthquake and subsequent tsunami offers just one prominent example. Efforts to design and build a sea gate that protects the Port of Houston – home to world's largest petro-chemical complex – from hurricane-related storm surge offers another prospective example. We look forward to further work on these complex and ongoing interactions with our natural world.

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Table 1. Variables, Descriptions, and Univariate Statistics (Values are logged)

Variable	Description	t_1		t_2-t_1		t_3-t_2	
		Mean	(SD)	Mean	(SE)	Mean	(SE)
Developed Land Area (t_1=2001, t_2=2006, t_3=2011)							
Total	Total area covered by impervious surfaces in square miles	2.019	(0.956)	0.048	(0.001)	0.033	(0.001)
Extensification	With total developed land area in 2001 for t_1, change in impervious surface area due exclusively to construction on previously undeveloped land	2.019	(0.956)	0.031	(0.001)	0.026	(0.000)
Intensification	With total developed land area in 2001 for t_1, change in impervious surface area due exclusively to further construction on already developed land	2.019	(0.956)	0.026	(0.001)	0.018	(0.000)
Natural Disasters (t_1=2000, t_2=2005, t_3=2010)							
Property Damage	Total property damage from natural disasters, with cumulative damage between 1960-2000 as the baseline for t_1, damage between 2000-2005 for t_2, and damage between 2005-2010 for t_3 (inflation adjusted dollars)	17.278	(1.249)	0.225	(0.008)	0.157	(0.006)
Control Variables (t_1=2000, t_2=2005, t_3=2010)							
Population Size	Total residents living in the county	10.245	(1.418)	0.024	(0.001)	0.019	(0.001)
Urban Population	Residents living in Census-defined urban areas	7.591	(4.420)	0.170	(0.017)	-0.020	(0.012)
Percent White	Percent of population who is non-Hispanic White	4.450	(0.243)	-0.005	(0.000)	-0.006	(0.000)
Percent Elderly	Percent of population who is 65 years or older	4.051	(2.356)	0.234	(0.015)	-0.887	(0.017)
Percent Voting Republican	Percent of votes received by Republican presidential candidate	4.018	(0.236)	0.057	(0.001)	-0.068	(0.002)
Percent Bachelor's Degree	Percent of population 25 years or older with a Bachelor's degree	2.710	(0.410)	0.074	(0.001)	0.051	(0.001)
Residential Building Permits	New single family housing units authorized by building permits	4.051	(2.356)	0.234	(0.015)	-0.887	(0.017)
Median Household Income	Median household income (inflation adjusted dollars)	10.423	(0.235)	-0.002	(0.001)	-0.032	(0.001)
Total Employment	Number of employed people	9.448	(1.539)	0.059	(0.002)	0.020	(0.002)
Total Number of Businesses	Number of business establishments	6.451	(1.462)	0.029	(0.002)	-0.022	(0.001)

Note: The values for percent voting for Republican presidential candidate were measured in 2000, 2004, and 2008. Change-scores are reported under the columns labeled t_2- t_1 and t_3- t_2; all these change-scores are significant at $p<0.001$ (one-tailed test).

Table 2. Results from the Regression of Developed Land on Property Damage from Natural Disasters, 2001-2011

	Total (Model 1)		Outfill (Model 2)		Infill (Model 3)		Total (Model 4)		Outfill (Model 5)		Infill (Model 6)	
	b	SE	b	SE	b	SE	b	SE	b	SE	b	SE
Natural Disasters												
Property Damage	0.007 ***	0.002	0.005 ***	0.001	0.002 *	0.001	0.004 *	0.002	0.002	0.001	0.002	0.001
Property Damage × 2006	. . .	. . .	. . .	. . .	. . .	. . .	0.002 **	0.001	0.002 ***	0.001	0.000	0.000
Property Damage × 2011	. . .	. . .	. . .	. . .	. . .	. . .	0.004 ***	0.001	0.004 ***	0.001	0.001	0.001
Control Variables												
Population Size	0.196 ***	0.026	0.199 ***	0.025	0.030 *	0.012	0.187 ***	0.025	0.192 ***	0.025	0.028 *	0.012
Urban Population	-0.001	0.001	-0.001	0.001	0.000	0.001	-0.001	0.001	-0.001	0.001	0.000	0.001
Percent White	-0.213 ***	0.040	-0.163 ***	0.031	-0.077 ***	0.022	-0.204 ***	0.039	-0.154 ***	0.031	-0.075 ***	0.021
Percent Elderly	0.025 *	0.012	0.019	0.011	0.009	0.007	0.028 *	0.012	0.022 *	0.011	0.010	0.007
Percent Voting Republican	0.001	0.006	0.001	0.004	0.001	0.004	0.005	0.006	0.004	0.004	0.002	0.004
Percent Bachelor's Degree	0.001	0.008	0.010	0.006	-0.008	0.006	0.000	0.008	0.009	0.006	-0.008	0.006
Residential Building Permits	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Median Household Income	-0.038 ***	0.009	-0.037 ***	0.007	-0.009	0.006	-0.037 ***	0.009	-0.037 ***	0.007	-0.009	0.006
Total Employment	0.041 ***	0.009	0.032 ***	0.006	0.011	0.008	0.045 ***	0.009	0.036 ***	0.006	0.012	0.008
Total Number of Businesses	0.045 ***	0.010	0.038 ***	0.008	0.014 **	0.005	0.044 ***	0.010	0.037 ***	0.008	0.014 *	0.005
Year Dummy (2006)	0.013 ***	0.001	0.005 ***	0.001	0.009 ***	0.001	-0.020	0.010	-0.031 ***	0.009	0.008	0.008
Year Dummy (2011)	0.021 ***	0.002	0.007 ***	0.001	0.017 ***	0.002	-0.041 **	0.014	-0.057 ***	0.011	0.004	0.011
ρ	0.477 ***	0.021	0.386 ***	0.023	0.612 ***	0.026	0.471 ***	0.021	0.376 ***	0.024	0.611 ***	0.026
Within R^2	0.675		0.606		0.584		0.675		0.612		0.585	
N = Counties × Years	3079 × 3 = 9,237 County-Years											

*p<0.05; **p<0.01; ***p<0.001 (two-tailed significance tests)

Note: Spatial panel models are estimated with a queen, first-order contiguity weights matrix.

Figure 1. County level Maps of Land Development and Property Damage. (Darker shading indicates higher values.)

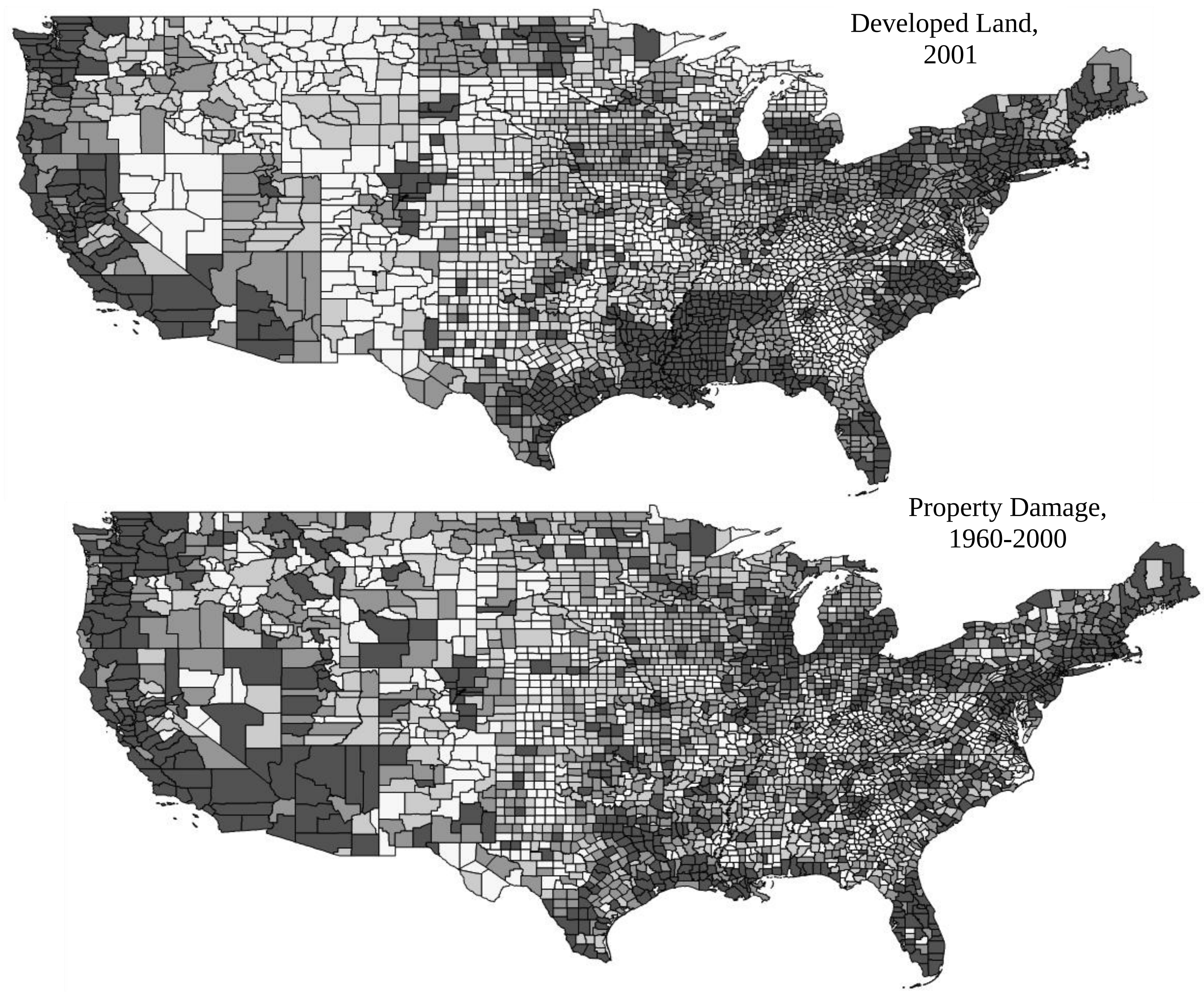
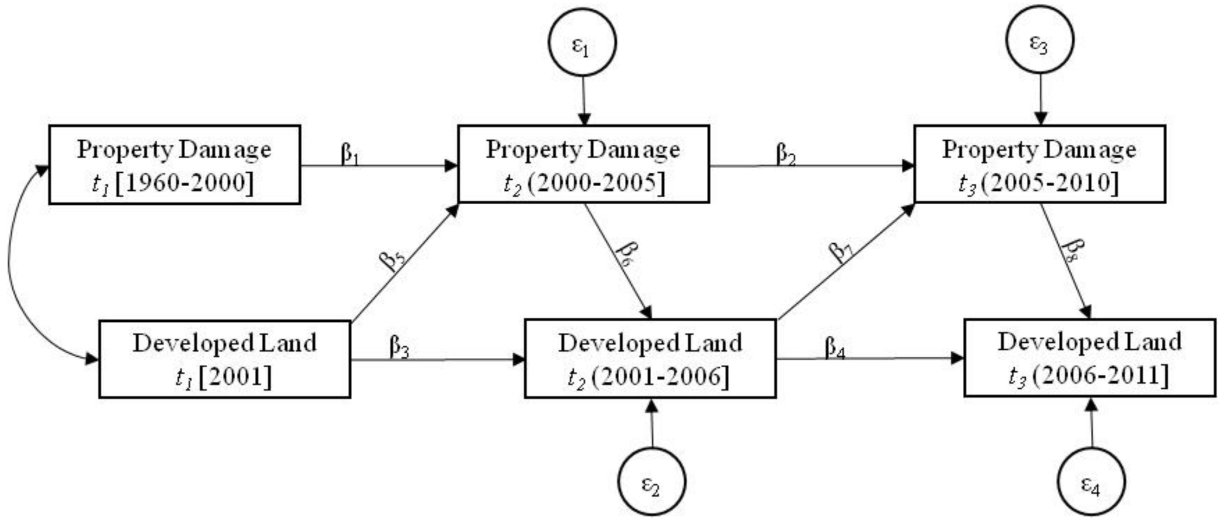


Figure 2. Generic Structural Equation Model



Note: Controls not listed.

Figure 3. Correlations between Land Development and Property Damage over Time (All Values are Logged)

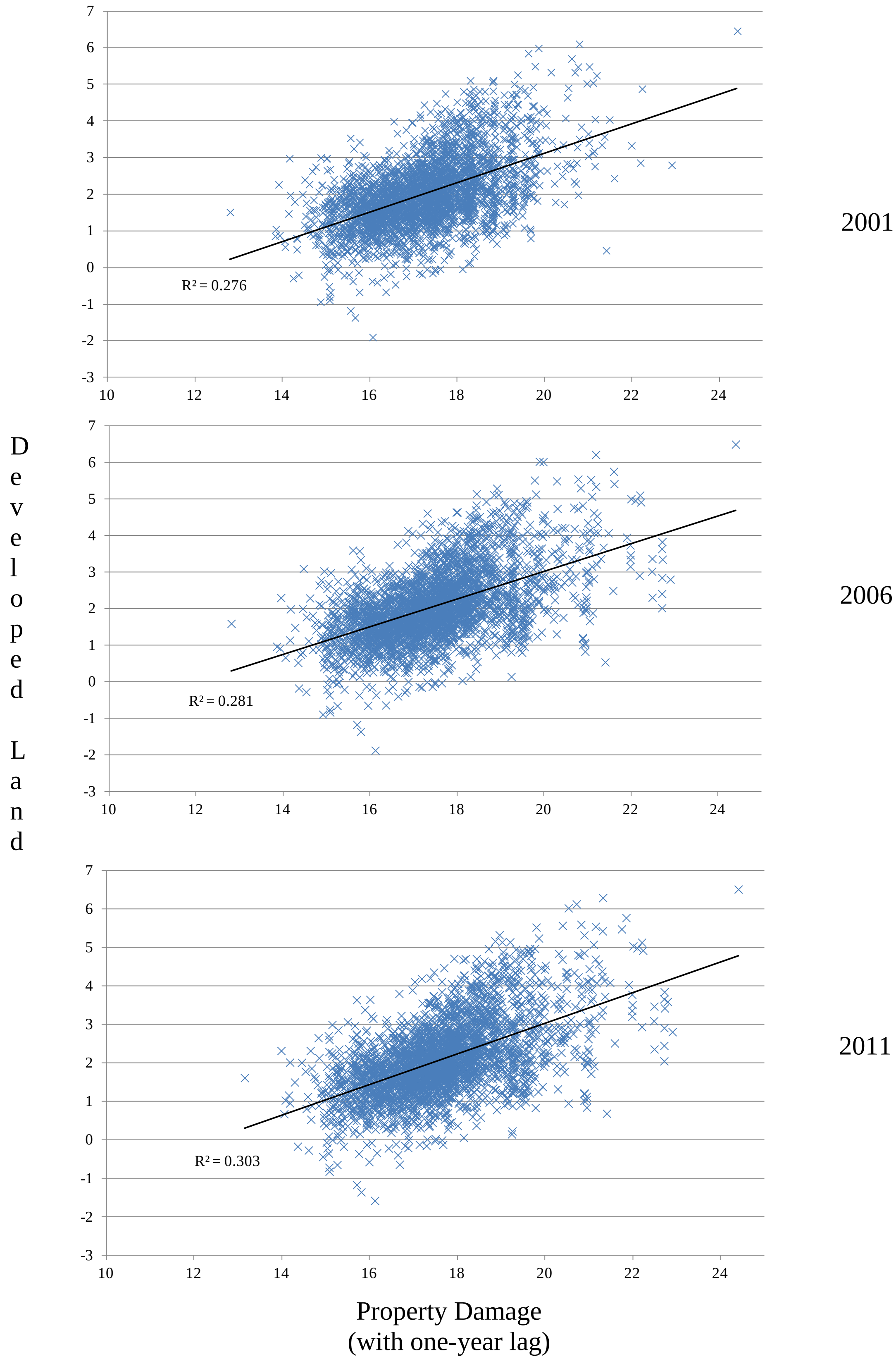
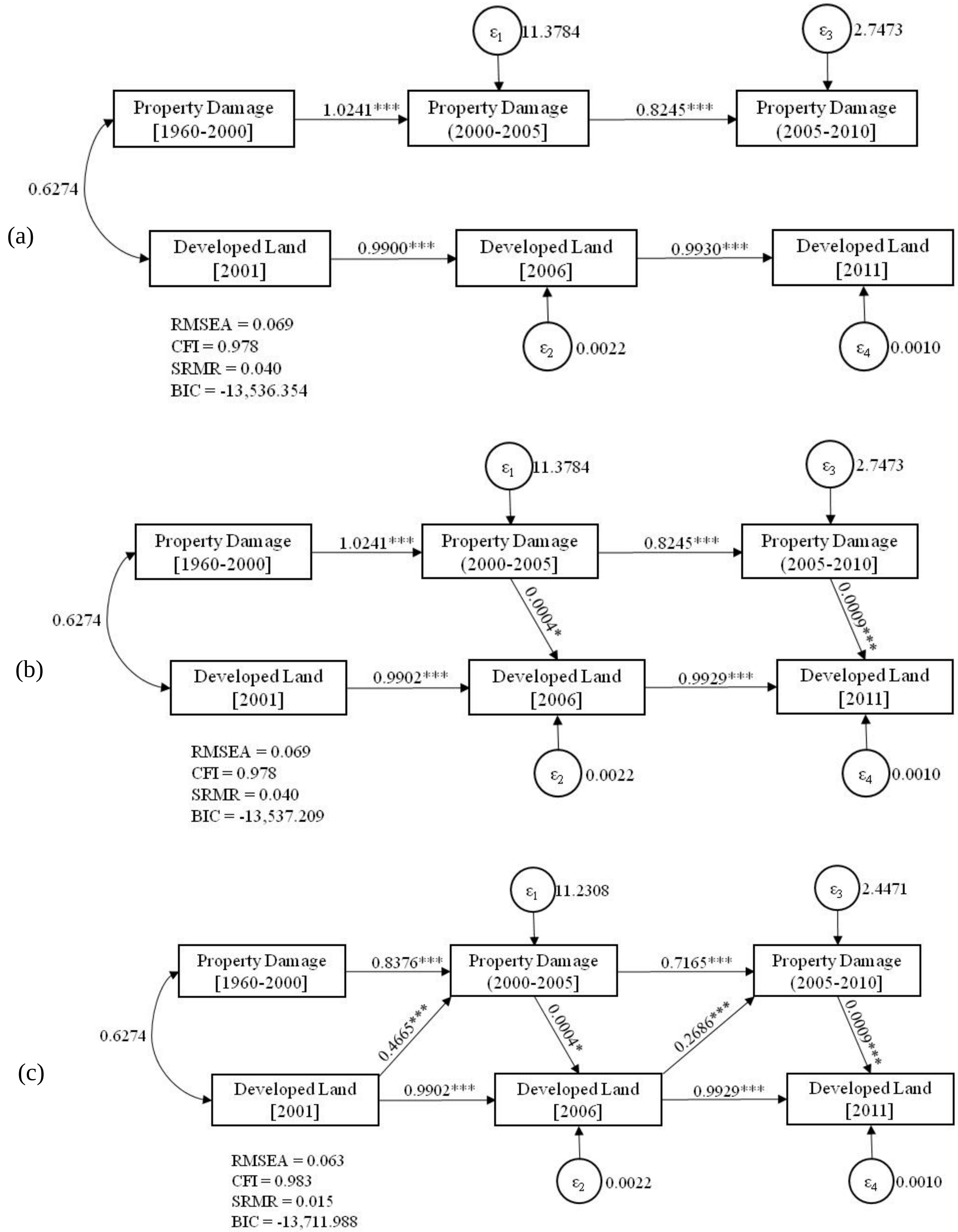


Figure 4. The Reciprocal/Feedback Relationship between Land Development and Property Damage



Note: Controls included but not displayed in all three models.