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Space-Time Granger Analysis of the War in Iraq: A Study of Coalition and Insurgent Action-Reaction

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We investigate insurgent-coalition interaction using the WikiLeaks dataset of Iraq war logs 2004–2009. After a review of existing theoretical interventions on the dynamics of insurgency and presenting a baseline model of violent events, we test a conceptual model of reciprocity using an innovative space-time Granger causality technique. Our estimation procedure retains predicted probabilities of reaction in response to a previous opponent's action across different temporal and spatial configurations in Iraq and in Baghdad. Our conclusions about conflict in Iraq are based on these profiles of risk—what we call space-time signatures. We find strong evidence of "tit-for-tat" associations between coalition/Iraq forces on one side and insurgents/militants on the other. Specifically, we find that the action-reaction association varies strongly by majority ethnic region across Iraq and in Baghdad, by urban and nonurban location, and within Sunni-dominated areas, by district income. While violence is strongly temporally dependent in the same location, the effect of distance varies significantly across the different subsets of the Iraq data.

We thank Nils Weidmann and Idean Salehyan for sharing their spatial representation of ethnosectarian populations among Baghdad's neighborhoods, Nancy Thorwardson for preparing the publication graphics from our drafts, and our anonymous reviewers for helpful suggestions. Any errors are ours. Replication code is available on the *International Interactions* dataverse page at http://dvn.iq.harvard.edu/dvn/dv/internationalinteractions and at http://www.colorado.edu/ibs/johno/iraq/. Authors are graduate research assistant, post-doctoral research associate, and professor of distinction in Geography, respectively.

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Despite the United States' termination of formal combat operations in Iraq on May 1, 2003, conflict in the country intensified and beginning in late 2005 ethno-sectarian assassinations, bombings, and other attacks plunged the country into civil war (Fearon 2007).[1] With conditions in Iraq worsening, the mounting death toll of violence served as a rationale for a US troop surge by the Bush Administration (January 10, 2007). Alongside the elevated number of coalition soldiers, rates of insurgent violence across the country soared to unprecedented levels. In applying geographic approaches to the study of violence in Iraq, we use a Granger causality estimation that incorporates both spatial neighborhood effects and temporal dependencies. Our key question is: How does coalition- and insurgent-initiated violence interact? If a "tit-for-tat" pattern emerges, is it contingent upon underlying social and political conditions? We expect some level of reciprocity between actors, but move beyond this to identify how the spatial and temporal scales of retaliation vary across the country and by initiating actor.

POLITICAL VIOLENCE AND INSURGENCY

One vein of the conflict studies literature analyzes how weak actors, usually insurgents, often defeat more powerful foes (Arreguín-Toft 2005; Merom 2003; Mocktaitis 2008; Record 2007). A number of social and structural factors, especially a local population's loyalties, condition the ability of armed actors to successfully respond to one another's actions. The community caught in a crossfire often determines the outcome of an insurgent campaign. Excessive and indiscriminate violence by an incumbent may push the population to favor rebels through harboring militants or keeping secret their knowledge of insurgent operations (Kalyvas and Kocher 2007; Kocher, Pepinsky, and Kalyvas 2011; Lyall and Wilson 2009). Iyengar and Monten (2008) suggest that uncertainty about the final outcome of the Iraq war results in the unwillingness of a local population to share information with coalition (United States and allies, and Iraqi government) forces—those who are apprehensive about the end result of the conflict become fence-sitters. Attributing their results to the information-sharing mechanism, Condra and Shapiro (2012) find that insurgent attacks in Iraq rise in the wake of civilian deaths caused by coalition forces and that insurgent strikes fall following insurgent collateral damage. Furthermore, they find that the effect is strongest

[1]Following Williams and Simpson (2008, 194), we use "ethno-sectarian" to characterize Sunni, Shi'a, and Kurdish communities, fully acknowledging the complexity of debates surrounding how "ethnicity" is defined.

in urban areas and regions with mixed (no single majority) ethnicities. The specific mechanisms driving insurgent reactions to casualties may vary, however, as Condra, Felter, Iyengar, Radha, and Shapiro (2010) show using different temporal windows for insurgent reactions to coalition-caused deaths in both Afghanistan and Iraq. Our goal in this short article is not to examine individual-level mechanism that drives participation in violence. Instead, we use a space-time extension of Granger analysis to interrogate the nuances of the spatial and temporal scales of where and when reciprocal action by both actors takes place.

The mechanisms driving populations toward insurgent sympathy is not limited to *deliberate* targeting of civilians, or even to civilian fatalities. Support for rebels may be a result of other negative externalities of conflict, such as the destruction of infrastructure, loss of employment, forced relocation, and brutal law enforcement. Some studies use civilian casualties as a predictor of subsequent insurgent-initiated violence (for example, Condra and Shapiro 2012 use Iraq Body Count data). Because any attack introduces the risk of widespread negative externalities identified by Bueno de Mesquita and Dickson (2007), we do not limit our analysis only to instances of civilian death. At a formal level, US military doctrine now reflects greater concern about unintended consequences of operations, evidenced in the release of the *Counterinsurgency* field manual by the Department of the Army (Petraeus and Amos 2006). Understanding that violence can alter local opinion, insurgents often goad incumbent or occupying forces into risky battles during guerrilla war, documented in accounts of earlier irregular conflicts (Bueno de Mesquita and Dickson 2007). It is known that insurgents hide among the Iraqi civilian population (Mocktaitis 2008:20, 110), and thus coalition and Iraqi National Security Forces are drawn into engagements where the potential for civilian harm exists. Since 52 percent of Iraqi civilian deaths from conflict are estimated to be caused by coalition forces (Hicks, Dardagan, Serdan, Bagnall, Sloboda, and Spagat 2011), this does not bode well for counterinsurgency.

If government violence pushes civilians toward support for insurgents, we expect to observe higher rates of conflict in an area following counterinsurgent operations: "security force abuses and the social upheaval caused by collateral damage from combat can be major escalating factors for insurgencies" (Patraeus and Amos 2006:9).[2] This response or tit-for-tat trend can be formally understood as similar to a series of prisoners' dilemma games when both actors could opt for cooperation or conflict on the first encounter and from that point forward, mimic the other actor's previous move in following games (Axelrod 1984). Many studies of reciprocal conflict and cooperation have been developed within the interstate system. Ward

[2]Repression can be associated with lower levels of violence, as Lyall (2009) has found for the aftermath of targeted bombing campaigns by Russian forces in Chechnya (see also Bueno de Mesquita 2005).

(1982:87), for instance, identified a positive pattern of reactivity ("behavior-begets-behavior") in the Cold War interaction between the United States and the Soviet Union, a finding later complicated when a finer temporal resolution showed action-reaction models to be overly simplistic (Rajmaira and Ward 1990). Following this reciprocity line of inquiry, we direct our attention to subnational scales and non-state actors instead of foreign policy, diplomacy or arms races; our approach is similar to a study of Egyptian counterinsurgency where Fielding and Shortland (2010:445) found "evidence for a cycle of violence in which increased activity on one side is followed by increased activity on the other" (see also Jeagar and Passerman 2006).

Violent events within a broader war exhibit spatial dependencies at a subnational level (O'Loughlin and Witmer 2011; O'Loughlin, Witmer, and Linke 2010); it is the nuances of such dependencies that we investigate here. Extending more basic time-series analysis into spatial time-series methods, we can examine whether a government event during a specific time period is associated with higher risk of insurgent events *in a nearby location* in the next time period. We define spatial and temporal boundaries specifically to capture a possible reciprocal interaction in the same location, but also across nearby locations and through several ranges of time. In Iraq, Townsley, Johnson, and Ratcliffe (2008) showed that the highest risk of further Improvised Explosive Device (IED) attacks exists within one kilometer of a previous IED incident, and for a period of two days. The authors argue that insurgents make calculated assessments of risk, because when circumstances allow for safe travel, insurgent activities develop a level of predictability. Iraqi insurgent actions cluster in space and time, but IED attacks form tighter space-time clusters than non-IED events (Johnson and Braithwaite 2009). The authors speculate that planting IEDs requires a greater level of planning and more substantial training than other event types (for example, shooting attacks), and also requires a particular set of materials, expertise, and local support.

DATA

Data for our analysis were released by the WikiLeaks organization in October 2010 and debate continues whether or not it is appropriate to use these "secret" data (Bohannon 2010). Despite possible limitations of the information related to censoring bias ("top secret" events are not included in the WikiLeaks file), or inaccuracies of data-gathering on the ground, these data reveal noteworthy trends in the Iraq war. Access to the raw SIGACTS data (what WikiLeaks obtained) is generally not allowed for academic and other public use but they have been released to selected researchers. Subsets of the Iraq SIGACTS database have been examined in Weidmann and Salehyan (2011), Condra et al. (2010), Condra and Shapiro (2012), and Berman, Callen, Felter, and Shapiro (2011).

The WikiLeaks data for Iraq suffer from two specific deficiencies. First, data are missing for mid-April through the end of May 2004, and February through March 2009. Additionally, the location coordinates for each event are truncated at a tenth of a degree (about 10 km) for Iraq outside of Baghdad and at a hundredth of a degree (about 1 km) for the military zone of Baghdad and surrounding areas. The spatial distribution of the WikiLeaks violent events is presented here in proportion to the district's population (Figure 1). For presentation of the raw data, our shapefile of district boundaries is taken from the database of Global Administrative Areas (GADM).[3] Population estimates are derived from the United Nations World Food Program report 2004.[4] For missing data in the Kurdish region, we use LandScan estimates for 2008, which are derived from subnational census data apportioned to 30-by-30 second grid cells (or about 1km resolution).[5] Totaled over 6 years of war (2004–2009), the number of insurgent-initiated events in Baghdad is extremely high, at 45,311, with coalition-initiated events at 12,957. Controlling for population, Sala ad-Din, just north of the capital, experienced the highest rate of violence at over 58 events per 1,000 people. Districts in Anbar province in the "Sunni triangle" have the highest rates of coalition-initiated violence, ranging from 17 to 47 events per 1,000 people.

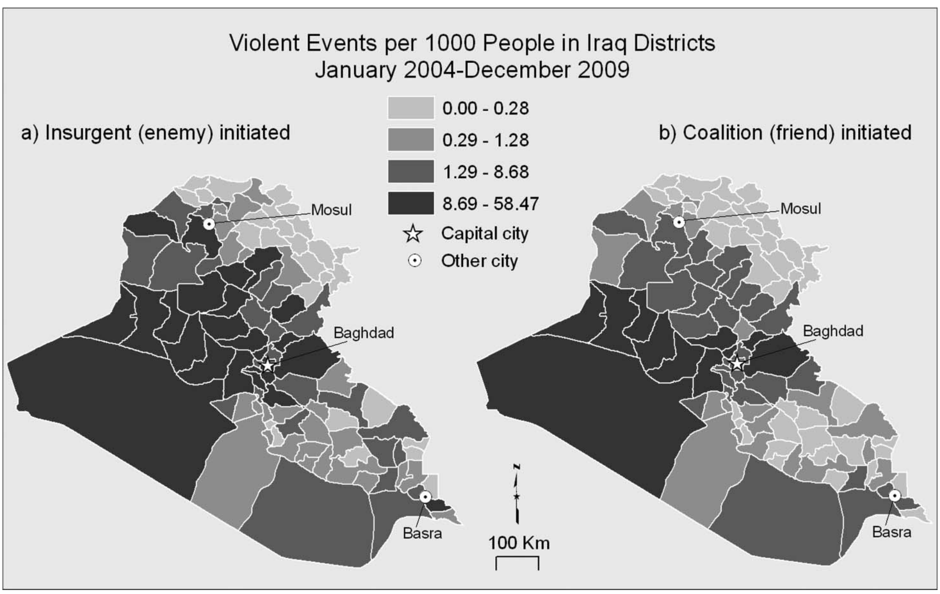

FIGURE 1 Violent events per 1,000-people district in Iraq, 2004–2009.

[3]http://www.gadm.org/
[4]http://www.iauiraq.org/reports/WFP%20Baseline%20Food%20Security%20in%20Iraq%20%20Sept%20 2004.pdf
[5]http://www.ornl.gov/sci/landscan/

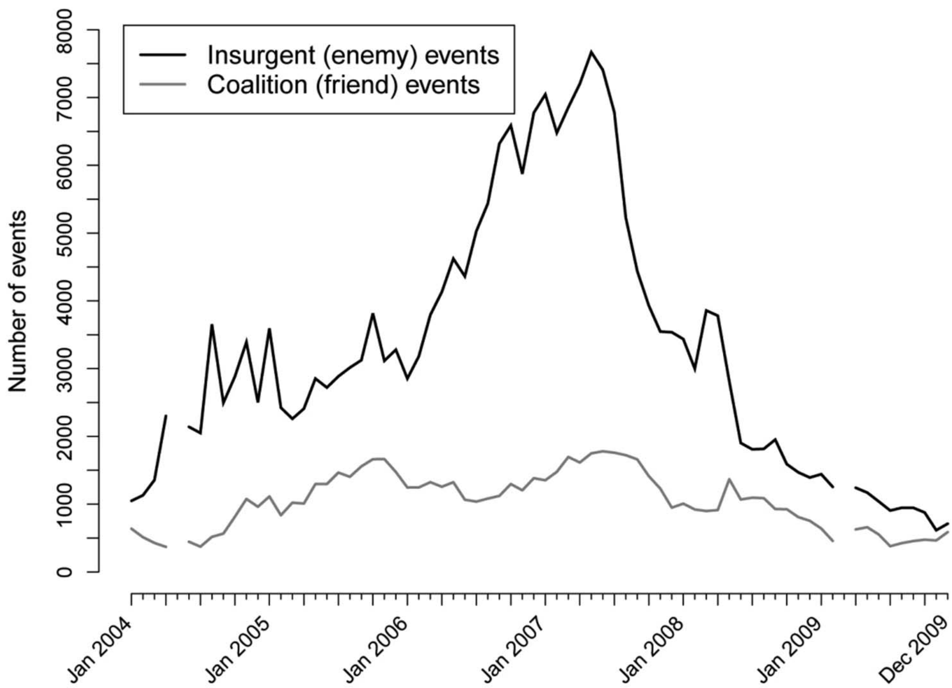

FIGURE 2 Monthly Iraq violence by initiating actor, 2004–2009.

Not surprisingly, in the Southeast (predominantly Shi'a) and northern Kurdish regions, coalition events are relatively few compared to insurgent events (Figure 1).

The oscillation of insurgent violence is clear in Figure 2, with 2004 and 2005 activity much higher than immediately following the US invasion. In January 2007, after the surge of nearly 20,000 new US troops, rates of violence initially rose to unprecedented levels, but conflict then abated rapidly through 2007 and after. We eliminated both nonviolent and criminal events from the data to leave a total of 301,374 events in our analysis.

Our Iraq ethno-sectarian data come from the Gulf/2000 project at Columbia University.[6] We focus on the three largest ethno-sectarian communities for our country level analysis; their distributions are shown in Figure 3 by our gridded (0.1 degree) analysis units. The countrywide demographic data are only available for 2008. The ethnic grid cell subsets were selected based on the ethnicity for the center of each grid cell. Of the 4,423 Iraq grid cells, 645 are dominated by Kurds, 735 by Shi'a, and 914 by Sunni.

For our analysis of Baghdad, we examine only the Sunni and Shi'a majority areas. The original population data source is the Gulf/2000 project and the information was transferred into a spatial representation for

[6]http://gulf2000.columbia.edu/

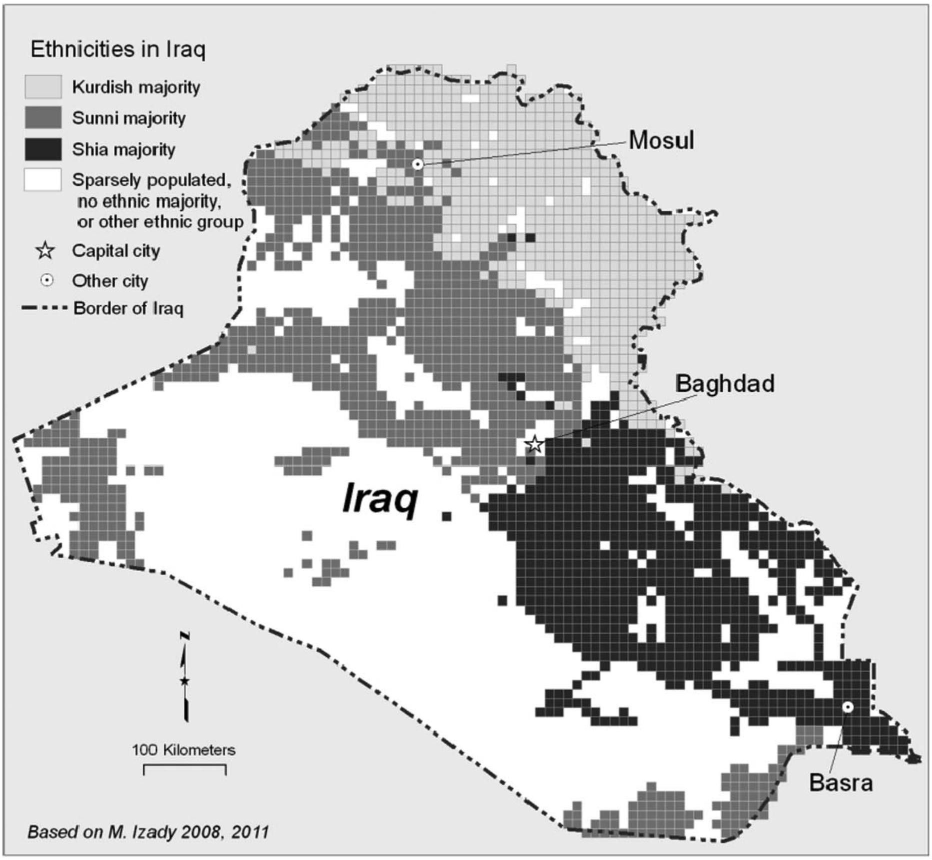

FIGURE 3 Ethno-sectarian population distributions in Iraq. Based on M. Izady, Gulf/2000 project, Columbia University, New York.

Weidmann and Salehyan's (2011) study. These distributions are time-sensitive, available for 2003, 2006, early and late 2007, and 2009. Using our gridded analysis units for Baghdad, the ethnic distributions for start and end years are displayed in Figure 4. For the Baghdad grid cells (0.01 degree), there is a very obvious polarization of ethnicities over time. In 2003, mixed areas dominated the capital but by 2009, few such areas remained.

Our poverty data for Sunni majority areas of Iraq were coded from the World Food Program survey.[7] According to the survey, the combined lowest two income quintiles are defined as poor. We assigned each grid cell the percentage living below the second income quintile. Our distinction between urban and nonurban areas is defined using nighttime lights imagery

[7] http://www.iauiraq.org/reports/WFP%20Baseline%20Food%20Security%20in%20Iraq%20%20Sept%20 2004.pdf

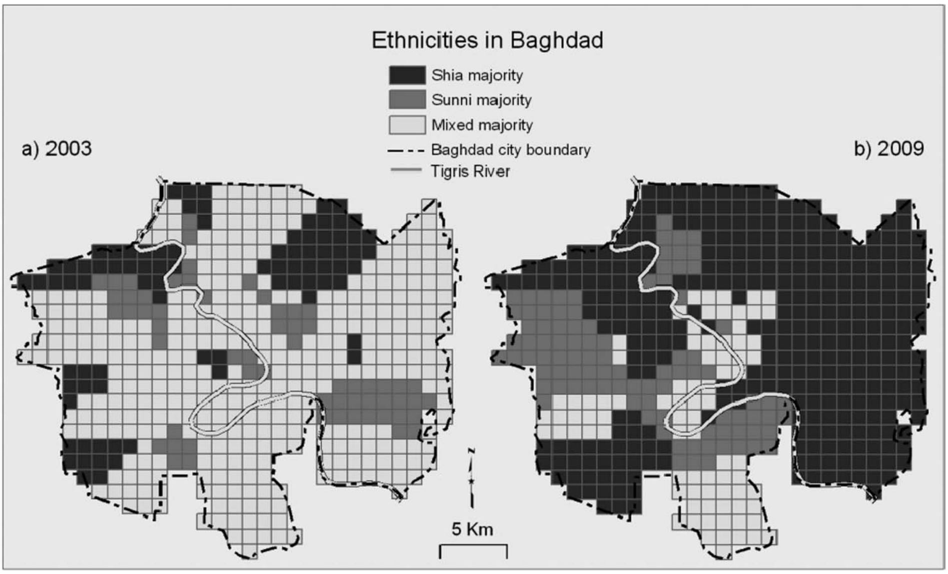

FIGURE 4 Ethno-sectarian division in Baghdad, 2003 and 2009. Based on M. Izady, Gulf/2000 project, Columbia University, New York.

for 2002.[8] We selected all pixels of brightness greater than 30 (from the 0–63 range), and verified that these regions coincided with urban areas using Google Earth imagery. Due to the significant gas flaring that occurs in Iraq (Elvidge, Zisken, Baugh, Tuttle, Ghosh, Pack, Erwin, and Zhizhin 2009) we further refined the urban areas by manually removing lights caused by gas flaring. We then overlaid these urban areas on the Iraq national level grid and designated cells as urban if 25% or more of the cell area was filled with bright light.

For both the National and Baghdad analysis grids, we aggregated point events to polygons and calculate first- and second-order spatial lags (using queen contiguity). To examine temporal autocorrelation, we aggregated events to 3-day periods, and added five temporal lags. Periods overlapping the missing data months were omitted. We extracted spatial subsets from the master space-time data structure, which has the advantage of retaining all grid cells and their space-time lags.

BASELINE EMPIRICAL RELATIONSHIP

As a baseline country wide model, we establish an empirical relationship between violent events and a space-time lag, ethnic character, income level and urban setting by estimating:

[8]Image and data processing were conducted by NOAA's National Geophysical Data Center. DMSP data were collected by US Air Force Weather Agency.

$$V_{ait} = \beta_1 V_{ajt-1} + \beta_2 V_{bjt-1} + \beta_3 Z_{it} + \varepsilon_{it}$$

where V represents a violent event initiated by actor a at location i or in first-order spatial neighborhood j during t three-day period or the preceding three-day period, *t-1*. Coefficients $\beta_{1,2}$ characterize the association between each party's action and the opponent response. The matrix Z contains Sunni, Shi'a, and urban binary classifications for location i and time t. β_3 is a vector of coefficients capturing the influence of these socioeconomic variables. For areas where data are available, Z includes a continuous 2005 poverty measure. Residual error is captured in ε. The model is run with insurgents and coalition forces alternatively defined as actor a. The estimation is made with a negative binomial model.

Table 1 shows that all independent variables are statistically significant, a result influenced by the large number of observations. Previous events initiated by an actor are a consistently positive predictor of future activity. Lending support to the notion of reciprocity, events within a first-order spatial neighborhood during the previous time period are a positive predictor of violence for both opposing coalition and insurgent initiated events. Comparatively, Shi'a and Sunni areas are more likely to experience violence than either mixed or Kurdish regions. Similarly, urban areas are more likely to witness conflict than nonurban. Higher levels of poverty are associated with greater conflict whether initiated by coalition or insurgent forces. Next we extend our analysis to varying spatial resolutions and finer temporal ranges. Our baseline model shows that coalition events predict insurgent reciprocal action at the first order neighbor scale and 3-day period. However, these base models cannot show how the two parties interact *within* those areas. Rather than controlling for underlying variables by holding them constant at statistical averages, we estimate coefficients for reciprocity across space-time scales for data subsets defined by each key variable.

RECIPROCITY PROPOSITIONS

From a baseline model of the variables that influence conflict in Iraq, we have evidence that reciprocity between actors exists. Also, we found that ethnicity, urbanity, and income condition the likelihood of violence. Our further analysis investigates the details of how these variables influence patterns of reciprocity. The degree to which a coalition action predicts violence perpetrated by insurgents may be strong for a very small area (for example, in the same town), slightly weaker for a larger area (for example, in a first-order neighboring analysis unit), and nonexistent for higher order distances. Similarly, the distances between events in time are expected to vary. In a

TABLE 1 Negative Binomial Baseline Model Results for Independent Variable Influences on Conflict in Iraq

	All grid cells				Poverty survey grid cells			
	(a) Coalition violence		(b) Insurgent violence		(c) Coalition violence		(d) Insurgent violence	
Dependent variable	*Estimate*	*z value*	*Estimate*	*z value*	*Estimate*	*z value*	*Estimate*	*z value*
(Intercept)	−5.612	−486.181**	−4.680	−619.508**	−6.451	−268.024**	−5.622	−320.597**
Coalition space-time lag	3.266	154.746**	1.765	85.006**	3.184	152.952**	1.674	81.691**
Insurgent space-time lag	0.656	103.737**	2.155	350.261**	0.624	100.123**	2.062	339.993**
Shi'a dummy variable	1.155	67.545**	0.977	80.951**	0.952	54.321**	0.778	62.829**
Sunni dummy variable	1.766	124.485**	1.396	135.565**	1.614	110.995**	1.260	119.529**
Urban dummy variable	1.260	47.023**	0.947	39.189**	1.324	49.882**	1.018	42.360**
Poverty 2005 (%)					0.055	44.498**	0.061	65.713**
AIC	425224.0		814918.0		420317.4		804848.4	
AUC	0.888		0.896		0.885		0.897	
N	3,113,792		3,113,792		2,953,280		2,953,280	
Num. dep. var. events	72,618		228,756		72,466		228,465	
Non-zero percentage	1.31		2.53		1.38		2.65	
True/false positives (%)	True	False	True	False	True	False	True	False
	41.72	1.37	56.25	2.35	41.98	1.45	56.80	2.66

AIC = Akaike Information Criterion. AUC = area under the curve.
True and false positives calculated using a threshold of 0.1.
$^{*}p < .05$; $^{**}p < .01$.

series of propositions we investigate how these space-time signatures vary by ethnicity, urbanity, and income subsets of the data.

> Proposition 1: *Patterns of reciprocity across space and time will be comparable for coalition and insurgents.*

Insurgents have an advantage over the coalition in their knowledge of local surroundings and their ability to blend into the population. On the other hand, incumbent forces have a significant military advantage. Applying this information despite the force asymmetries, we expect that the space-time tit-for-tat model will show patterns of reciprocity that between actors are similar across many combinations of spatial and temporal scales.

> Proposition 2: *Patterns of insurgent reciprocity across space and time will be more robust in Sunni regions than in others. Coalition responses will be more limited in Sunni areas.*

On the whole, Iraq's majority Shi'a population supported the Iraqi Governing Council, which was formed in the aftermath of the initial US-led occupation in 2003. Shi'a support stems from decades of the community's exclusion from power by Saddam Hussein's Sunni Ba'ath party. Serving as Chief Administrator of the Coalition Provisional Authority in the year after the invasion, L. Paul Bremer effectively purged the administration of tens of thousands of Sunni officials. Shortly thereafter the Iraqi armed forces were dissolved, driving tens of thousands of trained fighters into the arms of a burgeoning insurgency. To the Sunni community, "coalition policies such as the dissolution of the Iraqi army and the Ba'ath Party and indifferent treatment of the Sunnis seemed deliberately designed to ensure their marginalization" (Hashim 2006:78–79). During the 1990s, a trained Sunni militia called the *Sadaam Fedayeen* were charged with fending off discontent in minority regions. The group's tactics (small arms attacks, explosives, and sabotage) would bedevil coalition forces after 2003 (Mocktaitis 2008:106). We expect that insurgent reactions to coalition actions will occur across all time periods and with a greater spatial range in Sunni areas of Iraq than in others.[9] In comparison, we predict that coalition patterns of reciprocity will be restricted in scope.

> Proposition 3: *Patterns of insurgent reciprocity across space and time will be more robust in poor regions than in nonpoor. Coalition responses will be more limited in poor regions.*

[9]There were foreign fighters in the Iraq insurgency. Dramatic tactical and social rifts between domestic Sunni and international Sunni insurgents existed, however, as in Fallujah during 2004 (Mocktaitis 2008:127). The foreign contingencies of the insurgency were also largely *jihadist*.

The opportunity costs of joining or sympathizing with insurgents is expected to be related to poverty or unemployment status (Berman et al. 2011:3; Kavanagh 2011). The emergence of the core of the insurgency in the Sunni Anbar province was due partly to poverty and unemployment according to Malkasian (2006:429). In the ethnically-mixed Sunni-Kurdish northern city of Mosul, unemployment was as high as 75% in 2004 (Napoleoni 2005:185). Insurgency can be a livelihood supplement, and government repression can create circumstances where participation in the official economy is an unattractive or impossible option for citizens (Bueno de Mesquita 2005:527). Explaining results that point in the exact opposite direction—that lower employment is associated with reductions in violence—Berman et al. (2011) outline a feasible alternative scenario: government forces can buy information from a population, which allows them to counteract insurgent actions. While relative wealth is an important consideration in the conflict studies literature, some research does not include socioeconomic status (for example, Condra and Shapiro 2012). We test the proposition that insurgent responses will be strong and consistent in poorer regions of Iraq's majority Sunni areas.

> Proposition 4: *The patterns of reciprocity across space and time for both actors will vary between urban and nonurban areas.*

The prevailing view of insurgency is that rural areas offer better sanctuary for militants (Kalyvas 2006; McColl 1969), whereas cities tend to maintain a higher level of policing and state control. Many studies focus exclusively on rural guerilla wars, which are relatively common in the historical record. Our aim in this section is to characterize reciprocity in urban *and* nonurban areas. While on one hand urban areas may hinder insurgent activity because of increased military presence, urban areas also host robust communication networks associated with larger populations and access to technology, potentially allowing for greater militant mobilization. Condra and Shapiro (2012) show that insurgent strikes follow coalition inflicted collateral damage with greater tenacity in areas with urban populations. Shapiro and Weidmann (2011), however, show that mobile phone network coverage (stronger in urban areas) can be a detriment to insurgent collective action. Finally, proper counterinsurgency training in Iraq—including urban guerilla confrontations—was initially limited to special operations troops (Mockaitis 2008:79), provoking difficulties for ordinary soldiers fighting in such a setting. Conceptually, the urban setting could grant either actor the upper hand.

> Proposition 5: *Patterns of insurgent reciprocity across space and time will be more robust in Sunni regions of the capital. Coalition responses will be more limited in Sunni regions.*

After probing the patterns of conflict at the country scale, we focus on Baghdad as a microcosm of the larger conflict. Weidmann and Salehyan (2011) also examine patterns of ethno-sectarian conflict in the capital, and support earlier claims (such as Agnew, Gillespie, Gonzalez, and Min 2008) that spatial polarization of the Shi'a and Sunni communities took place as a function of the city's ongoing violence. With similar justification as our proposition at the national level, we expect that coalition violence will elicit a more vigorous (across all time ranges and both spatial scales) insurgent reaction in Sunni areas compared to Shi'a or mixed neighborhoods of Baghdad. Relative to insurgent patterns of response, coalition reactions will be constrained.

ESTIMATING RECIPROCITY

We outline a model where we estimate a coefficient that summarizes the direction and strength of any link between action and subsequent reaction across actors. Such an understanding is represented,[10]

$$X_t = \beta_{11} X_{t-1} + \beta_{12} Y_{t-1} + \varepsilon_1$$

$$Y_t = \beta_{21} Y_{t-1} + \beta_{22} X_{t-1} + \varepsilon_2$$

where the choices of an actor X and an opponent Y at time t are influenced by their previous actions at t–1, that of the opponent at t–1, and unspecified influences $\varepsilon_{1,2}$.[11] If the estimate of β_{12} or β_{22} is positive and distinct from a zero effect, it provides evidence of an action-reaction effect for the corresponding actor upon the opponent. We reduce $\varepsilon_{1,2}$ by introducing spatial lag effects (similar to the spatial vector autoregression in Kuethe and Pede (2011)). Illustrated below, the effect of nearby opponent events on X_t or Y_t is most often positive. This addition reflects the cumulative evidence that spatial dependency is an important characteristic of conflict.

The specific estimator we use is a Granger causality procedure (Granger 1969; Freeman 1983). Maney (2005) shows its value in the temporal dimension for understanding ethno-nationalist violence in Northern Ireland. We use a Wald F test to determine whether adding X_{t-1} into a temporal autoregressive model more accurately predicts Y_t. X_{t-1} is said to Granger-cause Y_t in the case of improved prediction, and we use β_{22} to evaluate the risk of observing a reaction given opponent action. The autoregressive coefficient β_{21} controls for persistence in violence by a given actor and typically contributes more

[10]As in Goldstein (1991:196), Rajmaira and Ward (1990:463), and in the work of others developing upon Richardson (1960).

[11]In the traditional model, it is the opponent's action at t. With a time aggregation of three days, we are wary of endogenous effects within the same period and prefer a minimum lag of one period.

to the predictive capabilities of the model than opposing actor violence. We develop upon the simple models above by expanding the temporal lags, X_{t-1} from one to five. We also include sets of lagged first- and second-order neighboring violence terms that add a spatial component to the traditional temporal Granger-causality model. This yields a total of 15 autoregressive terms (three spatial zones and five temporal periods) and 15 opponent predictors. The coefficients of all 30 terms are interpreted similarly to β_{12} and β_{22} above.

All coefficients are estimated using a negative binomial generalized linear model in the R MASS package. We purposefully retained the full distribution of our data to estimate count models (rather than binary logit models) and truncate the fitted values to allow for the use of binary model diagnostics, such as the area under the receiver operator characteristic curve (AUC). The curve is drawn as a function of the true positive rate (number of correctly predicted violent grid-periods divided by the total number of violent grid-periods) and false positive rate (number of incorrectly predicted violent grid-periods divided by the total number of nonviolent grid-periods).

VALIDATION OF THE ACTION-REACTION ASSOCIATION

In Table 2, we present the global results of a space-time Granger analysis that includes first- and second-order spatial neighborhood lags and five 3-day temporal windows. We present the AUC metric as a measure of the effectiveness of our model predictions. We also present the percent true and false positives for a given threshold of 0.1 (predicted levels of violence above 0.1 are designated as "positives"). Finally, for each model, we present the number of events across grid cell periods (the dependent variable), the nonzero percentage of these events, and the number of grid-periods.

The space-time Granger model reveals evidence of reciprocity between actors, which is similar to the results of our baseline model. All Wald *F* statistics are statistically significant with 99% confidence intervals. For comparable models, the AUC is always higher in the parsimonious space-time Granger analysis than it is for the baseline model. Because our Granger estimation includes the space-time autoregressive terms which account for each actor's prior level of activity, we can isolate the strength of a reaction by the other actor. Comparing the Wald *F* values between the coalition and insurgent rows in any data category (All Iraq, Kurdish areas, Shi'a areas, etc.) will then indicate the strength of the direct reciprocal effect. (Caution: the Wald *F* values between two data categories should not be directly compared since the values are sensitive to the number of observations.) Similar to the baseline model, previous coalition events across space and time are better predictors of subsequent insurgent violence than insurgent events are of coalition violence (compare Wald *F* value of 1079.5 for insurgent to 713.8 for coalition):

TABLE 2 Results of Coalition and Insurgent Negative Binomial Reciprocity Models for Iraq and for Baghdad

	Wald F	AUC	True pos. (%)	False pos. (%)	Num. events	Non-zero (%)	N
All Iraq							
Coalition	713.8	0.95	46.0	0.7	72, 618	1.3	3, 113, 792
Insurgent	1079.5	0.96	54.3	1.0	228, 756	2.5	3, 113, 792
Kurdish areas							
Coalition	163.6	0.93	41.4	0.4	7, 484	0.9	454, 080
Insurgent	80.2	0.93	45.6	1.2	34, 146	2.1	454, 080
Shi'a areas							
Coalition	154.0	0.90	39.0	0.9	10, 627	1.5	517, 440
Insurgent	204.6	0.93	52.2	1.3	35, 136	3.2	517, 440
Sunni areas							
Coalition	272.7	0.93	50.7	2.4	39, 868	3.4	643, 456
Insurgent	401.4	0.94	65.2	4.2	114, 556	6.5	643, 456
Sunni poor							
Coalition	177.5	0.92	53.2	3.0	19, 320	3.6	326, 656
Insurgent	402.8	0.92	65.1	5.2	50, 673	6.5	326, 656
Sunni not poor							
Coalition	105.0	0.93	48.1	2.0	20, 548	3.3	311, 168
Insurgent	74.3	0.95	66.0	3.5	63, 883	6.7	311, 168
Urban areas							
Coalition	55.3	0.88	36.9	1.6	32, 736	31.1	38, 016
Insurgent	58.3	0.90	69.2	7.5	110, 038	48.0	38, 016
Nonurban							
Coalition	719.1	0.93	39.8	0.7	39, 882	0.9	3, 075, 776
Insurgent	916.1	0.95	50.2	0.9	118, 718	2.0	3, 075, 776
All Baghdad							
Coalition	87.4	0.76	15.8	2.0	12, 230	2.9	376, 640
Insurgent	17.0	0.79	56.8	15.2	42, 358	8.4	376, 640
Shi'a Baghdad							
Coalition	9.8	0.75	18.2	2.6	2, 052	3.1	59, 136
Insurgent	2.6	0.79	52.8	13.0	6, 212	7.5	59, 136
Sunni Baghdad							
Coalition	9.3	0.77	21.5	3.4	1, 462	3.1	42, 240
Insurgent	5.4	0.79	58.8	16.5	4, 933	8.7	42, 240

True and false positive percentages calculated using a threshold of 0.1, except for the urban area models, which use a threshold of 1.0 due to the higher levels of violence there. AUC is area under the curve.

military strength does not place coalition troops on an equal footing in their ability to respond to insurgent actions.

Disaggregating Proposition 1 into its space-time signature, the detailed power of reciprocity across spatial and temporal scales is shown in Figure 5. These are coefficients from each term in the Granger causality model presented above. Temporal and spatiotemporal lags of the predictor variable appear along the X axis, and are grouped by coalition- and insurgent-initiated violent events. The designation "s0t1" indicates space lag zero (none) and time lag 1 (3 days); similarly, the designation "s1t4" means space lag one (first-order neighbor) and time lag 4 (four 3-day slices), and so on. The relative risk indicates the multiplicative change in violence, and is plotted on

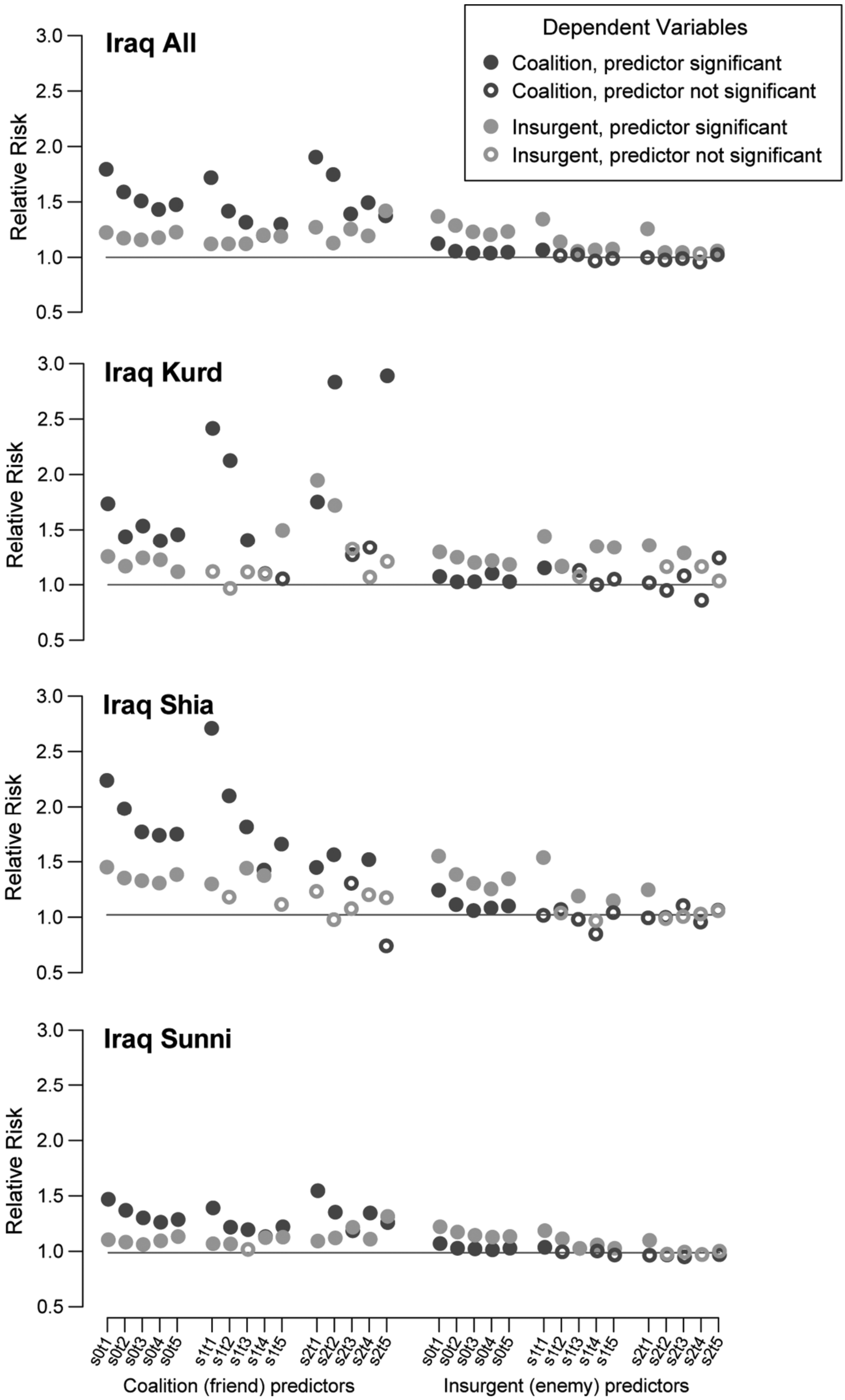

FIGURE 5 Relative risk of reciprocal conflict (1.0 = no change) for Iraq coalition and insurgent models by majority ethno-sectarian region.

the Y axis (for example, 1.35 translates to a 35% increase in the number of predicted violent events and 1.0 is no change).

The dependent variable event category is represented by dark-grey circles for coalition and light-grey circles for insurgent. Filled circles indicate that the relative risk associated with the predictor is statistically distinct (95% confidence interval) from no effect (1.0). Since we are interested in the additive effect of non-autoregressive terms, interpretations of a tit-for-tat effect must be made across categories—that is, from coalition predictors to insurgent dependent variables and vice versa. The space-time results corroborate the basic Wald *F* statistic as coalition reciprocity for insurgent attacks trails off in the first and second order spatial lags. We know from Tables 1 and 2 that coalition reprisals are weaker than insurgent responses, but in Figure 5, variation is evident in the likelihood of a response across space and time. Coalition forces respond consistently to lagged insurgent violence within the same grid cell, but retaliate less frequently to nearby insurgent violence.

Mirroring the trend for the whole country, stronger insurgent reprisals relative to coalition reactions exist for majority Shi'a (204.6, insurgent compared to 154.0, coalition) and majority Sunni (401.4, insurgent compared to 272.7, coalition) regions of the country. The pattern changes in Kurdish areas, however, where the opposite is true (163.6, coalition and 80.2, insurgent). Coalition event prediction of insurgent reciprocity is characterized by space-time decay in Shi'a and in Kurdish areas (light-grey points, left half of Figure 5). There, insurgents strongly react in the same grid cell (s0 series), but not as consistently in locations farther removed (s1 and s2). In contrast, coalition-initiated violence is met with a strong and consistent insurgent reaction uniformly across all space-time configurations in majority Sunni areas (with one exception at s1t3). These results lend support to our second proposition. The pattern of coalition reaction to insurgent events appears to be similar across ethno-sectarian regions, however.

Our third consideration is the variation in patterns of reciprocity within poor and not-poor areas of Sunni majority Iraq. In poor regions, insurgent reactions are strongest (402.8, insurgent compared to 177.5, coalition), but in wealthier areas, the relationship is the opposite: coalition reactions are stronger (105.0, coalition and 74.3, insurgent). This comparison supports the argument that poorer regions are better recruiting grounds for insurgents. Decomposing the space-time analysis for Proposition 3 (see Figure 6), the risk of insurgent reciprocity is high across all space and time combinations (with one exception at s2t4) in poor Sunni-majority areas (light-grey points, left half of Figure 6). In nonpoor areas, the influence dissipates in the first spatial neighborhood, but then it rises again in second-order lags. Coalition reciprocity is nonsignificant at any distance beyond the immediate cell in either poor or nonpoor areas with one exception for each category (dark-grey points, right half of Figure 6). Providing evidence favoring Proposition 3, insurgent patterns of response are more robust in poor areas than nonpoor. Coalition patterns of response are relatively consistent, however.

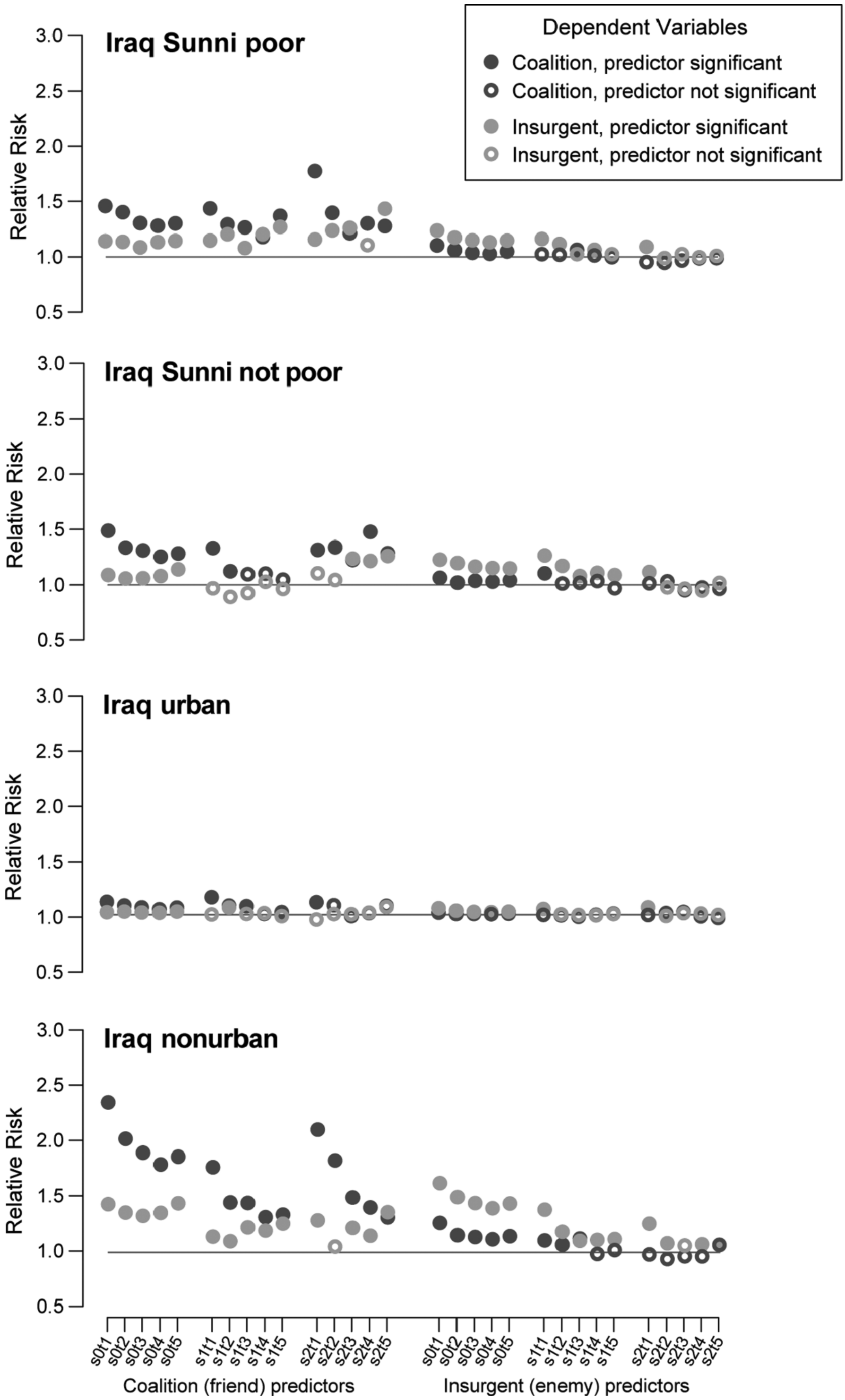

FIGURE 6 Relative risk of reciprocal conflict (1.0 = no change) for Iraq coalition and insurgent models by regional income and urban subsets.

In urban areas, there appears to be near parity in the degree to which insurgents (58.3 Wald *F*) and coalition troops (55.3 Wald *F*) respond to events initiated by one another. In nonurban areas, this tit-for tat dynamic also holds with insurgent reciprocity (916.1) higher than that of the coalition (719.1). Turning to the details of action-reaction patterns for Proposition 4 (Figure 6), it is clear that urban area reciprocal effects decay quickly in space and time: at any location beyond the immediate cell neither insurgent nor coalition violence shows a strong tit-for-tat trend. In nonurban regions of Iraq, the relative risk of an insurgent event following coalition violence within the same cell is very high (light-grey points, left half of Figure 6), about 50% more of what it would have been had coalition violence not taken place. At the scale of first- and second-order spatial lags, the reciprocal effect remains (with one exception at s2t2), but its magnitude falls slightly. Coalition reaction to insurgent events (dark-grey points, right half of Figure 6) extends through the second temporal lag and the first spatial lag in nonurban areas, which is further than the effect extends in urban regions. Fighting could be highly localized in cities, and not well captured by the spatial scale of the analysis (about 10 km); to examine this possibility, we examine violence in Baghdad at a finer resolution (about 1 km).

Narrowing our focus on Baghdad for Proposition 5, we find that coalition reciprocity in the wake of an insurgent event is much greater than vice versa (Wald *F* statistics of 87.4, coalition and 17.0, insurgents). In Baghdad, power dynamics have shifted in favor of the U.S.-led coalition. Coalition troop levels are densest in Baghdad, allowing for a critical mass and more clout in implementing effective reactions to insurgent strikes. The general trend holds across both Sunni (9.3, coalition and 5.4, insurgent) and Shi'a (9.8, coalition and 2.6, insurgent) dominated areas of the capital. In our nationwide analysis that compared urban to nonurban areas, we found that the strength of reciprocity in urban areas was nearly equal for coalition and insurgents (55.3 and 58.3 are near parity), indicating that an advantage for insurgents (found consistently elsewhere in our analysis) is more tenuous in towns and cities. In all of Baghdad, coalition-insurgent tit-for-tat behavior exists only at small ranges across space (see Figure 7). Only at s1t1 is coalition reciprocity significant beyond the immediate cell. In predominantly Sunni areas, there is a rapid temporal decay for insurgent reciprocity to coalition events (light-grey points left half of Figure 7), a pattern that diverges from the national trend, and from our expectation in Proposition 5.

A noteworthy characteristic of the insurgent reciprocity profile in Sunni areas is that at least one time period of both the first- and second-order spatial lags also exhibits tit-for-tat insurgent reciprocity, though it does not either for the entire capital or in majority Shi'a regions. Interestingly, the pattern of coalition reciprocity exhibits an influence in first- and second-order

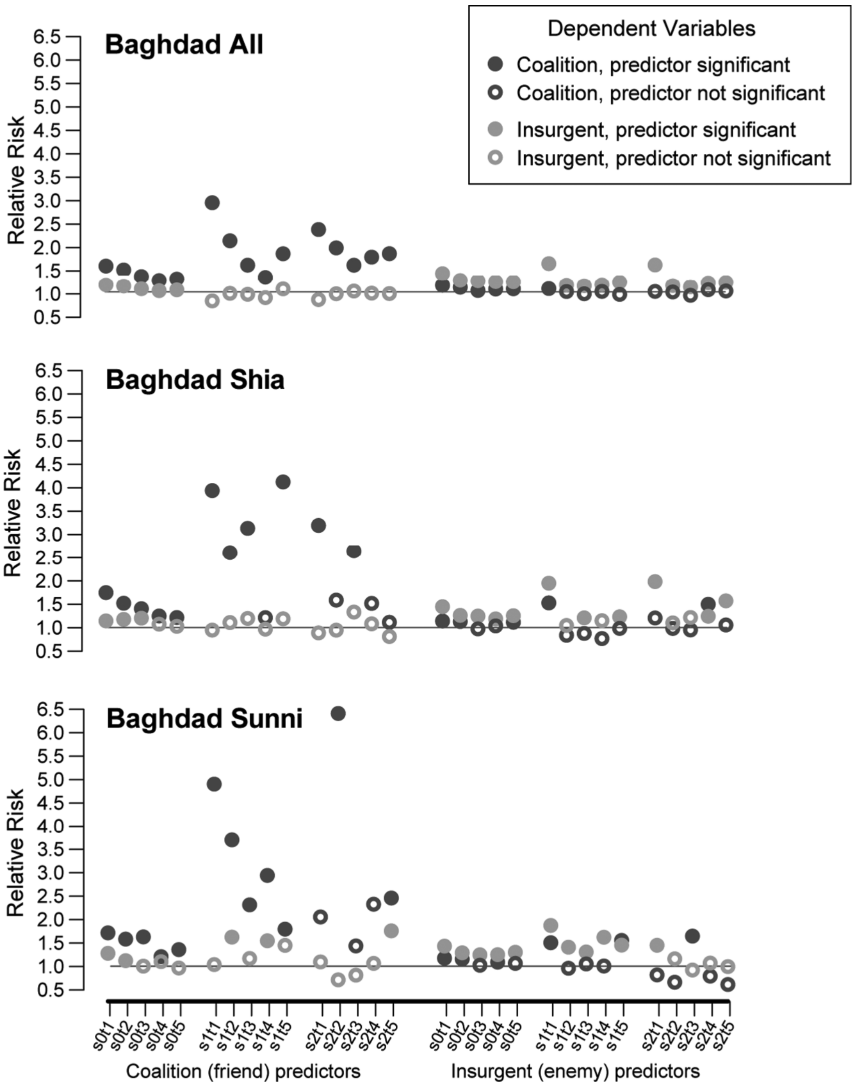

FIGURE 7 Relative risk of reciprocal violence (1.0 = no change) for Baghdad coalition and insurgent models by ethnicity.

neighborhoods for both Shi'a and Sunni areas, which is not our expectation in Proposition 5. All Baghdad models fare worse than countrywide analysis in terms of model fit (for instance in-sample AUC < .80), likely reflecting the greater spatial variability in violence captured by the smaller grid cells. It also raises the issue of the modifiable areal unit problem and the important selection of a space-time unit of analysis that corresponds to the underlying processes influencing violence in Baghdad and Iraq.

CONCLUSION

Both academic research and military doctrine suggest that violence during irregular wars increases the risks of alienating a local population and raises their support for insurgency. An observable outcome in support of this argument is a higher rate of insurgent attacks following government-initiated violence, and vice versa. Examining variations by spatial and temporal lags, we find evidence of a tit-for-tat association between US-led coalition- and insurgent-initiated events in Iraq that varies by region and actor. This trend points to the importance of regional social and political climates for understanding conflict in Iraq. In majority Sunni areas of Iraq (the core of the opposition to the US-led invasion), insurgency reactions to coalition actions are not characterized by the typical space-time decay trends. In other Iraqi areas, such decay is apparent; the regional differences suggest the ability of a Sunni-based insurgency to organize information more effectively in locales they traditionally dominate. Coalition violent events strongly predict subsequent insurgent activity in poor Sunni areas (more so than in nonpoor regions), providing evidence for the claim that poor areas provide opportunities for recruitment and organization of insurgents. Nonurban regions of Iraq show a first- and second-order spatial lag effect for insurgent reciprocity, one that is not found in urban areas. Within Baghdad, insurgent violent reciprocity is weaker than coalition responses.

Recent research on civil war dynamics has tended to pinpoint the locations of violence and to try to account for its distribution by recourse to spatial data. This correlative approach, however, does not always take full advantage of the date-location nature of the violence. Expanding the range of techniques applied for studying political violence we have used such detailed data to see if, and at what space-time scale, parties to conflict respond to each other's actions in a predictable manner.

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