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A spatio-temporal model of homicide in El Salvador

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Abstract

This paper examines the spatio-temporal evolution of homicide across the municipalities of El Salvador. It aims at identifying both temporal trends and spatial clusters that may contribute to the formation of time-stable corridors lying behind a historically (recurrent) high homicide rate. The results from this study reveal the presence of significant clusters of high homicide municipalities in the Western part of the country that have remained stable over time, and a process of formation of high homicide clusters in the Eastern region. The results show an increasing homicide trend from 2002 to 2013 with significant municipality-specific differential trends across the country. The data suggests that links may exist between the dynamics of homicide rates, drug trafficking and organized crime.

Keywords: Bayesian mapping, Homicide trends, Violence corridors, Bayesian spatio-temporal models, El Salvador

Background

Crime is one of the many outcomes of decision processes taking place within the contexts surrounding human routine activities. A number of political, economic, social and other factors determine whether crimes occur. Criminal events concentrate more or less heavily at different scales both across locations and over time. Spatial variation in crime arises from differences in the environmental features of locations, places or larger geographic demarcations. Temporal variation may arise from changes in the routine activities of individuals, households, businesses and places over time. In recent years there has been an upsurge in research on identification and formation of crime clusters at different geographical scales aimed at supporting situational crime prevention and control. Crime mapping, geographical analysis and spatial statistics have become important elements in the search of effective approaches to the control and prevention of crime. Most research on these issues has been conducted in Western countries.

With a total population of about 6.5 million distributed over 20,000 square kilometers; El Salvador is organized in 262 municipalities varying widely in terms of size and number of residents. El Salvador extends on the Pacific coast sharing borders with Guatemala on the West, and Honduras on the North and the East. Roughly, its territory divides into 3 well differentiated regions: A coastal region running along the Pacific Ocean; the most densely populated central plateau, covering 85 percent of the territory; and the northerly mountain ranges. These regions define climatic and environmental zones characterized by varying land uses, economic activities and potentials.

The so called Northern Triangle Region of Central America—Guatemala, El Salvador and Honduras—is one of the most violent regions in the world. Official data enable one to assess the annual average homicide rate for these countries at 39.5, 52.0 and 61.8 per 100,000, respectively, over the 13 years spanning from 2000 to 2012 (UNODC 2013).[1] Cross-national research on homicide and other forms of violence provides support to the view that Latin America has historically been a violent region and has offered explanations from a number of perspectives, many of them pointing towards inequality and socio-political instability as the main factors underlying which has been characterized as structural violence (Neapolitan 1994). During the last 20 years or so, researchers have paid attention to the role that factors

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[1] These rates were computed from official data (UNODC 2013, p. 121–133) by eliminating the lowest and highest counts over 2000–2012.

related with the strength of democracy and its institutions seem to play in explaining cross-national differences in violence. In the Central American case and because of its geographical position, interest has focused on organized crime, drug trafficking and widespread gang activity (Cruz 2010; World Bank 2011; UNODC 2012).

The view that violence in a country like El Salvador could be explained by most of these factors is a reasonable one, especially when one focuses on the years following the 1992 Peace Agreement that brought to an end the 12-year civil war. But El Salvador did also record large homicide rates prior to the 1980s. Historical data compiled from different sources show that the homicide rate averaged 44.8 per 100,000 over the 80 years elapsed between 1934 and 2014.[2] This rate is high by any standard. Despite the empirical evidence, it is not yet clear why such a small country as El Salvador has experienced a recurrent history of high homicide rates. It seems reasonable to argue that the factors underlying such dynamics go beyond those considered in the traditional debate on the relationships of inequality and underdevelopment with violence. El Salvador is heavily marked by drug trafficking, smuggling, transnational gangs and other organized crime groups.

Understanding the distribution of homicide and other forms of violence at different levels of spatial aggregation is a necessary step in order to develop efficient approaches to the prevention and control of crime. Research on the spatial distribution of homicide in El Salvador is scarce. An exploratory analysis by Carcach (2008) found evidence of spatial concentrations of homicide among Salvadorian municipalities, a finding that has been confirmed in a recent study by Ingram and Curtis (2014). Using a geo-statistical approach; Rosa Alvarado (2011) detected strong spatio-temporal variability of homicide across municipalities of El Salvador over the years from 2003 to 2008. At the time of writing there were no more studies on the topic, either published or not.

This research addresses geographical concentrations of homicide over time to test the hypothesis that a clustering of violence along a well identified geographic corridor has remained stable over time. Stability of crime patterns remains a key issue in spatial criminology due to its theoretical and policy implications. That spatial effects of homicide are of greater magnitude than local characteristics is a consistent finding in the literature (Townsley and references there in, 2009) and that general crime patterns are similar at all spatial scales (Andersen and Malleson 2011).

Our findings point towards the presence of significant clusters of high homicide municipalities in the Western part of the country that have remained stable over time, and a process of formation of high homicide clusters in the Eastern region. The results show an increasing homicide trend from 2002 to 2013 with significant municipality-specific differential trends across the country. The data suggest possible links between the dynamics of homicide rates, drug trafficking and organized crime.

Methods

A Bayesian approach was implemented to develop a model aimed both at the description of relative risk for homicide in space and time, and also at detecting unusual aggregations of this extreme form of violence in El Salvador. The data for this study consisted of the numbers of homicides occurring at each of the 262 municipalities across the country over the 12 year period spanning from 2002 to 2013. Data were obtained from the National Civilian Police (PNC) for the period running from 2002 through to 2007, and the Legal Medicine Institute (IML) for the remaining years. Official population projections (DIGESTYC, 2009) were used in the computation of rates.

Let the i index designate a municipality, $(i = 1, 2, \ldots, 262)$, and the k index, a specific year, $(i = 1, 2, \ldots, 12)$. The number of homicides in municipality i during year k, Y_{ik}, follows a Poisson distribution with mean $E_{ik}\theta_{ik}$. In this expression, θ_{ik} is the unknown relative risk of homicide and E_{ik} is the expected number of homicides in municipality i and year k. Risks are estimated by (indirectly) standardized mortality rates (SMRs). In order to implement the Bayesian approach to the modeling of homicide risk, a same Poisson distribution was assumed at the first level of hierarchy, given by

$$Y_{ik}|\theta_{ik} \sim Poisson(E_{ik}\theta_{ik}) \tag{1}$$

The use of SMRs as estimates of relative risk assumes a constant homicide rate over each local area and year so that all the residents of each municipality experience the same risk at any time. For rare events such as homicides the variation in the numbers of incidents exceeds that predicted by a Poisson process. Extra variation may arise either from heterogeneity of individual risk levels within municipalities, or from the clustering of incidences in either space or time, or both. Allowing area-specific risks to depend on a latent variable (a random effect), the variance of which reflects the degree of extra-Poisson

[2] Data for the period 1934–1949 came from the Archer and Gartner study (1971); 1950–1990 from the WHO Mortality Data Base; 1991–1994 and 2003–2008 came from Attorney General's Department or *Fiscalía General de la República de El Salvador*; 1995–2002 from El Salvador's Institute of Forensic Medicine or *Instituto de Medicina Legal* (1995–2002); and 2009–2014 from National Civilian Police or *Policía Nacional Civil*. Population data came from the National Direction of Statistics and Censuses or *Dirección General de Estadística y Censos* (DIGESTYC).

variation, is a standard approach to accommodate overdispersion in counts in the epidemiological literature (Mollié 2000; Lawson 2013 and references therein).

At the second level of the hierarchy, the logarithm of relative risk, θ_{ik} was defined as

$$\log(\theta_{ik}) = \alpha + \beta t_k + V_i + U_i + \delta_i t_k, \tag{2}$$

where U_i and V_i represented correlated and uncorrelated spatial components, defined to be constant in time and corresponding to the latent variables, βt_k was a linear trend term in time, $\delta_i t_k$ represented an area-specific trend, and α was an intercept representing an overall relative risk. This model represents a relative risk of homicide that varies both over time and space around an overall homicide rate. It extends the model in Besag et al. (1991) by including an overall and an area-specific temporal trend and is similar to the one proposed by Law et al. (2013) for the modeling of property crime.

From a criminological perspective, the latent spatial variables may help in accounting for unmeasured differences in individual routine-activities (Cohen and Felson 1979), social disorganization (Bursik and Grasmick 1993), the physical environment and the opportunity structure for crime within local areas (Brantingham and Brantingham 1995; Clarke 1995).

Inclusion of a time effect allows for the possibility that each municipality has its own time slope.

The Deviance Information Criterion (DIC) (Spiegelhalter et al. 2002) was used to assess the fit and identification of the model in (1)–(2) relative to a simpler model without spatio-temporal interaction terms. Models with smaller DIC are considered better. The DIC for the model in (1) and (2) was 18,232 compared to a value of 19,153 for the simpler model.

Prior distributions needed to be assigned to the parameters. The α parameter was assigned an improper uniform prior on the whole real line and the mean time trend (β) was given a vague prior normal distribution with a zero mean and a variance of 1000. The choice of these priors expressed the absence of genuine prior expectations on the parameter values. A normal prior with zero mean and a variance σ_v^2 was given to the unstructured random effects (V_i).

Conditionally autoregressive (CAR) priors (Besag et al. 1991) were used for the spatially structured random effects (U_i) and the spatio-temporal interaction terms (δ_i). Under the CAR specification and for a given municipality, the mean of U_i and δ_i depends upon the $U_i's$ and $\delta_i's$ of its neighboring municipalities. More formally,

$$U_i|U_j, j \neq i, \tau_u \sim Normal\left(\bar{U}_i, \sigma_{ui}^2\right), \tag{3}$$

and

$$\delta_i|\delta_j, j \neq i, \tau_\delta \sim Normal\left(\bar{\delta}_i, \sigma_{\delta i}^2\right), \tag{4}$$

where, $\bar{U}_i = \frac{1}{m_i}\sum_{j\neq i} w_{i,j}U_j$, $\bar{\delta}_i = \frac{1}{m_i}\sum_{j\neq i} w_{i,j}\delta_j$, $\sigma_{ui}^2 = \frac{\sigma_u^2}{m_i}$, and $\sigma_{\delta i}^2 = \frac{\sigma_\delta^2}{m_i}$, with $w_{i,j} = 1$ if the *ith* and *jth* municipalities were neighbors and m_i was the number of municipalities that were neighbors to the $i - th$ municipality.

Variance parameters σ_u^2 and σ_δ^2 control the variability of the random effects U_i and δ_i conditional upon the random effects in the neighboring municipalities, respectively. At the next level of hierarchy, the choices of hyper-priors for all variance parameters $\left(\sigma_\beta^2, \sigma_v^2, \sigma_u^2, \sigma_\delta^2\right)$ were assumed to be uniformly distributed (i.e. $U(0, 10)$).

The joint posterior distribution of all the variables was proportional to:

$$\pi(\boldsymbol{Y}|\boldsymbol{E},\boldsymbol{\theta})\pi\left(\beta|\sigma_\beta^2\right)\pi\left(\boldsymbol{V}|\sigma_v^2\right)\pi\left(\boldsymbol{U}|\sigma_u^2\right)\pi\left(\boldsymbol{\delta}|\sigma_\delta^2\right)$$
$$\pi\left(\sigma_\beta^2\right)\pi\left(\sigma_v^2\right)\pi\left(\sigma_u^2\right)\pi\left(\sigma_\delta^2\right)\pi(\alpha), \tag{5}$$

where the likelihood $\pi(\boldsymbol{Y}|\boldsymbol{E},\boldsymbol{\theta})$, was defined as

$$\pi(\boldsymbol{Y}|\boldsymbol{E},\boldsymbol{\theta}) = \prod_{i=1}^{262}\prod_{k=1}^{12} Poisson(Y_{ik}|E_{ik}\theta_{ik}). \tag{6}$$

Besides estimation of local relative risks, θ_{ik}, our interest focused in the estimation of the pure spatial random effects and spatio-temporal interaction terms, U_i and δ_i, respectively. The parameters in the model have fixed dimension and posterior sampling for each parameter was carried out by a Markov Chain Monte Carlo (MCMC) algorithm with joint implementation of Metropolis–Hastings and Gibbs sampling (Gamerman & Lopes, 2006).

The model was fitted using WinBUGS (Lunn et al. 2000), a programming language based software implementing MCMC algorithms to generate random samples from the posterior distribution in (5). The WinBUGS code for model (2) is available on request from the author. Two chains were run and convergence was achieved by 20,000 iterations. A further 20,000 samples were run for each chain to obtain the desired posteriors with Monte Carlo errors lower than 5 % of the posterior standard deviation.[3] The Bayesian approach estimates the whole density of each parameter and not just the value that maximizes the likelihood function.

[3] The apparently large number of iterations obeys to the high dimension of the parameter space and to the need to cover most of the distribution for each parameter. One way to assess how well the estimation goes is by comparing the mean of the samples and the true posterior mean. This is called the Monte Carlo error. A rule of thumb is to have a number of iterations that is required to achieve an MC error lower than 5 % of the true error.

Results and discussion

The data in Table 1 show the posterior means of the overall log-relative risk (α) and the time trend (β), with their respective lower and upper credible interval limits. These results indicate that both the overall mean log-relative risk and the mean trend are significant at their 95 % credible intervals.

Municipal-level relative risks vary around an average of 0.499 ($= exp(-0.696)$). The mean time trend (β) was positive (=0.013), indicating that nationally, the homicide rate increased by 1.3 % a year over the 2002–2013 period.

Consistent with expectations spatial variation dominated the total variance of municipal homicide rates around the national average, indicating the presence of time persistent regional clusters of homicide rates. Table 1 shows that all the variances of posterior distributions of area-random effects were significant, with variation due to spatial correlation (U_i) being greater than variation due to heterogeneity (V_i) and variation due to spatio-temporal interaction (δ_i).

Figure 1 shows the map of the posterior means of the pure spatial random component for the 262 municipalities of El Salvador. This component represents the additional risk of living in a specific municipality. With two exceptions, clusters of high-incidence municipalities, including the capital city of San Salvador, were located in the western side of the country. The data indicate the presence of several clusters[4] defining time-stable homicide corridors, shown with colored lines in the map[5]. A first corridor connects municipalities located southwest on the Pacific coast with municipalities located northwest on the Honduras border (blue-colored line). There is a second corridor linking the same municipalities located on the Pacific coast together with the municipality of San Salvador (light-green-colored arrow), and a third corridor connecting San Salvador with both the Honduras border on the north and the Pacific coast on the south (blue-colored line). There are two additional clusters of high-risk municipalities, one located on the banks of a lake (black-colored circle) and another located in north-east direction heading towards the Honduras border (blue-colored circle).

Figure 1 also shows time-stable clusters of low-incidence municipalities all but two located in the eastern side of the country (grey shaded areas). Note however that these municipalities are interconnected through what seems to define another route running from the Pacific Ocean to several points on the Honduras border.

Table 1 Overall log-relative risk (α), time trend (β) and variance of posterior distributions of area random effects

	Coefficient	Lower bound 95 % CI	Upper bound 95 % CI
α	−0.696	−0.787	−0.609
β	0.013	0.007	0.019
σ_U	0.847	0.497	1.170
σ_V	0.519	0.387	0.655
σ_δ	0.119	0.102	0.139

The model in (2) included spatio-temporal trends. Figure 2 shows clusters of municipalities with higher than average temporal trend were located in the eastern side of the country whereas those of municipalities with lower than average temporal trend were located in the northwest, mainly. The latter might be associated to municipalities where homicide rates tend to become stable over time. Some of these local government areas belong to the cluster of high-incidence municipalities identified in Fig. 1. The geographic pattern of the municipalities with higher than average temporal trend suggests that some homicide corridors have gone through a process of expansion over the 12-year period under study. In these clusters, homicide risk has increased over time in a way that is similar to that in the neighboring regions.

Figure 3 shows variation in homicide rates due to unstructured heterogeneity. There were five municipalities spread over the Salvadoran territory with very-high variation due to unobserved variables. Some of the few municipalities with highest posterior means for V also appeared as part of the group with highest posterior means for U (refer to the map in Fig. 3). An examination of the WinBUGS output for these places showed that the posterior mean of V represented more than half the sum of the posterior means of the random components ($U + V + \delta$). This result suggests that for the referred (red-colored) places, homicide risk is due to characteristics other than spatial variation. There was one municipality corresponding to San Miguel, the most important city of the Eastern region (blue-colored circle), for which variation in homicide risk was dominated by unobserved heterogeneity.

The spatial patterns identified with the Bayesian spatio-temporal model in (1) and (2) give support to the hypothesis that in a country like El Salvador, homicide risk concentrates according to well-formed geographic corridors that tend to remain stable over time. This is particularly true for municipalities located in the Western

[4] Although the analysis is spatio-temporal, a preliminary exploration to the data indicated significant Moran I statistics for all the years over the period under study. The values of the Moran I statistic varied from a low 0.09 in 2002 to a high 0.294 in 2009 that indicates a significant clustering of homicide relative risk among El Salvador municipalities.

[5] For the purpose of this paper, corridors are areas connecting two or more municipalities. They may be parts of a municipality or segments across roads that maintain connectivity between extremes. Corridors maintain the geographic continuity of crime related processes by allowing territorial control as in the case of gangs, the movement of individuals and illegal goods and drugs, and the flow of criminal events across designated areas.

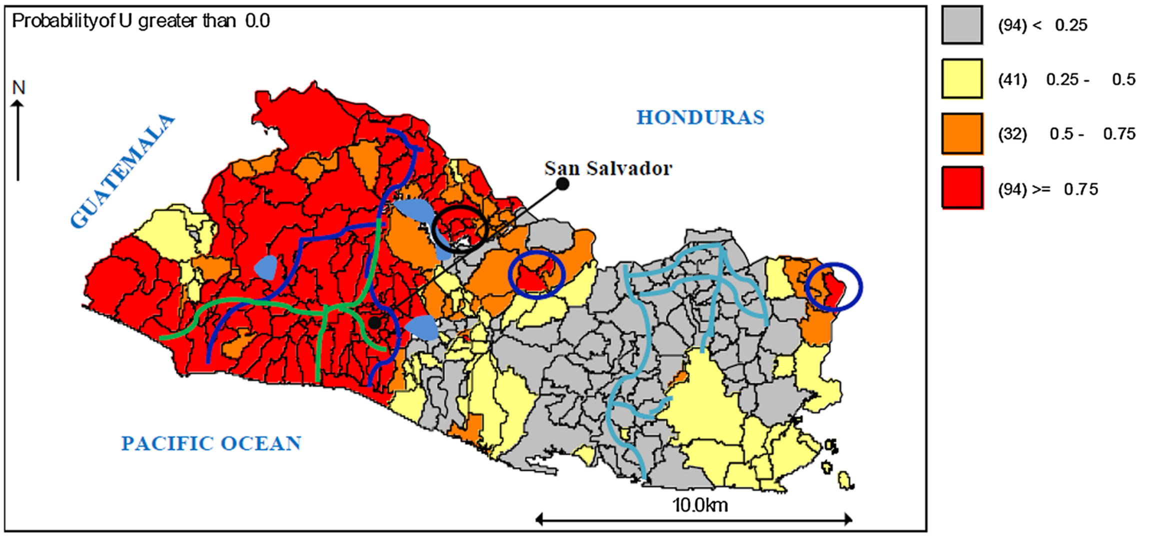

Fig. 1 Spatial random effects (U_i) based on the posterior mean

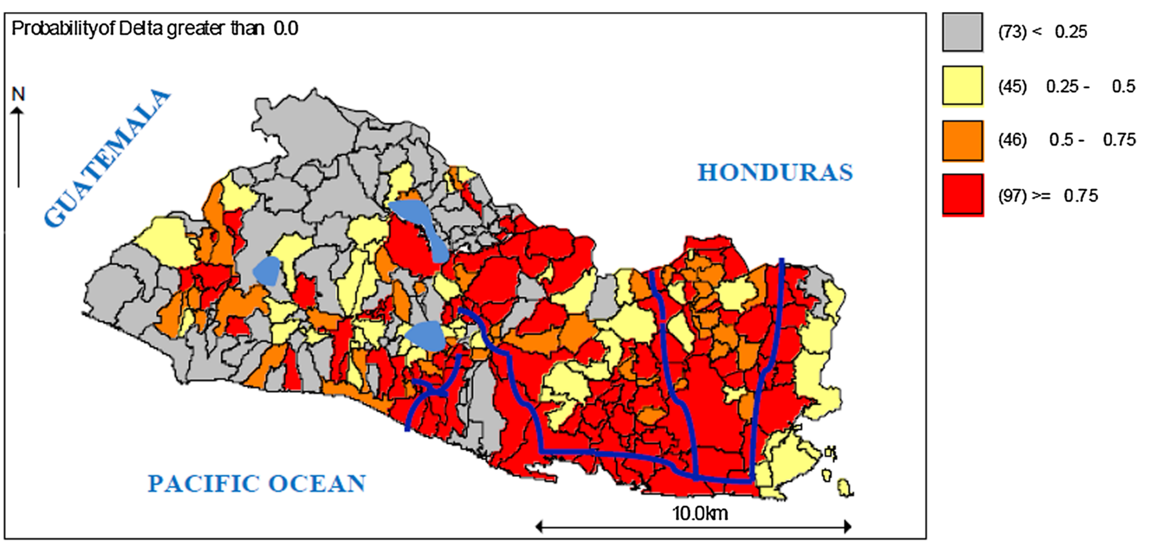

Fig. 2 Area-specific differential trends (δ_i) based on the posterior mean

region. Our results also show that in recent years, these corridors have been going through a process of expansion towards the East side of the country.

These corridors run along major roads such as the Pan-American Highway (which crosses the country in west-east direction from the Guatemala border to the Honduras border), the Litoral Highway running along the Pacific coast from Guatemala to the Fonseca Gulf (common to El Salvador, Honduras and Nicaragua), and the Northern Highway (running north from San Salvador to the Honduras border).

These patterns suggest that some homicides might be the outcome of conflicts related to drug trafficking, smuggling and other illegal activities that have been using the Salvadoran territory as a sort of logistic facility for the movement of goods, persons and drugs from South America to the United States, and vice versa. Towns and other minor localities of many of the municipalities located along the historically stable and newly formed clusters are strongholds to gangs (mostly MS-13 and Barrio 18) that suggest that these groups might be taking over some segments along these corridors.

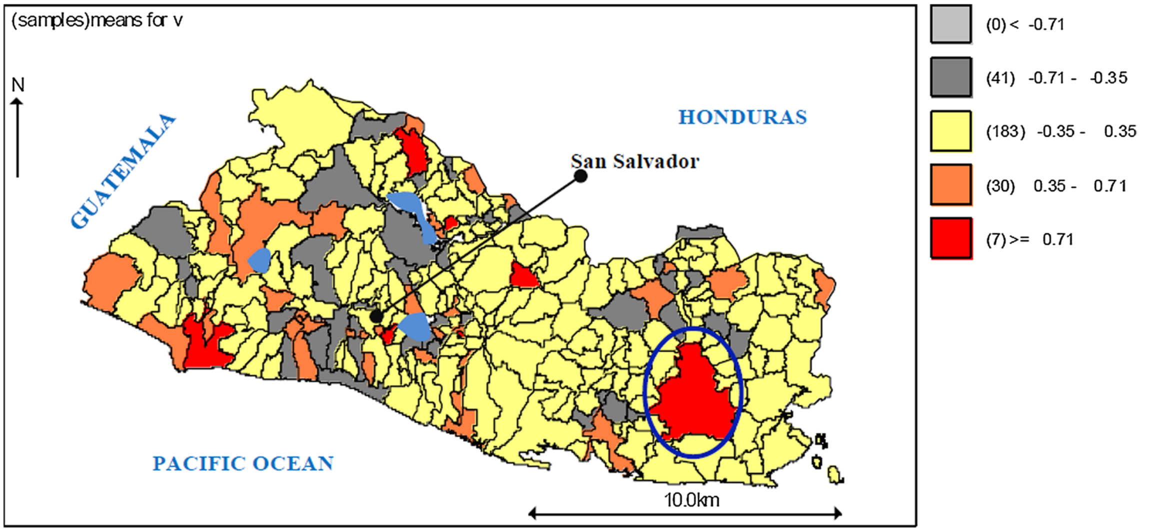

Fig. 3 Area-specific heterogeneity effects (V_i) based on the posterior mean

The choice of highly noninformative uniform priors for the precision parameters intended to account for the fact that homicides do not distribute at random across the territory of a municipality and that there may be some places within a local area concentrating larger number of crimes than others. The identified spatial patterns might be sensitive to this modeling decision.

Conclusions

This research was to implement a Bayesian spatio-temporal model to analyzing homicide trends in El Salvador, one of the countries with the highest homicide rates worldwide. The results from this study reveal the presence of significant clusters of high homicide municipalities in the Western part of the country that have remained stable over time, and a process of formation of high homicide clusters in the Eastern region. The results show an increasing homicide trend from 2002 to 2013 with significant municipality-specific differential trends across the country. Because homicide has already had negative impacts on the economy and wellbeing of El Salvador and its citizens, it is important to develop a forecast system for this crime. The lack of time based official data on the socioeconomic characteristics at the municipal level makes modeling approaches such as the one presented in this paper useful to gain understanding of both the temporal and spatial dynamics of homicide and other forms of crime.

Following the ecological tradition in criminology, municipal data on income, employment, family structure, education, access to public services and other aspects of municipalities might help in disentangling within-area variation in crime. The findings of this research are consistent with the empirical evidence indicating spatial effects dominate crime variability and that area characteristics, by themselves, seem to be insufficient to explain the distribution of homicide. Future research should address multivariate modeling of homicide, injuries, suicide and other forms of violence. These analyses would help in identifying municipalities where homicide is the main source of violence and for elicitation of impacts that gang, drug and organized crime activity might have on the formation of clusters of violence.

The main policy implication deriving from this research has to do with the role that main highway and roads connecting municipalities seem to play in the formation of corridors of violence. This confirms the centrality of place in the dynamics of homicide. Salvadoran police might develop crime prevention strategies based upon the intervention of crime routes through increased presence and surveillance in places that appear to be the network nodes involved in the processes leading to crime stability and expansion.

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Compliance with ethical guidelines

Competing interests
The authors declare they have no competing interests.

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