Spatio-temporal difference in model outputs and parameter space as determined by calibration extent

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Abstract

The wider availability of spatial data and increased computational power have created a renaissance in urban land use modeling. While the proliferation of urban models has benefited the geographic sciences, their use in and implications for public policy decisions may not yet be warranted. There is still much to be understood about these models, especially the calibration of these models, from which forecasts are derived. This paper looks at the calibration of a model for a large geographic region at several spatial extents, showing the differences between the forecasts based on each extent, and the how these differences can proliferate their way into making policy decisions based on these forecasts.

1. Introduction

During recent years, models of land use change and urban growth have drawn considerable interest. Despite past failures in urban modeling (Lee, 1973; 1994), there has been a renaissance of spatial modeling in the last two decades due to increased computing power, improved availability of spatial data, and the need for innovative planning tools for decision support (Geertman and Stillwell, 2002; Brail and Klosterman, 2001). Spatial modeling has become an important tool for city planners, economists, ecologists and resource managers oriented towards sustainable development of regions, and studies have attempted inventories and comparisons of these models (Agarwal et al., 2000; EPA 2000). These new models have shown potential in representing and simulating the complexity of dynamic urban processes and can provide an additional level of knowledge and understanding of spatial and temporal change. Furthermore, the models have been used to anticipate and forecast future changes or trends of development, to describe and assess impacts of future development, and to explore the potential impacts of different policies (Pettit et al, 2002; Verburg et al, 2002). Because many of these models are being used to provide information from which policy and management decisions are made, it is important that modelers have a clear understanding of how the geographic extent at which that they are calibrating and modeling influences the forecasts that their models produce. This is directly linked to a larger geographic issue in modeling. Can large scale (geographic extent) models accurately forecast local growth compared to smaller scale applications, or should state/nation/global modeling be done at a local level and then aggregated to create a more realistic view?

The concept of geographic extent and how changing it alters a model's parameter space, and subsequently model outputs and forecasts is not something that has been studied extensively. In this work, extent is defined as the geographic boundary of a system. Generally speaking, when the extent of a geographic system is changed, so should the statistics that describe the system, and the interactions that take place within that system. Only in the unique case of an infinite surface of a checkerboard pattern is this not true. In the case of urban models, the effects of geographic extent on model calibration and outputs may be overlooked or brushed aside due to two constraints that inhibit this type of modeling in general: (1) many times researchers struggle to get the necessary data to run the models, at any spatial extent; and (2) as the spatial extent of data gets larger, the computational time increases, sometimes in more of an exponential manner than a linear one. These two issues have prohibited urban modelers from sufficiently addressing the issue of geographic extent and how it relates to urban model output, but even more importantly, how calibration at different extents can impact model forecasting and final outputs.

With any model, there is an explicit need to calibrate and parameterize the model to fit the dataset. Recently modelers have increased their focus on the calibration phase of modeling to gain a better understanding of how models, in particular cellular automata, work (Straatman et al, 2003; Wu, 2002; Silva and Clarke, 2002; Li and Yeh, 2001a; Abraham and Hunt, 2000). The calibration phase of modeling is one, if not the most important, stage in modeling because it allows the fitting of model parameters to the input data, to be further used in forecasting. Failure to calibrate a model to the input data results in an application that is not robust or justifiable. While these efforts have focused on better calibration and definition of the parameters for these models, none of them have focused on how calibration at different resolutions changes the parameter set and the model outputs. For all models, the “best” parameter space is defined as the area or volume of parameters that is searched to find the parameter set. The parameter set is then the 'best-fit' set of parameters that describe the behavior of the system within the framework of the model. The parameter space is defined as an area or volume depending on the number of individual parameters. If there are only two parameters, then the parameter space in an area; any more than two then it is a *n*-dimensional volume. A better understanding of how resolution changes a model's parameter set, and hence its outputs, is an important area of research, especially when many of these models are used in the decision making process.

Should modelers take into account that an urban area may be a transition zone between two metropolitan areas or is influenced by a larger region in the calibration process? And how does incorporating the influence of these areas change the parameter space, and hence the spatial output of the model? Inclusion of outside influential areas into local urban models is not a new idea (Haake, 1972), but perhaps the study of how their inclusion changes the parameter space of current models may be. Advances in computing, especially the advent of parallelization and the cost effective strategy of 'clusters' have significantly deflated the geocomputational cost of modeling larger spatial areas at fine resolutions, so inclusion of possibly influential, but outside, areas is not as much of a taxing task as it once was. Capitalizing on these advances, this research focuses on the relationship between spatial extent and parameter space, and how calibration of an urban cellular automata model at varied spatial extent can allow for forecasts that are more typical of the local-regional interactions taking place.

The SLEUTH urban model is a cellular automaton model that has been widely applied (Yang and Lo, 2003; Esnard and Yang, 2002) and has shown its robust capabilities for simulation and forecasting of landscape changes (Clarke et al, 1997). The model makes use of several different data layers for parameterisation, e.g. multi-temporal land use and urban extent data, transportation network routes and digital elevation model data. Application of the model necessitates a complex calibration process to train the model for the spatial and temporal urban growth (Silva and Clarke, 2002). This paper documents work done on the role that geographic extent plays in the calibration of urban models by working with SLEUTH. A large geographic area was calibrated and modeled at three different geographic extents: global (extent of the entire system), regional, and county. The derived parameters are then used to forecast urban growth from 2000 to 2040. The results from the model forecasts were then compared to determine the extent that calibration at different geographic extents had on model forecasts. This analysis is then used to examine some general considerations about the geographic extent over which urban models are calibrated and used, and the implications that this has for using these models to evaluate policies and scenarios.

2. Calibrating Urban Automata

Modeling geographic systems using cellular automata (CA) models is a recent advance relative to the history of the geographic sciences (Silva and Clarke, 2002). Tobler (1979) was the first to describe these models in geography, briefly describing five land use models that were based on an array of regular sized cells, where the land use at location *i*, *j* was dependent on the land use at other locations. Applying this method of modeling to urban systems for planning applications was recognized early (Couclelis, 1985), and application of these models has proliferated in the last decade (de Almeida, 2003; Li and Yeh, 2001b; Ward et al, 2000), including the development of SLEUTH. While the models themselves have proliferated, work on the calibration phase has lagged, and the need for stronger and more robust methods for calibrating and validating CA models has been noted (Torrens and O'Sullivan, 2001).

Model calibration has become an increasingly important consideration in the development phase of modeling (Batty & Xie, 1994; Landis & Zhang, 1998). Yet the high flexibility in rule definition used in cellular automata modeling, and application of these rules to manipulate cell states in a gridded world, makes parameter estimation a more difficult process (Wu, 2002). In the case of CA models where the transition rules consist of equations for calculating future state variables, they generally consist of several linked equations for each land use, and these are complexly linked, so calibrating a model may require the fitting of tens, if not hundreds of parameters (Straatman et al, In Press).

The general difficulty in finding the 'golden set' of parameter values of cellular automata is due to the complexity of urban development (Batty et al, 1999). Methods for calibration such as the use of off-the-shelf neural network packages have been suggested by some (Li and Yeh, 2001a), but some have argued that these sort of methods produce a 'trained' model and not one that has intrinsic meaning in terms of known geographic principles (Straatman et al, In Press). Due to these difficulties and the parameters of CA models being dependent on the transition rules for the model, there has been little research on the parameter space or sets of urban cellular automata and how they are related to the geographic extent of calibration, although the work that has been done on calibration is a good starting point for looking at how the parameter space can be approached. This is in contrast to work on CA in computer science, where rules and parameters impacts on behavior have been studied exhaustively.

2.1 SLEUTH Calibration

Calibration of SLEUTH produces a set of five parameters (coefficients) which describe an individual growth characteristic and that when combined with other characteristics, can describe several different growth processes. For this model, the transition rules between time periods are uniform across space, and are applied in a nested set of loops. The outermost of the loops executes each growth period, while an inner loop executes growth rules for a single year. Transition rules and initial conditions of urban areas and land use at the start time are integral to the model because of how the calibration process adapts the model to the local environment. Clarke and Gaydos (1998) describe the initial condition set as the ‘seed’ layer, from which growth and change occur one cell at a time, each cell acting independently of the others, until patterns emerge during growth and the ‘organism’ learns more about its environment. The transition rules that are implemented involve taking a cell at random and investigating the spatial properties of that cell’s neighborhood, and then urbanizing the cell, depending on probabilities influenced by other local characteristics (Clarke et al, 1997). Five coefficients (with values 0 to 100) control the behavior of the system, and are predetermined by the user at the onset of every model run (Clarke et al, 1997; Clarke and Gaydos, 1998; Candau, 2000). These parameters are:

1. *Diffusion* – Determines the overall dispersiveness nature of the outward distribution.
2. *Breed Coefficient* – The likelihood that a newly generated detached settlement will start on its own growth cycle.
3. *Spread Coefficient* – Controls how much contagion diffusion radiates from existing settlements.
4. *Slope Resistance Factor* – Influences the likelihood of development on steep slopes.
5. *Road Gravity Factor* – An attraction factor that draws new settlements towards and along roads.

These parameters drive the four transition rules which simulate spontaneous (of suitable slope and distance from existing centers), diffusive (new growth centers), organic (infill and edge growth), and road influenced (a function of road gravity and density) growth.

By running the model in calibration mode, a set of control parameters is refined in the sequential 'brute-force' calibration phases: coarse, fine and final calibrations (Silva and Clarke, 2002), although other methods of calibration, including the use of genetic algorithms have been suggested and tested (Goldstein, 2003). In the coarse calibration, the input control data is resampled to one quarter of the original size (i.e. 100m is resampled to 400m), and then a Monte Carlo simulation of a broad range of parameters are tested for their fit in describing the input data. The results of the calibration run are then analyzed to narrow the range of tested parameters, based on metrics that describe spatial characteristics of the calibration runs against the input control data, specifically using the Lee-Sallee metric because of it's 'spatial matching' of the control data, although there has been some suggestion that other metrics can be used (Jantz et al, 2002). This metric is a shape index that measures the spatial fit between the model's growth and the known urban extent for the calibration control years. Upon narrowing the range of parameters based on the metrics, the original input data are resampled again, but to one half of the original size (i.e. 100m is resampled to 200m), and simulated over the narrowed range of parameters. Again, the results are analyzed, and the range of parameters narrowed. This final set of parameters is simulated with the full resolution original data. The resultant parameters are then used to forecast urban growth.

2.2 Study Area and Data

Using the San Joaquin Valley (CA) as a study area (Figure 1), input data for modeling urban growth using SLEUTH were compiled at 100m resolution (Table 1). Data sources for historical urban extent are listed in Table 1. Urban extent data for San Joaquin Valley for the years 1940, 1954, and 1962 were digitized from historical USGS 1:250,000 maps and based on air photo interpretation and supplemental ground survey information. Data from 1974 and later were captured directly from space-based remotely sensed imagery. The urban extent data for 1974 and 1996 were based on Landsat MSS and Landsat TM mosaics compiled by the USGS Moffet Field, California office (http://ceres.ca.gov/calsip/cv/). Additional data for 1984, 1992, 1996, and 2000 were obtained from the California Farmland Mapping and Monitoring Program (CA-FMMP) that utilized aerial photography as a base mapping source (http://www.consrv.ca.gov/DLRP/fmmp/). The 1996 CA-FMMP data were merged with the USGS data to create a composite image of growth. Urban extent through time was treated as a cumulative phenomenon so that each time period built on the previous one, and urban extent was not allowed to disappear once it was established. All data processing was accomplished within a GIS environment.

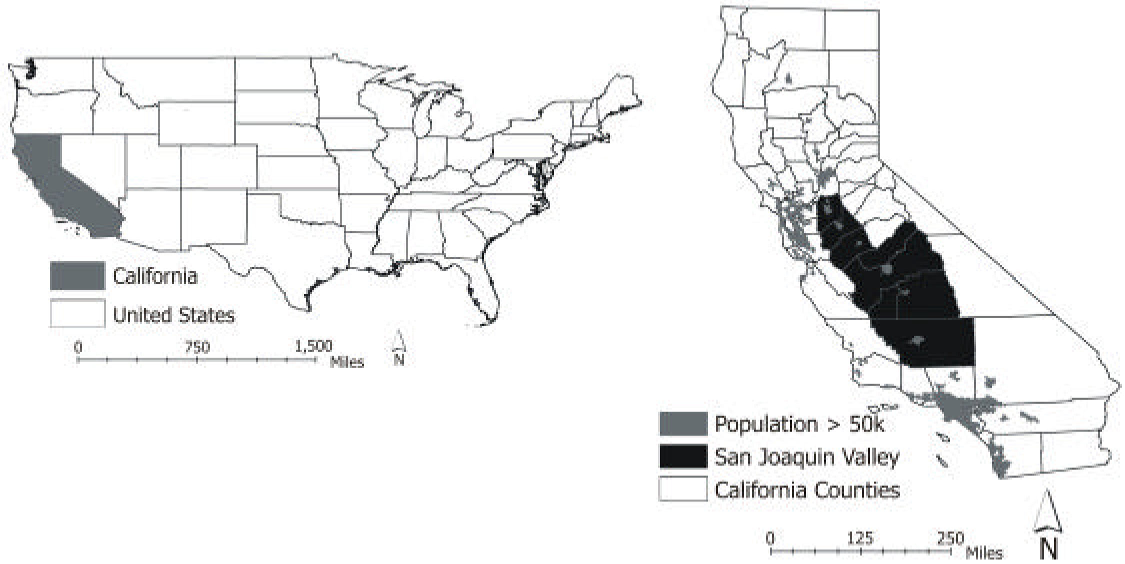

Figure 1. Location of California, population centers greater than 50,000 people, and the location of the San Joaquin Valley.

Data Layer	Source	Description	Resolution
Topography/Slope	USGS	30m DEM	30m
Land Use	CA-DWR	Not used in this modeling	
Exclusion	CaSIL	Vector coverage of Federal and State owned land	N/A
Urban Extent	USGS	Urban extent for 1940, 1954, 1962, 1974, 1996	100m
	CA-FMMP	Vector coverage of developed land from 1984 to present in 2 year intervals	N/A
Transportation	CalTrans	Vector coverage of functionally classified roads from 1940 in 5 year increments	N/A

Table 1. Sources, description, and resolution of data used in SLEUTH modeling of the San Joaquin Valley (CA).

The San Joaquin Valley, while one large geographic and cultural area, is comprised of eight independent counties (Figure 2): San Joaquin, Stanislaus, Merced, Madera, Fresno, Kings, Tulare, and Kern. Additionally, these counties can be grouped into three distinct regions, based primarily on their economy (Figure 2). The Bay Area Region (San Joaquin, Stanislaus, Merced) is heavily influenced by the San Francisco Metropolitan Area economy and commuting patterns. Agriculture creates the economic base of Madera, Kern, Kings, and Tulare counties, uniting them as the Agricultural Heartland; and oil dominates Kern County which doubles as a county and region due to its unique natural resource and commuter patterns with the Los Angeles Metropolitan Area.

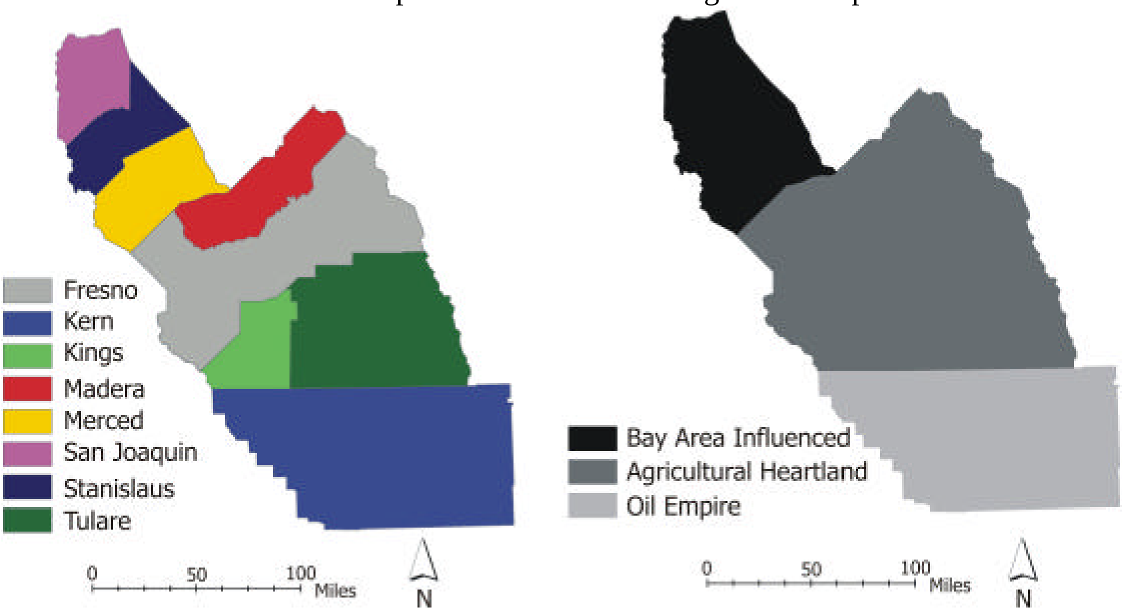

Figure 2. The eight independent counties in the San Joaquin Valley (left) and the three economic regions (right).

Input data for SLEUTH were calibrated for the San Joaquin Valley as a whole, each of the three regions, and each of the eight counties. The resulting parameter spaces were then used to forecast urban growth from 2000 to 2040, and using both tabular and graphical outputs, the results of the forecast were compared. Growth for San Joaquin, Madera, and Kern counties was then forecast using the global (San Joaquin Valley), regional, and county parameter sets to determine how that area grew specific to the others.

3. Calibration and Forecasting Results

Calibration of the San Joaquin Valley and subsequent datasets resulted in a parameter set describing the growth of each area that was different for all areas included in this study (Table 2).

		Coefficients				
Area	**Extent**	Diffusion	Breed	Spread	Slope	Road
San Joaquin	County	2	2	54	1	3
Stanislaus	County	2	7	54	29	100
Merced	County	2	2	41	35	15
Madera	County	2	2	25	83	21
Fresno	County	2	5	58	41	52
Kings	County	2	2	45	1	2
Tulare	County	2	2	32	41	2
Kern	County/Region	2	2	58	46	31
Bay Influenced	Region	2	4	47	30	3
Agricultural Heartland	Region	2	2	45	36	41
San Joaquin Valley	Global	2	2	83	10	4

Table 2. Resultant growth coefficients for the 11 geographic extents calibrated using the SLEUTH model

San Joaquin, Madera, and Kern counties were forecast using the global parameters along with their respective region and county parameters. Total urban area and new urban growth over time under each of the parameter sets were plotted for these three areas (Figure 3)

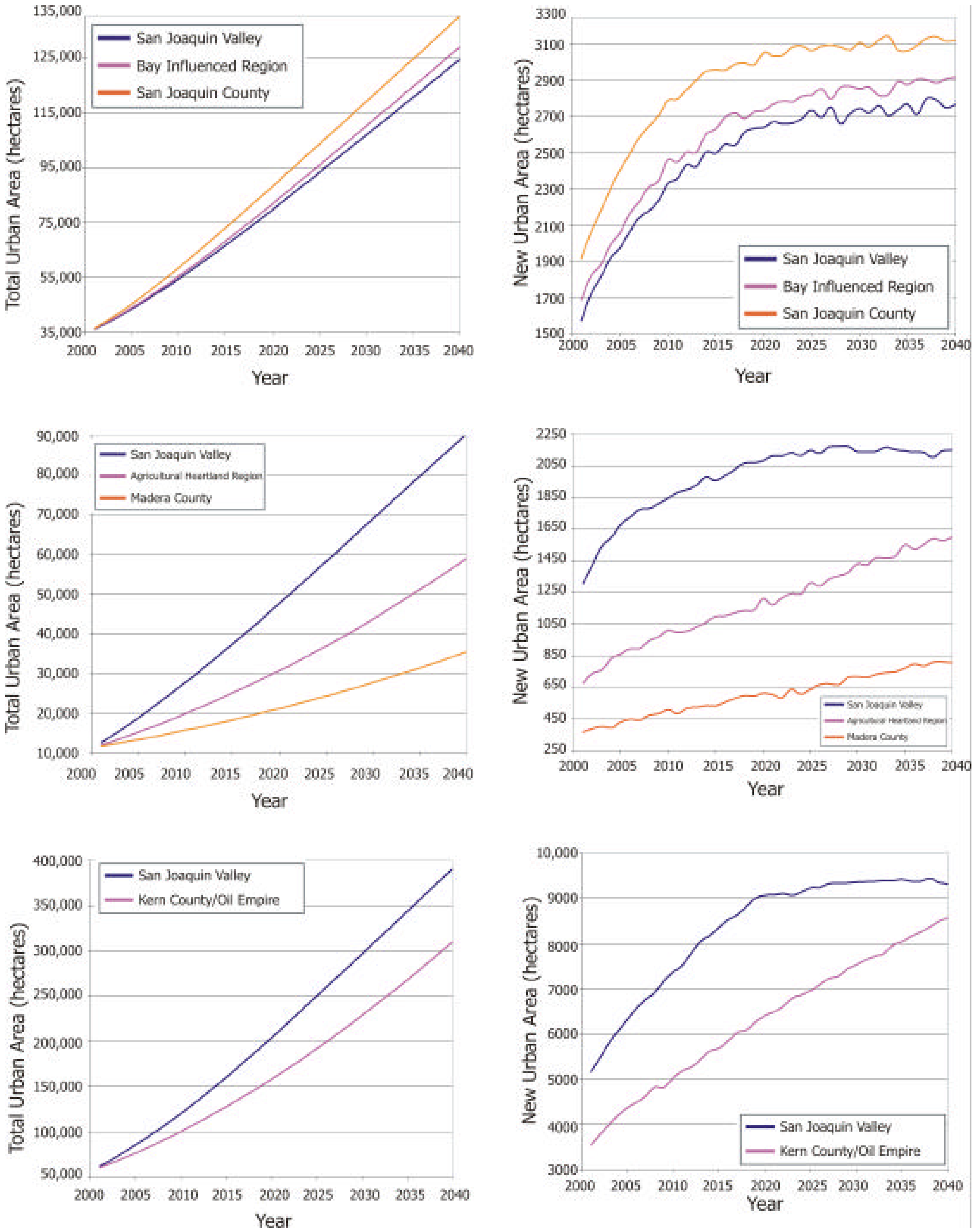

Figure 3. Total urban area and new urban area for each year for San Joaquin, Madera, and Kern counties, projected using the global parameters along with their regional and county parameter sets.

Total urban area from 2000-2040 in San Joaquin County was greater when the local county parameter set was used in forecasting compared to that of the Bay Influenced region and the global San Joaquin Valley (Figure 4). This is further supported by the total hectares of new urban growth for the county parameters set than the region and valley parameters (Figure 3), yet the difference between the three was slight over the forty year forecast. Total urban area is predicted to cover 125,000 hectares under the county parameter set, 127,000 and 135,000 hectares under the region and valley parameters.

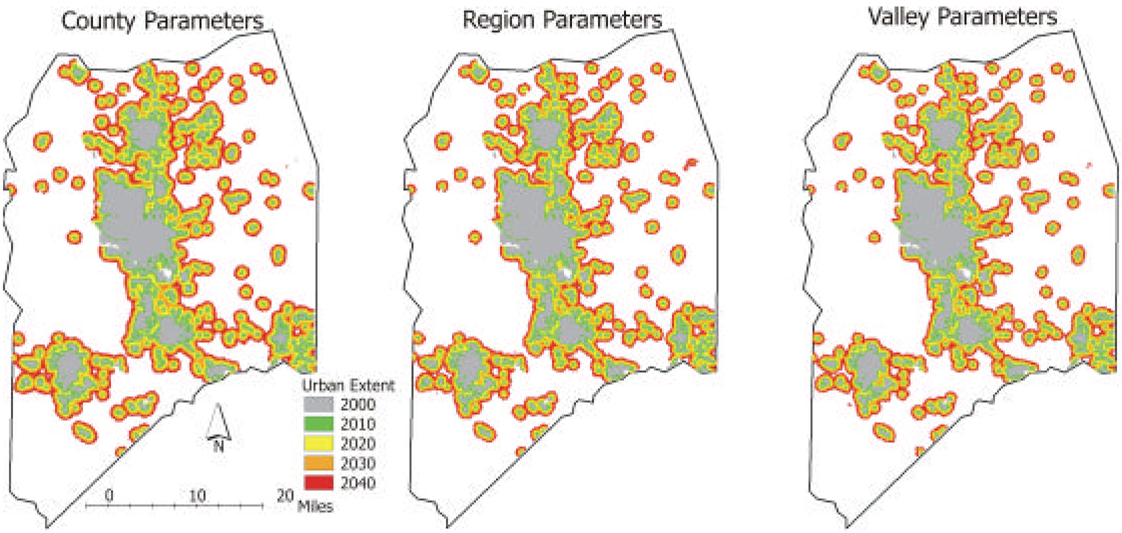

Figure 4. Predicted urban growth for San Joaquin County using the county (left), region (middle), and valley (right) parameter sets.

Growth trends in Madera County under the three parameter set forecasts were opposite of San Joaquin County. Using the global San Joaquin Valley parameters to forecast future growth produced a county that grew three times faster than when the local county parameters were used, and twice as fast when the regional Agricultural Heartland parameters were used in forecasting (Figure 5). Total urban area under the county parameters was 36,000 hectares, opposed to the 60,000 and 90,000 predicted using the region and valley parameters.

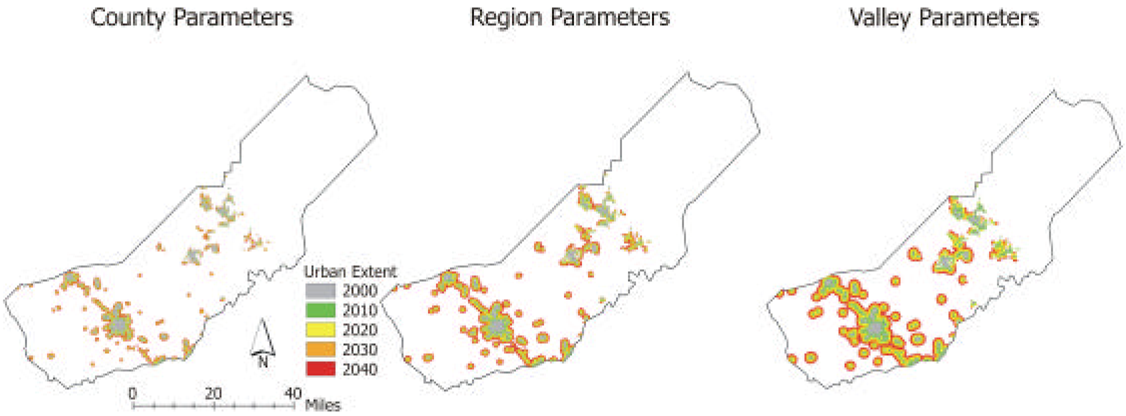

Figure 5. Predicted urban growth for Madera County using the county (left), region (middle), and valley (center) parameter sets.

Kern County, a unique area that itself is a region, had growth curves that were lower than those of the global San Joaquin Valley (Figure 6). The number of hectares of urban growth is predicted to be 305,000 for the county and region parameters, and 395,000 under the valley parameters. This difference between the total urban area forecast by the different parameter sets was not as great as was found for Madera County, but larger than the minute differences found in San Joaquin County.

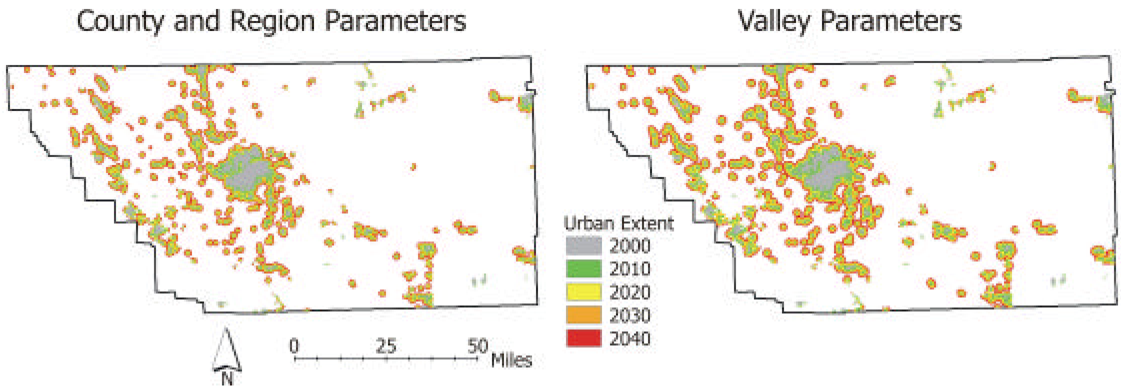

Figure 6. Predicted urban growth for Kern County using the county and region (left), and valley (right) parameter sets.

Using a GIS to overlay the model outputs, geo-algebra was done to determine the total area that was both unique and common between all parameter set forecasts for the year 2040 for each of the three areas (Table 3). In concurrence with the total urban area curves in figure 3, the urban area common between growth forecasts using the county and regional parameters, compared to the valley parameters, were most similar in San Joaquin County. The total urban area in common between the county and valley parameters was 89%, while there was an 94% similarity between the region and valley parameter forecasts. The contrast between the three forecast for Madera County was further demonstrated, and their was only a 36% spatial agreement between the county and valley forecasts, and 63% between the region and valley. Urban growth forecast for Kern County had a 79% spatial agreement between the county/region and valley forecasts.

	Between Valley and County Parameter Forecasts in 2040							Between Valley and County Parameter Forecasts in 2040						
	County Only		Both		Valley Only		Total urban area between both	County Only		Both		Valley Only		Total urban area between both
County	Area	% of Urban	Area	% of Urban	Area	% of Urban		Area	% of Urban	Area	% of Urban	Area	% of Urban	
San Joaquin	15685	10.53	132988	89.26	311	0.21	148984	6479	4.64	130892	93.64	2407	1.72	139778
Madera	52	0.05	37113	36.18	65406	63.77	102571	76	0.07	64882	63.24	37637	36.69	102595
Kern	1167	0.30	304858	78.56	82041	21.14	388066							

Table 3. Spatial agreement between urban growth forecast under the county and valley parameters (left side) and between region and valley (right side). Urban area is measured in hectares.

4. Discussion

Taking a hierarchical approach to modeling urban growth in three counties, each part of a different region in one large geographic area, resulted in a different parameter set for modeling at each level within the hierarchy. While the differences in the parameter set were small between the diffusion and breed parameters, the differences in the spread, slope and road gravity parameters were greatest, and probably had the largest impact on the differences in urban growth forecast under the different parameter sets. The total urban area forecast in San Joaquin County appeared to be similar under all three parameter sets, while Madera County growth differed by two or three times the amount forecast using the local county parameters. County and region parameters for Kern County produced urban forecasts that differed by less than 20%, which was more than San Joaquin County, but much less than Madera County.

The differences in total urban area forecast using the different parameter sets was further illustrated by the spatial agreement between the forecast of the county and region parameters against the valley (Table 3). Spatial agreement is defined as an area that forecast to be urban under the forecasts of each parameter set. San Joaquin County had the highest percent agreement between the county and valley parameters (89), and the region and valley parameters (94). The large difference in growth under the county and valley parameters for Madera County showed in the low 36% agreement between the county and valley parameters, and the 63% between the region and valley. Kern County, the county that was itself a region, had a 79% agreement. Both Kern and Madera counties, were areas where growth under the valley parameter set produced more urban area in 2040, had a large portion of urban growth that only occurred with the valley parameters. None of the parameter sets used in forecasting growth produced a significant portion of urban growth under the county and region parameters that was not captured by the valley parameters.

5. Conclusions

Calibration and forecasting of a hierarchical system has provided insight into whether large scale (geographic extent) models can accurately forecast local growth compared to smaller scale applications. Using the San Joaquin Valley (CA) as a study area for this investigation provided examples that demonstrated that regional and global calibration and forecasting of models can provide similar outputs (up to 94%) as local scale application. But there are also cases, such as Madera County, where large scale (San Joaquin Valley and Agricultural Heartland scale) modeling was grossly different from the local modeling effort. The question is then, how to distinguish when it is appropriate to and when not to use global and regional modeling to look at local spatial phenomena, because it is the local scale at which most policy and land use decisions are made? This question is most likely dependent on the model being used and its parameters, since they are what determine the model output. One noticeable feature that may play a role in most models is topography. In SLEUTH this is addressed by the 'slope resistance' parameter, but it is undoubtedly used, differently in many other models. Focusing on Madera County, the local parameterization of the model showed a slope resistance of 83 as opposed to 36 and 10 by the region and valley parameters. These lower slope resistance parameters allowed growth to occur where it would not normally have under conditions characterized by local parameters. This is different from the parameters from San Joaquin and its respective region, where local slope resistance was 1, regional was 30, and the valley parameter was 10; not as strikingly different as in the case of Madera County. Taking this into account, a general rule for determining whether a large scale application can be useful for looking at a local area might be that if the topography is uniform across the entire geographic area, then the model is more likely to accurately capture local growth patterns at a larger scale. Under this line of thought, it would be possible to model many of the states and geographic regions in the United States, and look at county/metropolitan growth patterns, as well as countries like the Netherlands. But this will most likely not be the case, especially when the modeling is being done at the national, continental, and global scale. For these size applications it will most likely be necessary to model at a smaller state or region level, and then aggregate the results, producing a composite output that is more reflective of local behavior and growth.

The issue of whether large scale modeling efforts can accurately forecast local growth compared to smaller scale applications is inevitably also tied to resolution and how changes in resolution change the parameter space and model forecasts. Although this issue has not been directly address in this paper, the link between resolution and geographic extent is one that should not be ignored. Coarser resolution modeling will undoubtedly dilute model outputs at the local level, but may capture regional growth better. The converse may also be true, but these are areas of research than need exploration.

Modelers should continue to work to find the proper geographic extent to model local urban growth, while still allowing the inclusion of influences from surrounding urban areas. While the role of geographic extent issues within the calibration and forecasting routine might appear to be a too finely detailed area to warrant extensive research efforts, this paper has demonstrated that changes in geographic extent can create significantly different model outputs, and in some cases, gross differences between results using large and small scale calibration. Future efforts should continue to research this area using current working models, building on the knowledge gained to improve them, or create new ones to better forecast the future. Only once models, their behavior, and their proper use are fully understood with honesty, will they be able to be used in a understandable and believable manner for application to the planning and decision making process.

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