Space-Time Topological Graphs

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Abstract

The integration of space and time in geospatial analyses is an active research area. While methods for characterizing sequences of spatial point objects over time have evolved greatly over recent years, the treatment of space-time change in complex geographic objects such as linear features and polygons has seen much less attention. In this paper we consider the directed graph as a representation for temporal change in spatial objects, where edges are formed by spatial relationships. With this representation, the large foundation of graph-theoretic metrics and algorithms can be used for the analysis of space-time change in geographic objects. We present preliminary findings using several exemplar datasets: range expansion of polygons representing animal home ranges, the spatial path of Hurricane Katrina, and a forest insect outbreak. In particular, we investigate the dynamics of space-time change in these datasets using well-known metrics for characterizing graph structures.

1. Introduction

Understanding space-time change continues to be a challenging and increasingly required task for geospatial analysis, as more spatial datasets are evolving into long-term records of spatial and temporal change (e.g, satellite archives, long-term radio collar studies). However, models of space-time change remain to be fulll developed. Stell et al. (2011) introduced a bigraph representation of space-time change, whereby objects were represented as nodes at discrete time points, and linked through relations. As well, Del Mondo et al. 2012 further developed this model with an explicit spatiotemporal graph representation, distinguishing between filial relations (based on explicit identity) and purely topological relations (derived from spatial relationships). We build on these ideas from the perspective of space-time analysis in order to analyze spatial changes in polygon objects over time. We use several space-time polygon datasets in order to explore a how space-time topological graphs can be used as a representation for spatial-temporal analysis generally.

1.1 Polygon models of space-time change

Sadahiro and Umemura (2001) introduced a framework for the analysis of spatio-temporal polygon distributions based on events derived from spatial overlap relations in neighbouring time-steps. The scope of events was extended in Robertson et al. (2007) to include proximity-based spatial relations, describing various types of movement occurring over the change interval, known as spatial-temporal analysis of moving polygons (STAMP). The STAMP framework is temporally discrete, such that an appropriate temporal grain is required a priori in order to represent change. Metrics associated with space-time change include counts of event types, area change, directional change, all of which can be accumulated along paths of the graph representing continuous spatial relationships over time. In Sadahiro (2001) the graph representation of polygon change events was introduced. In this paper we build on this framework order to integrate existing graph metrics into the spatial-temporal analysis of polygon distributions.

2. Methods

2.1 Space-time topological graphs

We define the space-time topological graph *g* by the set of edges *E* and vertices *V* representing polygons where each edge e_{ij} represents a spatial relationship between polygons from neighbouring time periods *i* and *j* (Figure 1). Since edges are determined by time, *g* is both directed and acyclic, while edges can be either binary or weighted. Each change interval generates a bipartite graph, yielding a *k*-partite graph for the full set of time periods. We could conceive of *g* as a set of dynamic spatial weights matrices. The properties of *g* in this context have not been explored in great detail since its inception in Sadahiro (2001), which examined changes in polygon area and event types. We therefore examine some properties of *g* derived from different datasets with the aim of exploring *g* as a general representation for spatial-temporal analysis. Weights were derived as the ratio of T1∩T2 area to the T2 area in each polygon event-grouping. In general, weights can be tailored to the application and spatial representation being used.

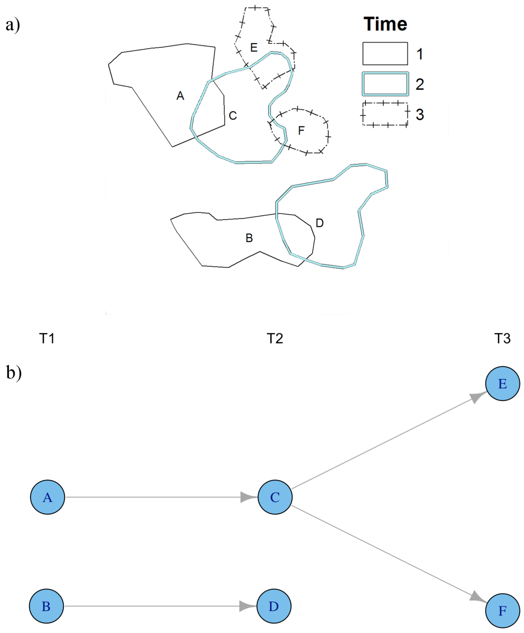

Figure 1. a) Space-time polygon distribution and b) its representation as a space-time topological graph.

2.2 Datasets

Three polygon datasets were used to investigate *g* based on the STAMP event framework (Robertson et al. 2007) as outlined in Table 1. The forest insect (mountain pine beetle – MPB) outbreak data were obtained for the Morice Timber Supply Area in west-central British Columbia. These data represent hotspots derived from thresholded kernel density estimates of points representing clusters of attacked trees, during the initial years of the mountain pine beetle outbreak that occurred in British Columbia. The caribou range polygons represent winter seasonal home ranges derived from radio-collared caribou in the Bathurst herd. Finally, the Hurricane Katrina dataset was obtained from US NOAA Hurricane Research Division's H*Wind product and polygons represent 39 miles per hour isotachs (contours derived from wind speed fields) at 3 hour intervals. Each of these represents significant environmental change events at least in part due to climate change, and phenomena for which better spatial forecasting models are needed.

Table 1. Space-time polygon exemplar datasets of environmental change.

Dataset	Temporal Scale	N	Location
MPB	Annual (1995 - 2003)	711	British Columbia, Canada
Caribou	Annual (1996 - 2014)	36	Northwest Territories, Canada
Katrina	3 hours (Aug 25 21:00 - Aug 29 21:00)	33	Southeast USA

2.3 Analysis

Analysis of graph data typically describes properties of the graph as a whole, its edges, or its nodes. Depending on the application, different properties may be of interest. For example, measures of centrality are often used to identify important nodes in social networks (i.e., super nodes) that are connected to a disproportionate number of nodes in the network. We used three well-known metrics for exploring node centrality, connectivity, and community/clustering of *g* in our space-time polygon datasets (Table 2).

Table 2. Graph metrics used to explore space-time topological graphs.

Metric	Level	Property	Description
Betweenness centrality	Node	Node importance	Number of shortest paths from all nodes to all others that pass through that node
Degree Assortativity	Graph	Topology	Similarity in number of edges among connected nodes
WalkTrap	Node	Community / cluster detection	Modularity maximizing algorithm based on random walks from each node

3. Results

The caribou data had a graph size of 48 edges and 32 nodes, and a density of 0.048, while the MPB data exhibited 613 edges, 557 nodes, and density of 0.002. The Katrina graph was much less complex, as splitting and merging events did not occur, yielding a graph with 45 edges, 33 nodes, and density of 0.043. These graphs along with their clusters detected from the WalkTrap algorithm are presented in Figure 2. The results obtained from the community detection methods for all three datasets provided interesting partitions for identifying sub-periods and polygon groups that align with our understanding of these spatio-temporal processes. Graph metrics showed expected patterns with the MPB and Katrina having more spatial-temporal centrality, and higher similarity in node degree (representing topological relations between polygons).

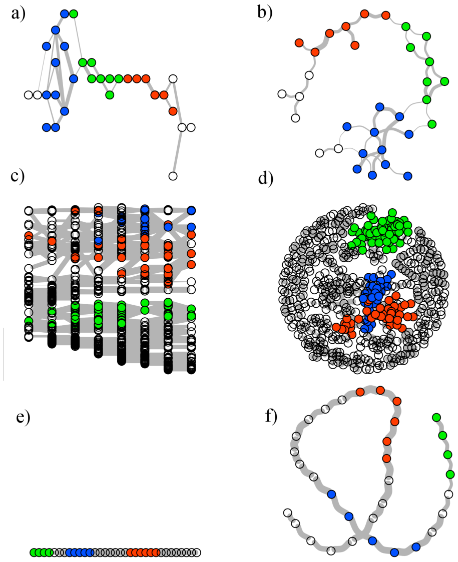

Figure 2. Graphs and cluster nodes (coloured) for a-b) caribou home ranges, c-d) forest insect outbreaks, and e-f) Hurricane Katrina. Left plots have temporal ordering maintained, right use the Fruchterman & Reingold (1991) graph layout algorithm.

Table 3. Graph metrics used to explore space-time topological graphs.

Metric	Caribou	MPB	Katrina
Betweenness centrality	0.08188	0.00004	0.16667
Degree Assortativity	0.03534	-0.16276	1.0

4. Conclusions

While interpreting the patterns of these analyses is beyond the scope of this short paper, the results highlight the potential utility in using mathematical graphs as general models for spatial-temporal analysis and relating spatial processes to their space-time topology. In particular, the community detection of clusters of nodes relating to important events in the space-time process may help to characterize signatures of environmental change events as they arise. Further research into which metrics are ideal in different contexts and the ways spatial measures can be integrated as edge weights remain areas to explore.

References

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