[AM-03-012] Cartographic Modeling

Abstract

Cartographic modeling is an integrated sequence of data processing tasks that organize, combine, analyze and display information to answer a question. Cartographic modeling is effective in GIS environments because they rely heavily upon visualization, making it easy to show input and output layers in map form. In many GIS platforms, the sequence of tasks can be created and modified graphically as well. The modeling is visual, intuitive, and requires some knowledge of GIS commands and data preparation, along with curiosity to answer a particular question about the environment. It does not require programming skill. Cartographic modeling has been used in applications to delineate habitats, to solve network routing problems, to assess risk of storm runoff across digital terrain, and to conserve fragile landscapes. Historical roots emphasize manual and later automated map overlay. Cartographic models can take three forms (descriptive, prescriptive and normative). Stages in cartographic modeling identify criteria that meet an overarching goal; collect data describing each criterion in map form; design a flowchart showing data, GIS operations and parameters; implement the model; and evaluate the solution. A scenario to find a suitable site for biogas energy production walks through each stage in a simple demonstration of mechanics.

Keywords: descriptive models, flowchart, map overlay, prescriptive models, sensitivity analysis, suitability modeling

Author & citation

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Explanation

1. What is Cartographic Modeling?
2. A Worked Example
3. Summary

1. What is Cartographic Modeling?

Cartographic modeling is a practice that guides the various steps in a type of spatial analysis based in superimposing map layers either manually or digitally. Texts and references define it in a variety of ways, as an analytical approach, as a designed workplan, as a visualization of processing tasks or as a holistic framework for recording a sequence of operations. Although the practice of manual map overlay was used in town planning a century ago (Coppock and Rhind 1991), it was discussed systematically by McHarg (1969) as a method for the impacts of multiple environmental factors in landscape design. Tomlin (1990) first coined the term in referring to digital cartographic modeling. He described the practice as stating objectives, setting criteria to parameterize those objectives, selecting data layers for each criterion and compiling that data into map form. Tomlin initially demonstrated the practice with raster data layers, formalizing the practice within the language of Map Algebra (see BoK Entry AM-06). The modeling practice expanded to vector and other data types as the GIS community adopted it widely that the practice is sufficiently robust to broaden its scope (see for example Mennis et al, 2005). Inputs and outputs from each stage of cartographic modeling are often represented in map form. Some GIS platforms (such as Esri ™ ModelBuilder) extend cartographic modeling into a visual programming capability, permitting a user to drag and drop icons representing data files and GIS operators onto a graphical window, to link them graphically to represent a desired processing sequence, and then to validate and run the resulting cartographic model. It is possible to prioritize or weight the relative importance of criteria and refine a final analytic result, although cartographic models do not demand weighted parameters (Jankowski and Richard, 1994). Validation of a cartographic model can be accomplished by sensitivity analysis, which systematically adjusts criteria parameters to determine stability of the results and to confirm the relative contribution of each criterion.

1.1 What Role Does Cartographic Modeling Play in GIS?

Cartographic modeling is intuitive and highly visual, and thus offers an easily understood introduction to integrating GIS operations into models. The method is quite flexible and readily applied to natural and social science problems. Additionally, the selection of criteria can be based on individual choice, group decision support, published literature or accepted national standards (Tomlin 2013). For all of these reasons, cartographic modeling is commonly utilized in urban and regional planning, where decisions made by a council of decision-makers may impact a large community, and steps in the decision process must be clear and justifiable to all stakeholders (Malczewski, 2004). Other application areas span the full range of GIS analysis, for example monitoring forest succession in post-agricultural lands (Szostak, 2020); determining populations at risk for infectious disease outbreaks (Tatem et al 2012); and assessing snowpack to predict water availability (López-Moreno et al 2007).

Cartographic modeling is especially useful for analyzing spatial suitability. For example, one might want to determine the most suitable location for a new hospital in a fast-growing urban area (Church 2002), a habitat suitability model for old-growth forests (Store and Jokimäki 2003) or a site for a restoring elk populations in North Carolina (Williams et al 2015). Any of these problems must account for a number of related factors, and cartographic modeling provides a powerful and intuitive analytic methodology to examine how these spatial relationships are reflected in the landscape. GIS queries and processing combine the mapped data layers either to mask unsuitable or to highlight suitable locations (Tomlin, 2013). The method is commonly applied to establish suitability of locations for public or private facilities and institutions (schools and hospitals for example), or for particular functions of interest to communities or local governments (land evaluation, natural habitat delineation or impacts of environmental events such as storms or flooding) and it plays a major and significant role in planning decisions.

1.2 How Did Cartographic Modeling Originate and Evolve?

The practice of cartographic modeling stems from manual map overlay techniques that were standard practice in Landscape Architecture, which is a discipline cognate to GIScience. Landscape architects are planners, developers and builders. As a foundation for their work, landscape architects acknowledge the prominence of nature in the human world, and design to align ecological, societal and economic factors in their designs and built products. GIScience coupled the focus on natural and social factors with digital mapping technology and digital database development as they emerged in the mid-1960's and 1970's (Coppock and Rhind, 1991) to offer more powerful computational opportunities in environmental modeling and analysis (Nijhuis, 2016).

One comprehensive explanation of cartographic modeling is provided by Ian McHarg's (1969) Design with Nature (although he did not apply that terminology) in which he describes a number of case studies from his own work as a professional landscape architect. In one case study to build a major highway, McHarg walks through the stages of the design process. Beginning with stated natural and social objectives such as improving traffic flow and convenience, safeguarding the quality of land, air, water resources and sustaining productive land uses, he articulates costs and benefits as for example construction costs, changes in fuel costs, modifications to land values and impacts on animal and plant habitats). He re-expresses these as categorical and numeric parameters, drawing upon ancillary spatial information drawn from multiple sources. Examples of parameters include topography (roughness and slope), hydrography (streams and irrigation channels, surface drainage), soils and erosion risks, proximity to population centers, and impacts on recreation, historic preservation, visual and sonic aesthetics. Data for all of these can be spatially referenced and mapped. Mapping and overlaying the data layers brings the design and planning into the stage of actual modeling.

Later, Tomlin's (1990) eponymous text proposed an evolution of cartographic modeling from manual to automated methods, drawing upon the foundations established earlier by McHarg. Tomlin defined a vocabulary called Map Algebra to systematize the tasks and commands that make up the practice and the associated modeling framework.

1.3 How Does Cartographic Modeling Work?

Cartographic models can be descriptive, prescriptive or normative. The distinction among these is not based on research questions or on what GIS methods are applied. Instead it is based upon the underlying assumptions and overarching model goal or purpose (Demers, 2002). Descriptive models illustrate actual conditions and characterize spatial position, form or arrangement: they often comprise a first exploratory step in examining local conditions. Prescriptive models advise on what is considered an optimal or nearly optimal solution to a given question or issue following evaluation of predicted conditions. Normative models take this one step further, offering solutions that follow existing regulations, standards or policies. The three types are not mutually exclusive and should be considered a continuum of increasing analytic constraint (from a description to a proposed optimum to a solution based on existing regulations) rather than discrete categories. It is important in reporting results to explain assumptions and goals utilized in developing a model, and equally important in using any model results to be aware of the design and chronology of processing. This underscores the need for metadata about the models (i.e., not just about the data). One foundational advantage of cartographic modeling is that it records the sequence of modeling steps directly, along with the specific parameters utilized for each operation, thus preserving these important metadata elements explicitly. Sharing the cartographic model effectively shares the model's metadata as well.

Another key advantage was brought up by Tomlin (1990; 2013), commenting on the ease with which simple operations can be combined to create more complex functions. For example, a simple cartographic modeling operation might select a subset of rural settlements on the attribute of some population threshold. This could be combined with an operation to generate a distance raster to establish travel times to existing urgent care clinics or hospitals. The resulting two-operation cartographic model could then be inserted as a single function into another cartographic model with additional GIS operations (essentially, a model within a model) and applied to several counties or an entire state to establish travel times from rural communities to adequate health care, in preparation for a statewide policy discussion on vaccinating pre-school children for measles and chicken pox.

2. A Worked Example

Several steps are involved in Cartographic Modeling. And contrary to some users' expectations, the first step does not involve launching a GIS software package and beginning to run GIS commands. In fact, much of the work happens outside a GIS environment, to think through the model goals and intentions, to identify goals and criteria, to establish needed data layers, to create a plan of work, to design the model, implement and test it (Demers, 2002). In practice, only the final steps (implementation and testing) take place in a GIS environment. The next section walks through an example to show how a model is designed, built, launched and evaluated.

2.1 Scenario - Suitability Model for Siting a Biogas Energy Plant in a Rural Community

Imagine that you are a GIS analyst working for a regional planning office where agriculture forms an important rural economy. A bond has been passed to provide funding to install a renewable energy plant in a rural county that your office serves. Due to the dominance of agriculture in your state, it is decided that the renewable energy site will accept animal manure, crop silage and municipal solid waste.

2.2 Problem Context and Model Goals

Biowaste forms an inexhaustible source of renewable energy, and biogas energy is acknowledged to be cost-effective given a reasonable outlay of capital funding (Holm-Nielsen et al 2009). As such it provides a promising renewable energy source in smaller rural areas especially where wind, solar or geothermal energy are not uniformly reliable throughout the year (Chintala et al 2012). Biogas energy production has been widely adopted outside the U.S. and especially in the European Union and the Global South (Scarlat et al 2018; Vögeli et al 2014). Within the U.S. adoption has been slow due to several factors, notably lobbying by fossil fuel advocates (Vergragt et al 2011). The situation is changing however due to an increase in greenhouse gases and rising electricity prices as well as fossil fuel depletion.

The model in this scenario is prescriptive. A small number of current geographic factors will be taken into account, thus some might call it a descriptive model. But the analysis moves beyond simple characterization to satisfy stated objectives, providing a number of potential sites that meet the criteria. Modeling parameters set forth in this example do not accommodate specific standards, policies or regulations, however, as mandated in a normative model. These options could be introduced in subsequent refinements, but for purposes of demonstrating a simple cartographic model, the prescriptive option should suffice to explain the procedure. Steps in the procedure include creating a workplan and setting initial parameters (flowcharting), collecting the data and putting it into GIS format, testing and refining the model. The rest of this entry will cover the first and last steps. The GIS&T Body of Knowledge contains a number of entries on data capture and formatting in the sections on “Data Capture” and “Data Management” and that material is not replicated here.

2.3 Crafting a Plan of Work (Flowcharting)

A cartographic model is designed using a flowchart, which lays out a plan of what data layers must be input to particular GIS commands and in what specific sequence. Flowcharts reduce the workload by organizing the GIS processing steps that need to be taken, by confirming what data layers are needed and initiating modeling parameters for each step. Essentially, a flowchart provides metadata for the modeling steps. Some GIS environments provide visual programming interfaces to automate flowcharting and (in some GIS environments) to actually run a model directly from the flowchart, but it is quite possible to craft a flowchart separately (or even on paper), as will be done in this scenario.

The workplan must consider multiple criteria to identify a suitable location, following best practice for location models (Church, 2002). The cartographic model adds the practice of mapping input criteria as well as outputs as the model comes together (Tomlin, 2013). One criterion for the biogas energy site include finding a parcel with a suitable land use (for example, open space, agriculture or grassland) and of a size large enough to situate the digestor and associated sheds and buildings. The biogas site should be near to but not inside settlements or towns in the county to minimize costs of transporting municipal waste. Road network data is needed to identify larger arterials to accommodate trucks transporting waste. The biogas site will need access to a water body that can serve as a cooling pond. Finally, the site should be relatively flat. The flowchart in Figure 1 illustrates how these five criteria are parametrized and combined to identify suitable locations.

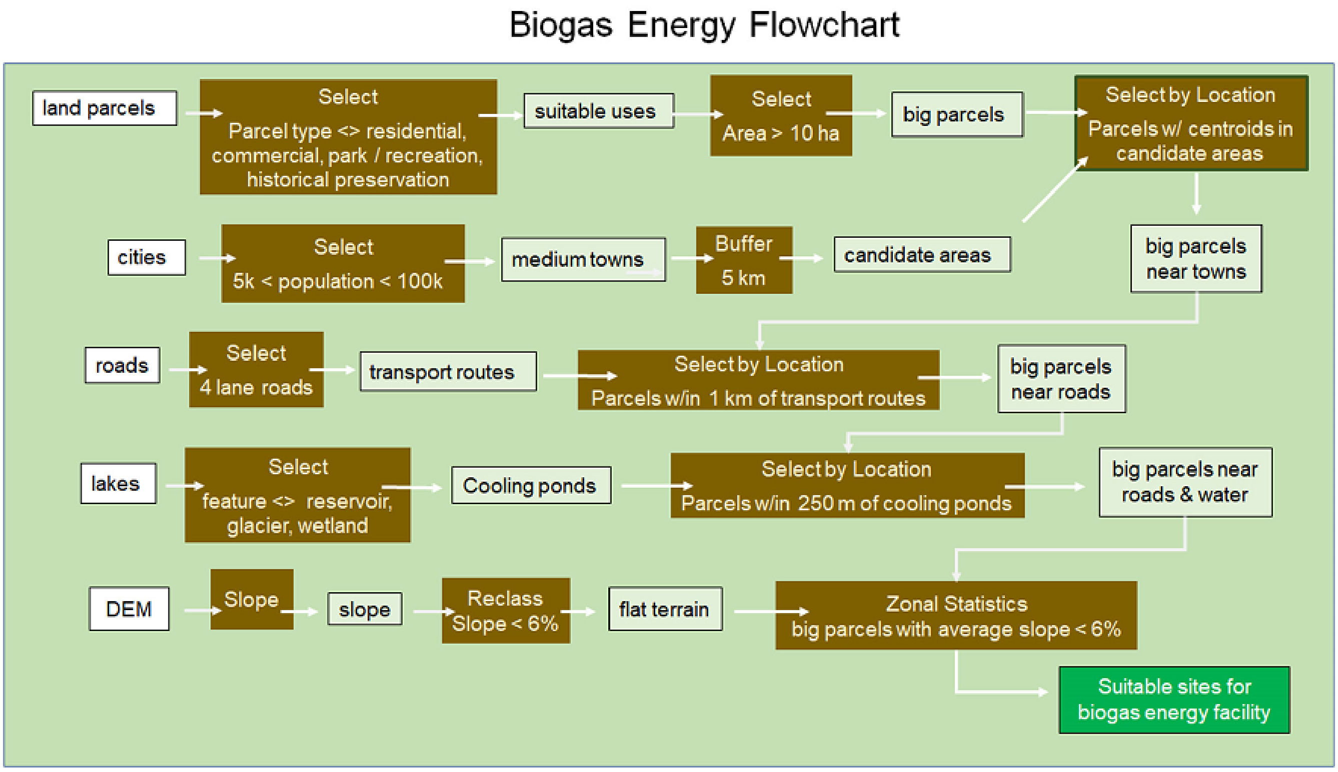

Figure 1. A flowchart showing the design of a simple suitability model to identify sites for a renewable (biogas) energy processing plant in a rural county. White boxes show input data layers, gray boxes show intermediate outputs from each GIS operation. Brown boxes identify specific GIS operators along with the parameters to guide those commands. The green box shows the final output resulting from this model. Details on the flow of processing are described in the text. Source: authors.

Original data layers (in white boxes) are listed down the left side, so that the GIS processing sequence reads left to right. GIS operators are shown in brown boxes and intermediate outputs are shown in light gray. White arrows indicate how data layers flow through the various GIS operators. The initial processing step for the first four criteria filters data records by selecting data subsets that meeting specific parameters of land use type and parcel size, settlement size, road size and type of water body. The fifth criterion (relatively flat terrain) is handled by creating a slope layer and then reclassing to select flatter terrain.

Each GIS operation appears in a separate flowchart box. Some criteria are met by a single GIS operation, such as selecting roads by the number of lanes. Other criteria warrant multiple operations, such as selecting suitable land use types and then selecting a subset of these that exceed a certain size (here, 10 hectares). A buffer is created around settlements to ensure siting the biogas facility outside of residential areas and business districts. On the right side of the flowchart, one can see that some GIS operations combine two intermediate data layers. For example, a Select by Location operator identifies big parcels within 5 kilometers of candidate settlement areas; and these parcels are later filtered to identify those lying within 1 kilometer of 4 lane roads. These parcels are next filtered to identify those within 250 meters of a potential cooling pond. The final GIS operator uses a Zonal Statistics command to select large parcels near roads and cooling ponds that are also on relatively flat terrain (i.e., with average slope under 6%).

Figure 2 shows the input data layers and the modeling result derived using the parameters specified in the flowchart.

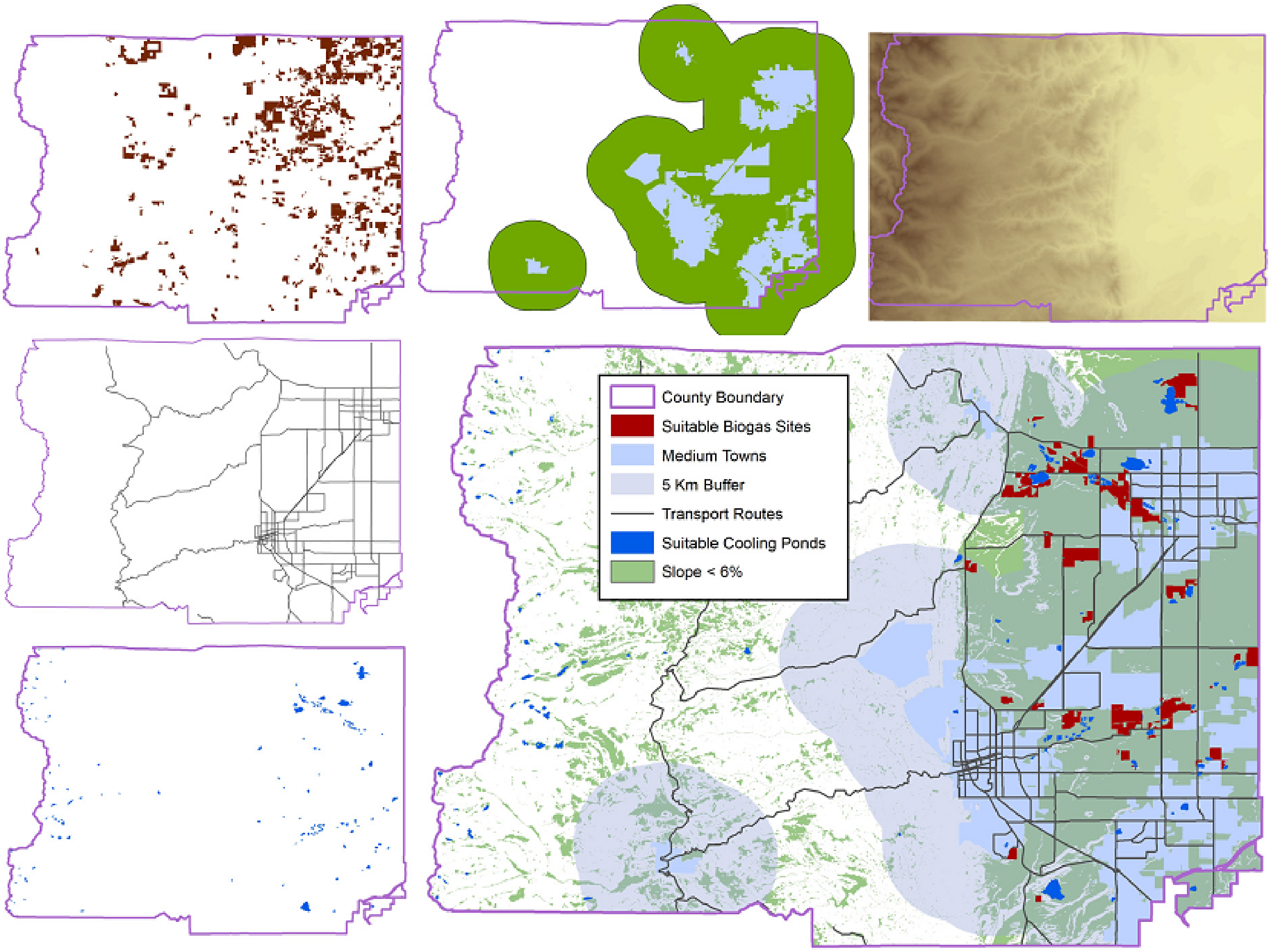

Figure 2. The modeling result. Source: authors.

2.4 Model Implementation, Testing, and Refinement

Model implementation is the stage at which the work moves directly into a GIS environment, whether that is commercial or open source. While creating a flowchart can reduce the time required to develop the cartographic model, as described above, it is also useful during model implementation and testing, for several reasons. First, the sequence of GIS operations can be monitored and modified in a systematic way. In this scenario, buffering suitable towns early on reduces the number of land parcels considerably, as can be seen in comparing the parcels layer that is input and the parcels still under consideration in the final output; and setting the model up with this sequence makes it run more efficiently. Second, a well-designed flowchart will list parameters for each GIS operation. If the modeling result shows too few or too many suitable sites then parameters can be modified systematically, which speeds implementation. In this scenario, an initial buffer around settlements was set at 10 km, which generated a search distance that covered a much larger portion of the county, spanning many areas where few settlements exist (and thus the suitable site might not serve the county effectively). This raises a specific advantage of a cartographic model, in that each step in the modeling process generates a visual outcome. In the biogas example, it was easy to constrain search space by reducing the buffer size to 5 km and immediately visualize that the smaller suitability region is closer to areas where agriculture and settlements are better served.

It is also important to point out that in this scenario as in most cartographic modeling problems, initial modeling results should be tested and refined. Model testing and refinement are primary elements of model evaluation, which can follow several strategies. One strategy is called sensitivity analysis, in which a modeler modifies parameters and then compares final results to see what changes in the final model are brought about by slight parameter modifications. Dramatic changes indicate that the model is highly sensitive to a particular criterion, and should lead to further and more focused evaluation, or possibly to introducing additional criteria. On the other hand, slight changes in modeling output indicate that a particular criterion may not be an important contributor to the model in the end, and in some cases that criterion (and associated GIS processing) can be eliminated. In the biogas scenario for example, one might introduce a size criterion to further constrain the number of suitable cooling pond candidates. A second strategy (that often follows sensitivity analysis) will implement the model in another county with similar or different geographic conditions (different settlement patterns, different terrain, different water access, etc.) (Thompson et al 2013).

3. Summary

Cartographic modeling is a method commonly applied in GIS environments. The method offers benefits that can improve modeling efficiency and demonstrate model reliability. Because GIS relies largely upon spatial data, original inputs as well as intermediate output layers can be shown in map form, which in turn permits visual determination that the modeling steps are moving toward a logical end point. Cartographic models can take three forms (descriptive, prescriptive and normative). Descriptive models are used to characterize position and form, or to synthesize spatial relationships and establish spatial association, suitability, and possibly determine if relationships are hierarchical (Tomlin, 2013). Descriptive models can be transformed into prescriptive models by focusing attention on one particular factor, examining the range of parameters that could be modified to meet a specific objective.

In the biogas example, a descriptive model would articulate land use, settlement, transportation, hydrography and terrain as factors that can facilitate or limit viable energy site locations. The transformation to a prescriptive model is achieved by setting and modifying parameters such as population, slope, distance to roads and water in order to identify a set of locations for an energy facility that serve medium sized settlements, that do not conflict with residential, recreational or historic land uses and that will not incur heavy construction costs to level the terrain. Tomlin (2013) refers to the transformation to a prescriptive model as “inverting” the descriptive model. Normative models are not covered here but could be achieved by transforming the prescriptive model so as to limit the choice of parameter values in accordance with existing regulations and policies in place in the county. In addition, it would be possible to add steps to the model to assign weights to each criterion and then compute a score for each biogas site reflecting how close is its location to optimality (i.e., the highest scored site would be established as most optimal for these criteria). Weights could be chosen in accordance with established regulations to bring the model closer to normative status.

Cartographic modeling proceeds by creating an inventory of relevant criteria, identifying data layers that permit examination of the criteria in map form, generation of a flowchart to plan the sequence of GIS operations and parameters that will combine the data layers, implementation and evaluation. Evaluation demonstrates the degree to which the selected locations satisfy the criteria. This last step can proceed by sensitivity analysis, by implementing the model in a variety of geographic conditions and by reviewing the model design to determine if additional criteria or data layers could be considered. In the biogas scenario, one might consider three factors not built into this model. One might check the county to see if a power plant exists, since situating the biogas facility at the power plant would obviate the need to move the biogas to the power plant and possibly increasing costs. Data on land prices might constrain the choice of suitable sites if a land parcel needs to be purchased. Soils data could be relevant for estimating site preparation costs. A road distance cost surface could be generated to each selected site to assist in selecting a final energy site that reduces transport costs for farms and settlements in the county as a whole or that ensures equitable transport costs for the most distant clients.

In the end, cartographic modeling is a simple but robust practice that utilizes GIS technology in a manner that is visually intuitive. While it does warrant some prior knowledge about GIS operators and data preparation, it does not require advanced programming skills, extensive mathematics or statistics necessarily, although many advanced GIScientists use it as a first exploratory pass on a problem, essentially as a tool to think quickly through alternate solutions (i.e. to "map out loud"). It provides a powerful and enduring analytic method to use mapped information to ask and answer questions about the world we live in, supporting the design and implementation of a variety of GIS analyses.

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