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Using Bayesian belief networks to identify potential compatibilities and conflicts between development and landscape conservation

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Abstract

Experts with different land use interests often use differing definitions of land suitability that can result in competing land use decisions. We use Bayesian belief networks linked to GIS data layers to integrate empirical data and expert knowledge from two different land use interests (development and conservation) in Maine's Lower Penobscot River Watershed. Using ground locations and digital orthoquads, we determined the overall accuracy of the resulting development and conservation suitability maps to be 82% and 89%, respectively. Overlay of the two maps show large areas of land suitable for both conservation protection and economic development and provide multiple options for mitigating potential conflict among these competing land users. The modeling process can be adapted to help prioritize and choose among different alternatives as new information becomes available, or as land use and land-use policies change. The current model structure provides a maximal coverage strategy that allows decision makers to target and prioritize several areas for protection or development and to set specific strategies in the face of changing ecological, social, or economic processes. Having multiple options can generate new hypotheses and decisions at more local scales or for more specific conservation purposes not yet identified by stakeholders and decision makers in the region. Subsequently, new models can be developed using the same process, but with higher resolution data, thereby helping a community evaluate the impacts of alternative land uses between different prioritized areas at finer scales.

Keywords: Bayesian networks, Conservation Development, GIS, Land use Smart Growth

1 Introduction

Rapid conversion of forests and agriculture lands has spurred new efforts to develop strategic visions for guiding future development and conservation of open space in the U.S. Land suitability assessment (LSA) is one planning approach that has been widely used for determining the fitness of a given tract of land for a defined use (Steiner et al., 2000). In theory, LSA provides a means of pre-planning which lands are most appropriate for specific future land use activities, including resource protection. Unfortunately, the concept of LSA is generally applied without a consistent set of guidelines or metrics. Thus, for example, experts in the field of urban planning and conservation assessment often use different criteria to evaluate desirable landscape features, optimal weighting schemes, and the capacity of the land to support their objectives and values (Dramstad et al., 1996; Jongman and Pungetti, 2004; Turner et al., 2001). This leads to differing definitions of suitability, and hence a lack of standard methodologies among different fields of expertise. Different definitions of suitability are also incorporated into different environmental, socio-economic, and cartographic indices (Carrion-Flores and Irwin, 2004; Dong et al., 2008; Marull et al., 2007; Seto and Kaufmann, 2003). While useful, such indices are often complex, difficult to understand, not easily adaptable to new data, and not easily transferrable between different spatial scales (Frohn, 1998; Neel et al., 2001; Wickham and Riitters, 1995; Wickham et al., 1997; Wu et al., 2002).

A number of approaches have been developed to articulate a framework for identification and protection of high value conservation lands. The goal of systematic conservation assessment (SCA) is to represent the biodiversity (usually at the species or community level) of a region and allow the persistence of ecological processes that maintain resilience (Margules and Pressey, 2000). Reserves have typically been designed as contiguous corridors or isolated patches occurring in remote areas that are unsuitable for commercial activity (Margules and

Pressey, 2000). The challenge is to identify priority areas that incorporate representative biological communities (e.g., vegetative land cover types), and their processes (e.g., dispersal and migration), while striking a balance between biodiversity conservation and socioeconomic development (Klein et al., 2008; Rouget et al., 2006).

Models such as Marxan facilitate the design of protected areas by minimizing the total length of their perimeter (i.e. edge) relative to the total planning unit cost of a reserve (Ball and Possingham, 2000; Possingham et al., 2000). Such models are crucial for designing reserves and corridors that incorporate spatial connectivity and species persistence (Possingham et al., 2000; Pressey et al., 2003; Rouget et al., 2003). However, these landscape-scale design approaches do not typically also consider socioeconomic factors or the social and economic sustainability of rural economies (Anderson and Berglund, 2003). Furthermore, they provide few options over a large area that would allow communities to prioritize different strategies, adapt their strategies to future policy changes, or consider future land use pressures.

Urban and conservation planners often lack the luxury of time, money, and certainty when searching for scientific evidence to evaluate the effectiveness of alternative management options. Augmenting this is the fact that scientific literature can be voluminous and difficult to interpret, and models often support a wide range of forecasts due to their interpretive flexibility (Finlayson, 1994). All of these factors add to the uncertainty of scientific knowledge. Thus, land use decisions are often made without considering the most up-to-date information of physical, biological, and anthropological phenomena and their interactions (Pullin et al., 2004). Even when scientific evidence is available for land use decisions, the framework may not be available to ensure that it is used in the planning and evaluation process (Pullin et al., 2004). Thus, approaches that can integrate experience (i.e., expert knowledge and opinion) with available data and are easily updated as new information becomes available would be invaluable to practitioners, policy makers, and the public.

Several studies have demonstrated the use of Bayesian belief networks (BBN) for integrating expert knowledge and empirical data (Chow and Sadler, 2010; Henriksen et al., 2007; Marcot et al., 2006; Smith et al., 2007). Many of these studies focus on identifying species occurrence or habitat suitability based on environmental variables (i.e., empirical data) and management actions (i.e., experience) (Dlamini, 2010; Prato, 2005; Smith et al., 2007; Steventon, 2008). The few BBN models that address the field of urban development suggest such models can be useful for detecting drivers of urban land use change and for exploring alternative planning scenarios (Kocabas and Dragicevic, 2007; Ma et al., 2007; Pourret et al., 2008). BBN models are particularly useful when empirical data are limited and decisions are based largely on expert knowledge as is often the case with endangered species and land tenure changes (Norberg and Cumming, 2008; Smith et al., 2007). In addition, BBNs are easy to calibrate, validate, and update as new information becomes available (Smith et al., 2007). Thus, BBN models fit well with the concepts of adaptive management (Prato, 2005) and can be a useful tool for organizing current thinking, generating testable hypotheses, and comparing alternatives.

We develop a process designed to help urban and conservation planners to begin building relationships with each other and to provide a diversity of ideas as well as transparency among the different groups, thereby creating flexibility in decision making. The model building exercise explained here is a first step in this process that we believe can be used to facilitate future decision making. We suggest that BBNs are the best tool to use in this process because: (1) they are dynamic and take spatial complexity into consideration; (2) the model parameters have clear semantic interpretation and the conditional probabilities are easily understandable unlike weights in more complex models (i.e., it is not a black box); (3) BBNs have a learning component such that probabilities can be updated as new information becomes available; and (4) they incorporate the uncertainty of scientific knowledge (Kocabas and Dragicevic, 2007). By using diverse stakeholder input to build BBN models, we are developing an adaptive organizational process that will be useful for bringing people together to organize current thinking, generate multiple working hypotheses, and compare possible alternative futures that are guided by observation, inference, and careful thinking (Chamberlain, 1897).

We use expert opinion from two fields of interest – urban planning and conservation assessment – along with available remote sensing and Geographic Information System (GIS) data linked to two BBN models. Our aim is to use an idealized scenario for development using simple Smart Growth principles (e.g., directing development towards existing communities, stakeholder collaboration on development decisions, and mixed land uses) thought to limit sprawl for urban and amenity-based development (Smart Growth Network, 2002). We use a similar approach to identify potential areas for future conservation land by identifying riparian and large wetland connectivity corridors, as well as isolated patches of high value natural habitat and their proximity to current conservation lands. Rather than compare scenarios of alternatives and assumptions for these different land use interests, we seek a useful and practical way to identify suitable areas for urban and amenity-based development, areas that provide connectivity to existing conservation lands, and areas of common ground between developers and conservation managers. Our goal is to develop a land use planning and cooperative stakeholder analysis tool that provides decision makers with multiple options for targeting and prioritizing areas for conservation protection and development.

2 Study area and methods

The Lower Penobscot River Watershed (LPRW) is a 9974 km^2 area located in Penobscot and Piscataquis Counties of Northern Maine (Fig. 1). Land use change in the area is largely driven by forest management (Acheson and McCloskey, 2008; Lilieholm et al., 2010), conservation (Cronan et al., 2010), and urbanization (Stein et al., 2005; White et al., 2009). Many of the problems facing the LPRW, such as urban sprawl, increasing tax rates, and increased pressure on wildlife habitat areas (e.g., loss of wetlands) are also found in other areas throughout the United States and Canada (Kocabas and Dragicevic, 2007; Ma et al., 2007; Radeloff et al., 2010; Rouget et al., 2003, 2006; Stein et al., 2005; White et al., 2009). We focus on linking social, economic, and ecological variables in order to develop a cooperative stakeholder analysis and land use planning tool that would enhance the sustainability of human and natural systems in the LPRW.

We identify these variables by conducting a review of the current literature (e.g., Kocabas and Dragicevic, 2007; Lilieholm et al., 2010; Ma et al., 2007; Radeloff et al., 2010; Rouget et al., 2003, 2006; Stein et al., 2005; White et al., 2009), engaging stakeholders in the research process through focus groups, and holding several meetings with scientists with expertise in ecology, economics, and forestry. Input from stakeholders were obtained through individual interviews, focus groups, and state conferences and included town planners, land trust practitioners, Non-governmental organizations, economic developers, land use consultants, and government officials from the Maine State Planning Office. We used the elicited information to develop two BBNs that represent the functional relationships among the variables identified by experts to be important for: (1) encouraging Smart Growth principles for development, and (2) identifying future conservation lands (Smart Growth Network, 2002).

In the following section, we describe the model building process by first building influence diagrams as proposed by Marcot et al. (2006) (Figs. 2 and 3). We then explain each layer of the diagram as well as the rationale for the chosen variables, their functional relationships, and the discrete states used to represent the influences that each variable has on suitability (Marcot et al., 2006). We use the Netica® BBN software (version 4.09; Norsys Software Corporation, Vancouver, British Columbia) to create BBNs with boxes and arrows (i.e., nodes and links) representing functional relationships among variables (Steventon et al., 2006). In our BBNs, each node has two to four user-defined states with a table that expresses the probability of each state either as prior distributions or as conditional on the probability of each state for the nodes feeding into it (Steventon et al., 2006). The nodes and states used in each model are further explained in Appendices A and B. The prior probability tables are specified from case files of the empirical GIS data, whereas the conditional probability tables (CPT) are entered manually based on expert opinion (Marcot et al., 2006). Maps representing the GIS variables used within each BBN model were stacked pixel-for-pixel using an ITTVIS (ITT Visual Information Solutions, 2009, Boulder, CO) programming code. We used a combination of ITTVIS and ERDAS Imagine (2010, ERDAS, Inc., Atlanta, GA) software to produce the final suitability maps for both BBN models.

2.1. Creating the BBN model for development suitability

The influence diagram for the development model (Fig. 2) contains seven remotely sensed and GIS data layers (variables) thought to influence Smart Growth development principles in Maine as identified by the literature (e.g., Brookings Institution, 2006; Kocabas and Dragicevic, 2007; Ma et al., 2007; Radeloff et al., 2010; Rouget et al., 2003, 2006; Stein et al., 2005; White et al., 2009), experts, and stakeholders. We use GIS and remote sensing data currently available from the Maine Office of GIS (MEGIS) because it represents the data most likely to be used by decision makers in the region.

2.1.1. Land available for development

The amount of land available for development in the LPRW was determined from a land cover map obtained from MEGIS and created using LandSat TM data acquired in June of 2004. The initial 23 class map was recoded using ERDAS Imagine and represents the two states (i.e., available and unavailable) for all potential development in the LPRW (Appendix A). Because we are interested in future development and potential sprawl, we assume areas classified as urban to be unavailable. Likewise, because we are interested in finding common ground between developers and conservation interests, wetlands and forested wetlands are assumed unavailable for development. Areas already classed as current conservation lands are also assumed to be unavailable for development.

2.1.2. Population data layer

The LPRW includes of 145 municipalities, 8 of which are designated by the State of Maine as regional hubs or service centers that provide the majority of jobs, commercial activity, and social resources for the area (Brookings Institution, 2006). The largest of these regional hubs is Bangor, which has a population of 31,473 people (U.S. Census, 2000). The larger Bangor Metropolitan area (population 87,333) consists of Bangor and 13 surrounding towns (three of which are also considered hubs). The remaining towns include 14 large rural towns (combined population 43,640; includes the remaining four hubs), 46 moderately sized rural towns (combined population 48,699), and 71 small towns and Unorganized Territories (combined population 5750). The towns outside the Bangor Metropolitan area and the four remaining hubs average less than one housing unit per 10 hectares of land (Brookings Institution, 2006).

We obtained town boundaries for the LPRW from MEGIS. The population states were based on the 14 towns that comprise the Bangor Metropolitan area and the number of people per square mile for each of the remaining 131 towns within the LPRW (MEGIS and U.S. Census Bureau 2000) (Appendix B). The population variable assumes that amenities that are accessible from metropolitan centers are more desirable (Radeloff et al., 2010).

2.1.3. Municipal property tax rates

While the overall population of Northern Maine has increased since 2000, the regional hubs have lost population to the rural town periphery (Brookings Institution, 2006). This population dispersal or “sprawl” is driving-up costs of service provisions for surrounding rural towns. Although an increased tax base can lower per-capita expenditures early in a town’s growth cycle, evidence suggests that costs in Maine increase significantly as the population surpasses a threshold of 2500–6000 people (Brookings Institution, 2006). In fact, average property tax rates in regional hubs of Maine are currently 48% higher than those found in outlying towns (Brookings Institution, 2006). Thus, we assume that rising costs lead to an increase in taxes that leads to further sprawl.

The states for the municipal property tax rates (the socio-economic variable) came from the 2008 Municipal Valuation Return Statistical Summary (MVRSS; Maine Revenue Office) and are based on equal frequency in three of the four range classes (Appendix B). The MVRSS reported tax rates for 94 of the 145 towns in the LPRW. The 51 towns with unreported tax rates were Unorganized Townships containing between one and nine people per square mile (2.6 km^2) of land and were classified in the low tax rate category (Appendix B). The municipal tax rate variable assumes that areas with higher tax rates are less desirable for development and thus encourages sprawl (Brookings Institution, 2006).

2.1.4. Amenity-based and urban development

Compounding the trends of rising costs and sprawl is the fact that nearly 16% of all dwellings in Maine are designated as seasonal homes (Brookings Institution, 2006). In the LPWR, many of these homes are located on shorefront property, near existing conservation lands, or in other rural areas high in natural amenities. While amenity-based development may bolster the local tax base, it can also increase home prices in rural towns, thereby compounding the problem of sprawl.

Through a combination of increased taxes, home prices, and desire to live in less densely populated areas, sprawl results in the conversion of rural fields and woodlots, thereby placing increased conversion pressure on forest resources in the LPRW. In addition, much of the sprawl occurs along once scenic roads and along the Interstate Highway I-95 corridor in the form of shopping centers. The great North Woods, quaint town centers, and rural scenic roadways are all part of the quality-of-place that makes Maine and the LPRW an attractive area to live (Reilly and Renski, 2007). Sprawl threatens the aesthetic quality and the ecological and economic integrity of these features within the LPRW and throughout Maine (Brookings Institution, 2006).

The final drivers of urban development (i.e., the distance layers; Fig. 2) and their states were chosen based on information from the Brookings Institution (2006), Smart Growth principles, and expert opinion (Appendix B). The initial road and urban area layers were obtained from MEGIS and created from the original land cover map using various functions in ERDAS Imagine. Distances were based on the assumption that being close to current roads and urban areas makes best use of existing infrastructure while lessening the effect of sprawl and the conversion of rural fields and woodlots (Brookings Institution, 2006; Kocabas and Dragicevic, 2007). Development in such locations should decrease pressure on natural resources and maintain opportunities for agriculture and working forests.

Likewise, the amenity-based development variables and their states were chosen based on information from the Brookings Institution (2006) and expert opinion (Appendix B). The initial current conservation land and large water body (i.e., lakes and ponds greater than 4.05 ha) layers were created from the original land cover map using various functions in ERDAS Imagine. Distances were based on the assumption that being close to lakes and ponds or current conservation land was more preferable than areas far away from such amenities (Brookings Institution, 2006; Radeloff et al., 2010).

2.2. Creating the BBN model for conservation suitability

We again reviewed the current literature, consulted scientists, and used the elicited information to build an influence diagram for conservation suitability as proposed by Marcot et al. (2006) (Fig. 3). The diagram contains five GIS data layers (variables) identified by experts and stakeholders thought to be important for identifying riparian and large wetland connectivity corridors as well as isolated patches of high value natural habitat and their proximity to existing conservation lands.

Nearly 90% of Maine's land area is under private ownership and subject to the development and land use pressures described above. In response to these pressures, over 100 land trusts operating in partnership with landowners, foresters, recreationists, environmental NGOs, and state and federal programs have permanently protected over two million hectares of land – approximately 17% of the State – through a variety of voluntary, market-based approaches ranging from fee simple acquisition to conservation easements (Cronan et al., 2010). In the LPRW, 8.2% (81,585 ha) of the land exists under some form of conservation designation. Many of these lands, while protected from development, remain as part of Maine's working landscape producing wood fiber for the State's forest products sector, food and forage under agricultural production, and open space for recreation. This innovative mix of conservation and working landscape protection is in many ways unique to the Northeast (Fairfax et al., 2005; Foster, 2009; Foster et al., 2010; Ginn, 2005; Lilieholm et al., 2010).

There are several approaches for designing conservation corridors that incorporate biological pattern and process (Possingham et al., 2000; Pressey et al., 2003; Rouget et al., 2003). These approaches generally involve trade-offs between representation and persistence (Margules and Pressey, 2000; Rouget et al., 2006). In addition, connectivity corridors can sometimes be harmful for biodiversity and isolated patches of natural habitat may instead be a desired outcome

(Dobson et al., 1999). Rouget et al. (2006) used systematic design principles of representation and persistence to address these issues and designed corridors to achieve biodiversity patterns and processes. We used the Beginning with Habitat (BWH) Focus Areas (see below) identified by biologists from Maine's Department of Conservation and the Department of Inland Fisheries and Wildlife along with riparian corridors and wetlands to represent fixed spatial processes (i.e., corridors and isolated patches) that act as surrogates of ecological and evolutionary processes (Rouget et al., 2006).

It has been shown that riparian buffers perform as well as corridors in achieving vegetation type targets and are often used to ensure biodiversity persistence (Rouget et al., 2006). BWH Focus Areas represent documented locations of rare plants, animals and natural communities, high-quality common natural communities, significant wildlife habitats, and their intersection with large blocks of undeveloped habitat. These focus areas are a planning tool for conservation entities and towns in Maine to help them concentrate conservation initiatives and open space planning in the areas with the greatest biodiversity significance.

2.2.1. Land available for future conservation

The amount of land available for future conservation lands in the LPRW was created from the same land cover map previously described. The initial 23 class map was re-coded differently than above in order to represent the two states (i.e., available and unavailable) for all potential future conservation lands in the LPRW (Appendix A). Unavailable land includes urban areas, roads, water, and current conservation lands (Appendix B). All other land cover types were considered available as potential future conservation land.

2.2.2. Data layers

The initial riparian corridor GIS layer was obtained from MEGIS and published by the United States Geological Survey in 2004. The initial layer represents all perennial streams (first to eighth order) in the LPRW. The BWH GIS layer represents “Focal Areas” of statewide ecological significance that merit special conservation attention. The large wetlands map was created from the National Land Cover Database (2001) land cover layer using ArcGIS (ESRI, 2008, version 9.3, Redlands, CA) and selecting all wooded and emergent wetland features in the LPRW greater than or equal to 8.1 ha.

2.2.3. Conditional probability tables for both BBNs

For the availability layer (i.e., the land cover map that acts as a filter; Figs. 2 and 3), the prior probability was assigned based on the percent of the study area covered by each state. CPTs for the linked GIS variables were populated using conditional probabilities calculated from the combined GIS variables. There are no empirical data for the two pressure nodes and the overall suitability node (Fig. 2) or the connectivity and overall suitability nodes (Fig. 3). Therefore, the CPTs for these nodes were populated using expert opinion as described by Marcot et al. (2006) (see Tables 1 and 2 for an example). For the development BBN, the first state for each of the four distance variables (Fig. 4) represents the actual location of the road, town, conservation land, and water body. These states (or categories) represent pixels that are already developed (e.g., an actual road) or cannot be developed (e.g., water). Thus, they assume an impossible state when combined with other states and cannot be developed (i.e., they are treated as a negative state finding in the BBN model). This leaves nine rows remaining in both pressure CPTs that represent logical conditions that drive development of amenity-based development pressure. Likewise, for the conservation BBN, the first state of the distance to current conservation land variable (Fig. 5), represents the actual location of current conservation land and thus also assumes an impossible state when combined with the other states. This leaves 12 rows remaining in the connectivity CPT that represent logical conditions that determine connectivity availability.

The CPT assessments among experts did not differ in terms of the logic involved (e.g., areas that were close to a road and close to town were chosen by everyone to be 85–100% suitable for development). Thus, for the purposes of this paper, we assumed that changes in logic would have a greater effect on map output than changes in CPT value. Since there were no differences in logic among the participants, we did not systematically explore the possible map outputs resulting from the many possible differences in CPT values. The actual numbers in the expert opinion CPTs were obtained by taking the average from the input of several experts who "pegged the corners" while filling-out the CPTs as suggested by Marcot et al. (2006).

2.3. Suitability maps

The ITTVIS code was used to create a case file in which each row contained the GIS variable for a single pixel in the study area. The case file was run through each BBN model using the "Process Cases" function in Netica®. The probability distribution for the suitability node was output for each case (i.e., pixel). The outputs obtained were joined back to the attribute table of the original layer and mapped. We measured the sensitivity or influence of the variables on overall suitability using entropy reduction (see Marcot et al., 2006; Smith et al., 2007) within the Netica® software. Our goal is not to produce the "best" model for the LPRW, so we do not examine how different possible values for the states and CPTs or different model structures may affect the map outputs. Instead, our goal is to show how a participatory modeling process using BBN can be used to identify potential areas suitable for development and conservation. Thus, we use the values and structure chosen by the experts and stakeholders and assume that no one model will provide a panacea for understanding and managing complex natural and human systems (Pourret et al., 2008).

2.4 Accuracy assessment

The final classification for both the development and conservation maps was stratified by the suitability categories of each map (Congalton, 1991). For the development map, 100 sites (i.e., 20 for each suitability category) were randomly chosen for assessment. For the conservation map, 90 sites (30 for each suitability category) were chosen. Each assessment site was identified visually from 2005 digital orthoquad photographs obtained from MEGIS and ground surveys and checked against suitability type to determine if the location met the criteria of each model (e.g., whether or not the location was actually close to a road). Because some pixels may contain more than one suitability type (i.e., mixed pixels), each assessment site was deemed acceptable if there was a 5-pixel class majority within a 3 x 3 pixel window (Congalton, 1991). An error matrix quantified accuracy of the final suitability maps (Congalton, 1991). The producer accuracy (i.e., omission errors) provides the probability that an area on the ground that was identified as a particular suitability type (e.g., urban area) was depicted as such on the map (Congalton, 1991). User accuracy (commission errors) is the probability that a point on the map classified as a particular suitability category will actually be that category on the ground (Congalton, 1991). KHAT summarizes the overall results and measures the difference between the actual agreement in the error matrix (i.e., between reference data and the suitability map and indicated by the diagonal) and the chance agreement indicated by the row and column totals (i.e., marginals) (Congalton, 1991).

3 Results

3.1. Development model

The complete model for development suitability is shown in Fig. 4. The states of the urban development pressure variables (i.e., distance to roads and urban areas) assume a compact growth scenario and represent distances important to the principles of Smart Growth. These two layers create different amounts of pressure for development depending on the combination of distances to roads or towns (Appendix B and Fig. 4). The municipal tax rate variable modifies development pressure and assumes that areas with higher taxes are less desirable for development and encourages sprawl (Brookings Institution, 2006). The states of the amenity-based driver variables are based on the assumption that being close to either large bodies of water or current conservation land will increase the pressure for seasonal home development in the LPRW (Brookings Institution, 2006). The population variable acts to modify this pressure by assuming that amenities that are accessible from metropolitan centers are more desirable (Radeloff et al., 2010). Sensitivity analysis suggests that urban suitability is the most influential factor for development suitability (Table 3).

3.2. Conservation model

The states of the connectivity driver variables (i.e., distance to riparian areas and current conservation lands) assume an environmental growth scenario (Fig. 5). Distances (states) for the current conservation lands are described above and in Appendix B. Distances for the riparian areas were based on forestry Best Management Practices (BMPs) for riparian buffers that have been identified as important to various wildlife species and water quality issues (Briggs et al., 1998). We assumed that riparian areas would provide the most suitable land form to connect current conservation lands with future lands or with each other. Large wetlands and areas designated as BWH Focal Areas were then used as modifiers to assume that areas with high connectivity that also include either of these attributes are more suitable than areas without these attributes (Appendix B and Fig. 5). Sensitivity analysis suggests connectivity is the most influential factor for conservation suitability (Table 3).

3.3. Suitability maps

The area of land within the LPRW considered as potentially available for development (i.e., the top filter node in Fig. 4) represents 75% (752,925 ha) of the total area, almost 20 times the 38,550 ha currently classified as urban or developed by the original MEGIS land cover map (Appendix A). Fig. 6 shows the probability of development suitability being high. The total area identified as high probability (60–100% probability) of high suitability for development is 279,532 ha (37% of the available area) (Fig. 6).

The area of land considered potentially available for future conservation (i.e., the top filter node in Fig. 5) represents 83% (830,889 ha) of the total area, 10 times the 81,575 ha currently held as conservation land within the LPRW (Appendix A). Fig. 7 shows the probability of future conservation suitability being high. The total area identified as high probability (60–100% probability) of high suitability for future conservation land is 305,268 ha (37% of the available area) (Fig. 7).

Fig. 8 shows overlapping and non-overlapping areas of high probability of high suitability for development and conservation. Non-overlapping areas for development represents 21% (157,834 ha) of the land considered available for development. Likewise, non-overlapping areas for future conservation represents 22% (183,570 ha) of the land considered available for conservation. Areas of conflict represent about 15–16% of the available land, whereas areas with low probability for development and conservation represent 42–47% of the available land.

3.4. Accuracy assessment

The overall accuracy of the development map was 82%, with producer’s and user’s accuracy for each suitability class ranging from 69 to 94% and 65 to 95%, respectively (Table 4). The overall accuracy of the conservation map was 89%, with producer’s and user’s accuracy for each suitability class ranging from 80 to 97% and 77 to 97%, respectively (Table 4).

4 Discussion

The primary finding of this study was that in a growing, yet still largely rural area, our modeling process can identify large areas of land suitable for conservation protection and economic development, while providing multiple options for avoiding conflict among competing land users. The current structure of our models provides a strategy that allows decision makers to target and prioritize several areas for protection or development, and to set specific strategies in the face of changing ecological, social, or economic processes. For example, our models allow decision makers to conserve 100% of wetlands in the LPRW, while still identifying 157,834 ha of land highly suitable for development (more than four times the amount currently classified in the LPRW as Urban; Appendix A). This same area of land for development does not conflict with the spatial ecological processes represented by riparian corridors and BWH Focus Areas or with conservation implementation opportunities to incorporate existing conservation areas. Furthermore, we used BWH Focus Areas, wetlands, and riparian corridors to represent fixed spatial processes (i.e., corridors and isolated patches) that act as surrogates of ecological and evolutionary processes (Rouget et al., 2006). Thus, our models are designed to identify areas that capture biological processes and represent diverse vegetation patterns, while also providing options for areas that integrate with existing conservation lands or act as isolated patches.

Having multiple options can generate new hypotheses and decisions at more local scales (e.g., deciding on the location of one or more shopping centers or housing developments) or for more specific conservation purposes (e.g., protection of an endangered plant or animal) as of yet unidentified by stakeholders and decision makers in the region. Subsequently, new models can be developed using the same process, but with higher resolution data, thereby helping a community decide between different prioritized areas at finer scales. For example, identifying suitable areas for conservation and urban development will provide multiple potential locations for future development projects that do not interfere with the protection of important ecosystems (e.g., wetlands). However, there are factors not considered in the current suitability models (e.g., ownership and land value). Thus, higher resolution spatial data will likely be needed for specific, smaller-scale (i.e., parcel-level) planning. This will require new or updated BBN models, informed by the existing modeling framework, to allow planners and stakeholders to continue to build relationships and learn from past experience.

Song and M’Gonigle (2001) suggest that the road to good science “is to break free of the stranglehold that centralized institutions have long had on our concepts of what is true and what is possible.” The key is a democratic approach to knowledge itself through a participatory process with open dialogue and debate among various stakeholders (Song and M’Gonigle, 2001). We envision the process developed here as a starting point for such an approach. For example, by combining the current model with other land use interests (e.g., agriculture and forestry) a land use strategy could be further developed through a stakeholder-driven process, perhaps similar to the mega conservancy network concept suggested by others (Brunckhorst, 2000; Hobbs and Saunders, 1991; Rouget et al., 2006). These networks help to strategize and align visions for landscape futures and cooperatively manage capital flows (e.g., ecological, economic, or social) to better ensure achievement of competing land use outcomes (Brunckhorst, 2000; Hobbs and Saunders, 1991; Rouget et al., 2006).

The need for conservation assessment in the LPRW is evidenced by the potential change and escalation in land use pressure in the area (Brookings Institution, 2006; Stein et al., 2005; White et al., 2009). Our modeling process is one tool in addressing the challenge of providing economic opportunity, while preserving quality-of-place. When implemented with other conservation instruments (e.g., laws and guidelines, BMPs, etc.), we hope to ensure conservation of biodiversity as well as economic opportunities important to coupled human and natural systems. For example, we are currently working to combine the current development and conservation models with similar models for forestry, agriculture, and ecotourism into an overall model that will use BBN, decision networks, and cellular automata to assess trade-offs from differing stakeholder perspectives (Kocabas and Dragicevic, 2007). The outcomes of such assessments could then be used to guide land use legislation and policy.

This level of stakeholder involvement is a key Smart Growth principle that ensures transparency and defensibility and should increase stakeholder capacity to develop, understand and react to alternative futures (Smart Growth Network, 2002). By using such models to engage a diverse set of stakeholders, we expect to foster increased collaboration, expanded social capital, and better-targeted development and conservation proposals. To the extent that these outcomes are realized, we would expect to gain incremental improvements in quality-of-place and more sustainable rural and urban economies across the region.

5 Conclusion

Efforts to develop a democratic, holistic view of the environment will benefit from decision tools that allow for comparisons of the consequences and trade-offs associated with different land use alternatives. We believe that the cooperative stakeholder planning and analysis process described in this paper can be a starting point for such an approach. Because we cannot know with certainty the spatial distribution of future land uses (Ma et al., 2007), our modeling process provides maps showing several possible locations (options) for both economic development and conserving important ecological areas. Our current models offer a low-cost, easily understood, standardized, and rapid assessment tool that can be used as a first-step to identify and implement Smart Growth principles of development and minimize conflict with land conservation efforts. Future models can be adapted to help prioritize and select among different alternatives as new information becomes available (e.g., land tenure and land value) or as policy changes occur. The process allows us to synthesize experience and scientific knowledge and accelerate the movement of knowledge between academic institutions, practitioners, policy makers, and the public. Together, we can facilitate the transfer of scientific knowledge into meaningful action.

Acknowledgements

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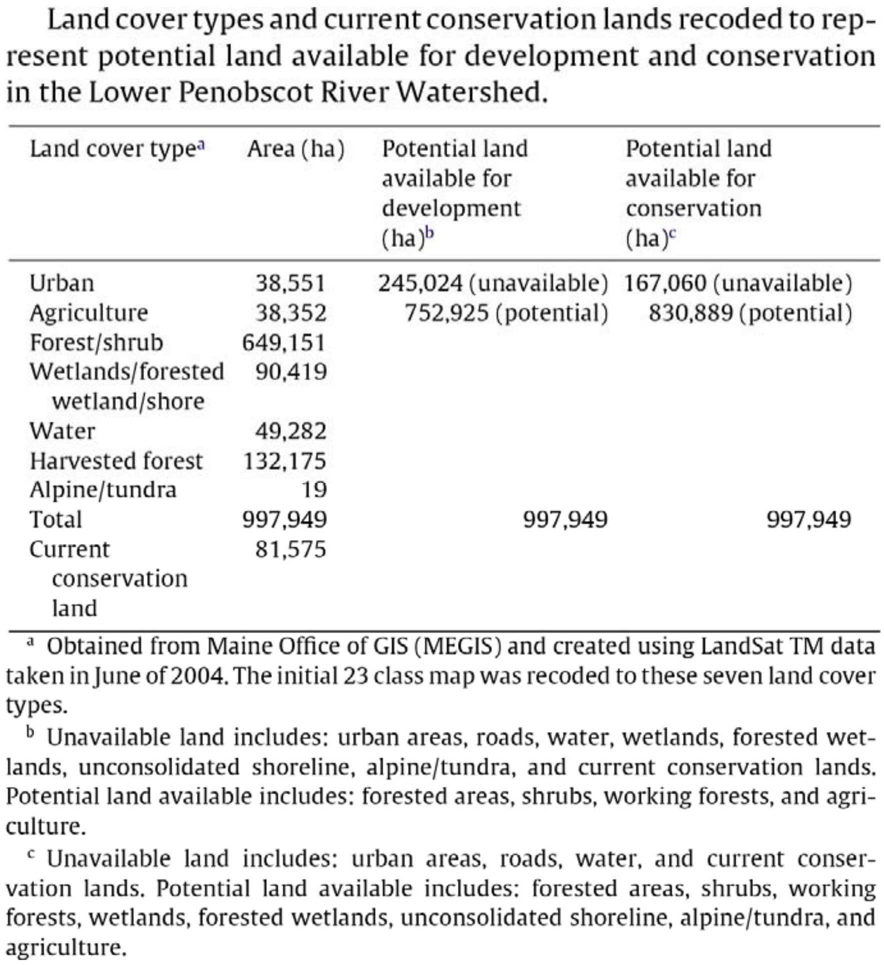
Appendix A.



Land cover types and current conservation lands recoded to represent potential land available for development and conservation in the Lower Penobscot River Watershed.

Land cover type[a]	Area (ha)	Potential land available for development (ha)[b]	Potential land available for conservation (ha)[c]
Urban	38,551	245,024 (unavailable)	167,060 (unavailable)
Agriculture	38,352	752,925 (potential)	830,889 (potential)
Forest/shrub	649,151		
Wetlands/forested wetland/shore	90,419		
Water	49,282		
Harvested forest	132,175		
Alpine/tundra	19		
Total	997,949	997,949	997,949
Current conservation land	81,575		

[a] Obtained from Maine Office of GIS (MEGIS) and created using LandSat TM data taken in June of 2004. The initial 23 class map was recoded to these seven land cover types.

[b] Unavailable land includes: urban areas, roads, water, wetlands, forested wetlands, unconsolidated shoreline, alpine/tundra, and current conservation lands. Potential land available includes: forested areas, shrubs, working forests, and agriculture.

[c] Unavailable land includes: urban areas, roads, water, and current conservation lands. Potential land available includes: forested areas, shrubs, working forests, wetlands, forested wetlands, unconsolidated shoreline, alpine/tundra, and agriculture.

Appendix B. - Bayesian belief network nodes and states used in the development and conservation land suitability model.

Node	Description	States
Development model		
Land availability	Unavailable land includes: urban areas, roads, water, wetlands, forested wetlands, unconsolidated shoreline, alpine/tundra, and current conservation lands. Available land includes: forested areas, shrubs, working forests, and agriculture	Unavailable, Available
Distance to road (m)	Close = 0–390 m; Moderate = 390–810 m; Far = beyond 810 m (Kocabas and Dragicevic, 2007)	Actual road, Close, Moderate, Far
Distance to urban centers (km)	Close = 0–1.6 km; Moderate = 1.6–4.8 km; Far = beyond 4.8 km (Kocabas and Dragicevic, 2007)	Actual Town Center, Close, Moderate, Far
Municipal property tax rate	High (>0.016); Moderately High (>0.013 and ≤ 0.016); Moderate (>0.0109 and ≤ 0.013); Low (≤ 0.0109) (Maine Revenue Office)	High, Moderately High, Moderate, Low
Distance to current conservation land (km)	Close = 0–1.6 km; Moderate = 1.6–4.8 km; Far = beyond 4.8 km (Brookings Institution, 2006)	Actual Conservation Land, Close, Moderate, Far
Distance to water (m)	Close = 0–810 m; Moderate = 810–1620 m; Far = beyond 1620 m (Brookings Institution, 2006)	Actual Water body, Close, Moderate, Far
Population	Bangor Metro includes Bangor and 13 surrounding towns; Large rural towns includes all towns with > 2000 people; Medium rural towns includes all towns between 500 and 2000 people; Small rural towns includes all towns with $\leq$500 people (U.S. Census Bureau, 2000)	Bangor Metro, Large rural, Medium rural, Small rural
Urban development pressure	We assume areas beyond 810 m from roads and 5 km from urban centers to be least suitable for urban development (Kocabas and Dragicevic, 2007)	High, Medium, Low
Urban suitability	Tax rate modifies urban development pressure by making areas with higher taxes less desirable for development and encouraging sprawl (Brookings Institution, 2006)	Suitable, Moderate, Low
Amenity-based development pressure	We assume areas beyond 5 km from current conservation land and 1620 m from large water bodies to be least suitable for amenity-based development	High, Medium, Low
Amenity-based suitability	Population modifies amenity-based development pressure by making areas that have more people, but are still not densely populated and close to recreational and employment areas, more suitable for amenity-based development	Suitable, Moderate, Low
Suitability	We assume that areas close to roads, urban centers, water, and current conservation land will be highly suitable for either urban or amenity-based development and weighted by tax rates and population	Suitable, Moderate, Low
Conservation model		
Land availability	Unavailable land includes: urban areas, roads, water, and current conservation lands. Available land includes: forested areas, shrubs, working forests, wetlands, forested wetlands, unconsolidated shoreline, alpine/tundra, and agriculture	Unavailable, Available
Distance to riparian areas (m)	Close = 0–120 m; Moderate = 120–300 m; Far = beyond 300 m (Briggs et al., 1998)	Actual Stream, Close, Moderate, Far
Distance to current conservation land (km)	Close = 0–1.6 km; Moderate = 1.6–4.8 km; Far = beyond 4.8 km (Brookings Institution, 2006)	Actual Conservation Land, Close, Moderate, Far
Large wetlands	All wooded and emergent wetland features in the LPRW greater than or equal to 20 acres	No, Yes
Beginning with Habitat (BWH)	Documented locations of rare plants, animals and natural communities, high quality common natural communities, significant wildlife habitats, and their intersection with large blocks of undeveloped habitat	No, Yes
Connectivity	We assume areas within 120 m from streams and 1.6 km from conservation land to be areas of greatest connectivity	High, Moderate, Low
Priority lands	Areas designated as a BWH Focus Area and wetlands $\geq$20 acres makes an area more suitable for future conservation land	No, Yes
Suitability	We assume that areas close to streams and current conservation land will be highly suitable for future conservation land as will BWH Focus Area and wetlands $\geq$20 acres	Suitable, Moderate, Low

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Figures

Fig. 1. Location of the Lower Penobscot River Watershed in Maine, USA.

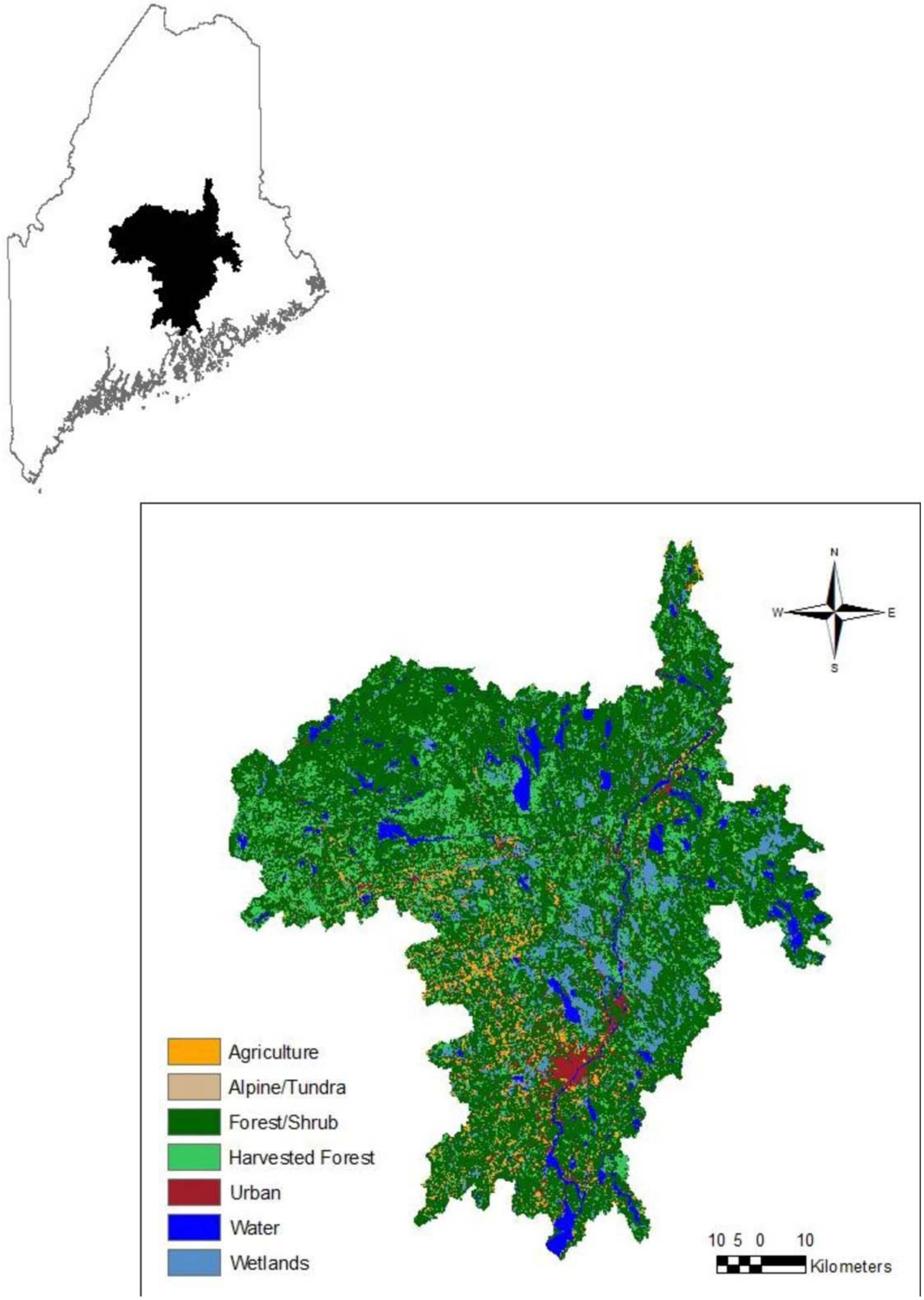

Fig. 2. Influence diagram showing key factors affecting urban and amenity-based development in the Lower Penobscot River Watershed.

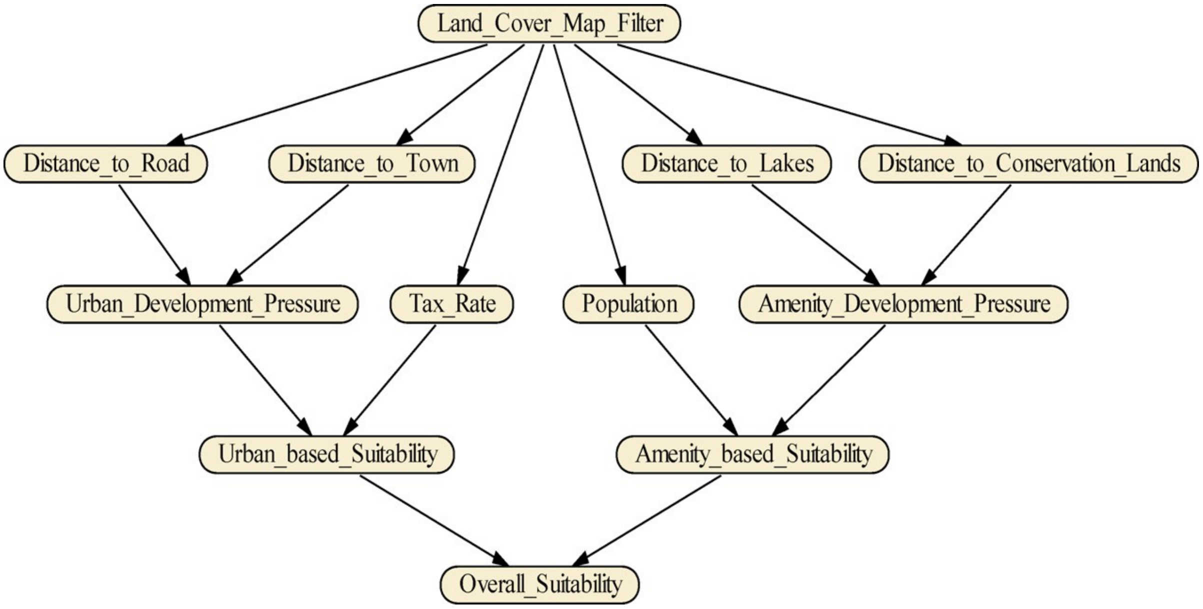

Fig. 3. Influence diagram showing key factors affecting connectivity to current conservation lands in the Lower Penobscot River Watershed.

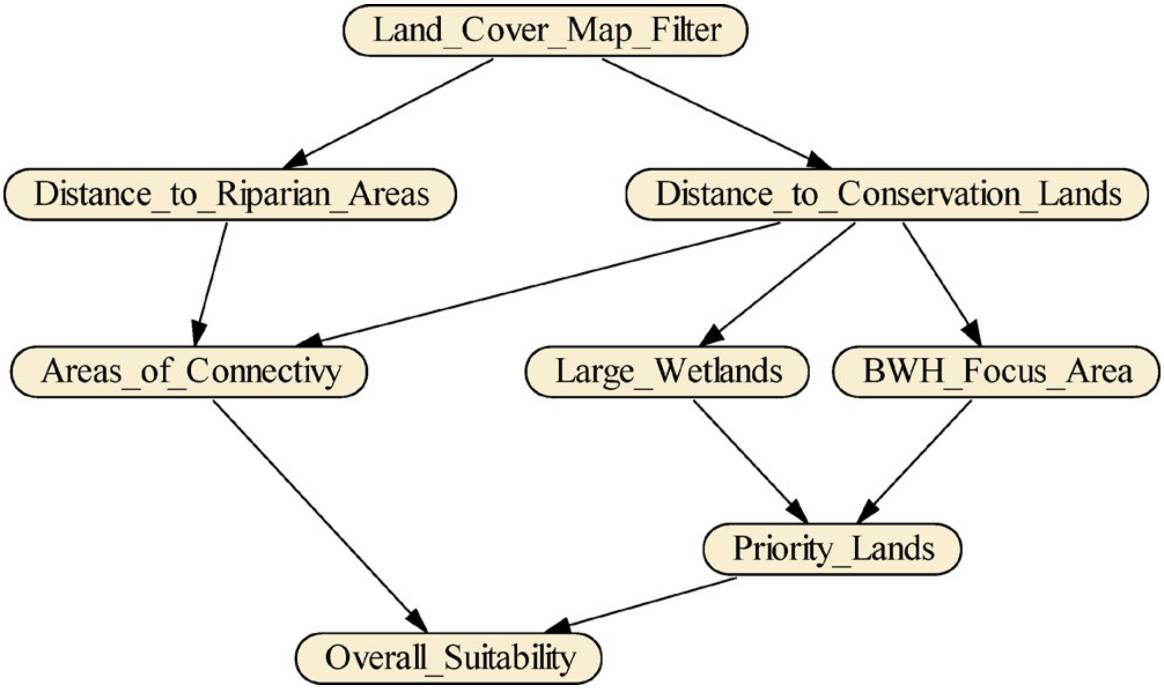

Table 1
Example of a conditional probability table for the development pressure node as filled-out using expert knowledge of how proximity to roads and urban centers influence development.

GIS layers		Expert knowledge[a]		
Distance to roads	Distance to town	High	Medium	Low
Close	Close	90	10	0
Close	Moderate	80	20	0
Close	Far	60	30	10
Moderate	Close	75	20	5
Moderate	Moderate	60	25	15
Moderate	Far	40	20	40
Far	Close	0	25	75
Far	Moderate	0	15	85
Far	Far	0	10	90

[a] Values sum to 100 across each row and represent the probability that a pixel that corresponds to the GIS layer criteria is suitable (High, Medium, Low) for development.

Table 2
Example of a conditional probability table for the conservation connectivity node as filled-out using expert knowledge of how areas close to streams and current conservation lands influence connectivity to current conservation lands.

GIS layers		Expert knowledge[a]		
Distance to streams	Distance to conservation land	High	Moderate	Low
Actual corridor	Close	100	0	0
Actual corridor	Moderate	90	10	0
Actual corridor	Far	0	20	80
Close	Close	100	0	0
Close	Moderate	90	10	0
Close	Far	0	20	80
Moderate	Close	90	10	0
Moderate	Moderate	80	20	0
Moderate	Far	0	10	90
Far	Close	80	20	0
Far	Moderate	0	60	40
Far	Far	0	0	100

[a] Values sum to 100 across each row and represent the probability that a pixel that corresponds to the GIS layer criteria is suitable (High, Medium, Low) for conservation land.

Fig. 4. The parameterized Bayesian belief network model for identifying areas suitable for commercial and residential development within the Lower Penobscot River Watershed. Black bars represent prior and conditional probabilities (Marcot et al., 2006). Grey boxes show a negative state finding that is represented as 0 percent probability for that state (see Section 2).

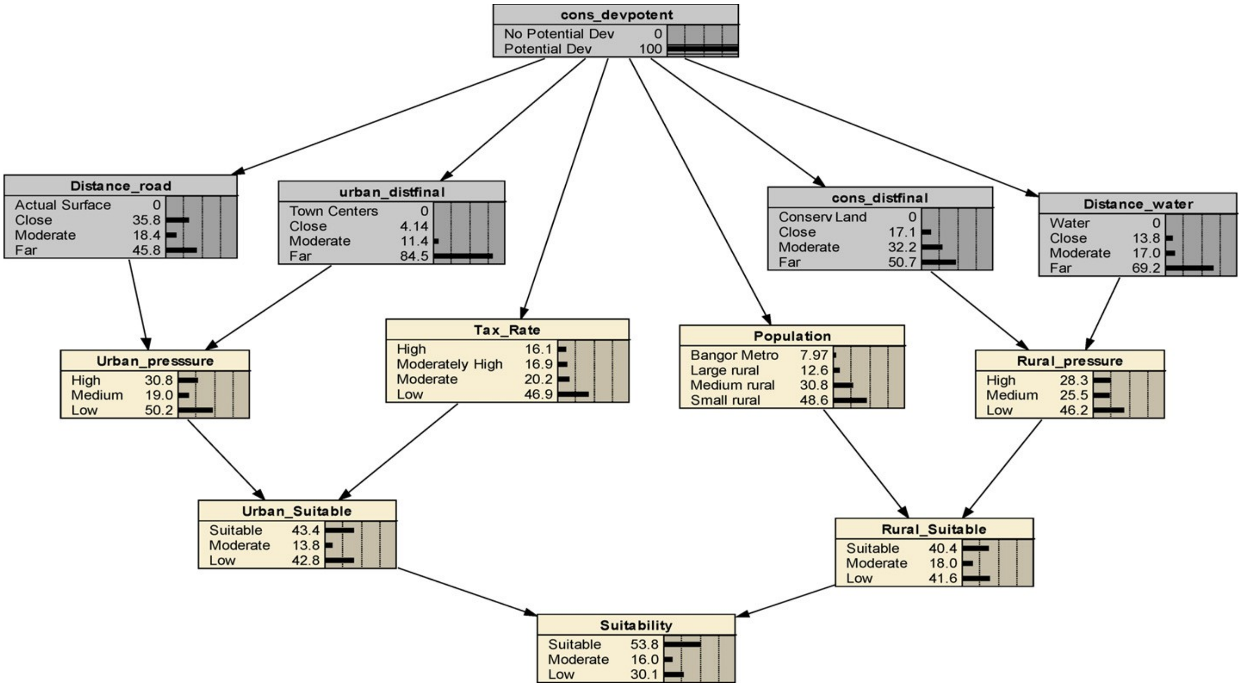

Fig. 5. The parameterized Bayesian belief network model for identifying areas of connectivity to current conservation lands within the Lower Penobscot River Watershed. Black bars represent prior and conditional probabilities (Marcot et al., 2006). Grey boxes show a negative state finding that is represented as 0 percent probability for that state (see Section 2).

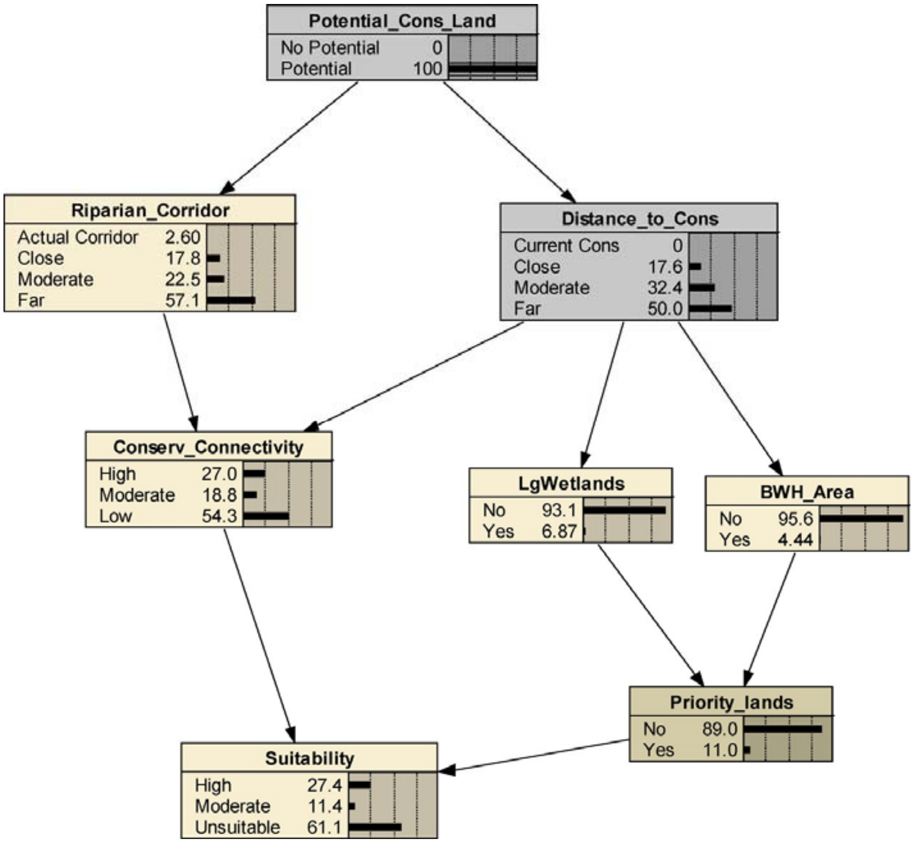

Table 3
Sensitivity analysis for development and conservation models (variables are listed in order of influence on suitability from most to least influential).

Node	Entropy reduction[a]
Development suitability	
Urban suitability	0.26594
Rural suitability	0.24024
Urban pressure	0.22190
Rural pressure	0.18485
Distance to roads	0.11759
Distance to water	0.05459
Distance to current conservation land	0.04288
Distance to town	0.00181
Tax rate	0.00161
Population	0.00021
Conservation suitability	
Connectivity	0.61447
Distance to current conservation land	0.34304
Priority lands	0.17462
Large wetlands	0.10302
Beginning with Habitat	0.06793
Distance to riparian areas	0.05006

[a] Calculated using entropy reduction analysis in Netica and after (Marcot et al., 2006).

Fig. 6. Map for the Lower Penobscot River Watershed showing the probability of an area being highly suitable for development (terms are defined in Section 2).

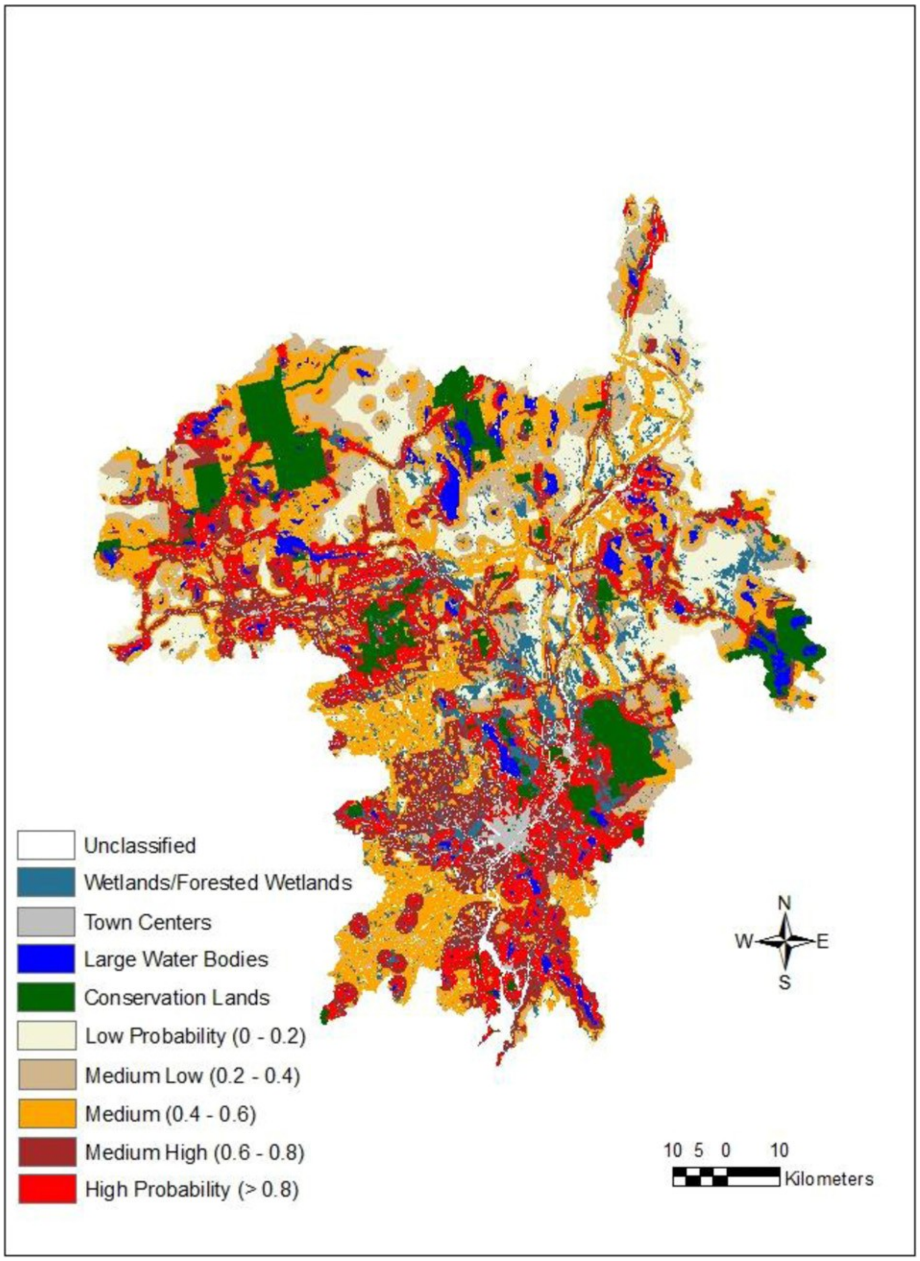

Fig. 7. Map for the Lower Penobscot River Watershed showing the probability of an area being highly suitable for future conservation land (terms are defined in Section 2).

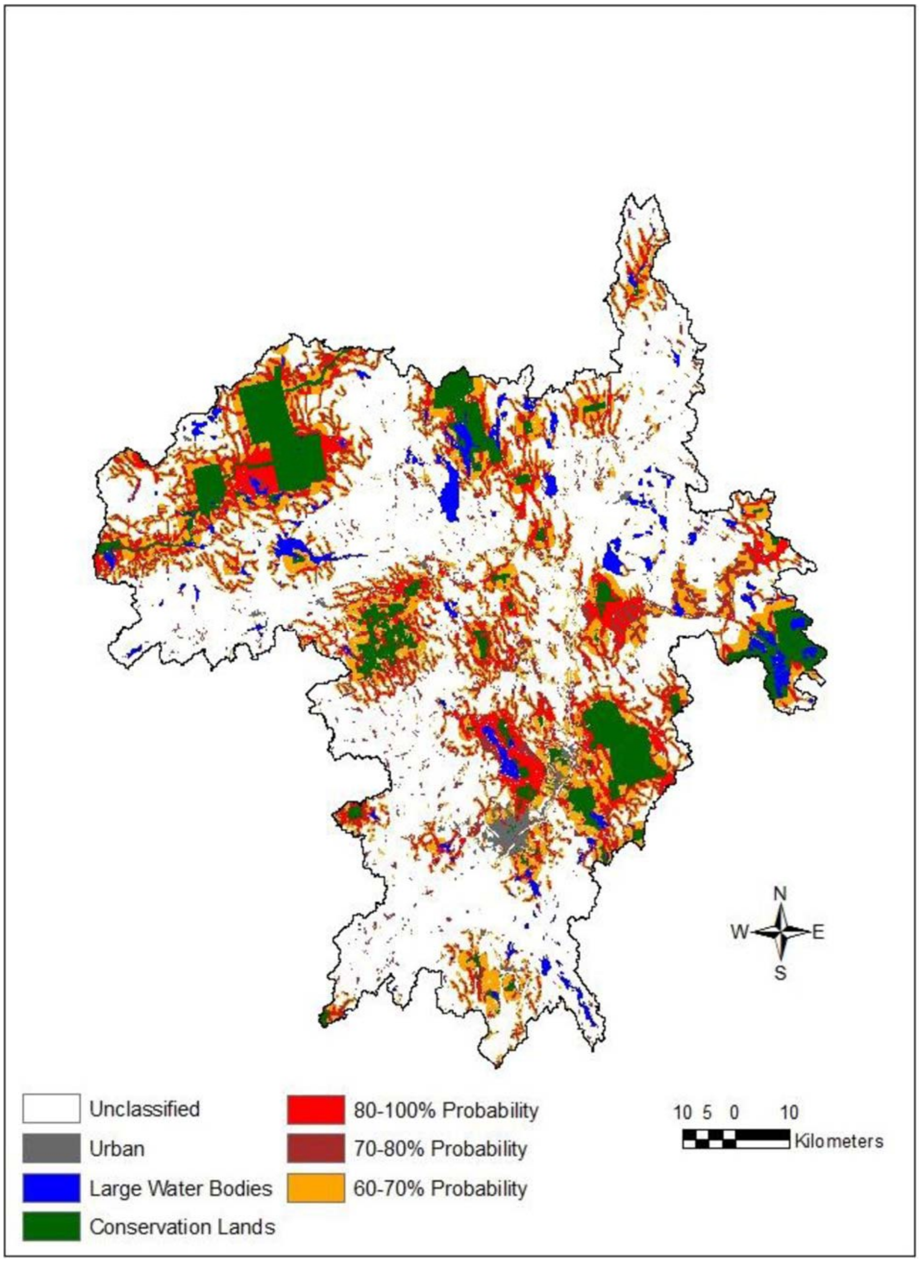

Fig. 8. The Lower Penobscot River Watershed showing areas of potential compromise and conflict between areas highly suitable for future development and conservation land.