Bayesian Network Decision Support for Multiple Models and Experts

New Methods to Mediate Contested Science for Ecosystem Services

The ocean and coastal waters of the world are critically important to the health and welfare of much of the world's population. These areas are also a complex interface of terrestrial, estuarine, coastal, and human systems that are increasingly facing human development pressures from use and urbanization (Millenium Ecosystem Assessment 2005). The sea and ocean provide a broad set of ecosystem services, though the marine environment is often solely viewed as a source of fishery production (Peterson and Lubchenco 1997). The implementation plan from the World Sustainable Development Summit focuses attention on this interface. The plan calls for an integrated approach to managing these areas to protect communities and the environment (United Nations 2002).

Problem of Combining Information and Values

The state of practice for CMSP for many governments is still an evolving arena. Several guides and publications from government agencies and non-governmental organizations have emerged to provide guidance (Ehler and Douvere 2009). Key to many of these is a call for integrated resource management, with intensive stakeholder involvement and science guided decision making (Allison, Lubchenco, and Carr 1998; Lubchenco 2010). However, resolving how to integrate these multiple values remains a challenge in implementation. Ecosystem services valuation approaches rely on different units of measure to allow for comparisons of tradeoffs. These include economic and non-economic models. This challenge often forces modelers to sacrifice the complexity and interconnected human and social nature of ecosystem services, undermining decision making (Fish 2011).

Barriers include conflicting and contested science that decision makers are unsure how to assemble. Additional barriers include the cognitive ability of participants to address multiple dimensions of information at once, and to synthesize it in decisions. Additionally, non-rational information is often included in decisions, and there are few ways to manages these pieces of information.

This poster tests a probabilistic model of ecosystem function and process responses to management. These functions and processes will be mapped to ecosystem services using a spatially explicit Bayesian decision support system. Bayesian models have been identified as important tools to bring different types of knowledge and data together to manage natural resources and to test various management choices (Glendining 2012; Haines-Young 2011; Walton and Meidinger 2006). There are some concerns in developing these models. Care must be taken not to overly simplify systems and underestimate feedback loops (Uusitalo, Kuikka, and Romakkaniemi 2005). The selection of a Bayesian based model is due to a survey of literature on decision-making and human cognitive abilities. The Bayesian models provide solutions to addressing complex interconnected problems. The goal of this poster is not to provide a new modeling tool, but rather a new decision support tool. The model outputs capture what a group may agree on, as opposed to how the underlying natural phenomenon operates.

Gray whale migration and forage habitat are used in this example. The whales provide an important year-round and seasonal attraction to Oregon State Parks and stimulate recreation and tourism spending. The whales are impacted by commercial shipping and fishing (Angliss and Allen 2007). The whales exist at a nexus between several important marine ecosystem services: recreation, fishing, shipping and now proposed ocean renewable energy development.

Methods

The example provided in this poster is based on three experts providing conflicting information in a decision making process. Each one is an expert on Gray whales off the Oregon Coast. Each expert has been tasked with aiding in planning protections for whales as well. For this example, the hypothetical experts are based on existing literature on Gray whale habitat and migration patterns. The first expert relies solely on bathymetric contours as the important area for whale migration protection. The second expert concurs on the depths, but also believes that distance from shore matters in the choices the whales make in migration. The third expert is focused not on migratory whales, but resident whales. This expert focuses on the forage opportunities for whales. Forage patterns are based on depth and substrate composition.

For the decision maker, the three experts provide differing opinions that are difficult to reconcile. This is a classic problem for environmental planning. To resolve the conflict, this poster details the application of a Bayesian Belief Net to assess, understand and work with conflicting opinions on environmental information.

Bayesian networks are acyclic conditional probability tools that attempt to replicate logic of systems and allow for analysis of interdependencies (Korb and Nicholson 2011). These nets run once for each question asked, and produce results measured in probabilities of various outcomes. The Bayes net for this project combines expert opinion and existing secondary data products allowing for a combination of qualitative and quantitative data. The Bayesian approach allows for various logics and understandings of ecological and social phenomenon to be combined. This example reflects a problem for ecosystem services management, combining contested information.

The study area is centered on Newport, Oregon. The study area extends north to Depoe Bay, approximately 22 km, and south to Waldport, approximately 24 km. The study area will also extends approximately 30 km out to sea from Newport. This study area was selected because it is centered on a key fishing and industrial port, and also includes many recreational and conservation priority areas north and south of Newport. The extent out to sea is set large enough to capture the three-mile state territorial sea defined in law, and the federal ocean area requires revenue sharing under energy development. This extent provides a diversity of ecological, economic and social factors to test various scenarios. The analysis was performed with spatial data at a 100m resolution. Using data from the State of Oregon's Territorial Sea Planning process. The Bayes belief nets were developed using Norsys's Netica software package. The nets were developed after a review of existing literature being used in the preparing process (Angliss and Allen 2007; Mate 2008; Newell 2009).

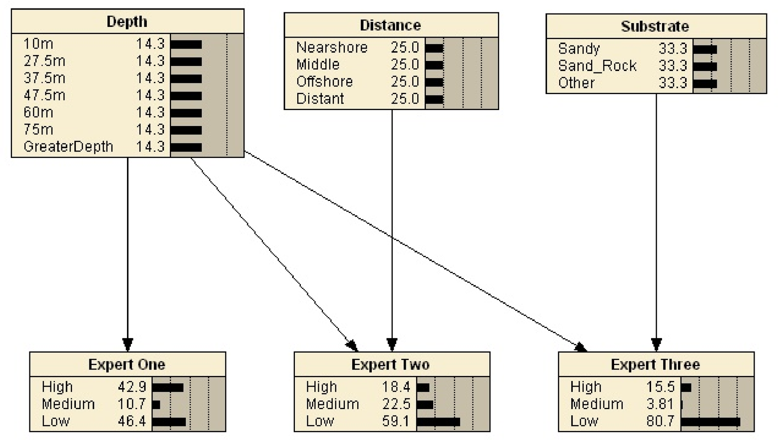

Figure 1: Base Model

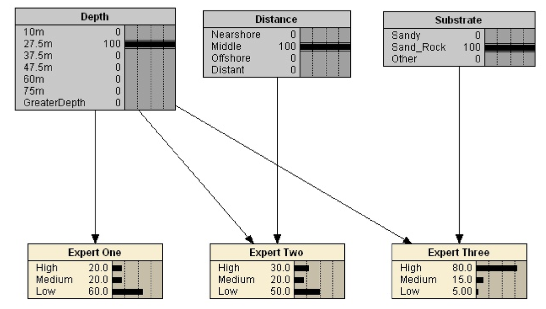

Figure 2: Adding Evidence

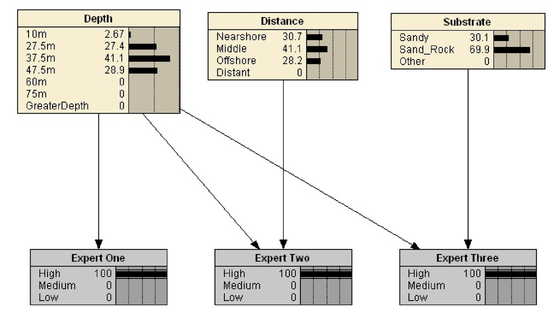

Figure 6: Conditions for Agreement

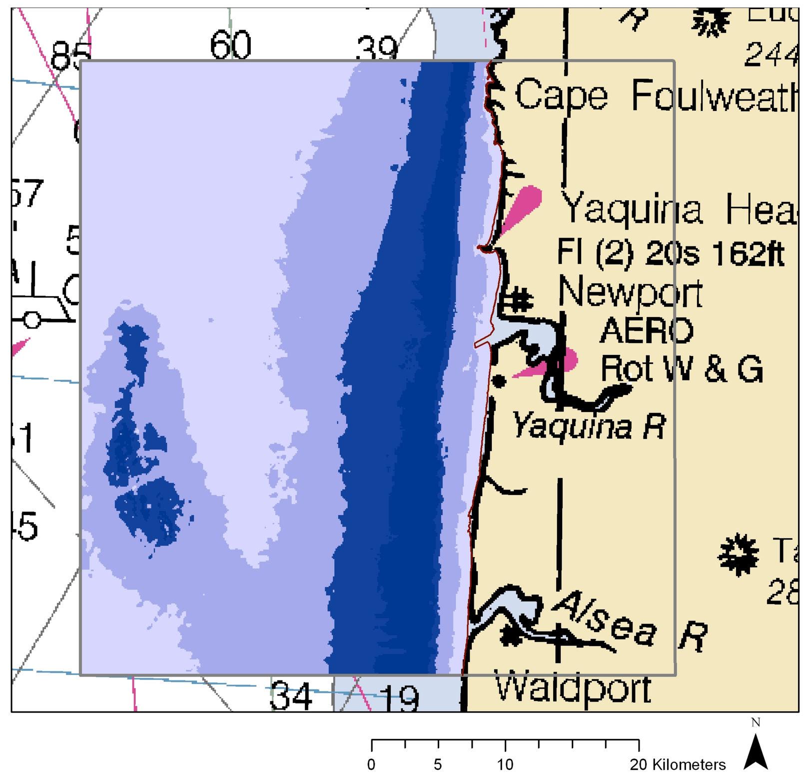

Figure 3: Expert One - Depth Model

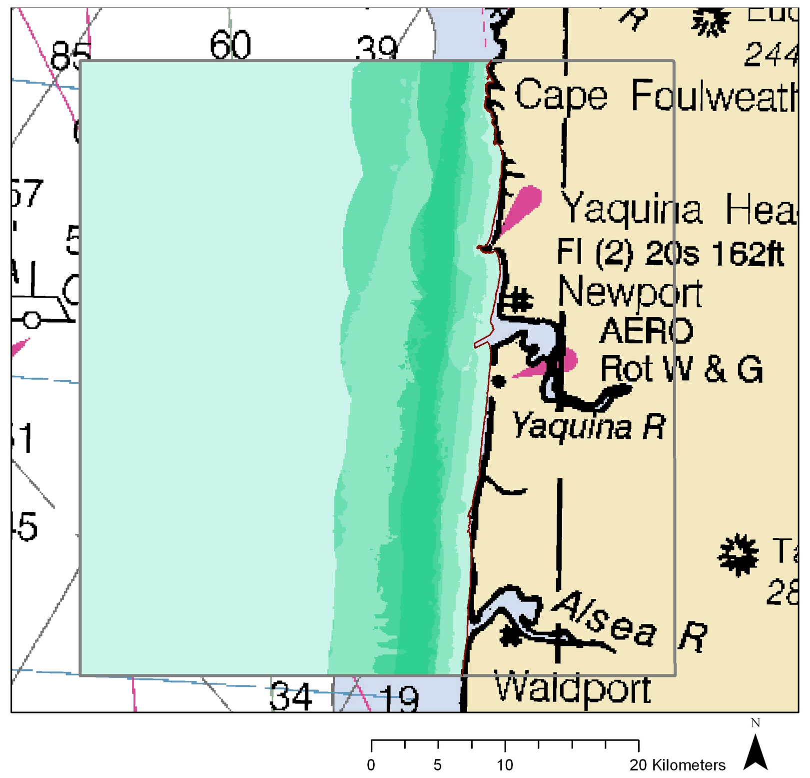

Figure 4: Expert Two - Depth and Distance Model

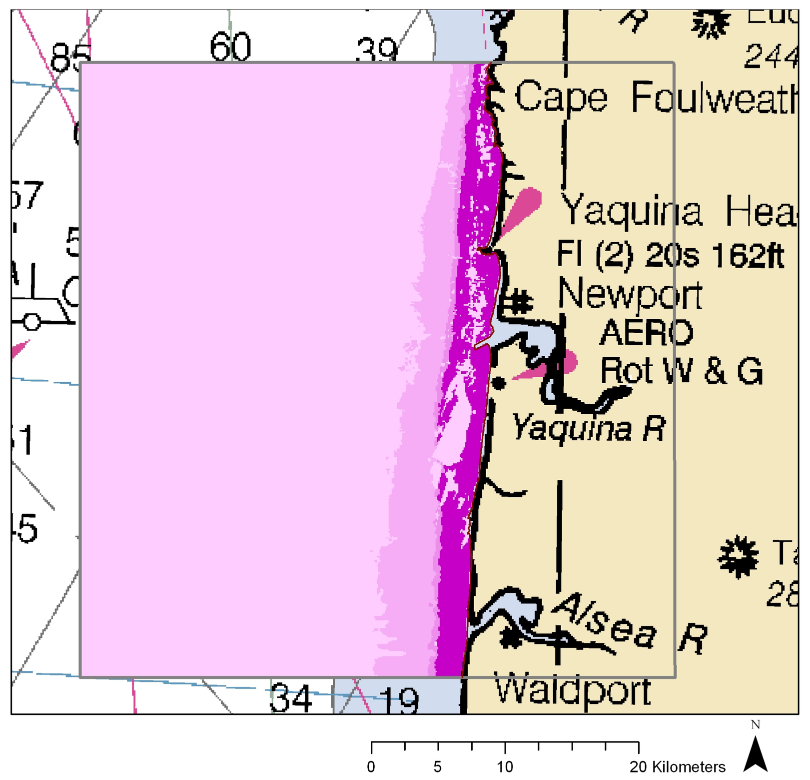

Figure 5: Expert Three- Forage Model

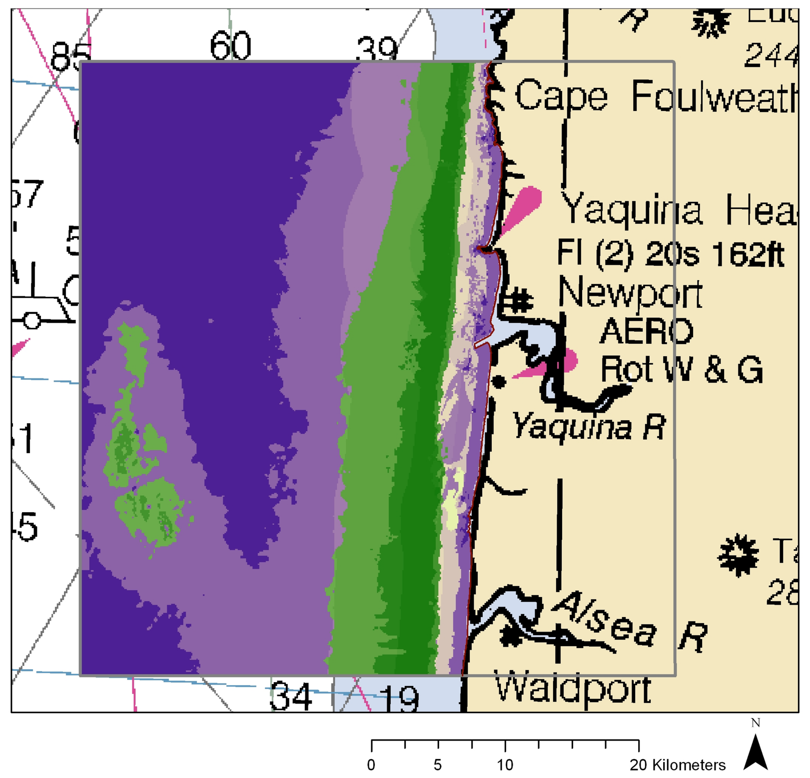

Figure 8: Spatial Agreement Output

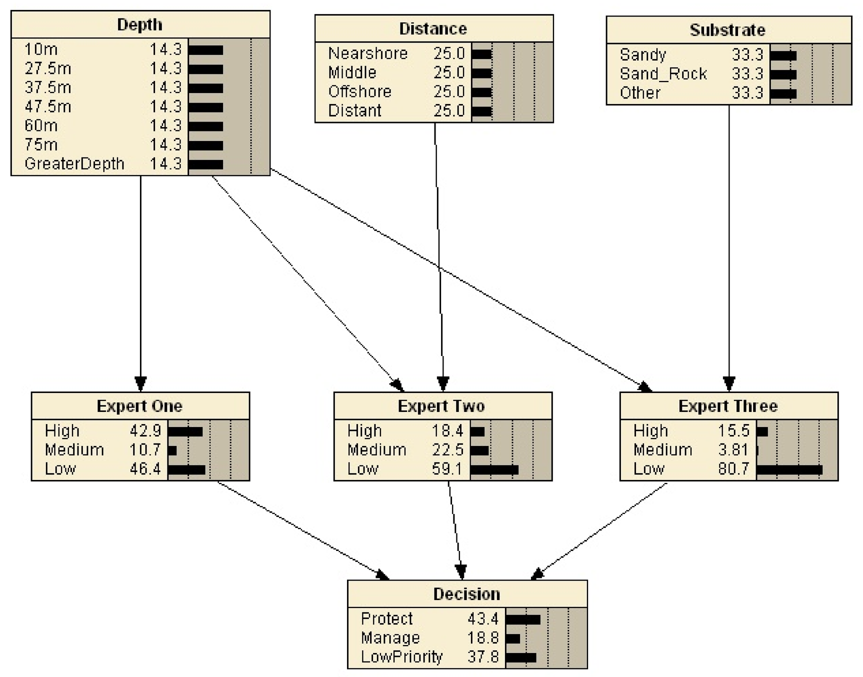

Figure 7: Agreement Based Model

Analysis

Figure 1 shows the base case model for the decision analysis. This is a Bayesian belief net and it shows the information included by each expert to make his or her assessment. The nets generate probabilities from conditional probability tables that are populated in consultation with the experts themselves. In this case, as a testing of the concept, the population of the table was done based on estimates provided in the published literature.

Using ArcGIS 10, the data was converted from raster datasets on a 100m grid to point estimates. 140,000-point observations were created for each of the three variables. Netica then processes the net for each case using the data from GIS to produce expected outcomes and probabilities. Figure 2 shows a sample case from one point. Using the case processing function, each expert's opinion is analyzed spatially. Figures 3 through 5 show the output of these experts opinion. The darker colors indicate areas where the expert most believes that high value habitat is present.

The immediate consequences of this first analysis are the difference of opinions on the ocean. An additional feature of using belief nets is the option to force agreement at the expert level and see how that propagates to the data. Figure 6 shows a scenario where all the experts are asked to agree on high values, and the distribution of the attributes is now displayed in the upper data nodes. This distribution suggests a possible solution set exists. To discover it a new net is developed to assess the experts' conclusions.

Figure 7 shows an expanded net that now has a new decision node at the bottom. This node incorporates all possible combinations of expert opinions and connects them with the decision to protect, manage or lower the priority of an area offshore. The protection decision is based on higher probabilities from all of the experts that the habitat is important. The management decision suggests some uses or development are more compatible with Gray whale use. Low priority areas are those that are not expected to be important to the animals.

Reprocessing the GIS data provides a new spatial representation of agreement. There is a 75% level of agreement in the best case. This suggests that some more work is needed to reach full agreement, but in the meantime a higher level of agreement is able to move the decision forward. Figure 8 provides the spatial outputs and shows high agreement in green for areas in need of protection.

Conclusions

Ecosystem services face the challenge of reaching acceptance as a valid scientific tool before managers and decision makers will accept it. It has been observed that the drive to come to a final single model for ecosystem services has limited progress as it oversimplifies or confuses data users (Daily et al. 2009; Norgaard 2010; Vira and Adams 2009). In marine systems ecosystem services provide an opportunity to resolve conflicts over public goods that have extensive dependencies across communities. Looking for the underlying functions and processes of ecosystem services is proposed as the most effective path forward for management choices (Granek et al. 2010).

Methods to deliberately and rigorously resolve scientific conflict in ecosystem services still need to be developed. This poster details one proposed method for handling differing expert opinion. Through the application of Bayesian belief nets (BBN), differing expert opinion on natural systems can be measured and understood for making decisions. It provides a model that can be transferred to other applications. It also provides the option of moving ecosystem services decision away from strictly valuation ones and into more satisfying models of decision-making.

These Bayesian based models allow for values to be managed at the core elements such as ecosystem functions and processes. The models then allow for analysis of the interaction of differing views and opinions before reaching complete scenarios. This increases the awareness among participants of how their understandings influence others, how data changes elements of their views, and how the final outcome may or may not depend on this information.

References

Allison, Gary W., Jane Lubchenco, and Mark H. Carr. 1998. "Marine reserves are necessary but not sufficient for marine conservation." Ecological Applications 8(sp1): S79–S92.

Angliss, R. P., and B. M. Allen. 2007. Marine Mammal Stock Assessment Report: Gray Whale: Eastern North Pacific Stock. National Oceanic and Atmospheric Administration. http://www.nmfs.noaa.gov/pr/sars/species.htm (Accessed March 12, 2011).

Daily, Gretchen C. et al. 2009. "Ecosystem services in decision making: time to deliver." Frontiers in Ecology and the Environment 7(1): 21–28.

Ehler, Charles N., and Fanny Douvere. 2009. Marine Spatial Planning: A Step by Step Approach Toward Ecosystem-based Management. Paris: Intergovernmental OceangraphicCommission and Man and the Biosphere Programme. IOC Manual and Guides.

Ellison, Aaron M. 1996. "An Introduction to Bayesian Inference for Ecological Research and Environmental Decision-Making." Ecological Applications 6(4): 1036–1046.

Fish, Rob D. 2011. "Environmental decision making and an ecosystems approach." Progress in Physical Geography 35(5): 671 –680.

Gigerenzer, Gerd, and Ulrich Hoffrage. 1995. "How to improve Bayesian reasoning without instruction: Frequency formats." Psychological Review 102(4): 684–704.

Glendining, N. 2012. "Development of Bayesian Network Decision Support Tools to Support River Rehabilitation Works in the Lower Snowy River." Human and Ecological Risk Assessment 18(1): 92–114.

Granek, Elise F. et al. 2010. "Ecosystem Services as a Common Language for Coastal Ecosystem-Based Management." Conservation Biology 24(1): 207–216.

Haines-Young, Roy. 2011. "Exploring ecosystem service issues across diverse knowledge domains using Bayesian Belief Networks." Progress in Physical Geography 35(5): 681–699.

Korb, Kevin B., and Ann E. Nicholson. 2011. Bayesian Artificial Intelligence. New York: CRC Press.

Lubchenco, Jane. 2010. "Changing course: A proposed Framework for Coastal and Marine Spatial Planning in the United States." National Wetlands Newsletter32(4): 4–7.

Mate, Bruce. 2008. Distribution and movement patterns of gray whales off central Oregon: Shore-based observations from Yaquina Head during the 2007/2008 migration. Oregon Wave Energy Trust.

van Merriënboer, Jeroen J. G.Sweller. 2010. "Cognitive load theory in health professional education: design principles and strategies." Medical Education 44(1): 85–93.

Miettinen, Reijo, and Jaakko Virkkunen. 2005. "Epistemic Objects, Artefacts and Organizational Change." Organization 12(3): 437–456.

Millenium Ecosystem Assessment. 2005. Ecosystems and Human Well-Being: Current State and Trends. Washington, DC: Island Press. http://www.maweb.org/en/Condition.aspx.

Miller, George. 1955. "The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information." Psychological Review 101(2): 343–52.

Newell, Carrie. 2009. "Ecological Interrelationships Between Summer Resident Gray Whales (Eschrichtius robustus) and Their Prey, Mysid Shrimp (Holmesimysis sculpta and Neomysis rayi) along the Central Oregon Coast." Master of Science Thesis. Oregon State University. http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/14583/CarrieNewell2010.pdf.

Norgaard, R.B. 2010. "Ecosystem services: From eye-opening metaphor to complexity blinder." Ecological Economics 69(6): 1219–1227.

Peterson, Charles H., and Jane Lubchenco. 1997. "Marine Ecosystem Services." In Nature's Services: Societal Dependence on Natural Ecosystems, ed. Gretchen C Daily. Washington, DC: Island Press.

United Nations. 2002. World Summit on Sustainable Development: Plan of Implementation. New York. http://www.un.org/esa/sustdev/documents/WSSD_POI_PD/English/WSSD_PlanImpl.pdf.

Uusitalo, Laura, Sakari Kuikka, and Atso Romakkaniemi. 2005. "Estimation of Atlantic salmon smolt carrying capacity of rivers using expert knowledge." ICES Journal of Marine Science / Journal du Conseil 62(4): 708–722.

Vira, Bhaskar, and William M. Adams. 2009. "Ecosystem services and conservation strategy: beware the silver bullet." Conservation Letters 2: 158–162.

Walton, Adrian, and Del Meidinger. 2006. "Capturing expert knowledge for ecosystem mapping using Bayesian networks." Canadian Journal of Forest Research36(12):

Paul Manson

Fellow, NSF IGERT - Ecosystem Services for Urbanizing Regions
PhD Student, Hatfield School of Government
Portland State University

mansonp@pdx.edu
(503) 804-1645

http://web.pdx.edu/~mansonp/

This material is based upon work supported by National Science Foundation IGERT Grant #0966376: "Sustaining Ecosystem Services to Support Rapidly Urbanizing Areas.