TITLE: A model to explore the tradeoff between the status of biodiversity and gas development through the optimal placement of gas surface infrastructure.

INTRODUCTION: The boom of below-ground natural gas development in the Central Appalachians is bringing with it significant aboveground infrastructure development. This poses a potentially large threat to terrestrial and freshwater species in one of the world's most biologically diverse areas (Stein et. al. 2000). Since the rise of natural gas in this region has been rapid, we know little about the factors governing surface infrastructure development or how biodiversity will respond.

Current natural gas regulations provide minimal protection for biodiversity, so the power to reduce impacts from future surface infrastructure development is largely in the hands of gas companies. Some companies are willing to go beyond compliance to further reduce impacts from their development (e.g. Chesapeake Energy, Triana Energy, Range Resources, EQT, *pers. comm.*). As such, the research I propose here takes the perspective of an environmentally conscientious gas infrastructure planner.

Conservation planners traditionally have attempted to address 'Where to protect?' However, the 'Where to condemn?' paradigm adopted here is closer to that faced during development. In the context of placing gas surface infrastructure – well pads, roads, and pipelines – deciding where to condemn creates an interesting mathematical/computational/biological problem with unknown implications for species and habitats in the Central Appalachians.

PROPOSED RESEARCH: I propose to build a model that estimates the response of biodiversity to alternative configurations of natural gas surface infrastructure. The model will take the perspective of an environmentally conscientious, optimizing gas infrastructure planner. Geologic and monetary considerations restrict potential locations of infrastructure. But there is some flexibility, and this flexibility increases as the planner invests more money in development, e.g. by allowing a longer road that circumvents a wetland rather than running through it. The objective of the optimizing planner is thus to minimize cumulative impacts on biodiversity at a fixed development cost. By incrementing the fixed cost of development, I can introduce greater flexibility into the planning process. Subsequently, I will be able to address the following questions:

1) How do indicators of the condition of biodiversity respond if gas developers do no more than comply with regulation (as has been the case to date)?
2) How do indicators of the condition of biodiversity respond if developers are willing to invest as much as needed in order to globally minimize impacts?
3) How do indicators of the condition of biodiversity change as gas developers increase their commitment to reducing potential impacts?

What makes this research interesting?

Biodiversity may respond nonlinearly to disturbance by linear features. For example, the baseline mobility of a species in a forest patch may not change greatly when that patch is partially penetrated by a road. This may continue until the road cuts the patch in two, at which point movement across the patch is impossible, one population becomes two, and each population is at increased risk of further impacts (Jaeger 2005). Biodiversity may also respond nonlinearly to areal disturbances. Placing a single well pad (~3 acres) in a developed area may result little or no effect on biodiversity. Conversely, the negative effect would be large if that same well pad was placed in critical habitat for a rare species.

The response of biodiversity to a single piece of surface infrastructure cannot be determined independently of all other pieces of infrastructure. For instance, the optimal location of a well pad in a forest patch will depend on the incision effect created by that pad's access road. Alternatively, the optimal path of a road will depend on whether the well pad displaces an endangered species' population. And because well pads must be spaced on the landscape but may share connecting infrastructure, the optimal location of one well pad depends on impacts from all other well pads.

An impact-minimizing configuration of infrastructure requires that all pieces be placed simultaneously. The problem outlined here is nonlinear in both cost and constraint and contains both linear and point/polygon features. Such research, to my knowledge, has not been attempted before. Once completed, it will be applicable to understanding biodiversity impacts from energy infrastructure placement more generally.

OBJECTIVES:

Objective 1: Program the infrastructure placement model.

Creation of the proposed model can be broken into several parts.

PART 1: The first part is to define the parameters of the model. I have already determined the major data-dependent parameters of the model and am in the process of gathering needed data. Indicators of the condition of biodiversity will include

a) fragmentation statistics: 1) forest patch-to-area ratio as a measure of edge complexity, and 2) effective mesh size (Jaeger 2000), which is analogous to average patch size (data to come from The Nature Conservancy of Pennsylvania [TNC PA] and public sources)
b) direct loss of habitat (e.g. forest, wetland) and 'high quality habitats' as defined by TNC PA (data to come from TNC PA and public sources)
c) proximity to streams as a measure of probability of impact on freshwater species (data to come from public sources)
d) proximity to known locations of threatened/rare species as a measure of probability of impact on those species (data to come from the Pennsylvania Natural Heritage Program)

Estimations of development cost will include those for building well pads, roads, and pipelines in various landscape contexts (e.g. through a forest vs. a field, high vs. low slope, etc.). This data is currently being gathered from four gas companies active in Pennsylvania. I currently have enough cost information to proceed with this project, but am pursuing more. Also used in determining the costs and constraints of infrastructure placement will be lease-hold boundaries, land cover, elevation, existing roads, setback requirements, and existing infrastructure.

PART 2: Once the model inputs have been defined, the next step is to code the placement of drainage units within a lease-hold. A drainage unit is a polygon defining the area of gas that will be extracted by the wells on a single pad. Developers follow a ‘no gas left behind’ policy, which means that as much gas must be extracted as possible. This leaves no room for reducing impacts on biodiversity. As such, this part of the model can be formulated as a packing problem in which the objective is to pack as many rectangles of identical dimension and orientation as possible into a polygon composed of several polynomial functions (Figure 1). I am considering a range of approaches to this problem, including branch and bound (e.g. Birgin and Lobato 2010) and more general heuristics (e.g. Cassioli and Locatelli 2010).

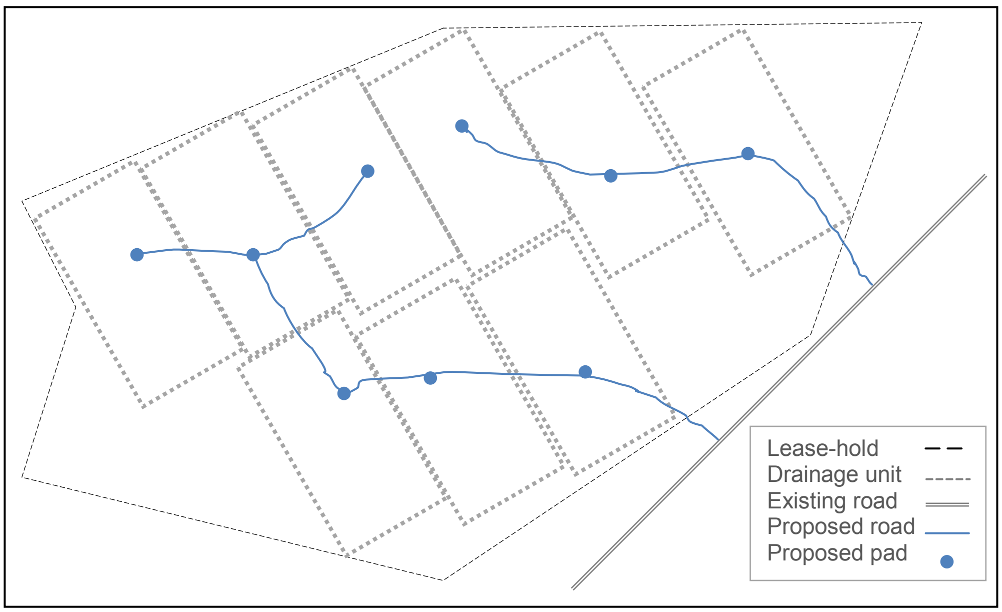

Figure 1. Hypothetical example of the infrastructure siting process. A maximum number of drainage units of equal dimensions and orientation are packed into the lease-hold. Proposed well pad locations and access road paths are connected to existing infrastructure.

PART 3: Conceptually more difficult than Part 2 is simultaneously placing all infrastructure pieces, because the optimal placement of each piece is dependent on all other pieces and because the model combines linear and point/polygon pieces (Figure 1). I have not yet identified the approach I will take to solve this problem. One possibility is to use a spatial branch and bound where drainage units are divided into sections, the minimum and maximum bounds (of biodiversity impacts) are approximated linearly, and this is used to eliminate potential areas of the drainage units for placing well pads.

The objective function will be a linear combination of the indicators identified in Part 1. I will explore different weighting schemes for this function, namely 1) all weights equal, 2) all weight in one category, and 3) weights determined by environmental stakeholders.

Objective 2: Execute and analyze the model.

Pennsylvania is where the majority of Appalachian gas development to date has occurred, so it makes for an excellent case study. The Pennsylvania data I am collecting will be used to parameterize the model and answer Questions 2 and 3. Further, to answer my first proposed research question, I will estimate the impacts from historical gas development in Pennsylvania. This will also provide a baseline for estimating the potential biodiversity benefit from increasing the flexibility of infrastructure planning.

The infrastructure placement model built in Objective 1 will find an impact minimizing configuration of infrastructure *at a fixed cost.* In order to answer my first proposed question, I will run the model at many incremental fixed costs. By doing so, I will be able to statistically estimate the tradeoff between increasing flexibility and reduced impacts (e.g. Figure 2).

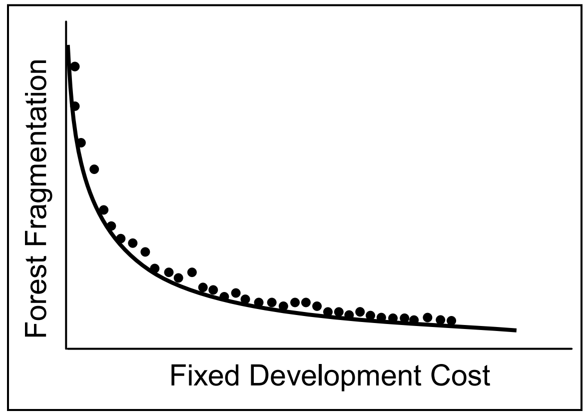

Figure 2. Hypothetical response of forest fragmentation to incremented fixed development costs. The curve estimates the minimum achievable forest fragmentation.

Finally, by setting the fixed bound of development cost very high, I will show how biodiversity may have responded to an overriding commitment to avoiding potential impacts (Question 2).

Objective 3: Report in a publication and to a broader audience.

The model proposed here, its implications for biodiversity in the Central Appalachians, and its potential to influence the trajectory of gas development should be of great interest to the scientific community. It is already of great interest to conservation groups, gas developers, and regulators (TNC, Delaware River Basin Commission, four gas companies, *pers. comm.*). I plan to publish the results from this work as a single manuscript in PNAS and as a chapter in my dissertation. Further, the model will be built in parallel with a tool targeted at natural gas developers. The tool will contain the model proposed here. It will be used by gas developers in their early infrastructure planning stages to reduce potential impacts I have identified, as well as other impacts defined by conservation groups and state agencies with which I am collaborating.

References

Birgin, E.G. and Lobato, R.D. (2010): Orthogonal packing of identical rectangles within isotropic convex regions. – Computers & Industrial Engineering 59: 595-602

Cassioli, A. and Locatelli, M (2010): A heuristic approach for packing identical rectangles in convex regions. – Computers & Operations Research 38: 1342-1350

Jaeger, J.A.G. (2000): Landscape division, splitting index, and effective mesh size: New measures of landscape fragmentation. – Landscape Ecology 15(2): 115–130

Jaeger, J.A.G., Holderegger, R. (2005): Thresholds of landscape fragmentation (in German; Schwellenwerte der Landschaftszerschneidung). – GAIA 14(2): 113-118.

Stein, B.A., Kutner, L.S., and Adams, J.S. (2000): *Precious Heritage: The Status of Biodiversity in the United States*. Oxford University Press.

A description of mathematical and computational skills that are relevant to work in the NIMBioS environment (e.g. experience developing or analyzing mathematical models; proficiency with mathematical software such as MATLAB, Mathematica, or R; programming experience; experience with cluster or large parallel computers, etc.)

- Recently (Fall 2011-current), I have been working on a spatially explicit population dynamics model to explore the consequences of cross-scale species interactions. It is common for interacting species to perceive the environment at different spatial scales, but these scale disparities are rarely addressed in ecological models. I am one of two working on this project; the other is Christine Dumoulin. My main responsibilities have been to propose and review functional forms of population processes (e.g. prey growth), to research and propose ways to quantify the structural similarities of multiple lattices/matrices, to program parts of the model in MATLAB, and to optimize this code.

- In 2007 and 2009 I applied a spatial ozone model (OZIPW) to modeling the effects of increasing biofuel use on ground level ozone formation. This included becoming familiar with the mathematics underlying the model and analyzing time-series outputs. I also wrote MATLAB scripts to automate some of the data preparation and analysis. See Milt, A.W., Milano, A., Garivait, S., Kamens, R. Effects of 10% biofuel substitution on ground level ozone formation in Bangkok, Thailand. Atmospheric Environment. Volume 43, Issue 37, Pages 5962-5970.

- In 2008 I developed a reserve design model that uses a genetic algorithm to optimize a reserve network for multiple spatial criteria. This project was coded and analyzed in MATLAB. It also required me to derive formulae for upper and lower bounds of each of the spatial criteria.

- In 2008-2010 I worked as research technician on paleoclimate modeling. My main responsibilities were to manage, visualize, and analyze time-series outputs from climate models of intermediate complexity. The vast majority of these tasks were done by writing scripts from scratch. I wrote MATLAB scripts to download time series data from a remote server, and to visualize time-series data in both static and movie formats. I wrote Perl and Python scripts to manage and extract specific information from large (>500 MB) data files, including ASCII and NetCDF formats. I also gained skills in working on UNIX systems and writing and running shell scripts in UNIX. This work also required me to run several existing climate models on medium sized, remote clusters.

- In 2009-2010 I worked on habitat modeling for Red-cockaded Woodpeckers. As part of this work, I developed an ArcGIS toolbox that integrates three modeling packages in a single workflow. This work required me to learn Python and ArcGIS, including geoprocessing scripting and tool development. See http://www.unc.edu/depts/geog/lbe/Connect/. I also programmed a gradient-climber to search for optimal thresholds of habitat classification in maxent outputs.

- In 2011 I developed software that creates binary matrices of fixed nestedness specifically for use in biology and conservation applications. It uses a heuristic search optimization (GA). This work has been presented at two conferences and is being prepared for publication in Ecography.

- I am proficient in MATLAB and Python, and I have some experience with Perl, C++, PHP, and Fortran. I have a little experiencing with cluster computing and parallel computing.

A description of biological background that is relevant to the activities at NIMBioS (e.g. field or laboratory experience, prior research activities in biology, biological modeling experience, workshops or courses attended, etc.)

- For the first chapter of my dissertation I have been looking at how additional surveys for rare species change our conservation priorities. This project is relevant to NIMBioS because it involves the use of a large species distribution dataset, an important component of biodiversity conservation, and immediately applicable to parameterizing biological models the deal with the spatial distribution of species. I have spent much time programmatically parsing the dataset, standardizing it for use in mine and other models, and removing erroneous data. This project is also relevant to NIMBioS because I have coded a genetic algorithm to solve the maximal species coverage problem for this data. Work with binary matrices and nonlinear optimization is well known at NIMBioS.

- In addition to the activities listed above, I have spent 6 weeks as a field technician for research on the effects of resource limitation on the morphology of bird bills.

part f)

Display Academic History

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This is academic history information. Courses which are in progress may also be included on this history.

Institution Credit Transcript Totals Courses in Progress

Transcript Data

STUDENT INFORMATION

Birth Date:	27-MAR
Student Type:	Returning

Curriculum Information

Current Program

Doctor of Philosophy

Program:	Ecol Evolut Biol-Ecology
College:	Arts and Sciences
Major and Department:	Ecology/Evolutionary Biology, Ecology/Evolutionary Biology
Major Concentration:	Ecology

***Transcript type:AHR Academic History is NOT Official ***

INSTITUTION CREDIT -Top-

Term: Fall Sem 2010

College:	Arts and Sciences
Major:	Ecology/Evolutionary Biology
Academic Standing:	Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	R
EEB	484	GR	Conservation Biology	A	3.000	12.00	
EEB	503	GR	Ecology/Evolution Biol Seminar	S	1.000	0.00	
EEB	511	GR	Core: Evolution	B	4.000	12.00	
EEB	560	GR	Biometry	A	3.000	12.00	
EEB	607	GR	Sem: Ecology/Evolutionary Biol	A	1.000	4.00	

Term Totals (Graduate)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	12.000	1.000	11.000	11.000	40.00	3.64
Cumulative:	12.000	1.000	11.000	11.000	40.00	3.64

*****Academic History*****

Term: Spring Sem 2011

College: Arts and Sciences
Major: Ecology/Evolutionary Biology
Academic Standing: Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	R
COSC	594	GR	Intro Program Scient Engineer	A	3.000	12.00	
EEB	503	GR	Ecology/Evolut Biol Seminar	S	1.000	0.00	
EEB	504	GR	Special Topics	S	1.000	0.00	
EEB	509	GR	Core: Ecology	A	4.000	16.00	
LFSC	593	GR	Independent Study	A	1.000	4.00	

Term Totals (Graduate)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	10.000	2.000	8.000	8.000	32.00	4.00
Cumulative:	22.000	3.000	19.000	19.000	72.00	3.79

*****Academic History*****

Term: Summer - Mini Term 2011

College: Arts and Sciences
Major: Ecology/Evolutionary Biology
Academic Standing: Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	R
FWF	590	GR	Model Methods Systems Ecology	A	3.000	12.00	

Term Totals (Graduate)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	3.000	0.000	3.000	3.000	12.00	4.00
Cumulative:	25.000	3.000	22.000	22.000	84.00	3.82

Academic History

Term: Summer Sem 2011

College: Arts and Sciences
Major: Ecology/Evolutionary Biology
Academic Standing: Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	R
LFSC	593	GR	Independent Study	A	3.000	12.00	

Term Totals (Graduate)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	3.000	0.000	3.000	3.000	12.00	4.00
Cumulative:	28.000	3.000	25.000	25.000	96.00	3.84

Academic History

Term: Fall Sem 2011

College: Arts and Sciences
Major: Ecology/Evolutionary Biology
Academic Standing: Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	R
AREC	505	GR	Microeconomic Analysis	A	3.000	12.00	
COSC	554	GR	Markov Chains/Computer Science	A	3.000	12.00	
EEB	503	GR	Ecology/Evolut Biol Seminar	S	1.000	0.00	
EEB	593	GR	Independent Study	A	1.000	4.00	
EEB	606	GR	Adv Top: Conservation Biology	A	1.000	4.00	

Term Totals (Graduate)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	9.000	1.000	8.000	8.000	32.00	4.00
Cumulative:	37.000	4.000	33.000	33.000	128.00	3.88

Academic History

Term: Spring Sem 2012

College: Arts and Sciences
Major: Ecology/Evolutionary Biology
Academic Standing: Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	R
EEB	503	GR	Ecology/Evolut Biol Seminar	S			

					1.000	0.00
EEB	507	GR	Sem: Ecology/Evolut Biology	S	2.000	0.00
EEB	593	GR	Independent Study	A	1.000	4.00
EEB	606	GR	Adv Top: Conservation Biology	A	1.000	4.00
LFSC	696	GR	Adv Top: Genome Science/Tech	A	1.000	4.00
MATH	405	GR	Models in Biology	A	3.000	12.00

Term Totals (Graduate)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	9.000	3.000	6.000	6.000	24.00	4.00
Cumulative:	46.000	7.000	39.000	39.000	152.00	3.90

*****Academic History*****

Term: Summer Sem 2012

College: Arts and Sciences
Major: Ecology/Evolutionary Biology
Academic Standing: Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	R
EEB	502	GR	Registration/Use of Facilities	NR	3.000	0.00	

Term Totals (Graduate)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	3.000	0.000	0.000	0.000	0.00	0.00
Cumulative:	49.000	7.000	39.000	39.000	152.00	3.90

*****Academic History*****

Term: Fall Sem 2012

College: Arts and Sciences
Major: Ecology/Evolutionary Biology
Academic Standing: Good Standing
Last Academic Standing: Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	R
EEB	493	UG	Independent Study	A	3.000	12.00	

EEB	503	GR	Ecology/Evolut Biol Seminar	S	1.000	0.00
EEB	606	GR	Adv Top: Conservation Biology	A	1.000	4.00
EEB	607	GR	Sem: Ecology/Evolutionary Biol	A	1.000	4.00

Term Totals (Graduate)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	3.000	1.000	2.000	2.000	8.00	4.00
Cumulative:	52.000	8.000	41.000	41.000	160.00	3.90

Term Totals (Undergraduate)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	3.000	0.000	3.000	3.000	12.00	4.00
Cumulative:	3.000	0.000	3.000	3.000	12.00	4.00

*****Academic History*****

TRANSCRIPT TOTALS (GRADUATE) **-Top-**

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Total Institution:	52.000	8.000	41.000	41.000	160.00	3.90
Total Transfer:	0.000	0.000	0.000	0.000	0.00	0.00
Overall:	52.000	8.000	41.000	41.000	160.00	3.90

*****Academic History*****

TRANSCRIPT TOTALS (UNDERGRADUATE) **-Top-**

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Total Institution:	3.000	0.000	3.000	3.000	12.00	4.00
Total Transfer:	0.000	0.000	0.000	0.000	0.00	0.00
Overall:	3.000	0.000	3.000	3.000	12.00	4.00

*****Academic History*****

COURSES IN PROGRESS **-Top-**

Term: Spring Sem 2013

College: Arts and Sciences

Major: Ecology/Evolutionary Biology

Subject	Course	Level	Title	Credit Hours
EEB	593	GR	Independent Study	9.000

RELEASE: 8.4.1