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Monitoring Marcellus Shale Development in the Appalachian Landscape Conservation Cooperative

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Decision Problem

The Pennsylvania Department of Conservation and Natural Resources (DCNR) and the Bureau of Forestry (BOF) are responsible for managing multiple uses on state forest lands (SFL) while ensuring long-term forest health, viability, and productivity. DCNR is in the process of developing a comprehensive monitoring program to support management of Marcellus shale development on SFLs. Such a monitoring program would identify social, ecological, and economic attributes for each fundamental objective and would optimize the allocation of monitoring resources to inform management decisions on SFLs. We therefore utilized a hierarchical decision structure for the Structured Decision Making (SDM) workshop. First, we considered a generalized framework for Marcellus development and coordination across multiple spatial scales. Second, we considered specific monitoring objectives and decisions specifically for SFLs. This yielded two SDM prototypes which may be linked by organizing monitoring designs to address the sources of uncertainty most relevant for management decisions. This approach may provide a model for Marcellus shale development across the Appalachian Landscape Conservation Cooperative (ALCC) region.

Background

The Marcellus shale formation spans the Appalachian mountains from New York to West Virginia and by some estimates is considered to be the largest proven reserve of natural gas in North America (Sample and Price 2011). Extraction of natural gas from Marcellus shale is expected to expand dramatically over the coming decades. For example, Pennsylvania currently supports about 1,800 Marcellus wells but over 60,000 wells could be developed by 2030 if current trends continue (Johnson 2010). Development of Marcellus shale may affect several social and ecological conditions, such as water quality and quantity, forest fragmentation, air quality, recreation, forestry operations, as well as species and ecological communities of concern. However, there is considerable uncertainty about cumulative or synergistic effects across spatial and temporal scales, as well as the optimal design for best management practices (BMPs) to mitigate potential effects. These sources of uncertainty, coupled with the rapid pace of shale development, make Marcellus shale management and monitoring a highly complicated and urgent endeavor.

Pennsylvania SFLs represent a major land holding (2.2 million acres) within the ALCC region and provide an opportunity for comprehensive management and monitoring of Marcellus development. Approximately 700,000 acres have been leased for Marcellus shale gas development on Pennsylvania SFLs. A comprehensive State Forest monitoring program has the potential to improve management decisions by implementing an adaptive management framework. Similar approaches on public lands have provided benefits for landscape conservation elsewhere (Williams et al. 2011). The intent of the SDM process is to develop a basic framework by which monitoring designs could be optimized to further inform management decisions. This process does not provide detailed guidance on monitoring protocols, but does provide a method to identify which attributes require detailed protocol development and which may not.

Two SDM prototypes were partially developed during the workshop (Figure 1). The first prototype set up a generalized shale gas development scenario as the primary decision problem. The second prototype considered monitoring allocation decisions that can be linked to the decisions regarding shale gas development. By taking this approach, the selection of attributes to monitor and allocation of monitoring effort can be targeted to reduce uncertainties that impede effective decision making.

First prototype: generalized development scenarios

<u>Decision Structure</u>

Objectives

The DCNR conserves and sustains Pennsylvania's natural resources for present and future generations' use and enjoyment by "ensuring the long-term health, viability, and productivity of the Commonwealth's forests and to conserve native wild plants" (DCNR 2010). The BOF allows multiple uses on SFLs which area consistent with this overarching mission. One of those uses is environmentally sound utilization of mineral resources. For the first prototype, the fundamental objectives specified a suite of ecological, social, and economic factors (Figure 2):

I. Maximize ecological values
    a. Enhance terrestrial and aquatic ecosystem structure and function
    b. Maximize persistence of native wild plants
II. Maximize social values
    a. Maximize wild character
    b. Maximize recreation

   c. Maximize knowledge of forestry and wise use
   d. Maximize public health and safety

III. Maximize economic values
   a. Maximize environmentally sound mineral resource utilization
   b. Maximize sustainable timber yields
   c. Minimize infrastructure maintenance costs
   d. Maximize local quality of life

Alternative management scenarios

To ensure that a monitoring program is relevant to management decisions, this is the point in the process where alternative management scenarios should be specified. A good set of alternatives should include a range of actions that address all of the fundamental objectives. In addition, the alternatives should be practical, in the sense of being legally, financially, and politically feasible. In the case of shale gas development, decision components include aspects of well pad site selection, infrastructure location, site and road construction (with controls for noise, erosion, discharge, and light), weed and invasive species control measures, water storage, wastewater disposal, water allocation, and reclamation. Selection of different alternatives within the decision components can be used to form strategic portfolios. For example, hypothetical portfolios could be developed to contrast a range of contractual coordination across the landscape. The portfolios could vary by degree of spatial coordination ranging from single tract management to multi-tract management to landscape scale management that allows for multi-landowner coordination. Density of well pads and infrastructure, which is another factor with the potential for landscape scale effects, could be combined with spatial coordination to form strategic portfolios. Further analysis of tradeoffs among these hypothetical portfolios could be relevant across the Appalachian region.

Predictive model

An influence diagram (Figure 3) was developed to identify the pathways between the natural gas development activities and the fundamental objectives, which are listed above and in Figure 2. These pathways are the basis for developing predictions for how alternative management actions will affect the objectives. There are different methods to make predictions including empirical estimates and expert elicitation. Characterization or quantification of uncertainty in the predictions can be used to help guide decisions about monitoring and research.

Decision Analysis

Because this is a multi-objective problem, a consequence table is useful for organizing the predictions and setting up the decision (tradeoff) analysis (Table 1). Of particular interest for this linked decision problem is the uncertainty in the predicted consequences. The relative magnitude of the uncertainties, particularly in combination with weights reflecting importance of the objectives, can be used to identify how monitoring effort should be among the objectives. Moreover, not all uncertainty interferes with making good management decisions. By following through with a tradeoff analysis at this step, the uncertainty that influences decisions can be identified and the relative value of reducing that uncertainty can be evaluated. Then monitoring can be designed to reduce the specific forms of uncertainty that influence decisions.

Second prototype: monitoring design

Decision Structure

The second prototype focused on the monitoring program design. The design of the monitoring program should be linked to the fundamental objectives and key uncertainties that impede effective decision-making identified from the first prototype.

Objectives

Because the predictions and tradeoff analysis were not completed for the first prototype, linking to key uncertainties was not possible. Instead, most objectives were specified in the form of standard power analyses where the monitoring objective is to detect meaningful change in fundamental objectives over a defined period and spatial scale. In addition, the issue of determining BMP effectiveness was raised and incorporated into the monitoring objectives.

The monitoring objectives were focused initially on allocation of monitoring effort among ecological and social attributes (whereas effort on economic attributes was assumed to be constant). For simplicity, monitoring objectives were limited to ecosystem structure and function, wild character, and recreation. The time period for detecting effects was defined to be 5 years. The underlying assumptions, monitoring objectives, and time period could be varied to incorporate greater detail or relevance as the prototype is further developed. The issue of spatial scale is recognized to be an important factor because ecological processes are expected to depend on spatial scale. Thus, local and landscape scale effects were considered separately.

1. Maximize ecological values by maximizing detection of biologically-significant effect on
    a. <u>Terrestrial</u> ecosystem structure and function at the <u>landscape</u> scale
    b. <u>Terrestrial</u> ecosystem structure and function at the <u>local</u> scale
    c. <u>Aquatic</u> ecosystem structure and function at the <u>landscape</u> scale
    d. <u>Aquatic</u> ecosystem structure and function at the <u>local</u> scale
2. Maximize social values by maximizing detection of socially-significant effect on
    a. <u>Wild character</u> at the <u>landscape</u> scale
    b. <u>Wild character</u> at the <u>local</u> scale
    c. <u>Recreation</u> at the <u>landscape</u> scale
    d. <u>Recreation</u> at the <u>local</u> scale
3. Maximize strength of inference on
    a. BMP effectiveness at the <u>landscape</u> scale
    b. BMP effectiveness at the <u>local</u> scale

Alternative monitoring designs

Alternative monitoring designs or strategies were structured by two factors: social-ecological objectives and local-landscape (broad) scale effects (Table 2). Total effort was fixed at 14,000 person-hours per year to reflect current staffing levels. Monitoring efforts for economic objectives were considered to be constant and thus were left out of the decision structure. Allocation among ecological or social objectives ranged from 4:1, 1:1, and 1:4. Allocation among broad to local scale monitoring ranged from 1:0 (landscape only), 3:7 (both), and 0:1 (local only). Teams discussed and specified attributes that should be monitored given each allocation. Through discussion, it was determined that neither landscape-only nor local-only monitoring would be optimal. Thus, the strategies that included both landscape and local scale monitoring, but differed by allocation among ecological and social objectives were included in a tradeoff analysis. Other allocation ratios could be considered using this framework.

Predictive model

Predictions for probability of detection and strength of inference were elicited from team members. The units were on a constructed scale with three levels as follows. A formal power analysis could be used to replace elicited values as the prototype is further developed.

1. Low defined by power ≤ 0.5
2. Medium defined by power > 0.5 and ≤ 0.8
3. High defined by power > 0.8

Decision Analysis

A consequence table with predictions for the strategies that included both landscape and local scale monitoring is shown in Table 3. Following a simple multiple attribute ranking technique, the predicted scores were standardized and weighted. This resulted in a single score for each alternative strategy. A swing weighting technique was used and several individuals' weights were applied to test the sensitivity of the results to variation in weights. Weights were applied at the fundamental objective level. The design that allocated most effort to monitoring ecological attributes performed best overall. Objective weights would have to shift dramatically from the ecological to the social values to alter that result. Scores for the BMP effectiveness objective was positively correlated with scores for ecological objectives. This analysis could be expanded to compare different designs based on allocations of effort, attribute set, or overall level of effort (i.e., sample sizes constrained by budget).

Discussion

Value of decision structuring

Monitoring plays three vital roles in natural resource management. First, monitoring can inform state-dependent decisions (e.g., triggering changes in management as changes in the forest are detected). Second, monitoring can evaluate the efficacy of BMPs or other mitigation actions to achieve their goals. Third, monitoring can serve adaptive management by reducing uncertainty critical to management (Lyons et al. 2008). Adaptive management is a special case of SDM and the decisions related to monitoring design are linked to resource management decisions. The value of SDM in this context is to focus the potentially infinite array of monitoring elements on the subset most closely connected to management decisions. The ultimate value of this approach may become more apparent as the process of Marcellus shale development unfolds on lands within the Appalachian region. For example, the SDM process can provide a defensible framework for determining which attributes (ecological, social, and economic) are monitored and how much effort is allocated to monitoring at differing spatial scales.

Recognizing uncertainty

Workshop participants generally recognized that sources of uncertainty for Marcellus development and monitoring increase at large spatial and temporal scales and that this would have implications for monitoring designs (Figure 4). For example, to evaluate "local" water quality conditions or the efficacy of BMPs, sampling sites could be located upstream and downstream from a particular pad site and revisited frequently (e.g., sondes). However, if landscape level inferences were required, stratified random sampling would probably be necessary (increasing the number of sites) but perhaps requiring few samples per site. Similarly, estimating environmental conditions across stream networks using spatially explicit modeling techniques would requires sampling designs to consider spatial lags among locations and the representation of sampled strata (Peterson and Ver Hoef 2010). Power analysis methods are available to calculate necessary sample sizes, once the spatial scale of inference is determined. Workshop participants recognized that some combination of "local" and "landscape" inferences would be necessary, but the relative weight of these objectives would need further consideration. The on-going technical review of BMPs by the Pennsylvania Chapter of The Nature Conservancy (T. Gagnolet, TNC, personal communication) could provide the bases for portfolio development in the first prototype and further inform the selection of BMPs for research-based monitoring.

A tradeoff analysis could identify not only the relative magnitude of uncertainties of decision consequences, but also the net effect of reducing uncertainty on the fundamental objectives. This could be applied to the first prototype as framed or by substituting BMP alternatives (e.g., conditional vs. unconditional BMPs based on TNC's review). Uncertainty regarding how Marcellus development might affect objectives (e.g., Figure 4) can be incorporated as multiple predictive models within an adaptive management framework. Analyses based on 'expected value of information' (Goodwin and Wright 2004) calculations can address fundamental cost-benefit analysis for monitoring program design. The designs that yield the 'biggest bang for the buck' are those with the highest expected value of information.

The strength of inference is greater when causality can be inferred. Aspects of experimental design can be nested into the monitoring designs. Before-after-control-impact (BACI) designs are useful when pre-impact measurements are possible. Space for time substitution or sampling along impact gradients is another method for creating control sites for comparison to impacts sites.

Recommendations

Workshop participants represented expertise in ecological and social aspects of Marcellus shale development, but by necessity did not represent the full range of potential stakeholders and decision makers. As a result, the optimized allocation of monitoring resources (second prototype) should be interpreted as one possible outcome of the process, not the only outcome. The prototypes in this report therefore provide a framework for more comprehensive development by DCNR and associated stakeholders. We recommend using the framework presented in this report to assist the development of a comprehensive monitoring framework for Marcellus development on SFLs. The model of comprehensive monitoring resulting from this effort could benefit management and monitoring of Marcellus development throughout the ALCC.

Literature Cited

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Table 1. Example layout for a consequence table for the first prototype. The table could be filled in with predictions based on empirical estimates or expert elicitations given measurable attributes for each objective. Of particular interest for this linked decision is the prediction uncertainty in combination with the relative weight or importance of the objectives. The uncertainty combined with objective weight can be useful for allocating effort in a monitoring design. Objectives in relation to shale development activities are shown conceptually in Figure 3.

Consequence table		**Alternative development scenarios**			
Objectives	**Goal**	**Single tract** **No coordination among tracts**		**Multiple tracts** **Landscape-level coordination**	
		Low well-pad density	**High well-pad density**	**Low well-pad density**	**High well-pad density**
Ia: Enhance ecosystem structure & function	Max				
Ib: Max persistence of native plants	Max				
IIa: Max wild character	Max				
IIb: Max recreation	Max				
IIc: Max forestry outreach/education	Max				
IId: Max public health & safety	Max				
IIIa: Max mineral extraction	Max				
IIIb: Max sustainable timber yield	Max				
IIIc: Min infrastructure maintenance	Min				
IIId: Max quality of life of local communities	Max				

Table 2. Example decision analysis framework. Monitoring design alternatives were based on allocating fixed effort (14,000 person hours per year) among two design factors: 1) landscape (broad) vs. local scale monitoring and 2) ecological vs. social objectives. Economic objectives were omitted for this exercise because it was assumed that the investment in economic attribute monitoring would be constant. This framework can be expanded to include tradeoffs among ecological, social, and economic objectives.

	Total person-hours/year:	14000								
		Alternative Monitoring Strategies								
		1	2	3	4	5	6	7	8	9
	Spatial scale	Broad only	Broad only	Broad only	Both	Both	Both	Local only	Local only	Local only
	Ratio of time on Ecol:Social attributes	4	1	0.25	4	1	0.25	4	1	0.25
Broad scale	# of sites	500	500	500	500	500	500	0	0	0
	Prop. of time	1	1	1	0.3	0.3	0.3	0	0	0
	Hours/site-year	28	28	28	8.4	8.4	8.4	0	0	0
	Hrs on Ecol. Attributes	22.4	14.0	5.6	6.7	4.2	1.7	0	0	0
	Visits/year for Ecol. attributes	5	3	1	1	1	1	0	0	0
	Hours/visit for Ecol. Attributes	3.5	3.7	4.6	5.7	3.2	0.7	0	0	0
	Ecological attributes:	Water qual. Air qual. Soil disturb. Noise Light Animal surveys Plant surveys BMP implem.	Water qual. Air qual. Soil disturb. Noise Light Animal surveys Plant surveys BMP implem.	Water qual. Air qual. Soil disturb. Noise Light nimal survey Plant surveys BMP implem.	Water qual. Air qual. Soil disturb. Noise Light Animal surveys Plant surveys BMP implem.	Water qual. Air qual. Soil disturb. Noise Light Animal surveys Plant surveys	Water qual. Air qual. Soil disturb. Noise Light	None	None	None
	Hrs on Social attributes	5.6	14	22.4	1.7	4.2	6.7	0	0	0
	Visits/year for Social attributes	4	4	4	1	2	3	0	0	0
	Hours/visit for Social attributes	0.4	2.5	4.6	0.7	1.1	1.2	0	0	0
	Social attributes:	Noise Visual devel. Industry traffic Road condition	Noise Visual devel. Visitor survey Recr. Use	Noise Lights Visitor survey Recr. Use Dist. To devel.	Noise Visual devel. Industry traffic Road condition	Noise Visual devel. Visitor survey Recr. Use	Noise Lights Visitor survey Recr. Use Dist. To devel.	None	None	None
Local scale	# of sites	0	0	0	50	50	50	50	50	50
	Prop. of time	0	0	0	0.7	0.7	0.7	1	1	1
	Hours/site-year	0	0	0	196	196	196	280	280	280
	Hrs on Ecol. Attributes	0	0	0	157	98	39	224	140	56
	Visits/year for Ecol. Attributes	0	0	0	12	6	4	12	6	4
	Hours/visit for Ecol. Attributes	0	0	0	12.1	15.3	8.8	17.7	22.3	13.0
	Ecological attributes:	None	None	None	Water qual.-hi Bioassess. to spp Water flow Plant plots-hi Pres/abs of verts Black light Bird counts	Water qual.-med Bioassess. to spp Water flow Plant plots-med Pres/abs of verts Black light	Water qual.-lo Rapid bioassess. Water flow Plant plots-lo Pres/abs of verts	Water qual.-hi Bioassess. to spp Water flow Plant plots-hi Pres/abs of verts Black light Bird counts Drift fences	Water qual.-hi Bioassess. to spp Water flow Plant plots-hi Pres/abs of verts Black light Bird counts Drift fences	Water qual.-hi Bioassess. to spp Water flow Plant plots-hi Pres/abs of verts Black light Bird counts
	Hrs on Social attributes	0	0	0	39.2	98.0	156.8	56	140	224
	Visits/year for Social attributes	0	0	0	4	8	12	4	12	12
	Hours/visit for Social attributes	0	0	0	8.8	11.3	12.1	13.0	10.7	17.7
	Social attributes:	None	None	None	Visitor survey Cabin use Hunter surveys Media event Angler survey Light/Noise Scenic driving Camping by type	Visitor survey Cabin use Hunter surveys Media event Angler survey Light/Noise Scenic driving Camping by type	Visitor survey Cabin use Hunter surveys Media event Angler survey Light/Noise Scenic driving Camping by type	Visitor survey Cabin use Hunter surveys Media event Angler survey Light/Noise Scenic driving Camping by type Trail use survey Truck traffic	Visitor survey Cabin use Hunter surveys Media event Angler survey Light/Noise Scenic driving Camping by type Trail use survey Truck traffic	Visitor survey Cabin use Hunter surveys Media event Angler survey Light/Noise Scenic driving Camping by type Trail use survey Truck traffic

Table 3. Consequence table for the second prototype comparing alternative monitoring strategies (designs) that differ by allocation of effort among ecological and sociological attributes. Allocations are 4:1, 1:1, and 1:4 for ecological:sociological attributes in Both 1, Both 2, and Both 3 designs, respectively. The monitoring objectives are in terms of statistical power on a constructed scale: 1 denotes power ≤ 0.5, 2 denotes power > 0.5 and ≤ 0.8, and 3 denotes power > 0.8. Scores were averaged among team members.

SIMPLIFIED MATRIX		**Alternatives**		
Objectives	**Goal**	**Both 1**	**Both 2**	**Both 3**
Detect bio-sign effect on terrestrial Eco S&F broad scale	Max	2.5	2.0	1.5
Detect bio-sign effect on terrestrial Eco S&F local scale	Max	3.0	2.0	1.5
Detect bio-sign effect on aquatic Eco S&F broad scale	Max	3.0	2.5	2.0
Detect bio-sign effect on aquatic Eco S&F local scale	Max	3.0	2.5	2.0
Detect soc-sign effect on Wild Char. broad scale	Max	2.0	2.0	3.0
Detect soc-sign effect on Wild Char. local scale	Max	1.0	2.0	3.0
Detect soc-sign effect on Rec broad scale	Max	1.0	2.0	3.0
Detect soc-sign effect on Rec local scale	Max	1.0	2.0	3.0
Strength of inference on BMP effectiveness broad scale	Max	2.0	1.0	1.0
Strength of inference on BMP effectiveness local scale	Max	3.0	2.0	2.0

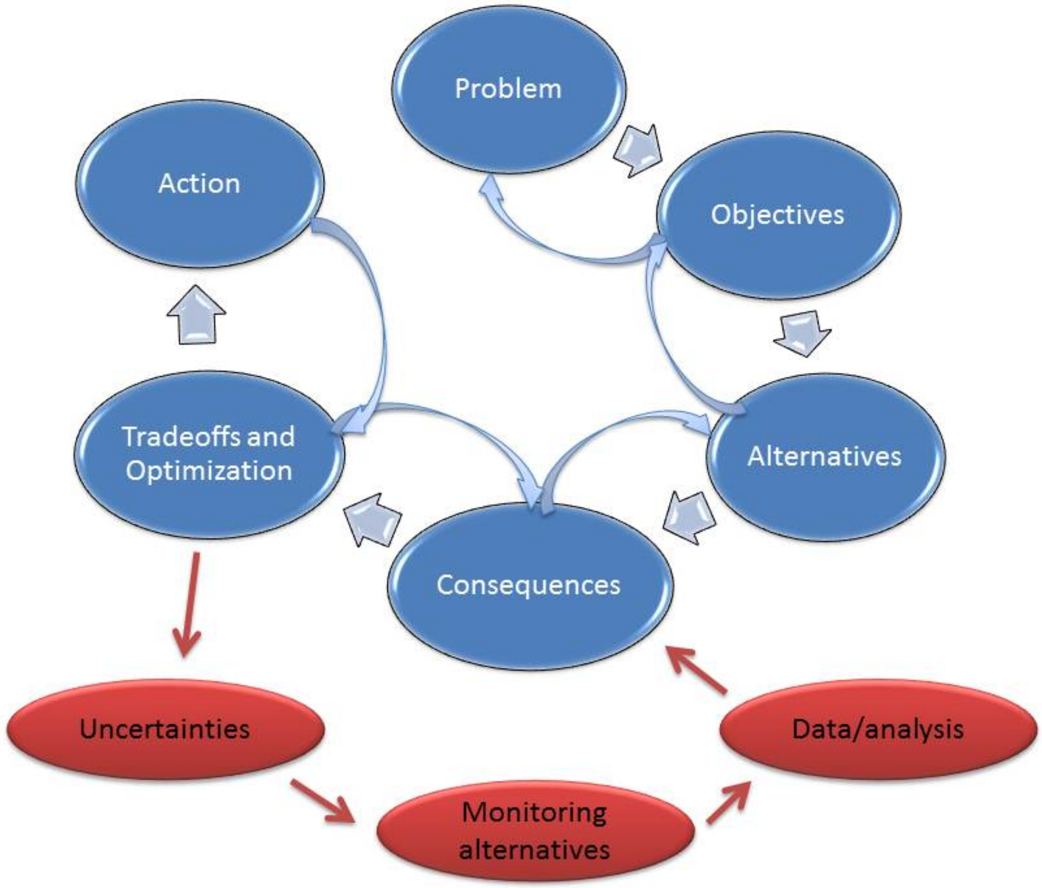
Figures

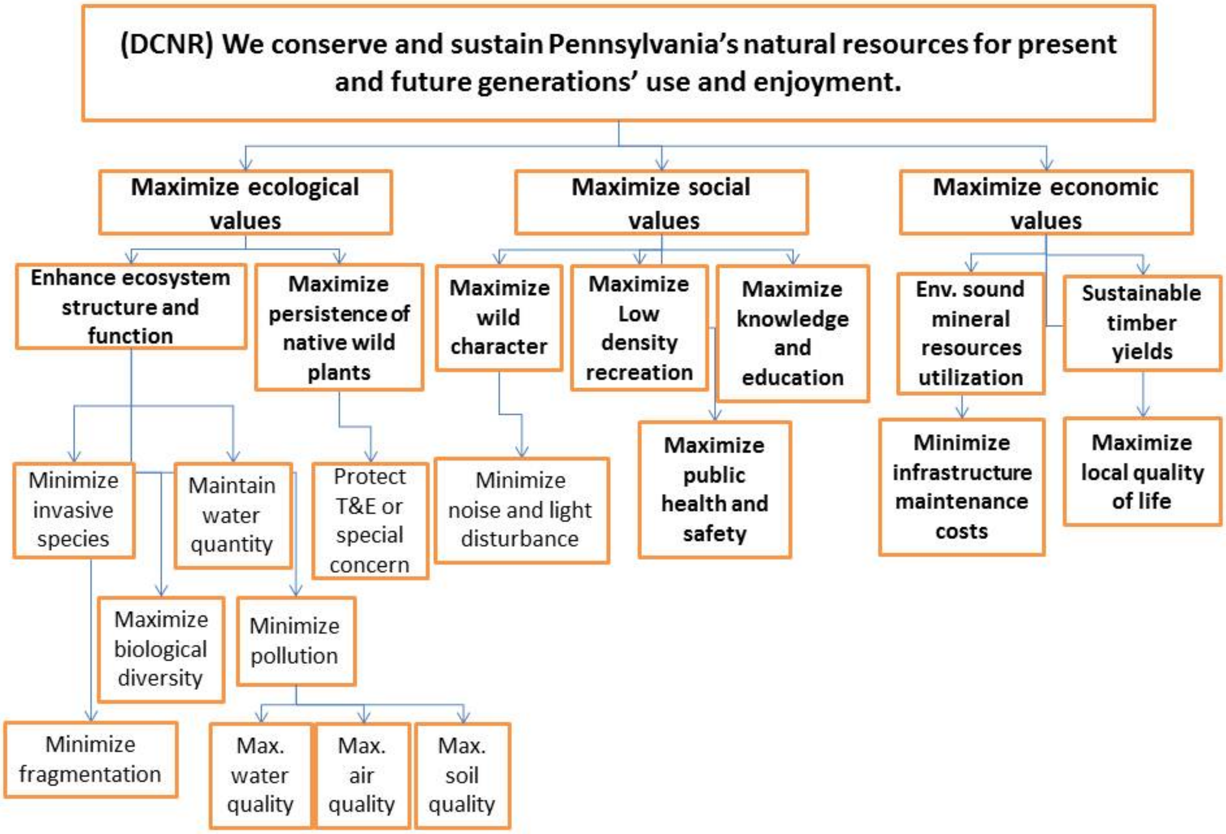
Figure 1. Hierarchy of linked decisions illustrating how development of a monitoring program can be targeted to address key uncertainties identified through an analysis of the decision set that are primary to the management issue. In this case, the primary decision (upper PrOACT loop) is related to management of natural gas extraction in a multi-objective environment, and the monitoring program is designed to support the primary decision. Monitoring alternatives are selected to reduce the key uncertainties, i.e., those uncertainties relevant to the management decision.

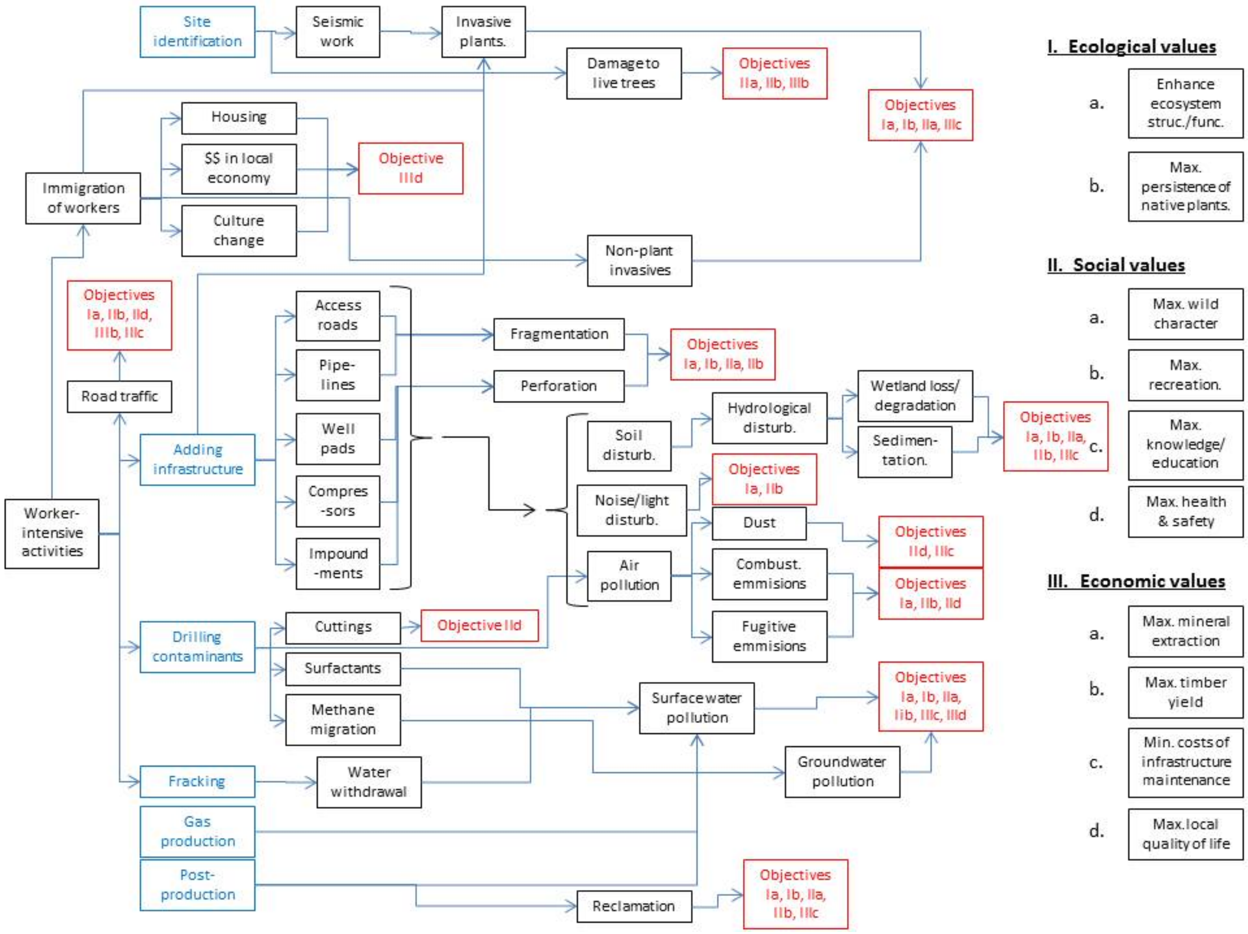
Figure 2. Objective hierarchy for the first prototype reflecting DCNR mission and values. Fundamental objectives are in bold text and a partial list of means objectives under the ecological objectives are shown.

Figure 3. Influence diagram reflecting potential pathways and effects of shale gas development on ecological, social, and economic objectives (i.e., values).

Figure 4. Hypothetical representation of uncertainty in the relationship between cumulative impacts of well and infrastructure density on stream health. Decisions regarding extraction of natural gas and BMPs would depend on the weight of belief given to each of these underlying models. Adapted from graph presented by J. Mead, The Academy of Natural Sciences.


Problem
Action
Objectives
Tradeoffs and Optimization
Alternatives
Consequences
Uncertainties
Data/analysis
Monitoring alternatives


(DCNR) We conserve and sustain Pennsylvania's natural resources for present and future generations' use and enjoyment.
Maximize ecological values
Maximize social values
Maximize economic values
Enhance ecosystem structure and function
Maximize persistence of native wild plants
Maximize wild character
Maximize Low density recreation
Maximize knowledge and education
Env. sound mineral resources utilization
Sustainable timber yields
Minimize invasive species
Maintain water quantity
Protect T&E or special concern
Minimize noise and light disturbance
Maximize public health and safety
Minimize infrastructure maintenance costs
Maximize local quality of life
Maximize biological diversity
Minimize pollution
Minimize fragmentation
Max. water quality
Max. air quality
Max. soil quality



Site identification
Seismic work
Invasive plants.
Damage to live trees
Objectives IIa, IIb, IIIb
Objectives Ia, Ib, IIa, IIIc
Housing
$$ in local economy
Objective IIId
Immigration of workers
Culture change
Non-plant invasives
Objectives Ia, IIb, IId, IIIb, IIIc
Access roads
Pipe-lines
Fragmentation
Objectives Ia, Ib, IIa, IIb
Perforation
Road traffic
Well pads
Hydrological disturb.
Wetland loss/ degradation
Objectives Ia, Ib, IIa, IIb, IIIc
Soil disturb.
Sedimen-tation.
Adding infrastructure
Objectives Ia, IIb
Compres-sors
Noise/light disturb.
Dust
Worker-intensive activities
Objectives IId, IIIc
Impound-ments
Air pollution
Combust. emmisions
Objectives Ia, IIb, IId
Drilling contaminants
Cuttings
Objective IId
Fugitive emmisions
Surfactants
Surface water pollution
Objectives Ia, Ib, IIa, IIb, IIIc, IIId
Methane migration
Fracking
Water withdrawal
Groundwater pollution
Gas production
Post-production
Reclamation
Objectives Ia, Ib, IIa, IIb, IIIc
I. Ecological values
a. Enhance ecosystem struc./func.
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a. Max. wild character
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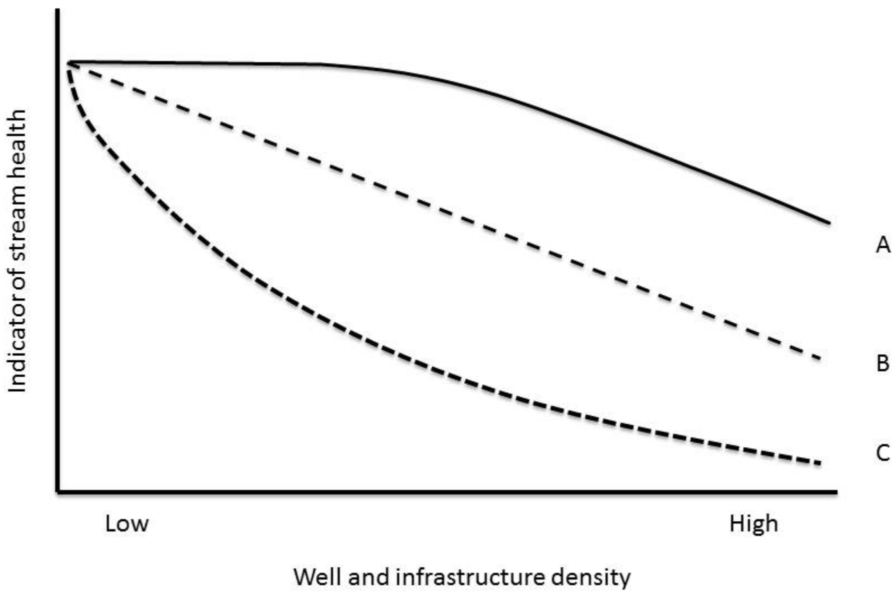
c. Max. knowledge/ education
d. Max. health & safety
III. Economic values
a. Max. mineral extraction
b. Max. timber yield
c. Min. costs of infrastructure maintenance
d. Max. local quality of life


Indicator of stream health
A
B
C
Low
High
Well and infrastructure density