Evaluating the Scientific Support of Conservation Best Management Practices for Shale Gas Extraction in the Appalachian Basin

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Extensive shale gas development is expected throughout the Appalachian Basin, and implementing effective avoidance and mitigation techniques to reduce ecosystem impacts is essential. Adoption of *best management practices* (BMPs) is an important approach for standardizing these techniques. For BMPs to be credible and effective, they need to be strongly supported by science. We focused on 28 BMPs related to surface impacts to habitat and wildlife and tested whether each practice was supported in the scientific literature. Our quantitative assessment produced four general conclusions: (1) the vast majority of BMPs are broad in nature, which provides flexibility in implementation, but the lack of site-specific details may hamper effectiveness and potential for successful conservation outcomes; (2) relatively low support scores were calculated for a number of BMPs, most notably those relating to noise and light pollution, due to existing research documenting effects on behavior rather than directly on species' survival and fitness—an indication that more research is needed; (3) the most commonly and strongly supported BMPs include landscape-level planning and shared infrastructure; avoidance of sensitive areas, aquatic habitats, and core forest areas; and road design, location, and maintenance; and (4) actions to enhance the development and implementation of BMPs should include public education, increased communication among scientists, improved data sharing, development of site-specific BMPs that focus on achieving ecological outcomes, and more industry collaboration.

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Technological advancements over the past several years have enabled the economical extraction of vast shale gas reserves found in the Appalachian Basin. The region's shale gas boom is evidenced by a sharp rise in the number of unconventional gas wells drilled over the last few years. For example, in Pennsylvania, approximately 200 Marcellus Shale natural gas wells had been drilled by 2008. By May of 2012, more than 5,300 Marcellus wells had been drilled, and thousands of miles of roads and pipelines were being developed or expanded in Pennsylvania alone (Drohan et al., 2012a; Johnson et al., 2010, 2011; Pennsylvania Department of Environmental Protection, 2012). The extent of unconventional shale gas drilling is not only affecting thousands of private forestland parcels in Pennsylvania, but over 385,000 acres of public state forestland, mainly in large, contiguous blocks, have also been leased in Pennsylvania (Pennsylvania Department of Conservation and Natural Resources, Bureau of Forestry, 2012). With much of this development occurring within a vast forested landscape, ecosystem impacts associated with land-use conversion could be significant.

Encouraging the gas development industry to adopt a group of practical avoidance, minimization, and mitigation strategies may be one of the most effective approaches for ecosystem conservation. Often, these types of strategies are outlined in a list of *best management practices* (BMPs). BMPs are practical planning and operational techniques that attempt to reduce impacts on the environment while

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still allowing a natural resource, such as natural gas, to be extracted. Numerous BMP documents have been created from a variety of perspectives, including industry, government, and nongovernmental organizations, for issues such as storm-water and surface-water management [Arthur, Coltharp, and Brown, 1998; Field et al., 2006; National Research Council, 2004; United States (US) Environmental Protection Agency, 2012; Wang, Lyons, and Kanehl, 2002; Yates, Bailey, and Schwindt, 2007], agricultural practices (Leitman, Gustafson-Minnich, and Hall, 1997; Michigan Department of Natural Resources, 2009; New Hampshire Department of Agriculture, Markets and Food, 2002; Simpson and Weammert, 2009), forestry practices (Brown, 1993; Chunko, 2001; Kittredge and Parker, 1999; Koehn and Hairston-Strang, 2009; Maine Forest Service, Department of Conservation, 2004), wildlife habitat conservation (Bakermans et al., 2011; Hebblewhite, 2008; Johnson, Igl, and Dechant, 2004; McCord, Grippo, and Eagle, 2007; US Department of Agriculture, Natural Resources Conservation Service, 2010), and oil and gas development (Marcellus Shale Coalition, 2012; Pennsylvania Department of Conservation and Natural Resources, Bureau of Forestry, 2011; US Department of the Interior and US Department of Agriculture, 2007).

Recommended BMPs related to the aboveground development of oil and natural gas cover a wide range of topics, including: air quality, human health, land-disturbance impacts, soil, vegetation, water quality and quantity, and wildlife (Natural Resources Law Center, University of Colorado Law School, 2012). A diversity of recommended aboveground practices can occur at any of the various stages of natural gas extraction, including site planning, infrastructure development, and restoration of well pads, roadways, and other features (Houston Advanced Research Center and Texas A&M University, 2012; Natural Resources Law Center, University of Colorado Law School, 2012).

BMPs are often developed with the support of expert committees with knowledge of the industry, the ecosystem at risk, or both. Typically, if BMPs are not developed for the specific application where they are recommended, they are adopted from previous related efforts, regardless of how relevant (or not) the practices may be to new ecological contexts. In addition, because the intent is for widespread adoption by the industry, logistical constraints and financial costs associated with BMP implementation often play an important role in the development of the BMP.

Because of these various factors, the scientific support that should be underlying all BMPs can often be disregarded. If the scientific support for practices does not play a lead role in the development of BMPs, then outcomes can range from recommending ineffective practices (which may further threaten the ecosystem at risk) to not recommending practices that are critical to ecosystem protection. Not having scientific support guide the development of BMPs can produce ineffective policies and cause financial (and other) resources to be misspent on less deserving endeavors. In addition, advancing unsupported BMPs might result in a breakdown in collaboration (where parties no longer see others as cooperators) and lead to distrust about whether the suggested BMPs are effective at reducing environmental impacts.

The Nature Conservancy assessed the extent to which existing gas development BMPs are supported by published scientific literature. Norris et al. (2012) emphasized the need for weight-of-evidence based approaches that use existing scientific results to support management decisions. We used this concept to develop a quantitative method to weight the contribution of literature in supporting the need for a BMP by calculating scores for the publication's relevance (e.g., development type, habitat setting) and strength of ecosystem response. We focused explicitly on above-ground ecological BMPs and did not evaluate belowground practices related to drilling and hydraulic fracturing. In addition to providing an assessment of how well scientific literature supports existing BMPs, this analysis highlights several BMP research opportunities and underscores the importance of developing a set of high-value BMPs that can be implemented by the oil and gas industry to reduce habitat impacts in the Appalachian Basin.

Methods

Our process to characterize scientific support for existing unconventional shale gas development BMPs involved five major steps (Figure 1): (1) compiling, summarizing, and selecting focal gas development BMPs, (2) for focal BMPs, conducting a literature review and assigning a relevance rating for each publication, (3) pairing BMPs with relevant literature and assigning a support rating to each BMP/citation pair based on the strength of documented responses, (4) calculating a pairing strength-of-support score for each BMP/citation pair based on its relevance ratings and support rating, and (5) averaging pairing strength scores to calculate an overall BMP support score for each focal BMP.

We created three separate databases for the quantitative assessment of unconventional gas BMPs. The first database

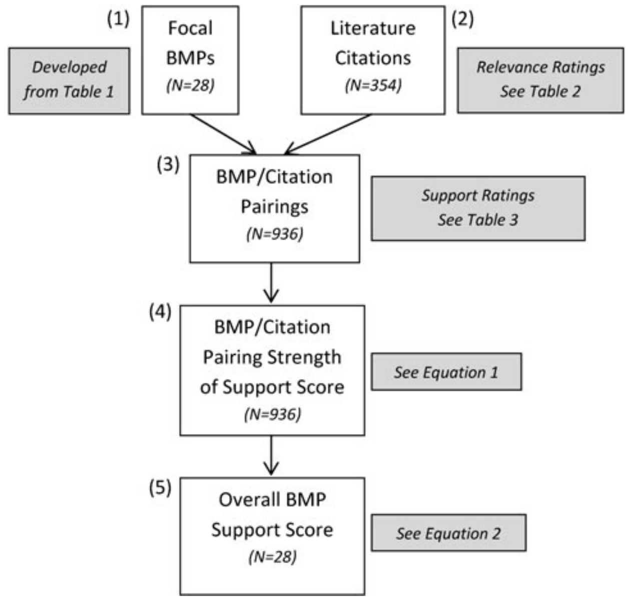

Figure 1. Diagram of analysis to evaluate scientific support for conservation best management practices (BMPs).

compiled existing, publicly available gas development BMPs related to surface infrastructure, natural habitats, and wildlife from across the US (Table 1). Each BMP was categorized by type (e.g., site selection, erosion control, vegetation management) and conservation target (e.g., vascular plants, invertebrates, birds). Redundant and similar practices were then grouped together to consolidate the list of BMPs. From this consolidated list, we selected a focal subset of BMPs that were directly related to reducing impacts to terrestrial and aquatic ecosystems during planning, construction, and operations phases of development. For terrestrial ecosystems, we focused on BMPs related to landscape planning, habitat fragmentation, noise and light pollution, and avoidance/setback distances of critical and sensitive areas. For aquatic ecosystems, we selected BMPs associated with land disturbances that are likely to impact the biological, physical, or chemical integrity of aquatic habitats. Scientific support for ecosystem impacts associated with water use and regional recommendations to minimize those impacts have been synthesized in other research and therefore were not selected as focal BMPs here (DePhilip and Moberg, 2010).

We then conducted an extensive literature review on numerous possible topics and keywords related to the focal BMPs. Citations were imported into a database and rated on five relevance metrics (Table 2) to determine their applicability to shale gas development in the Appalachian Basin: habitat type, taxonomic group, infrastructure type, development type, and geographic context. Higher relevance ratings were given for a citation if it was relevant to the ecological systems found in the Appalachians.

We thoroughly cross-referenced the literature that was relevant for each focal BMP. Each focal BMP in the BMP database was paired with all related citations from the literature database, and a support rating was assigned to every unique BMP/citation pairing to identify how well the citation supported the BMP. The support ratings ranged from −2 (study is indeterminate or does not support recommendation of BMP) to +2 (study supports recommendation of BMP) (Table 3). Literature was recorded as supporting a BMP if it agreed with the general purpose and spirit of the BMP, even if the details of the recommendations differed. For example, an article could support a BMP recommending buffer strips even if the recommended widths differed between the article and the BMP.

To evaluate how well each practice is supported by the scientific literature, the relevance ratings for each citation (Table 2) and support ratings for each BMP/citation pairing (Table 3) were combined into a pairing strength-of-support score for each BMP/citation pairing. We calculated these pairing strength scores using the following weighted algorithm:

$$PS = SR \times \{(DS \times 3) + (GS \div 2) + (HS \times 2) + (IS \times 2) + (TS \div 2)\} \qquad \text{(Equation 1)}$$

where

PS = pairing strength-of-support score

SR = BMP/citation support rating

DS = development-type relevance rating

GS = geographic-context relevance rating

HS = habitat-type relevance rating

IS = infrastructure-type relevance rating

TS = taxonomic relevance rating

The five relevance ratings were weighted based on how strong of a relationship we expected them to have to the systems impacted by shale gas development in the Appalachian Basin. For example, a publication that reported on unconventional gas development (the development type) was given the highest weight (×3) because it made the publication extremely relevant to our analysis. Alternatively, publications from the Appalachian Basin (geographic relevance) or on the species found there (taxonomic relevance) were given lower weight because effects would not be as variable across the range of ratings. We then

Table 1. To develop our set of best management practices (BMPs), we used these publicly available BMP documents

Colorado Parks and Wildlife (CPW). 2008, October 27. *Actions to Minimize Adverse Impacts to Wildlife Resources*. CPW, Denver, CO, 34 pp. Available at http://www.mde.state.md.us/programs/Land/mining/marcellus/Documents/CO26ColoradofinalBMP1008.pdf (accessed October 20, 2012).
Natural Resources Law Center, University of Colorado Law School. 2012. *Intermountain Oil and Gas Best Management Practices Project*. University of Colorado, Boulder, CO. http://www.oilandgasbmps.org/ (accessed October 20, 2012).
The Nature Conservancy, Central Appalachians Program. 2011. *Best Conservation Practices for Shale and Conventional Gas Drilling Activities*. Unpublished report. The Nature Conservancy, Arlington, VA, 5 pp.
New York Department of Environmental Conservation (NY DEC). 2011. *Revised Draft Supplemental Generic Environmental Impact Statement on the Oil, Gas, and Solution Mining Regulatory Program*. NY DEC, Albany, NY. Available at http://www.dec.ny.gov/energy/75370.html (accessed October 30, 2012).
Ohio Department of Natural Resources (Ohio DNR). 2005. *Best Management Practices for Oil and Gas Well Site Construction*. Mineral Resources Management, Ohio DNR, Columbus, OH, 22 pp. Available at http://cdm16007.contentdm.oclc.org/cdm/singleitem/collection/p267401ccp2/id/1131/rec/14 (accessed October 20, 2012).
Pennsylvania Chapter of the Wildlife Society (TWS). 2010. *Position Statement on Marcellus Shale Gas Development in the Appalachians and High Allegheny Plateau*. TWS, Bethesda, MD, 4 pp. Available at http://joomla.wildlife.org/PA//images/Position_Statements/ps-marcellus_shale_gas_development.pdf (accessed October 20, 2012).
Pennsylvania Department of Conservation and Natural Resources (PA DCNR). 2011. *Guidelines for Administering Oil and Gas Activity on State Forest Lands*. Bureau of Forestry, PA DCNR, Harrisburg, PA, 156 pp. Available at http://www.dcnr.state.pa.us/ucmprd2/groups/public/documents/document/dcnr_004055.pdf (accessed October 20, 2012).
Pinchot Institute for Conservation. 2010. *The Marcellus Shale: Protecting Watersheds During Natural Gas Development*. Pinchot Institute for Conservation, Washington, DC. Available at http://www.pinchot.org/gp/Marcellus_Shale (accessed October 30, 2012).
US Bureau of Land Management (US BLM). 2012. *Best Management Practices Technical Information*. US BLM, US Department of the Interior, Washington, DC. Available at http://www.blm.gov/wo/st/en/prog/energy/oil_and_gas/best_management_practices/technical_information.html (accessed October 30, 2012).
US Office of Surface Mining Reclamation and Enforcement (US OSM). 2012. *Appalachian Regional Reforestation Initiative*. US OSM, US Department of the Interior, Washington, DC. http://arri.osmre.gov/ (accessed October 20, 2012).
West Virginia Division of Natural Resources (WV DNR). 2008. *Guidelines for Oil and Gas Development and Fish and Wildlife Resources*. WV DNR, South Charleston, WV.
Wyoming Fish & Game Department. 2010. *Recommendations for Development of Oil and Gas Resources within Important Wildlife Habitats*. Wyoming Fish & Game Department, Cheyenne, WY, 244 pp. Available at http://pbadupws.nrc.gov/docs/ML1108/ML110810642.pdf (accessed October 20, 2012).

averaged pairing strength scores for each focal BMP to calculate an overall BMP support score:

$$\frac{\sum_{1}^{n}[PS]}{n} \qquad \text{(Equation 2)}$$

We tested the differences in final overall support scores by using analysis of variance with a Tukey multiple comparison test to identify specific BMPs that were significantly more or less supported. Analysis was conducted with the R statistical package (R Development Core Team, 2012) using AOV and GLHT commands from the MULTCOMP package. To minimize the complexity of multiple comparisons across the 28 grouped BMPs, we also report on the BMPs occurring in the lower and upper 25% percentiles.

Results

A total of 429 oil and gas development BMPs were identified related to surface infrastructure, natural habitats, and wildlife from across the US. Redundant practices were combined into 187 grouped BMPs, of which we selected 28 grouped BMPs for further assessment because of their relevance to aquatic and terrestrial ecosystems. These 28 focal BMPs included several topics, with the majority related to infrastructure planning, development, and maintenance (Table 4).

Using the keywords from those 28 grouped BMPs, we identified 354 expert documents and peer-reviewed journal articles that we entered into our citation database, over 60% of which had been published since the year 2000. To avoid

Table 2. Relevance ratings given to all literature citations (N = 354) used to evaluate best management practices

Development relevance rating	
1	Unconventional natural gas development
0	Other
Geographic relevance rating	
3	Central Appalachians/Mid-Atlantic (PA, NY, WV, MD, NJ)
2	Midwest and Northeast (including Ontario, Quebec, Maritime)
1	Southwest and West
0	Outside of US
Habitat relevance rating	
3	Commonly exists in the Appalachian Basin (e.g., wetlands, hardwoods)
2	Sometimes exists in the Appalachian Basin (e.g., boreal forest)
1	Similar habitat structure to the Appalachian Basin (e.g., tropical rainforest)
0	Does not occur in the Appalachian Basin (e.g., sagebrush)
Infrastructure relevance rating	
1	Similar to infrastructure used in development of unconventional natural gas extraction (e.g., forest roads, transmission line corridors)
0	Not used in development of unconventional natural gas extraction (e.g., paved roads)
Taxonomic relevance rating	
3	Species occurs in the Appalachian Basin
2	Edge of range or very similar to species in the Appalachian Basin
1	Similar to species in the Appalachian Basin
0	Does not occur in the Appalachian Basin

redundancy of research, review articles were not included. Each citation was scored in all five relevance ratings. Because unconventional shale gas development's effects on the landscape and wildlife have largely not been specifically studied, it was not surprising that a majority of citations were for a different form of energy development (96%) and infrastructure type (67%) and occurred outside the Appalachian Basin (34%). However, we were satisfied that the majority of the citations were in similar habitat types (60% with habitat relevance rating ≥2) and were written for similar species (87% with taxonomic relevance rating ≥2) as what would occur in the Appalachian region (Table 5).

Combining each focal BMP with a list of relevant citations, we developed a table with 936 pairings. Using the weighted algorithm (Equation 1), strength-of-support scores for each BMP/citation pairing ranged from indeterminate/weak support to strong support for the BMP. Whereas the vast majority of strength-of-support scores were positive (citation supports BMP recommendation; $n_{pairings} = 891 =$ 95%), negative strength-of-support scores (citation is indeterminate or does not support BMP recommendation) ranged from a moderate ($-10 < PS < 0$, $n_{pairings} = 12$) to strong lack of support ($PS \leq -20.0$, $n_{pairings} = 10$) (Figure 2). Pairings with negative strength-of-support scores ($PS < 0$, $n_{pairings} = 45$) occurred primarily with BMPs related to noise reduction (16%), landscape-scale planning (22%), and avoidance of sensitive areas, aquatic habitat, and core forest areas (38%). Pairings with the highest strength-of-support scores (>20, $n_{pairings} = 46$) involved BMPs related to avoidance of sensitive areas, aquatic habitats, and core forest areas (30%) and to road design, location, and maintenance (43%). A high number of BMPs and citations were related to avoidance of sensitive areas, aquatic habitat, and core forest areas, explaining why some pairings had a negative score while many others were positive.

Averaging pairing strength-of-support scores for each BMP, we obtained final overall support scores for each of the 28 focal grouped BMPs (Equation 2). The number of citations ranged from numerous for certain BMPs (avoid forested areas, $n_{citations} = 148$; plan at the landscape level and promote shared infrastructure, $n_{citations} = 141$) to extremely limited for other BMPs (three BMPs had fewer than five related citations for support-score calculation). No final support scores were found to be negative, indicating that using an averaging method (Equation 2) allowed the positive support scores to outweigh the negative scores.

Final overall support scores ranged from 3.4 to 17 (minimum possible support = −22; maximum possible support = +22). Four BMPs were significantly lower in scientific support than were higher-scoring BMPs [$F(27, 908) = 3.95$, $p < 0.01$; Tukey < 0.05]. These low-scoring BMPs were related to noise control (minimizing noise by colocating infrastructure and using noise-reducing devices) and lighting (directing light downward). Looking at the lowest 25 percentile (score < 8.4), we identified an additional seven BMPs that were weakly supported by the literature. These included BMPs related to disturbance around wildlife areas (bat roosts, breeding/nest sites, and sensitive habitats), vegetation removal, and colocating infrastructure. We determined that seven BMPs were strongly supported by the scientific literature. These seven BMPs were identified in the highest 25 percentile (score > 11.8) and also were significantly higher than the lowest-scoring BMPs [$F(27, 908) = 3.95$, $p < 0.01$; Tukey < 0.05] (Table 4).

Among the seven highly supported BMPs, topics such as managing pipelines for shrub cover and locating/timing development around wetlands and streams to avoid im-

Table 3. Definitions for support ratings given to each best management practice (BMP)/citation pairing to identify how well the BMP is supported by the individual study

	Rating	Definitions for BMP/citation support ratings
Supports BMP	2	The reference supports the BMP by providing direct evidence of a negative impact on one or more of the following: species composition and evenness, native species richness, population density, reproductive rate, survival rate, or habitat loss as a result of infrastructure development and/or presence (example: increased predation due to fragmentation).
	1	The reference supports the BMP by providing direct evidence of a change in species behavior, intraspecies communication, interspecies communication, movement, dispersal, etc., as a result of infrastructure development and/or presence (example: change in bird song frequency from traffic noise).
Inconclusive	0	The reference provides inconclusive or mixed evidence regarding the BMP.
Does not support BMP	−1	The reference does not support the BMP by providing direct evidence of no change in species behavior, intraspecies communication, interspecies communication, movement, dispersal, etc., as a result of infrastructure development and/or presence.
	−2	The reference does not support the BMP by providing direct evidence of a positive impact on one or more of the following: native species richness, population density, reproductive rate, survival rate, or habitat loss as a result of infrastructure development and/or presence (example: increased density of birds due to fragmentation).

pacts to aquatic species (including spawning times) are well supported by the literature. Other BMPs with scientific support include using erosion control mechanisms (e.g., proper drainage, using sediment barriers, and avoiding steep slope development), limiting removal of native vegetation, and minimizing road development in wet bottomlands and sensitive areas. Notably, two BMPs had extensive documentation ($n_{citations} > 140$) to develop their overall support score, including (1) colocating infrastructure to minimize overall landscape impacts, and (2) constraints mapping to avoid development in forested areas. Although both of these BMPs had significant positive support from much of the literature and far more paired references than did other BMPs, several negative citations ($n_{citations} < 10$) lowered their final overall support score, and in one case (colocating infrastructure) indicated weak support, when in fact most of the literature suggested strong support.

Discussion

With extensive shale gas development expected throughout the Appalachian Basin and elsewhere, it is critical that the development industry be able to implement effective avoidance, minimization, and mitigation techniques to reduce impacts to terrestrial and aquatic ecosystems. Adoption of BMPs is an important approach for standardizing acceptable methods of reduced-impact development, but it is critical that BMPs have a strong scientific foundation if they are to be credible and effective. We tested whether currently recommended BMPs related to shale gas development were supported by the scientific literature through the use of an algorithm that scored relevance and support associated with a BMP. These overall support scores should not be interpreted as a measure of BMP effectiveness but rather indicate whether BMPs are well supported by existing scientific literature. This quantitative assessment also can assist in identifying gaps in scientific research relevant to effective BMP development.

We draw several conclusions from this assessment of BMPs. First, most BMPs are quite broad in nature. This may be a result of the general consensus nature of the BMP development process or perhaps is a result of BMPs often being adopted from other sources and applied to different ecosystems. The broad language may be useful in many situations because it provides general flexibility in interpretation and implementation. However, the lack of specific details that would be critical to inform a precise BMP can significantly reduce actual effectiveness and potential for successful conservation outcomes. For example, we looked at BMPs that recommended reducing landscape fragmentation and another that recommended reducing noise from equipment. To make these recommendations specific for the Appalachian region, additional information is needed on thresholds. In other words, at what scale does fragmentation or at what decibel level does noise have detrimental

Table 4. The consolidated focal best management practices (BMPs) with general descriptions

BMP category	BMP subcategory	General summary description of BMP	*N* (rank) citations	Final support score
Comprehensive planning	Landscape-development planning	Plan and coordinate early at the landscape level and promote shared infrastructure. Well pad sites and infrastructure should be colocated with existing infrastructure (roads, pipelines, water sources) to minimize surface impacts.	141 (2)	8.6
Constraints mapping	Avoid forested areas	Generally, forested areas should be avoided in favor of open lands to reduce forest fragmentation, changes in storm runoff, protection of stream buffers, and preservation of existing water quality in streams.	148 (1)	8.5
	Avoid aquatic/riparian habitats	Operations should avoid riparian areas, floodplains, lakeshores, wetlands, and areas subject to severe erosion and mass soil movement.	65 (3)	10.0
	Avoid erosion-prone areas	Construction on steep slopes (over 15% or 30%) or highly erodible soils should be avoided. Level areas are preferred for site selection. If these areas cannot be avoided, the access road should be located in a manner that would minimize cuts and fills.	12 (22)	11.4
Erosion control	Buffer strips	A buffer strip of vegetation, width determined on a case-by-case basis, shall be left between areas of surface disturbance and riparian vegetation.	58 (5)	9.3
	Storm-water-control structures	It is strongly recommended to design storm-water-control structures and practices based on a 10 year/24 hour storm, not a 2 year/24 hour storm. This will provide better protection from the effects of larger storms on erosion, sedimentation, and stream stability.	17 (19)	10.4
	Road-construction limitations	Construct roads along the contour of the hillside. Avoid going directly up the slope or exceeding slopes of 15%. Properly space and install waterbars and/or culverts to prevent erosion problems.	23 (13)	10.8
	Erosion-control products	Surface roads within 50 ft of waterways with erosion-resistant materials. Immediately stabilize cut banks and fill by using vegetation, rock, erosion blankets, or other suitable material. Install silt-fence barriers at outlets of drainage structures.	22 (16)	11.0
	Sediment barriers	Use hay, straw bales, or silt fences for sediment barriers in areas where excessive soil loss or sediment loads to a watercourse.	14 (21)	11.4
Infrastructure development	Road location and design	Access roads should be kept out of lowland bottoms, drainages, wet areas, and special status and threatened and endangered species habitat.	23 (13)	10.1
	Road-construction guidelines	Provide proper road drainage and erosion control for all roads. Use the Pennsylvania Dirt & Gravel Road guidelines for construction of permanent nonpaved roads. Ensure the maximum volume, weight, and speed of vehicles on surface roads are marked and enforced.	20 (17)	11.7

(*continued*)

Table 4. Continued

BMP category	BMP subcategory	General summary description of BMP	*N* (rank) citations	Final support score
Infrastructure development (*continued*)	Stream-crossing guidelines	Design road crossings of streams to allow fish passage at all flows and to minimize the generation of sediment.	25 (12)	12.4++
	Dust suppression	Avoid dust-suppression activities within 300 ft of the ordinary high-water mark of any reservoir, lake, wetland, or natural perennial or seasonally flowing stream or river.	4 (28)	12.5++
	Stream-crossing guidelines	Locate and construct all structures crossing intermittent and perennial streams such that they do not decrease channel stability or increase water velocity.	18 (18)	13.0++
	Road location and design	Avoid crossings of wetland and riparian areas by linear features. Avoid road placements that bisect movement pathways (e.g., between wetlands). If a new road must cross a stream, it should be done at a 90° angle.	35 (9)	13.3++
Lighting	Minimize and contain lighting	Direct site lighting downward and internally to the extent possible and avoid uplights and wall washes, as well as lighting where the bulb is visible from the fixture.	23 (13)	3.5**
Noise control	Minimize noise	Reduce noise from industrial development or traffic by using effective sound-dampening devices and techniques or by colocating infrastructure, especially in breeding and brood-rearing habitats.	64 (4)	4.2**
Restoration	Reclaim roads	Design for retirement (minimum compaction). Retire roads not used for regular well access as soon as possible.	44 (6)	8.3
Timing of operations	Seasonal restrictions	Enact seasonal restrictions on drilling and developing in areas with sensitive species (e.g., migration, breeding, or dispersal of sensitive species) or during critical nesting and mating seasons	38 (7)	5.7*
	Seasonal restrictions	Operations should avoid wet seasons and wet periods.	4 (28)	12.9++
Vegetation management	Vegetation removal	Cutting by hand is the preferred method for removing/clearing vegetation. Use of mulchers and all-terrain vehicles should be avoided because they have significant potential to remove threatened and endangered species and introduce/spread invasives.	4 (28)	9.1
	Riparian vegetation	Do not remove native riparian canopy or streambank vegetation where possible. It is preferable to crush or shear streamside woody vegetation rather than completely remove it.	36 (8)	11.2
Wildlife	Bat roost sites	Avoid surface disturbance activities within 0.25 mile of all bat roost sites.	7 (23)	3.4**
	Raptor nest-site buffer	Well pads, access roads, and other aboveground facilities will not be located within 825 ft of an active raptor nest, within 1,000 ft of an active threatened species hawk nest, or within 2,640 ft of any bald eagle nest.	5 (25)	5.4*

(*continued*)

Table 4. Continued

BMP category	BMP subcategory	General summary description of BMP	*N* (rank) citations	Final support score
Wildlife (*continued*)	Breeding-habitat buffer	Although adequate buffer distances are unknown because of the tendency for brooding females and nesting yearling females to avoid gas-field infrastructure, areas designated as suitable breeding habitats need to be buffered from gas-field development.	29 (11)	5.7*
	Road closures	Road closures may be implemented during crucial periods (e.g., wildlife winter periods, spring runoff, and calving and fawning season).	35 (9)	8.4
	Seasonal restrictions	Schedule necessary construction in stream courses to avoid critical spawning times.	16 (20)	12.2^{++}
	Wildlife crossing	Manage pipelines for shrub cover rather than grass, and create forested linkages at intervals across rights-of-way to facilitate wildlife crossings.	6 (24)	17.0^{++}

The *N* indicates number of citations (and rank of BMP from highest to lowest count of citations). Final support score (Equation 2 with possible values ranging from −22 to +22) with **significantly low support ($p < 0.001$), *low support (<25% percentile), and $^{++}$significantly high support (>75% percentile, $p < 0.001$).

Table 5. Summary of relevance ratings for 354 citations related to focal best management practices

	Citation relevance ratings summary							
	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Development type	338	95.5	16	4.5	NA		NA	
Geographic type	123	34.7	94	26.6	99	28.0	38	10.7
Habitat type	59	16.7	81	22.9	114	32.2	100	28.2
Infrastructure type	243	68.6	111	31.4	NA		NA	
Taxonomic	12	3.4	35	9.9	142	40.1	165	46.6

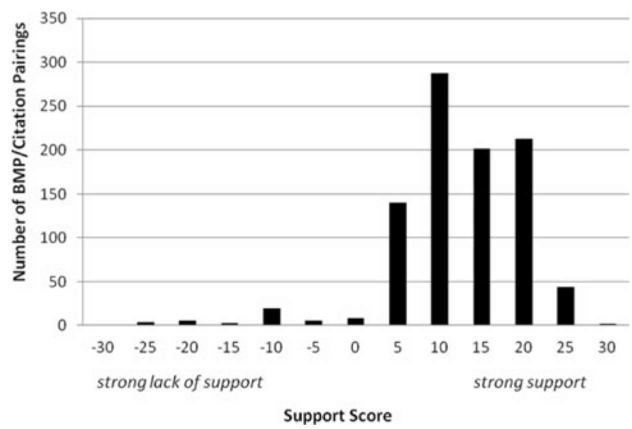

Figure 2. Histogram of strenght-of-support scores for each of 936 best management practice (BMP)/citation pairings. High negative scores indicate the citation does not provide evidence supporting the BMP; high positive scores suggest the citation does provide evidence supporting the BMP.

impacts on key species/populations? Many of these questions are currently unanswered, so much research remains necessary. For this study, we defined support as any literature that agreed with the general spirit of a BMP, and therefore we were unable to test BMPs at this level of detail. In addition, many of the potential surface effects of unconventional gas development cannot be extrapolated from studies on impacts of other types of extraction. If conservation is to be successful, additional assessments in the specific context of Appalachian shale gas development are necessary in order to determine proper thresholds and details of BMPs.

Second, there is relatively little support for a number of BMPs, especially those related to noise and light pollution [and their effects on forested ecosystems (vegetation, wildlife, etc.)]. Noise pollution and light pollution, more than any other BMP topics we reviewed, have only recently been recognized as possibly having a significant impact on wildlife (Baker and Richardson, 2006; Bayne, Habib, and Boutin, 2008; Brumm, 2004; Francis et al., 2010; Kempenaers et al., 2010). The available research shows more evidence of behavioral modifications in response to altered noise and light conditions rather than direct effects on mortality and reproductive success. For example, bats have changed foraging behavior in response to light (Rich and Longcore, 2005; Stone, Jones, and Harris, 2009), birds and mammals have altered avoidance behaviors in response to noise (Barber et al., 2009; Francis et al., 2010; Radle, 2007), and a diverse array of moth species are negatively affected by artificial lights, which can have cascading effects on biodiversity and ecosystem functioning of interior forest communities (van Langevelde et al., 2011). While these findings may have scored relatively low in our support-rating system (i.e., higher support rating for direct evidence of fitness effects and lower support rating for direct evidence of behavioral changes), the cumulative impact on wildlife in response to noise and light is largely unknown. Behavioral changes from noise/light pollution could have significant effects on wildlife populations, for example, when noise pollution or light pollution interferes with breeding, foraging, or predator/prey response (Barber et al., 2009; Rich and Longcore, 2005). Because noise pollution and light pollution might affect these critical elements of population and ecosystem health, we believe more research in these fields is critical so that more informed BMPs can be developed.

Third, several BMPs are particularly well supported by the scientific literature and should be at the center of any set of BMPs used in shale gas development. These include the following:

1. Manage pipelines for shrub cover rather than grass, and create forested linkages at intervals across rights-of-way to facilitate wildlife crossings.
2. Avoid crossings of wetland and riparian areas and crossings that bisect movement pathways (e.g., between wetlands).
3. Locate and construct all structures crossing intermittent and perennial streams such that they do not decrease channel stability or increase water velocity.
4. Avoid operations during wet seasons and wet periods.
5. Avoid dust suppression activities near the ordinary high-water mark of any reservoir, lake, wetland, or natural perennial or seasonally flowing stream or river.
6. Design road crossings of streams to allow fish passage at all flows and to minimize the generation of sediment.
7. Schedule necessary construction in stream courses to avoid critical spawning times.
8. Provide proper road drainage and erosion control for all roads.

In addition, the top two ranking BMPs in terms of quantity of supporting literature ($n_{\text{citations}} > 140$) should also become an important part of shale gas development efforts—namely, colocating infrastructure and using detailed spatial constraints mapping and landscape-level planning to minimize overall landscape impacts.

We believe several courses of action should be advanced to enhance development and implementation of effective BMPs. These actions involve public education, increased communication among scientists, improved data sharing, development of site-specific BMPs, and more industry collaboration and support for conservation BMPs. Educating the public, including informing potential lessors how BMPs can be written into a leasing agreement, is a critical step in ensuring BMP adoption and enforcement. For example, the Nature Conservancy is currently developing public education resources related to BMPs that will be written for a general audience and available online. In addition, other Internet resources, like the Pennsylvania State University (PSU) *Marcellus Field Guide* (Brittingham, Drohan, and Miller, 2012), are being developed to enhance public education. Increased communication among experts in the field is also an important part of enhancing BMP development, and professional conferences, such as the PSU Goddard Forum (Drohan et al., 2012b), should continue to serve as exchange opportunities. Similarly, communication should be enhanced among the private consulting companies hired by the industry and professional research and conservation organizations/universities. For example, significant information that could improve development of effective BMPs has been collected by industry-sponsored consulting companies but cannot be distributed or shared due to confidentiality agreements. Expanding information sharing critical to BMP development, while maintaining only essential confidentiality, could be significantly useful. The development of more intelligent, site-specific BMPs could also be very valuable at directing where and when certain activities can occur. A decision-tree flowchart of critical BMPs would allow more flexibility under certain conditions (e.g., use BMP 1 if condition A, but BMP 2 if condition B) and would provide industry with finer, more site-specific resolution on BMP implementation and also might improve the resulting ecological outcomes.

Finally, it is most critical that the shale gas industry be an active participant and collaborator in research on and development of the BMPs that are to be recommended (and potentially enforced). This collaboration could include improved information sharing or increased funding to support scientific research necessary to better understand ecological impacts from shale gas development. With enhanced industry involvement and cooperation, we may achieve effective conservation of Appalachian forest and aquatic ecosystems while extracting the valuable resources that drive our economy.

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References

Arthur, M.A., G.B. Coltharp, and D.L. Brown. 1998. Effects of Best Management Practices on Forest Streamwater Quality in Eastern Kentucky. *Journal of the American Water Resources Association* 34(3):481–495.

Baker, B.J., and J.M.L. Richardson. 2006. The Effect of Artificial Light on Male Breeding-Season Behaviour in Green Frogs, *Rana clamitans melanota*. *Canadian Journal of Zoology* 84(10):1528–1532.

Bakermans, M., J.L. Larkin, B.W. Smith, T.M. Fearer, and B.C. Jones. 2011, November. *Golden-Winged Warbler Habitat: Best Management Practices for Forestlands in Maryland and Pennsylvania*. American Bird Conservancy, The Plains, VA, 29 pp. Available at http://www.abcbirds.org/abcprograms/domestic/pdf/GWWA_bmp_FinalSmall.pdf (accessed October 20, 2012).

Barber, J.R., K.R. Crooks, and K.M. Fristrup. 2009. The Costs of Chronic Noise Exposure for Terrestrial Organisms. *Trends in Ecology & Evolution* 25(3):180–189.

Bayne, E.M., L. Habib, and S. Boutin. 2008. Impacts of Chronic Anthropogenic Noise from Energy-Sector Activity on Abundance of Songbirds in the Boreal Forest. *Conservation Biology* 22(5):1186–1193.

Brittingham, M., P. Drohan, and D. Miller. 2012. *Marcellus Shale: Electronic Field Guide*. Penn State Cooperative Extension, Penn State College of Agricultural Sciences, Center for Environmental Informatics, University Park, PA. http://www.marcellusfieldguide.org/ (accessed October 20, 2012).

Brown, D., ed. 1993. *Best Management Practices for Silvicultural Activities in Pennsylvania's Forested Wetlands*. College of Agricultural Sciences, Penn State Cooperative Extension, University Park, PA, 52 pp. Available at http://pubs.cas.psu.edu/freepubs/pdfs/uh090.pdf (accessed October 20, 2012).

Brumm, H. 2004. The Impact of Environmental Noise on Song Amplitude in a Territorial Bird. *Journal of Animal Ecology* 73(3):434–440.

Chunko, S.E., ed. 2001. *Best Management Practices for Pennsylvania Forests: Promoting Forest Stewardship through Education, Cooperation, and Voluntary Action*. College of Agricultural Sciences, Pennsylvania State University, University Park, PA, 52 pp. Available at http://pubs.cas.psu.edu/freepubs/pdfs/uh090.pdf (accessed October 29, 2012)

DePhilip, M., and T. Moberg. 2010, November. *Ecosystem Flow Recommendations for the Susquehanna River Basin: Report to the Susquehanna River Commission and U.S. Army Corps of Engineers*. The Nature Conservancy, Harrisburg, PA, 191 pp. Available at http://www.nature.org/media/pa/tnc-final-susquehanna-river-ecosystem-flows-study-report.pdf (accessed October 20, 2012).

Drohan, P., M. Brittingham, J. Bishop, and K. Yoder. 2012a. Early Trends in Landcover Change and Forest Fragmentation due to Shale-Gas Development in Pennsylvania: A Potential Outcome for the Northcentral Appalachians. *Environmental Management* 49(5):1061–1075.

Drohan, P.J., J.C. Finley, P. Roth, T.M. Schuler, S.L. Stout, M.C. Brittingham, and N.C. Johnson. 2012b. Oil and Gas Impacts on Forest Ecosystems: Findings Gleaned from the 2012 Goddard Forum at Penn State University. *Environmental Practice* 14(4) [this issue].

Field, R., A.N. Tafuri, S. Muthukrishnan, B.A. Acquisto, and A. Selvakumar. 2006. *The Use of Best Management Practices (BMPs) in Urban Watersheds*. DEStech, Lancaster, PA, 269 pp.

Francis, C.D., J. Paritsis, C.P. Ortega, and A. Cruz. 2010. Landscape Patterns of Avian Habitat Use and Nest Success Are Affected by Chronic Gas Well Compressor Noise. *Landscape Ecology* 26(9):1269–1280.

Hebblewhite, M. 2008. *A Literature Review of the Effects of Energy Development on Ungulates: Implications for Central and Eastern Montana*. Montana Fish, Wildlife and Parks, Miles City, MT, 125 pp. Available at http://fwp.mt.gov/fwpDoc.html?id=35572 (accessed October 20, 2012).

Houston Advanced Research Center (HARC) and Texas A&M University. 2012. *Environmentally Friendly Drilling Systems*. HARC, The Woodlands, TX; and Texas A&M University, College Station, TX. http://www.efdsystems.org/ (accessed October 20, 2012).

Johnson, D.H., L.D. Igl, and J.A. Dechant. 2004. *Effects of Management Practices on Grassland Birds*. Northern Prairie Wildlife Research Center, Jamestown, ND. Jamestown, ND. http://www.npwrc.usgs.gov/resource/literatr/grasbird/index.htm (accessed October 20, 2012).

Johnson, N., T. Gagnolet, R. Ralls, and J. Stevens. 2011, December 16. *Natural Gas Pipelines: Excerpt from Report 2 of the Pennsylvania Energy Impacts Assessment*. The Nature Conservancy, Harrisburg, PA, 9 pp. Available at http://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/pennsylvania/ng-pipelines.pdf (accessed October 20, 2012).

Johnson, N., T. Gagnolet, R. Ralls, E. Zimmerman, B. Eichelberger, C. Tracey, G. Kreitler, S. Orndorff, J. Tomlinson, S. Bearer, and S. Sargent. 2010, November 15. *Pennsylvania Energy Impacts Assessment: Report 1—Marcellus Shale Natural Gas and Wind*. The Nature Conservancy, Harrisburg, PA; Western Pennsylvania Conservancy/Pennsylvania Natural Heritage Program, Pittsburgh, PA; and Audubon Pennsylvania, Harrisburg, PA, 46 pp. Available at http://www.nature.org/media/pa/pa_energy_assessment_report.pdf (accessed October 20, 2012).

Kempenaers, B., P. Borgstroem, P. Loes, E. Schlicht, and M. Valcu. 2010. Artificial Night Lighting Affects Dawn Song, Extra-Pair Siring Success, and Lay Date in Songbirds. *Current Biology* 20(19):1735–1739.

Kittredge, D.B., Jr., and M. Parker. 1999. *Massachusetts Forestry Best Management Practices Manual*. Massachusetts Department of Environmental Protection, Boston, MA, 56 pp. Available at http://beta.hancocklumber.com/sawmill/sites/all/themes/HancockLumber/files/Massachusetts%20BMP's%20for%20Forestry.pdf (accessed October 20, 2012).

Koehn, S.W., and A. Hairston-Strang. 2009, April. *Forestry Best Management Practices in Maryland: Implementation and Effectiveness for Protection of Water Resources*. Maryland Department of Natural Resources Forest Service, Annapolis, MD, 44 pp. Available at http://www.na.fs.fed.us/watershed/pubs/bmp/09_md_bmp_report.pdf (accessed October 20, 2012).

Leitman, P.L., L.C. Gustafson-Minnich, and D.W. Hall. 1997. *Evaluation of Agricultural Best Management Practices in the Conestoga River Headwaters,* *Pennsylvania: Effects of Pipe-Outlet Terracing on Quantity and Quality of Surface Runoff and Ground Water in a Small Carbonate-Rock Basin near Churchtown, Pennsylvania, 1983–89—Water-Quality Study of the Conestoga River Headwaters, Pennsylvania*. Water-Resources Investigations Report 94-4206. US Geological Survey, Washington, DC, 62 pp. Available at http://pubs.usgs.gov/wri/1994/4206/report.pdf (accessed October 30, 2012).

Maine Forest Service, Department of Conservation. 2004. *Best Management Practices for Forestry: Protecting Maine's Water Quality*. Maine Forest Service, Augusta, ME, 97 pp. Available at http://www.maine.gov/doc/mfs/pubs/pdf/bmp_manual/sec_4.pdf (accessed October 20, 2012).

Marcellus Shale Coalition (MSC). 2012, April 26. *Recommended Practices: Site Planning, Development and Restoration*. MSC, Pittsburgh, PA, 34 pp. Available at http://www.mde.state.md.us/programs/Land/mining/marcellus/Documents/MSC_Recommended_Practices_SitePlanning_Development_Restoration(2012).pdf (accessed October 20, 2012).

McCord, S., R. Grippo, and D. Eagle. 2007. Effects of Silviculture Using Best Management Practices on Stream Macroinvertebrate Communities in Three Ecoregions of Arkansas, USA. *Water, Air and Soil Pollution* 184:299–311.

Michigan Department of Natural Resources (DNR). 2009. *Sustainable Soil and Water Quality Practices on Forest Land*. DNR, Lansing, MI, 79 pp. Available at http://www.michigan.gov/documents/dnr/IC4011_SustainableSoilAndWaterQualityPracticesOnForestLand_268417_7.pdf (accessed October 20, 2012).

National Research Council. 2004. *Adaptive Management for Water Resources Project Planning*. National Academies Press, Washington, DC, 113 pp.

Natural Resources Law Center, University of Colorado Law School. 2012. *Intermountain Oil and Gas Best Management Practices Project*. University of Colorado, Boulder, CO. http://www.oilandgasbmps.org/ (accessed October 20, 2012).

New Hampshire Department of Agriculture, Markets and Food. 2002. *Manual of Best Management Practices (BMPs) for Agriculture in New Hampshire*. New Hampshire Department of Agriculture, Markets and Food, Concord, NH, 41 pp. Available at ftp://ftp-fc.sc.egov.usda.gov/NH/Engineering_pubs/BMPs_NH_Agriculture.pdf (accessed October 20, 2012).

Norris, R.H., J.A. Webb, S.J. Nichols, M.J. Stewardson, and E.T. Harrison. 2012. Analyzing Cause and Effect in Environmental Assessments: Using Weighted Evidence from the Literature. *Freshwater Science* 31(1):5–21.

Pennsylvania Department of Conservation and Natural Resources (PA DCNR), Bureau of Forestry. 2011, April 26. *Guidelines for Administering Oil and Gas Activity on State Forest Lands*. PA DCNR, Harrisburg, PA, 156 pp. Available at http://www.dcnr.state.pa.us/ucmprd2/groups/public/documents/document/dcnr_004055.pdf (accessed October 20, 2012).

Pennsylvania Department of Conservation and Natural Resources (PA DCNR), Bureau of Forestry. 2012. *Natural Gas Development and State Forests: Shale Gas Leasing Statistics. February 2012*. PA DCNR, Harrisburg, PA.

Pennsylvania Department of Environmental Protection (PA DEP). 2012. *PA DEP Oil and Gas Reports: SPUD Data Reports*. PA DEP, Harrisburg, PA.

R Development Core Team. 2012. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. Available at http://www.R-project.org/ (accessed October 20, 2012).

Radle, A.L. 2007. The Effect of Noise on Wildlife: A Literature Review. In *World Forum of Acoustic Ecology*. Fairfield, Australia, 16 pp. Available at http://wfae.proscenia.net/library/articles/radle_effect_noise_wildlife.pdf (accessed October 20, 2012).

Rich, C., and T. Longcore. 2005. *Ecological Consequences of Artificial Night Lighting*. Island Press, Washington, DC, 458 pp.

Simpson, T., and S. Weammert. 2009. *Developing Best Management Practice Definitions and Effectiveness Estimates for Nitrogen, Phosphorus and Sediment in the Chesapeake Bay Watershed*. Chesapeake Bay Program, Annapolis, MD, 822 pp. Available at http://archive.chesapeakebay.net/pubs/BMP_ASSESSMENT_REPORT.pdf (accessed October 20, 2012).

Stone, E.L., G. Jones, and S. Harris. 2009. Street Lighting Disturbs Commuting Bats. *Current Biology* 19(13):1–5.

US Department of Agriculture, Natural Resources Conservation Service. 2010. *American Woodcock: Habitat Best Management Practices for the Northeast, by Scot J. Williamson*. Wildlife Insight, Washington, DC, 10 pp. Available at http://www.timberdoodle.org/sites/default/files/northern_forest_woodcock_bmp_nrcs_wildlife_insight.pdf (accessed October 20, 2012).

US Department of the Interior and US Department of Agriculture. 2007. *Surface Operating Standards and Guidelines for Oil and Gas Exploration and Development: The Gold Book*, 4th edition. BLM/WO/ST-06/021+3071/REV 07. Bureau of Land Management, Denver, CO, 84 pp. Available at http://www.blm.gov/pgdata/etc/medialib/blm/wo/MINERALS_REALTY_AND_RESOURCE_PROTECTION_/energy/oil_and_gas.Par.18714.File.dat/OILgas.pdf (accessed October 20, 2012).

US Environmental Protection Agency (US EPA). 2012. *National Menu of Stormwater Best Management Practices*. US EPA, Washington, DC. http://cfpub.epa.gov/npdes/stormwater/menuofbmps/ (accessed October 20, 2012).

van Langevelde, F., J.A. Ettema, M. Donners, M.F. WallisDeVries, and D. Groenendijk. 2011. Effect of Spectral Composition of Artificial Light on the Attraction of Moths. *Biological Conservation* 144(9):2274–2281.

Wang, L., J. Lyons, and P. Kanehl. 2002. Effects of Watershed Best Management Practices on Habitat and Fish in Wisconsin Streams. *Journal of the American Water Resources Association* 38(3):663–680.

Yates, A., R. Bailey, and J. Schwindt. 2007. Effectiveness of Best Management Practices in Improving Stream Ecosystem Quality. *Hydrobiologia* 583:331–344.

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