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Brook trout distributional response to unconventional oil and gas development: Landscape context matters

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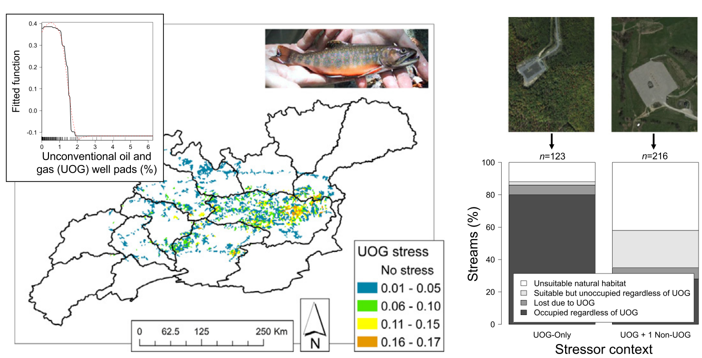
HIGHLIGHTS

- We assessed the role of landscape context in modulating brook trout response to UOG.
- UOG impacted 11% of streams and resulted in a loss of predicted occupancy in 126.
- Streams with a predicted loss of occupancy had intermediate non-UOG stress.
- Model results were supported by pre- and post-UOG disturbance samples.
- Effects of UOG are most relevant in streams with pre-existing habitat degradation.

GRAPHICAL ABSTRACT



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ABSTRACT

We conducted a large-scale assessment of unconventional oil and gas (UOG) development effects on brook trout (*Salvelinus fontinalis*) distribution. We compiled 2231 brook trout collection records from the Upper Susquehanna River Watershed, USA. We used boosted regression tree (BRT) analysis to predict occurrence probability at the 1:24,000 stream-segment scale as a function of natural and anthropogenic landscape and climatic attributes. We then evaluated the importance of landscape context (i.e., pre-existing natural habitat quality and anthropogenic degradation) in modulating the effects of UOG on brook trout distribution under UOG development scenarios. BRT made use of 5 anthropogenic (28% relative influence) and 7 natural (72% relative influence) variables to model occurrence with a high degree of accuracy [Area Under the Receiver Operating Curve (AUC) = 0.85 and cross-validated AUC = 0.81]. UOG development impacted 11% ($n = 2784$) of streams and resulted in a loss of predicted occurrence in 126 (4%). Most streams impacted by UOG had unsuitable underlying natural habitat quality ($n = 1220$; 44%). Brook trout were predicted to be absent from an additional 26% ($n = 733$) of streams due to pre-existing non-UOG land uses (i.e., agriculture, residential and commercial development, or historic mining). Streams with a predicted and observed (via existing pre- and post-disturbance fish sampling records) loss of occurrence due to UOG tended to have intermediate natural habitat quality and/or intermediate levels of non-UOG stress. Simulated development of permitted but undeveloped UOG wells ($n = 943$) resulted in a loss of predicted occurrence in 27 additional streams. Loss of occurrence was strongly dependent upon

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landscape context, suggesting effects of current and future UOG development are likely most relevant in streams near the probability threshold due to pre-existing habitat degradation.

1. Introduction

Production of oil and natural gas using unconventional extraction (i.e., horizontal drilling and high volume hydraulic fracturing) methods has increased nearly 4× and 12× in the last decade, respectively (USEIA, 2017a; USEIA, 2017b). Despite advances in domestic energy production and associated economic benefits, recent research highlights potential ecological impacts related to expanding oil and gas development (Brittingham et al., 2014). This is particularly true for aquatic ecosystems, which can experience impacts to water quality via leaks, spills, and inadequate treatment of produced waters, as well as changes in water quantity due to over-extraction for high volume hydraulic fracturing (Entrekin et al., 2011; Shank and Stauffer, 2014; Vengosh et al., 2014; Barth-Naftilan et al., 2015; Maloney et al., 2017; Patterson et al., 2017). Moreover, expansion of unconventional oil and gas (UOG) infrastructure (e.g., well pads, roads, and pipelines) increases land use disturbance (Preston and Kim, 2016), potentially impacting aquatic habitats by increasing runoff and through a loss of riparian vegetation (Williams et al., 2008; Entrekin et al., 2011).

Recent research has begun to quantify and characterize corresponding effects of UOG on vulnerable aquatic organisms (Brittingham et al., 2014). These efforts have greatly expanded our understanding of direct effects of UOG on diverse aquatic organisms, including biofilm (Johnson et al., 2017), macroinvertebrates (Johnson et al., 2015; Lutz and Grant, 2016), fishes (Dauwalter, 2013), and mammals (Godwin et al., 2015). However, pre-existing land use activities and associated environmental stressors likely mediate any direct and indirect effects of UOG on ecosystems (Smith et al., 2012; Entrekin et al., 2015), resulting in complex biological responses that are dependent upon the context within which new UOG activity occurs (i.e., pre-existing land use stressors and underlying habitat quality). Production of natural gas is projected to increase by two-thirds by 2050 (USEIA, 2017b). Thus, there is a need to develop models capable of predicting context-dependent ecological response to current and future UOG development and to assist in the management (i.e., restoration and conservation) of vulnerable species.

We provide the first such analysis for brook trout (*Salvelinus fontinalis*). Brook trout represent an umbrella species for the conservation of high quality, cold-water habitats throughout its native range. However, brook trout have experienced significant reductions in suitable habitat in the eastern US due to anthropogenic activities (e.g., activities that result in a loss of forested habitat), and remaining populations are extremely vulnerable to habitat degradation and fragmentation that may occur under UOG expansion (Hudy et al., 2008; Smith et al., 2012; Weltman-Fahs and Taylor, 2013). Consequently, our objective was to quantify and evaluate the potential impacts of current and likely future UOG development on brook trout distribution. We first developed a statistical model for predicting brook trout occurrence as a function of natural (e.g., stream temperature) and anthropogenic (e.g., agricultural and UOG development) attributes within the Upper Susquehanna River Watershed, USA. We then used this model to predict and compare brook trout response to existing UOG development occurring within various natural and anthropogenic landscape contexts. We compared model results with observed changes in occurrence via analysis of pre- and post-UOG disturbance samples within existing fish sampling databases. Finally, we predicted context-dependent future effects of UOG on brook trout distribution under a realistic UOG development scenario.

2. Study area

We focused our analysis on the Upper Susquehanna River Watershed in Pennsylvania and New York (Fig. 1). Historic and contemporary conventional oil and gas development are prevalent throughout the study area. UOG has been produced from the Marcellus shale formation since 2006 in Pennsylvania. In contrast, New York State issued a permanent moratorium on UOG production in 2015 after temporarily banning the practice in 2009. The Upper Susquehanna River Watershed contains key intact habitats for eastern brook trout (Hudy et al., 2008). Notably, the study area contains over 2000 km of Class A wild trout streams (Fig. 1). Class A streams are designated by the Pennsylvania Fish & Boat Commission as streams supporting populations of wild trout of sufficient size and abundance to sustain a long-term sport fishery. The study area also represents the headwaters of the Chesapeake Bay Watershed, which receives considerable attention for conservation and restoration science and planning. Relevant to the current effort is the goal of an 8% increase in occupied brook trout habitat throughout the Chesapeake Bay Watershed by 2025 (Chesapeake Bay Program, 2014).

3. Methods

3.1. Landscape and climatic data

We implemented the Spatial Hydro-Ecological Decision System (SHEDS) catchment framework to summarize local (i.e., individual catchments) and upstream (i.e., all upstream flow-connected catchments) landscape and climate attributes within SHEDS-derived 1:24,000 catchment boundaries (O'Neil, 2015). Delineated catchment datasets and scripts for tabulating land cover are available from the ecosheds.org website (http://conte-ecology.github.io/shedsGisData/).

Oil and gas infrastructure data included well pad area (polygon features) road and pipeline extents (line features) as identified and digitized in a geographic information system (ArcGIS, ESRI Inc.) using 2004, 2005/2006, 2008, 2010, and 2013 high-resolution National Agricultural Imagery Program aerial photography (Slonecker and Milheim, 2015). We examined road clearing and pipeline right-of-way widths and determined buffer widths of 10 m and 20 m accurately represented their respective footprints. We overlaid oil and gas infrastructure data with State of Pennsylvania permitting data to characterize well pads as using either conventional or unconventional extraction technologies. Pipelines and roads could not be designated as conventional or unconventional because they often serve both activities. However, the majority (76%) of wells drilled in Pennsylvania following the inception of oil and gas development from the Appalachian basin shale formations were UOG (Maloney et al., 2018). Thus, most land use change documented from pipelines and roads was likely associated with UOG development. Each oil and gas attribute was tagged with the date of first disturbance.

We converted all oil and gas polygon attributes to raster data, which we then integrated into the 2011 National Land Cover Database (NLCD, Homer et al., 2015). We resampled the 30-meter NLCD pixels to 10-meter pixels for better boundary and area correspondence with other, fine-scale data prior to integration. We calculated the area of each land cover and use attribute within the updated NLCD, including UOG and non-UOG attributes. We also calculated the density (no./km^2) of road and pipeline stream crossings. We compiled additional datasets to characterize other anthropogenic and natural landscape and climate