Environmental Pollution 231 (2017) 742–751

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Widespread legacy brine contamination from oil production reduces survival of chorus frog larvae☆

Blake R. Hossack [a,*], Holly J. Puglis [b], William A. Battaglin [c], Chauncey W. Anderson [d], R. Ken Honeycutt [a], Kelly L. Smalling [e]

[a] U.S. Geological Survey, Northern Rocky Mountain Science Center, 790 E. Beckwith Ave., Missoula, MT, 59801, USA
[b] U.S. Geological Survey, Columbia Environmental Research Center, 4200 New Haven Rd., Columbia, MO, 65201, USA
[c] U.S. Geological Survey, Colorado Water Science Center, 1 DFC MS 415, Denver, CO, 80225, USA
[d] U.S. Geological Survey, Oregon Water Science Center, 2130, SW 5th Ave, Portland, OR, 97215, USA
[e] U.S. Geological Survey, New Jersey Water Science Center, 3450, Princeton Pike, Suite 110, Lawrenceville, NJ, 08648, USA

ARTICLE INFO

Article history:
Received 12 May 2017
Received in revised form
18 August 2017
Accepted 18 August 2017

Keywords:
Amphibian
Energy shales
Freshwater salinization
Pollution
Prairie pothole region
Wetland

ABSTRACT

Advances in drilling techniques have facilitated a rapid increase in hydrocarbon extraction from energy shales, including the Williston Basin in central North America. This area overlaps with the Prairie Pothole Region, a region densely populated with wetlands that provide numerous ecosystem services. Historical (legacy) disposal practices often released saline co-produced waters (brines) with high chloride concentrations, affecting wetland water quality directly or persisting in sediments. Despite the potential threat of brine contamination to aquatic habitats, there has been little research into its ecological effects. We capitalized on a gradient of legacy brine-contaminated wetlands in northeast Montana to conduct laboratory experiments to assess variation in survival of larval Boreal Chorus Frogs (*Pseudacris maculata*) reared on sediments from 3 local wetlands and a control source. To help provide environmental context for the experiment, we also measured chloride concentrations in 6 brine-contaminated wetlands in our study area, including the 2 contaminated sites used for sediment exposures. Survival of frog larvae during 46- and 55-day experiments differed by up to 88% among sediment sources (Site Model) and was negatively correlated with potential chloride exposure (Chloride Model). Five of the 6 contaminated wetlands exceeded the U.S. EPA acute benchmark for chloride in freshwater (860 mg/L) and all exceeded the chronic benchmark (230 mg/L). However, the Wetland Site model explained more variation in survival than the Chloride Model, suggesting that chloride concentration alone does not fully reflect the threat of contamination to aquatic species. Because the profiles of brine-contaminated sediments are complex, further surveys and experiments are needed across a broad range of conditions, especially where restoration or remediation actions have reduced brine-contamination. Information provided by this study can help quantify potential ecological threats and help land managers prioritize conservation strategies as part of responsible and sustainable energy development.

Published by Elsevier Ltd.

1. Introduction

Domestic energy production is a national priority for the USA and Canada, resulting in rapid increases in activity in many areas (Fig. 1A). Modern techniques and regulations greatly reduce the chances of environmental damages and waste exposure from oil and gas production. Despite reduced risks, spills still occur at modern production sites, and historical (legacy) energy production sites, where waste disposal practices were less regulated than today, are widespread in many landscapes (Gleason and Tangen, 2014; Lauer et al., 2016; Maloney et al., 2017). Either of these situations can cause environmental contamination with largely unknown effects on aquatic organisms (Cozzarelli et al., 2017; Lauer et al., 2016). Investigating the persistence and potential ecological effects of contamination at legacy energy production sites is important for identifying restoration strategies that can inform responsible and sustainable energy development.

The Williston Basin, in North America's Great Plains, has

☆ This paper has been recommended for acceptance by Maria Cristina Fossi.
* Corresponding author.
E-mail address: blake_hossack@usgs.gov (B.R. Hossack).

http://dx.doi.org/10.1016/j.envpol.2017.08.070
0269-7491/Published by Elsevier Ltd.

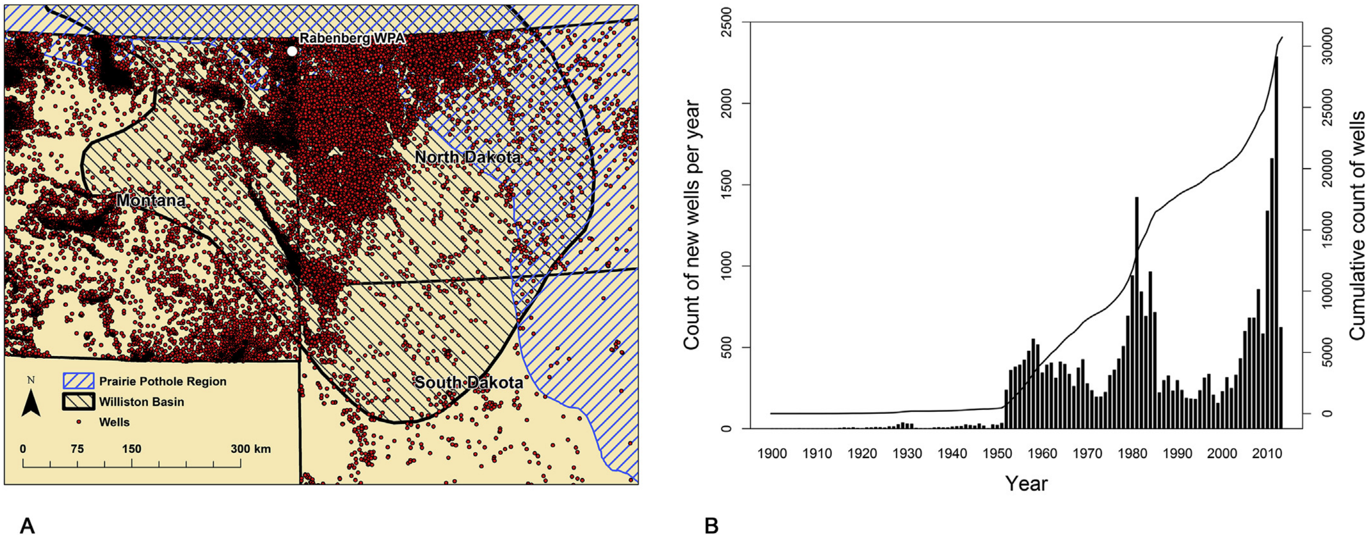

Fig. 1. (A) Distribution of permitted and drilled wells relative to the Prairie Pothole Region (blue hatching) and Williston Basin (black hatching) in Montana, South Dakota, and North Dakota (USA), 1900–2013. (B) Number of newly drilled and permitted oil related wells in the Williston Basin (USA only), 1900–2013 each year (y-axis) and cumulatively (z-axis) (Chesley-Preston, T. 2013. Petroleum related wells in Montana, North Dakota, and South Dakota; https://www.sciencebase.gov/catalog/item/528d0750e4b0c629af455a00). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

experienced an enormous increase in energy production during the last 20 years (Fig. 1A&B). Much of the Williston Basin overlaps with the Prairie Pothole Region, a region densely populated with wetlands that provide numerous ecosystem services and are critical habitat for many aquatic and semi-aquatic species, including waterfowl and amphibians (de Groot et al., 2012; Gleason and Tangen, 2014). As in many other major energy production areas, saline co-produced waters (hereafter, brines) are a byproduct of oil extraction (Cozzarelli et al., 2017; Gleason and Tangen, 2014). The ratio of brine to oil varies spatially and with the age of wells, but it can exceed 14:1 in the Williston Basin (Reiten and Tischmak, 1993). In addition to affecting water quality directly, chemicals in brines can precipitate or become associated with wetland sediments (Beal et al., 1987; Rouse et al., 2013), allowing them to persist long after contaminated water is removed or moves down gradient. Currently, >35% of Prairie Pothole Region wetlands in the Williston Basin are within 1 km of a petroleum-related well (Gleason and Tangen, 2014; Preston and Ray, 2016), which is likely to increase as development continues.

Until the 1970s, most brine from oil extraction in the Williston Basin was stored in unlined reserve pits that often leaked (Beal et al., 1987). Later regulations required a pit liner to prevent seepage, but until the late 1980s, these liners were commonly breached during site restoration (Beal et al., 1987). These brine disposal practices caused persistent contamination of surface and ground water, including on National Wildlife Refuges and other protected lands (Ramirez and Mosley, 2015). Nationwide, there are >5000 wells and >595 pipelines located on National Wildlife Refuge lands; many of these wells are inactive, abandoned, or have unknown status (Ramirez and Mosley, 2015). Today, brine is stored securely and is transported away from active oil fields by pipelines or by truck.

Brines from the Williston Basin and other major shale energy developments often contain high concentrations of total dissolved solids, sodium, and chloride (Lauer et al., 2016; Reiten and Tischmak, 1993). These high chloride concentrations create a distinct chemical signature compared to the ≤10% of regional wetlands that are naturally saline and are characterized primarily by sodium sulfate (Gleason and Tangen, 2014). Brine-contaminated wetlands can be distinguished from naturally-saline wetlands via a locally-developed Contamination Index, which is the ratio of chloride (mg/L) to specific conductance (μS/cm). Contamination Index values > 0.035 generally indicate contamination by brines from produced waters, whereas index values > 0.35 and chloride concentrations ranging from 10,000 to 100,000 mg/L indicate highly-contaminated sites (Preston et al., 2014; Reiten and Tischmak, 1993).

Despite the extensive legacy contamination in some developed oil and gas reserves and potential for contamination in more recently-developed reserves, there has been surprisingly little research into its effects on aquatic and wetland-associated species (Davis et al., 2010; Maloney et al., 2017; Souther et al., 2014), including amphibians in the Williston Basin. Surveys of 10 wetlands in the Williston Basin revealed that taxonomic richness of macroinvertebrates was inversely related to the Contamination Index (Preston and Ray, 2016). In a North Dakota stream affected by a brine spill, 96-hr field exposures to stream water caused reduced survival of larval Fathead Minnows (*Pimephales promelas*) > 6 months after the spill (Cozzarelli et al., 2017). By comparison, there is a large body of literature that shows runoff from road salts and other forms of anthropogenic salinization of wetlands can reduce survival and growth of amphibian embryos and larvae, ultimately simplifying communities (Karraker et al., 2008; Rood et al., 2007; Sanzo and Hecnar, 2006; Turtle, 2000). Importantly, however, negative effects of brine contamination likely extend beyond toxicity from single elements or compounds, because brines can contain lead, chromium, and other toxic heavy metals (Beal et al., 1987; Farag and Harper, 2014).

To help understand the potential effects of brine contamination on amphibians in the Williston Basin, we used a laboratory experiment to assess variation in survival of larval Boreal Chorus Frogs (*Pseudacris maculata*) reared on sediments from 2 moderately brine-contaminated wetlands, a neighboring reference wetland that was minimally contaminated by brines, and sediments from a control site outside of the study area. Boreal Chorus Frogs range from the Southwest USA to the Northwest Territories, Canada, and are the most abundant amphibian throughout much of their range, including in the northern Great Plains (Dodd, 2013; Hossack et al.,