Land Application of Hydrofracturing Fluids Damages a Deciduous Forest Stand in West Virginia

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In June 2008, 303,000 L of hydrofracturing fluid from a natural gas well were applied to a 0.20-ha area of mixed hardwood forest on the Fernow Experimental Forest, West Virginia. During application, severe damage and mortality of ground vegetation was observed, followed about 10 d later by premature leaf drop by the overstory trees. Two years after fluid application, 56% of the trees within the fluid application area were dead. *Fagus grandifolia* Ehrh. was the tree species with the highest mortality, and *Acer rubrum* L. was the least affected, although all tree species present on the site showed damage symptoms and mortality. Surface soils (0–10 cm) were sampled in July and October 2008, June and October 2009, and May 2010 on the fluid application area and an adjacent reference area to evaluate the effects of the hydrofracturing fluid on soil chemistry and to attempt to identify the main chemical constituents of the hydrofracturing fluid. Surface soil concentrations of sodium and chloride increased 50-fold as a result of the land application of hydrofracturing fluids and declined over time. Soil acidity in the fluid application area declined with time, perhaps from altered organic matter cycling. This case study identifies the need for further research to help understand the nature and the environmental impacts of hydrofracturing fluids to devise optimal, safe disposal strategies.

Hydrofracturing is a common method for releasing natural gas stored in layers of rock. Water in mixture with a variety of chemicals, biocides, and other proprietary constituents is injected underground through the drill bore at high pressures to open up small fractures and release the gas (Arthur et al., 2008). Some of these fluids, now mixed with rock fragments, are returned to the surface for disposal. The volume of these hydrofracturing fluids from a single well can range from around 50,000 L to more than 10 million L (Soeder and Kappel 2009). Land application of hydrofracturing fluids is permitted by some states as a means of disposal, among them West Virginia, Arkansas, and Colorado (Arkansas Department of Environmental Quality, 2010; Colorado Oil and Gas Conservation Commission, 2009). However, relatively little information exists in the scientific literature about the effects of these hydrofracturing fluids on natural resources and, in particular, the potential environmental impacts of land application of hydrofracturing fluids.

On 19 to 21 June 2008, approximately 303,000 L of hydrofracturing fluids were applied to an area of about 0.20 ha of mixed hardwood forest on the Fernow Experimental Forest in West Virginia. During application of the fluids, severe damage to ground vegetation was observed by field personnel. About 10 d later, foliage on overstory trees began to exhibit damage and to fall from the trees. This paper describes the effects of this particular land application of hydrofracturing fluids from a conventional natural gas well to a forested area. No pretreatment data were collected. However, postapplication monitoring of such events can provide us with insights about possible effects and help identify pressing research needs.

Materials and Methods

Site Description

The 1902-ha Fernow Experimental Forest (39.03°N, 79.67°W) is located in north-central West Virginia in the Allegheny Mountain section of the mixed mesophytic forest (Kochenderfer, 2006). The Fernow Experimental Forest (Fernow) was established in 1934 by the USDA Forest Service and set aside for forest-related research. Mean annual precipitation averages 145.8 cm, and the average length of the frost-free season is 145 d. Average annual air temperature is 9.2°C (Kochenderfer, 2006). Soils in the study area are Calvin channery silt loams (loamy-

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skeletal, mixed, active mesic typic Dystrudepts). Average soil pH in the surface horizon is 4.0, with about 35% organic matter content (loss-on-ignition) and cation exchange capacity of 15 $cmol_c kg^{-1}$. Vegetation consists of a mixed hardwood stand about 100 yr in age, dominated by a few large oaks (*Quercus* spp.), *Acer rubrum* L., and *Liriodendron tulipifera* L., with the subcanopy composed primarily of smaller *Fagus grandifolia* (Ehrh.), *A. rubrum*, and *Sassafras albidum* (Nutt.) (Table 1). Ground vegetation includes *Vaccinium* L., *Smilax rotundifolia* L., and *Kalmia latifolia* L.

The perimeter of the area with visibly damaged vegetation was marked in early July 2008. At that time, a total of 115 trees (≥2.54 cm diameter at breast height [dbh]) showing damage symptoms within the perimeter (including trees that were part of the perimeter) were individually tagged. Additional trees that developed damage symptoms were identified in summer of 2009 (total of 147 trees within the perimeter). Trees were identified to species level; the dbh was measured; and mortality status, percent defoliation, the presence of sprouting (a stress response), and any other indications of damage or recovery were noted. Trees were considered dead if there was no live foliage during the growing season. In 2009 and 2010, all tagged trees were remeasured and reassessed. No additional trees developed symptoms of damage between the summer of 2009 and the summer of 2010.

Soil samples were collected from the top 10 cm of the soil using a pushprobe. Three transects (~30 m in length) were laid out across the area to which hydrofracturing fluids were applied. Every 4.5 m along each transect, the leaf litter (Oi horizon, generally <2 cm) was gently brushed away, and a soil sample was collected. The samples were composited by transect to give a volume of about 1 L. Three transects were also sampled in an adjacent comparable area that had not received hydrofracturing fluids (reference area). The pushprobe was cleaned between each transect and between the area to which hydrofracturing fluids had been applied and the reference area. Soil samples were air-dried, passed through a 2-mm sieve to remove rocks and woody debris, and split for chemical analysis. Soil samples were collected at five time periods: July and October 2008, June and October 2009, and May 2010.

Soil samples were analyzed at the University of Maine Analytical Laboratory, using their Forest Soils Protocol. Total soil carbon (C) and nitrogen (N) were measured by combustion at 1350°C. Exchangeable acidity was extracted in 1 mol L^{-1} potassium chloride solution and measured by titration. All extractable cations were extracted in 1 mol L^{-1} ammonium chloride solution (1:20 extraction ratio) and measured by ICP–OES. Chloride was extracted in water and measured by ion chromatography.

We asked two questions about the soil chemistry in the fluid application area and the reference areas: (i) Did the soil chemistry differ significantly between the fluid application area and the reference area, and (ii) did the effect(s) change over time? To address these questions, a generalized linear model approach via PROC GLIMMIX (SAS Institute, 2004) was used. In all model runs, fluid application area or reference area (Site), sampling date (Period), and the Site × Period interaction were fixed effects in the model. Replication was a random model effect. To account for the correlation between time periods, an autoregressive order one covariance correlation structure was used to evaluate repeated measures over time.

Results

During land application of the hydrofracturing fluids, field personnel observed damage symptoms on ground vegetation (herbaceous vegetation, small trees, shrubs), including browning and wilting of foliage, leaf scorch and curling, and leaf drop. Within a few days, almost 100% of ground vegetation within the perimeter of the fluid application area had died.

Within 7 to 10 d, overstory trees began showing similar damage symptoms, and many of them dropped their foliage, as evidenced by a large amount of green leaves on the forest floor. Leaf fall mass was estimated to be 714 kg ha^{-1}, or about one quarter that recorded in a normal autumn leaf fall (Adams et al., 2011). The amount of light reaching the forest floor increased significantly as a result; canopy openness was measured as 15%, compared with 7.2% in a nearby reference area (Adams et al., 2011). In 2010, openness was still elevated at 10.3% (T.M. Schuler, unpublished data).

In late spring 2009, 51% of the trees within the perimeter had no foliage. By summer 2010, 2 yr after fluid application, 56% of the trees within the fluid application area were dead. Among the more common tree species within the application area, mortality was highest for *F. grandifolia* and lowest for *A.*

Table 1. Tree canopy characteristics on an area receiving application of hydrofracturing fluid in June 2008, by species or species group.

Tree species	Relative density†	Percentage of dead trees‡		Percentage of trees with ≥75% canopy	
		2009	2010	2009	2010
	%				
Fagus grandifolia Ehrh.	38.7	73.7	73.7	10.5	14.0
Acer rubrum L.	31.9	14.9	23.4	32.5	45.0
Quercus rubra, *Q. prinus*	10.2	40.0	53.3	4.0	20.0
Sassafras albidum (Nutt.) Nees	6.8	60.0	60.0	20.0	35.0
Liriodendron tulipifera L.	4.1	66.7	66.7	0.0	0.0
Betula lenta L.	3.4	100.0	100.0	0.0	0.0
Amelanchier arborea (Michx.) Fernald	2.0	66.7	100.0	0.0	0.0
Oxydendrum arboretum (L.) DC	1.4	100.0	100.0	0.0	0.0
Magnolia acuminata, *M. fraseri*	1.4	50.0	50.0	0.0	50.0

† Density of trees for each species/group expressed as number of trees relative to the total number of trees within the fluid application area.

‡ Percent of trees within the species group that had no live foliage during the growing season.

rubrum. All tree species present on the site were affected (Table 1). Average annual mortality from a nearby reference area was 1.3% (T.M. Schuler, unpublished data). Dead trees ranged from 2.54 to 68.6 cm dbh.

Although variability in soil chemical parameters was high, statistically significant differences between surface soil concentrations of the two sites were detected for Ca, Mg, Al, Mn, Zn, and C/N ratio (Table 2). Statistically significant Site × Period interactions were detected for Na, Cl, and exchangeable acidity. Soils in the fluid application area generally had greater concentrations of extractable bases and lower concentrations of Al, Zn, and Mn. The C/N ratio was greater on the area receiving hydrofracturing fluids. The significant interactions of Site and Period indicate that the difference in soil levels of Na and Cl as well as acidity between the two sites changed over time. In particular, Na and Cl were significantly elevated in surface soils of the fluid application area shortly after application of the hydrofracing fluids, and concentrations remained elevated for almost a year after application (Fig. 1) before declining to levels similar to those in the reference area. Exchangeable acidity also varied significantly by site and time, with concentrations significantly lower on the treated area after about 1 yr (Fig. 2).

Table 2. Mean surface soil (0–10 cm) chemical concentrations for an area receiving hydrofracturing fluids and an adjacent reference area.

Variable†	Reference area	Fluid application area
Ca, cmol kg^{-1}	2.29 (0.28)‡	5.09 (0.77)
Mg, cmol kg^{-1}	0.36 (0.03)	0.56 (0.08)
Al, cmol kg^{-1}	1.86 (0.14)	1.20 (0.16)
Zn, cmol kg^{-1}	0.02 (0.001)	0.01 (0.002)
Mn, cmol kg^{-1}	0.11 (0.01)	0.062 (0.01)
C/N ratio	20.8 (0.23)	22.69 (0.34)

† These variables differ significantly between the two areas at $\alpha = 0.05$.
‡ Numbers in parentheses are SE.

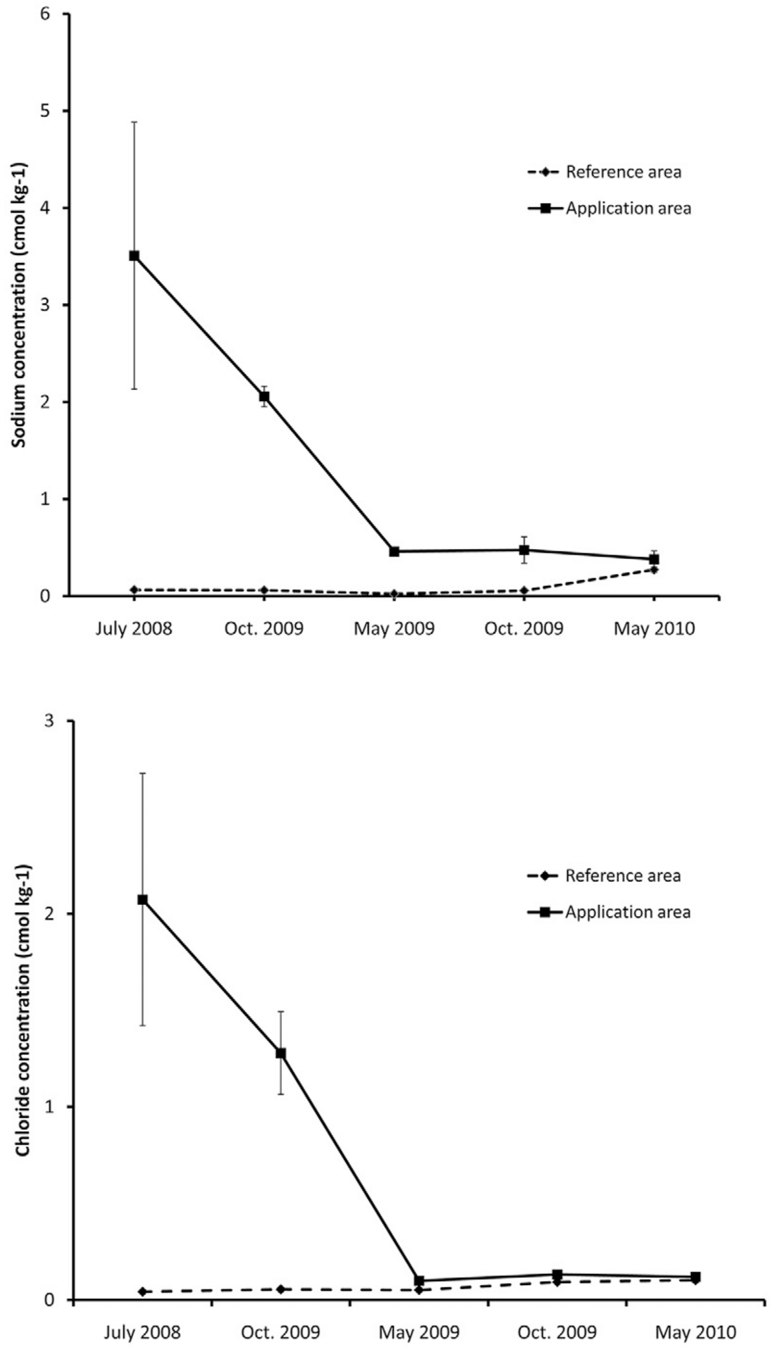

Fig. 1. Mean sodium and chloride concentrations in surface soil (0–10 cm) from fluid application area and reference area measured at several time points after the application of hydrofracturing fluid in June 2008. Vertical bars represent ±1 SE.

Discussion

Land application of hydrofracturing fluids is considered an acceptable form of disposal in several states and is regulated through a permit system. In West Virginia, to be permitted, the well operator must document that the fluids meet the following criteria: <12,500 mg L^{-1} chloride, pH between 6 and 10, and total iron <6.0 mg L^{-1} (West Virginia Office of Oil and Gas General Water Pollution Control Permit; GP-WV-1-88). The Well Operator's Report (filed after completion of drilling) indicated that the concentration of chlorides was 7500 mg L^{-1} and met all the other requirements for land application (Adams et al., 2011). The contents of the hydrofracturing fluids are considered proprietary, and additional information about the contents of the hydrofracturing fluid is not generally publicly available. However, based on the changes in surface soil chemistry over time, we surmised that the main constituents of the hydrofracturing fluids affecting this site were sodium and calcium chlorides, although there may have been other toxic constituents present (Auchmoody and Walters, 1988; DeWalle and Galeone, 1990; Adams et al., 2011).

The land application of hydrofracturing fluid to this forest stand resulted in immediate and longer-term impacts. The immediate impacts were the dramatic damage to ground vegetation (Adams et al., 2011), the rapid increase in concentrations of sodium and chloride in the surface soil within the fluid application area, and the premature leaf drop by overstory trees. At the fluid application site, a number of tree and understory species showed immediate responses to the fluid application, with leaves turning brown and wilting and mortality. Tall trees whose leaves were not likely to have been in direct contact with the fluids began showing symptoms about 10 d after the ground vegetation; these symptoms included leaf browning, leaf curling, and premature leaf drop. From these observations, we inferred that some of the vegetation was damaged almost instantaneously through contact with the hydrofracturing fluids, but many of the overstory trees were killed as a result of uptake of the fluid through roots from the soil. Both mechanisms have been documented in the literature in response to elevated salt levels in spray (Davison, 1971; Munck et al., 2010) or in soils through root contact and uptake (Auchmoody and Walters, 1988). Documented effects on plants occur through osmotic stress, direct toxicity of ions, altered soil pH and availability of nutrients, and altered nutrient balance within the plant (Davison, 1971; Walters and Auchmoody, 1989; Tester and Davenport, 2003).

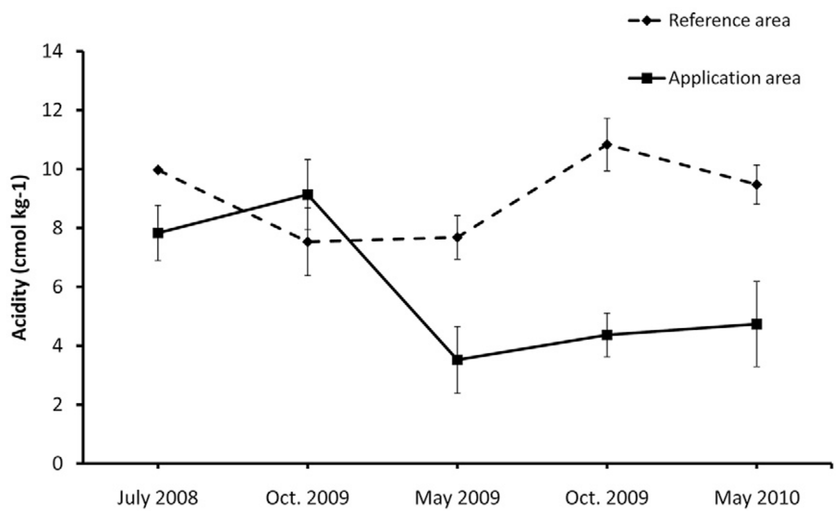

Fig. 2. Mean values of exchangeable acidity in the surface soil (0–10 cm) measured at several time points after the application of hydrofracturing fluid in June 2008. Vertical bars represent ±1 SE.

Over the longer term, mortality and recovery of overstory trees differed among tree species. Differential salt tolerance among tree species has been reported elsewhere (Townsend, 1984; Walters and Auchmoody, 1989; Fostad and Pedersen, 2000; Munck et al., 2010). Auchmoody and Walters (1988) noted that all the hardwood tree species on their site were affected equally by the leaked brine, except for large *F. grandifolia* trees, which were the last to die. In this study, *F. grandifolia* was one of the more affected species. On the Fernow application site, there were no *F. grandifolia* larger than 15 cm dbh, which may explain the discrepancy between both studies. Species believed to be particularly sensitive to elevated soil salt levels include *Tsuga canadensis* (L.) Carriere, *Platanus occidentalis* L., and *Cornus florida* L. (Walters and Auchmoody, 1989; Townsend, 1984). Dochinger and Townsend (1979) reported significant resistance to high salt levels in *A. rubrum*. Also in this study, *A. rubrum* was the least affected tree species (Table 1).

The percentage of trees with more than 75% of a full canopy increased from 2009 to 2010, suggesting some recovery (Table 1). However, most trees with approximately 75% of a full canopy displayed foliar damage (i.e., leaf discoloration, dwarfing of foliage, and dieback) in 2010. Also, basal and stem sprouting, an indicator of plant stress, increased from 6.1% in 2009 to 15% in 2010. Dead *F. grandifolia*, which usually sprouts prolifically in response to cutting or insect-caused mortality (Runkle, 2007), did not sprout from roots or stems.

The decline in soil concentrations of sodium and chloride with time (Fig. 1) is likely due to leaching of these highly mobile ions from the surface horizon as a result of precipitation. The changes in surface soil acidity over time are less easy to explain. These changes in acidity and some of the other significant differences in soil chemistry may relate to the premature leaf drop in early July 2008, which contributed a large pulse of nutrient-rich organic matter. Because the foliage dropped earlier than the usual autumnal leaf fall, concentrations of some nutrients (e.g., N, P, and K) were likely higher than might be found in "normal" autumnal leaf litter, there being little or no translocation of labile nutrients from leaves as usually occurs during autumnal senescence (Aerts 1996). This pulse of organic matter and nutrients earlier in the growing season could potentially result in increased decomposition of the freshly fallen leaves and faster cycling of certain nutrients. Thus, the decreased acidity of the surface soil of the area receiving the hydrofracturing fluids, which became apparent in May 2009, could be a result of increased organic matter and nutrient availability (Noble et al., 1996). Data are insufficient to further evaluate this hypothesis but suggest an area for additional research.

The small area of the fluid application area was selected to minimize the area of forest potentially affected by the fluid application. In retrospect, minimizing the area of application resulted in a larger dose (loading). Nonetheless, the application met the terms of the permit issued by the West Virginia Division of Environmental Protection, Office of Oil and Gas, which is a concentration-based standard. We suggest that a dose-based standard might be considered as a means to provide more protection to vegetation and that research to develop such a standard is a high priority.

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