The value of fracking wastewater treatment and recycling technologies in North Dakota

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ABSTRACT

The oil boom in North Dakota is aided by hydraulic fracturing, often referred to as fracking. Fracking uses a pressurized water, sand, and chemical mixture to break through layers of rock and release oil and gas. This procedure produces hundreds of truckloads of wastewater for each fracked well. In this study, we analyze the financial feasibility of a system of wastewater recycling and reuse to reduce total truck use and to conserve water supplies. We present a spatial mathematical programming model to assess the minimum cost of dealing with the potentially treatable portion of the fracking wastewater that flows back from North Dakota oil wells after fracking. Results of modeling demonstrate that mobile on-site treatment plants would be cost-effective. Both the public and private sectors have incentives to support the development of appropriate recycling technologies.

Key words | Bakken shale formation, fracking, North Dakota, spatial mathematical programming, transportation economics, wastewater recycling

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INTRODUCTION

The development of shale oil and gas formations is expected to provide increased energy supplies, economic development, and environmental challenges in many regions (International Energy Agency 2012). The oil boom in North Dakota's Bakken shale formation is aided by hydraulic fracturing, often referred to as fracking. This technology allows oil and gas to be extracted from hydrocarbon rich oil shale. Fracking uses a pressurized water, sand, and chemical mixture to break through layers of rock and release oil and gas. This technology uses large amounts of water and produces large amounts of wastewater. For example, in 2010, 300 wastewater wells in North Dakota disposed of 132 million barrels of fracking wastewater, also known as flowback (Bjorke 2011; MacPherson 2011).

The large amount of water used in fracking is a concern, given that western North Dakota is a semi-arid region with limited groundwater. Estimated annual water use for the North Dakota oil industry is expected to be nearly 4.24 billion gallons (Harms 2010). This equates to the average quantity of water used for 39,000 American households (Environmental Protection Agency 2014). Furthermore, unlike other water uses, fracking wastewater water in North Dakota remains permanently stored in deep wells and is not returned to the water cycle. In response to these constraints, the Army Corps of Engineers (ACE) proposed a plan to charge drillers for the use of surplus Missouri River water in Lake Sakakawea. However, the plan was temporarily withdrawn in May 2012. The North Dakota State Water Commission, which regulates water use and permits water withdrawals in North Dakota, is opposed to pricing of surplus water (Shaver 2012).

The proper disposal of fracking wastewater is also an issue. Currently, oil drillers in the Bakken region of North Dakota dispose of their drilling wastes primarily in saltwater disposal wells (SWDs) (Figure 1). Although the scarcity of injection wells in Pennsylvania has led natural gas drilling operations in the Marcellus Shale Basin to adopt systems to recycle fracking flowback water, the salinity of Bakken fracking wastewater has made recycling problematic (Stepan *et al.* 2010; Rassenfoss 2011).

In this study, we use a spatial mathematical programing model to assess the minimum cost of dealing with the

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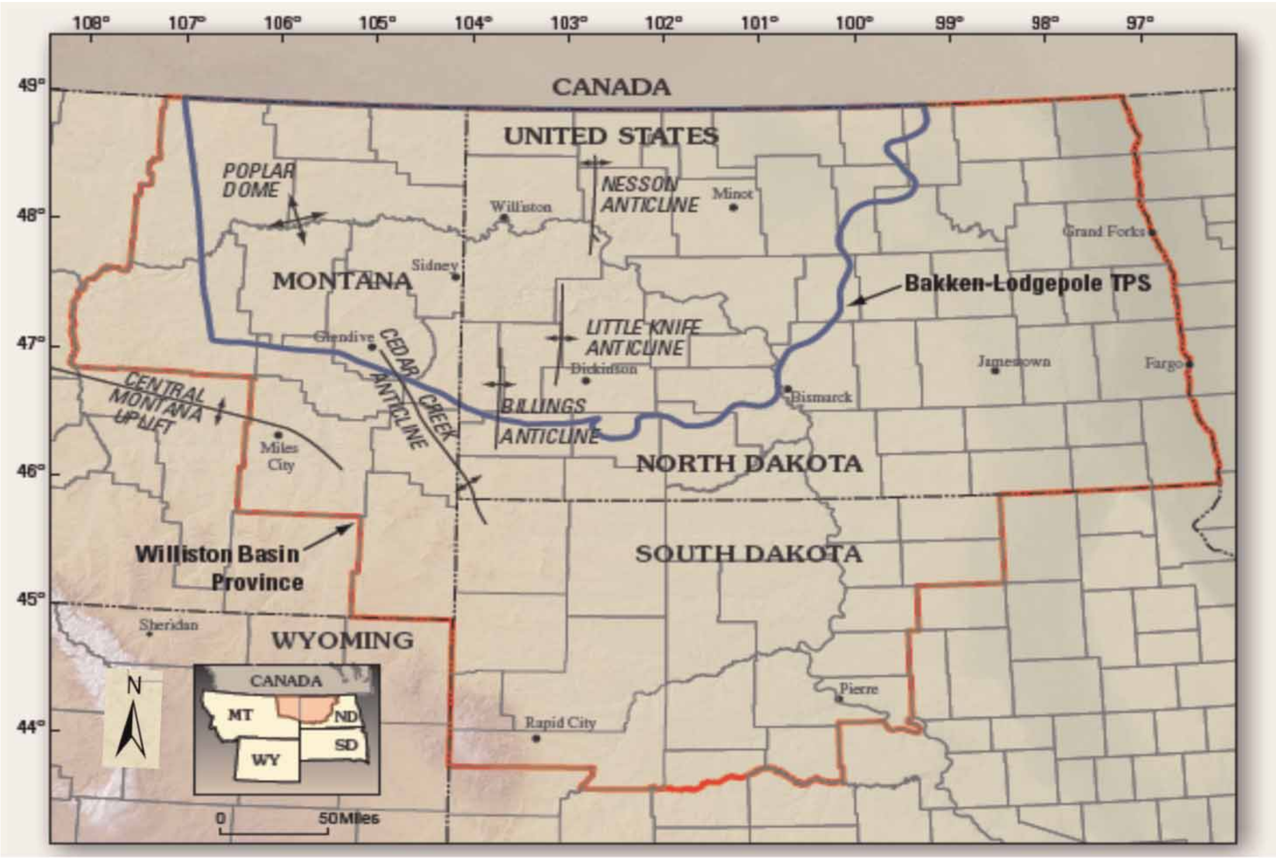

Figure 1 | Map of the Bakken region in the United States. *Source:* US Geological Service (2008).

treatable portion of the fracking wastewater produced from North Dakota oil wells. The results of this analysis can provide an estimate of the financial incentive toward implementing new treatment technology, and although North Dakota is an appropriate case study for the analysis of the feasibility of recycling frack flowback water, the model employed and the results of this analysis should be useful for other locations, including central Europe, China, and Oceana, as the use of fracking expands. Indeed, the realization that different shale gas formations may require different wastewater treatment systems is important as Poland, China, and Australia assess the development of shale formations (Johnson & Boersma 2013; Rahm *et al.* 2013; Vengosh *et al.* 2013; Xingang *et al.* 2013).

We begin with a background discussion on oil drilling and fracking in North Dakota. Subsequently, we present a least-cost spatial optimization model. Finally, we present the parameters used in our modeling analysis and results. Although the appropriate recycling technology that will eventually meet the needs of the Bakken oil producers has yet to be identified, and the associated costs remain speculative, we believe an initial assessment of the financial and environmental benefits of reducing truck transport of fracking wastewater will be useful in water management decisions. We conclude with a discussion of the financial incentives toward developing suitable wastewater treatment and recycling technology.

BACKGROUND

North Dakota has had a productive energy sector for many years prior to the current shale oil boom. North Dakota is one of the nation's leading coal producing states, with four lignite mines and six coal fired electricity generation plants located in the center of the state, just east of the core area of the Bakken. Oil has been produced in North Dakota since 1951. Before the introduction of horizontal drilling and fracking in the 2000s, the peak of oil production occurred during the period of high prices in the 1980s. At that time annual production surpassed 50 million barrels from 1983 until 1985 (one barrel is 0.159 m^3). Production declined to less than 30 million barrels in 1994, 1995, and 2003. Since 2007, and the advent of fracking, annual production has increased to 243 million barrels in 2012, with an all-time high of 770 thousand barrels per day in December 2012. This made North Dakota the nation's second leading oil producing state. Total annual North Dakota oil production revenue reached $20.4 billion in 2012. Production is expected to increase further and may approach Texas' nation-leading output of 1.1 million barrels daily. The four county (McKenzie, Dunn, Mountrail, and Williams) core area of the Bakken in North Dakota accounts for 80% of the state's oil production and 8% of national production (ND Department of Mineral Resources undated; MacPherson 2012; Energy Information Agency 2013, 2014; North Dakota Petroleum Council 2013). Table 1 presents data on oil production and population change in this four county area.

The process of fracking and flowback water retrieval varies widely for North Dakota oil wells. It typically takes 1–2 weeks to hydraulically fracture, or frack, a shale oil formation, but the time varies from a few hours to a month. Water is trucked into the site from one of the 85 permitted water depots in the Bakken region. Different figures are reported for the quantity of water used to frack a well, but 2–3.5 million gallons of water are used in most wells (Schuh 2010; Dalryrmple 2013). A fracking solution of water, sand, and chemicals is mixed in water tanks and injected into the well at high pressure. This solution opens channels in the formation that allow for the release of oil. Often the well is shut in after the frack in order to maintain pressure. Because of pressure in the formation, 10–70% of the water injected returns to the surface without pumping (Environmental Protection Agency 2012a). This initial flowback is mostly wastewater, with high concentrations of dissolved solids, sand, as well as some oil and gas. The remaining water will eventually return in low concentrations with the oil when the well enters production. Flowback wastewater and oil are separated and stored on site in temporary containments for later transport by truck.

The natural gas that is emitted from fracked oil wells is either collected for transport to a processing facility or flared. North Dakota does not have sufficient natural gas pipeline capacity to transport all of its gas to market. In 2011, one-third of natural gas released from oil wells in North Dakota was flared (Energy Information Agency 2011).

Much of this frack flowback wastewater has high salinity and total dissolved solids (TDS) levels, and is considered untreatable. The North Dakota State Water Commission does not permit flowback water to be returned to surface water sources. North Dakota law does allow temporary storage of flowback wastewater for up to 4 days in lined pits. Later, the flowback is trucked to SWDs, which are regulated by the state. SWDs are deep, allowing wastewater to be stored below aquifers, and like production wells, these wells are lined at their shallow depths to protect groundwater sources.

Although there has been controversy over the potential incursion of fracking water into groundwater aquifers, the oil and gas industry has consistently denied any such incursions. In 2005, the industry was granted an exemption from revealing the chemicals used in fracking solutions in the Safe Water Drinking Act (Environmental Protection Agency 2012b). However, in a move to settle this controversy, over 200 oil and gas drillers have voluntarily participated in Frac Focus, an Internet registry of chemicals used in over

Table 1 | Population change in four principle North Dakota oil production counties

County	Dec. 2012 barrels oil production	1990 population	2000 population	2010 population	2020 population (projection)
Dunn	3,751,120	3,980	3,600	3,536	5,254
McKenzie	5,906,015	6,383	5,737	6,630	15,550
Mountrail	6,308,263	6,973	6,631	7,637	13,527
Williams	4,014,066	21,129	19,761	33,398	47,075

Sources: Center for Social Research (2012); US Census Bureau (2001); and North Dakota Energy (2013).

40,000 fracked wells, including more than 2,000 in North Dakota. The US Environmental Protection Agency (EPA) has used these data in a nationwide study of the impacts of fracking (US Environmental Protection Agency 2012).

Truck traffic is becoming a critical concern in the Bakken region. There are an estimated over 2,000 rig-related truck trips per well, including 600 for shipping water and wastewater (Upper Great Plains Transportation Institute 2010). This truck traffic competes with other truck and passenger vehicles that have also greatly increased with the state's growing population and economic activity. The traffic situation is complicated by the many roads in the region that are narrow and unpaved. Table 1 presents population estimates and projections for the four counties in the core of the Bakken production area. County governments have had difficulties maintaining roads. Congested traffic, as well as dust from unpaved roads, has become an important concern. Road dust leads to poor visibility, crop and livestock losses, and human respiratory illness (Davidson *et al.* 2005; Baumgarten 2011). In the core, four-county, area of the Bakken oil region, truck traffic accidents have increased by 483% from 2004 to 2011 (Kubas & Vachal 2012).

There is a scarcity of scientific literature on the impacts of fracking in the Bakken. Most of the concern over the environmental impacts of fracking has focused on natural gas fracking in the more populous Marcellus and Barnett formations in the eastern USA and Texas. Schmidt reviewed the public health issues of fracking in Texas and mentioned that as of 2011, epidemiological studies on health impacts were 'nonexistent' (Schmidt 2011). Colborn *et al.* (2011) assessed potential health impacts of exposure to the chemicals found in fracking fluids. Air pollution from emissions was also discussed. More general policy and regulatory issues were presented by Rahm (2011) and Davis (2012). These authors contrasted the regulatory environments in pro-drilling states such as Texas and more regulated states like Colorado and New York, and Trail (2006) discussed the risks that open pit storage of flowback water and brine present to birds.

In research more closely associated with wastewater management, Vengosh *et al.* (2013) assess the impacts of fracking on water quality in the United States, and concluded that there were expected negative environmental impacts from wastewater management and disposal. These authors mentioned the possibility of seismic activity caused by deep well injection of wastewater. Schmidt (2013) and Rahm *et al.* (2013) reviewed fracking wastewater management in the Marcellus shale formation where much of this wastewater was originally sent to municipal treatment plants. Rahm *et al.* (2013) noted that there was poor management of data on fracking wastewater in Pennsylvania, and identified the promotion of well-regulated on-site treatment technologies as a key to improved wastewater management, and Xingang *et al.* (2013) identified wastewater management as a weakness that needs to be improved in the development of shale gas in China.

In North Dakota, both the State Water Commission (Schuh 2010) and the ACE have produced reports analyzing water needs for fracking in the Bakken (US Army Corps of Engineers Omaha District 2011). Also Stepan *et al.* (2010) have produced studies on flowback and brackish aquifer water treatment. These studies concluded that: (i) large scale recycling and reuse are not feasible under existing technologies; and (ii) reverse osmosis (RO) treatment of brackish groundwater for use in fracking would be feasible in the absence of water from Lake Sakakawea. Also, Stepan *et al.* (2010) stressed that flowback water in the Bakken is more saline with higher concentrates of TDS than Marcellus flowback water. The Upper Great Plains Transport Institute released a report on trucking and road conditions in the western North Dakota oil producing region. This report estimated the required road investments needed to meet the increased transportation demand from oil drilling and production at $907 million over a 20-year period (Upper Great Plains Transport Institute 2010).

In a national study on the potential environmental impacts of fracking on drinking water, the EPA is collecting and analyzing data on toxicity and treatability of flowback water (Environmental Protection Agency 2012a). This study will simulate potential incursions of fracking flowback water into drinking water sources, with case studies in four states. The case study in North Dakota focuses on the impacts of a Dunn County well head explosion in September 2010.

THE MODEL

In order to assess the potential incentives to develop feasible technology to treat and recycle fracking wastewater, we developed a minimum cost-optimization model. Although the parameters used are speculative, we gathered the best information available and used the model to simulate the financial feasibility of a system of wastewater treatment and reuse under alternative treatment costs. The results of this and most other cost-optimization models assume optimal behavior that is never expected, but does provide a baseline for analysis.

Three alternative disposal methods were considered: off-site deep well injection, on-site treatment and recycling, and off-site treatment and recycling. The decision variables in this model are: (i) the disposal method employed; (ii) the location of any off-site treatment plant; and (iii) truckloads of wastewater transported. This model incorporates both treatment and transportation costs, and thus attempts to holistically address the feasibility of alternative approaches. It does not separate the financial incentives to different activities, such as treatment and transportation. Instead, all of these activities are assumed to be implemented by the same contractor. We note that in the Bakken, there are contractors that specialize in water transportation and wastewater disposal.

The minimum cost-optimization model requires the disposal or reuse of all of the frack flowback water that is considered to be treatable.

In the model, let: $i = 1, 2, 3 \ldots\ldots I$ = number of off-site treatment plants; $j = 1, 2, 3 \ldots\ldots J$ = number of on-site treatment plants; $n = 1, 2, 3 \ldots\ldots N$ = number of disposal wells and sites; K = truckloads of wastewater considered to be treatable.

The objective function is to minimize total cost for each well, where

$$\begin{aligned}\text{Totalcost} = &\sum_{i=1}^{I}(TD_i^{\text{off}} + P_i^{\text{off}})\,K_i^{\text{off}} + \sum_{i=1}^{I}(TD_i^{\text{off-B}} - P_i^{\text{rep}})K_i^{\text{off-B}} \\ &+ \sum_{i=1}^{I}(TD_i^{\text{off-SWD}})K_i^{\text{off-SWD}} \\ &+ \sum_{j=1}^{J}(P_j^{\text{on}})K_j^{\text{on}} + \sum_{j=1}^{J}(TD_i^{\text{on-B}} - P_j^{\text{rep}})K_j^{\text{on-B}} \\ &+ \sum_{j=1}^{J}(TD_j^{\text{on-SWD}})K_j^{\text{on-SWD}} \\ &+ \sum_{n=1}^{N}(TD_n^{\text{dis}} + P_n^{\text{dis}})K_n^{\text{dis}},\end{aligned}$$

where T = transportation cost per truckload kilometer; $K_i^{\text{off-B}}$ = number of truckloads to three types of off-site treatment plants and their locations; $K_i^{\text{off-B}}$ = number of truckloads moving from off-site treatment plants to reuse wells; $K_i^{\text{off-SWD}}$ = number of truckloads moving from off-site treatment plants to SWD wells; K_j^{on} = number of truckloads moving to on-site treatment plants; $K_j^{\text{on-B}}$ = number of truckloads moving from on-site treatment plants to reuse wells; $K_j^{\text{on-SWD}}$ = number of truckloads moving from on-site treatment plants to SWD wells; K_n^{dis} = number of truckloads moving to SWD disposal sites; D_i^{off} = distance from the wastewater source location to off-site treatment plants location; $D_i^{\text{off-B}}$ = distance of treated water from off-site treatment plants to reuse wells; $D_i^{\text{off-SWD}}$ = distance of treated water from off-site treatment plants to SWD wells; $D_j^{\text{on-B}}$ = distance of treated water from on-site treatment plants to reuse wells; $D_j^{\text{on-SWD}}$ = distance of treated water from on-site treatment plants to SWD wells; D_n^{dis} = distance from the wastewater source location to SWD wells; P_i^{off} = cost per truckload for three types of off-site treatment plants; P_j^{on} = cost per truckload for on-site treatment plants; P_j^{rep} = cost per truckload for fresh fracking water; and P_n^{SWD} = cost per truckload for disposal sites, and $K = K_i^{\text{off}} + K_j^{\text{on}} + K_n^{\text{dis}}$; $K_i^{\text{off}} = K_i^{\text{off-B}} + K_i^{\text{off-SWD}}$; and $K_j^{\text{on}} = K_j^{\text{on-B}} + K_j^{\text{on-SWD}}$.

PARAMETERS AND METHODS

We use a standard tanker truckload of 8,000 gallons or 30.28 m^3 in our analysis. We reduced all volumetric figures to 30.28 m^3 or 190.5 barrel truckloads. A variety of figures have been reported for the quantity of water used to frack a well. Figures of 2,460–14,800 m^3 per well have been used by the ACE (US Army Corps of Engineers Omaha District, 2011). There are no economies of scale to treatment, and there are no capacity constraints to deep injection wells. Thus, in this analysis, the cost of treating a truckload of fracking wastewater is the same regardless of the quantity treated. We used 12,491 m^3, which equates to 412.5 truckloads or 3.3 million gallons of water, and was the quantity frequently reported in 2012 (Schuh 2010; Stepan et al. 2010; US Army Corps of Engineers Omaha District 2011).

The chemicals in flowback water will vary with the mix used in the fracking solution. Information on the quantity of flowback water that is potentially treatable is limited, but the majority of the wastewater is not suitable for treatment, due to high levels of TDS, and needs to be disposed of in SWDs. However, Stepan *et al.* (2010) present an analysis of flowback from 62 wells. The initial stages of flowback produces recovered water with lower concentrations of TDS, and was therefore more suitable for treatment. Flowback that returns to the surface during later stages has higher TDS concentrations. Stepan *et al.*'s (2010) analysis identified the percentage of flowback water with a TDS level less than 60,000 parts per million (ppm). Although 40,000 ppm is the water quality needed for traditional desalination procedures such as RO, 60,000 ppm was featured in Stepan *et al.*'s report, because it was the cutoff for the data that they received from one operator. Some wells produced no flowback water with TDS less than 60,000 ppm. The median well produced only 5% flowback water with TDS less than 60,000 ppm.

Baker *et al.* (2011) suggest that the initial 5% of flowback retrieved will have sufficiently low TDS to allow for treatment without dilution. However, they claim that retrieval rates up to the first 40% of flowback can be achieved by diluting the flowback with fresh or recycled water, which would reduce the TDS concentration. Dilution would allow a greater percentage of water to be recycled and would provide greater total water savings. These authors recommended that 40% of flowback wastewater should be treated, and where needed, the flowback should be diluted, with fresh or recycled water, in order to reduce the TDS concentration levels to the concentrations suitable for the different recycling technologies. Later stages of flowback would produce wastewater that far exceeds the TDS levels that allow for recycling. This water would need to be shipped directly to SWDs.

The particular technologies that may be used to treat and recycle Bakken flowback water are reviewed in Stepan *et al.* (2010) and Baker *et al.* (2011). These include thermal distillation and membrane filtration. In general, distillation requires significant energy that is often costly. Stepan *et al.* (2010) stress that energy intensive distillation processes might have an advantage in the Bakken, because there is readily available natural gas that is currently flared for lack of transport capacity. All of these processes are more effective with low levels of TDS concentration. This is why only a small percentage of flowback water is suitable for treatment.

RO is a membrane system that is used in most of the world's desalination plants. RO uses pressure to move water through membranes. Electrodialysis uses electric charges to separate ions and force a flow of water through membranes. Mechanical vapor recompression (MVR) is a relatively energy efficient thermal treatment technology that has been used in Texas to recycle Barnett shale frack flowback water. Another potential thermal distillation technology is brine concentration and evaporation (BCE). BCE is a multistage thermal treatment that is claimed to have considerable heat efficiency. The percentage of wastewater treated that can be eventually recycled and reused varies slightly across these technologies. All of these distillation processes, except for BCE, can be placed on flatbed trucks and made mobile. Mobile treatment plants can be transported directly to the recently fracked wells and reduce transportation and labor costs (Baker *et al.* 2011). Mobile treatment plants can be expected to reduce total transportation loads, by eliminating the transportation of wastewater to treatment plants. Recently, a new membrane procedure for treating fracking wastewater, forward osmosis, was assessed with positive results in Louisiana and Texas, but this technology was not considered in the Stepan *et al.*'s (2010) report (Hickenbottom *et al.* 2013). Table 2 summarizes pertinent parameters for four recycling technologies.

Cost information for recycling wastewater is not provided in the Stepan *et al.*'s (2010) report, which concluded that under 2010 technology constraints recycling fracking flowback wastewater was not feasible given high TDS levels in the Bakken. An unpublished report from the Civil Engineering program at North Dakota State University does provide cost estimates from various vendors (Baker *et al.* 2011). This cost information comes from different private vendors trying to sell different products. These estimates are based upon different assumptions, and are not based upon actual operations in the Bakken. Thus, this cost information is somewhat speculative, especially given elevated construction and transportation costs in the Bakken region.

The Stepan *et al.*'s (2010) and Baker *et al.*'s (2011) reports stress the differing capacities of these technologies to handle high concentrations of TDS. If the flowback wastewater is diluted with fresh or recycled water, then this diluted

Table 2 | Recycling costs and parameters use in the model

System type	% Water recovered	$/truckload	% Recovered water recycled	Notes
RO	40%	123	67	Mobility is feasible but price quote is for fixed location, without capital costs. Significant dilution required
ED	40%	52	95	Assumptions not specified. Significant dilution required
MVR	40%	1077	85	Includes equipment lease, operation, and maintenance, 75–95% water recycled. Some dilution required
BCE	40%	295	80	Assumptions not specified, 75–85% water recycled. No dilution necessary

Source: Baker *et al.* (2011).

water could meet the TDS standards applicable to the different technologies. However, this implies greater operating expense for technologies that are designed to desalinate water with relatively low TDS concentrations. Following Baker *et al.* (2011), our analysis focused on two technologies, RO and BCE, with a recovery rate of 40% of the initial frack wastewater. These authors favored a 40% recovery rate, because they considered it to be feasible with dilution, and because it could recycle more water than lower recovery rates.

RO and MVR treatment plants are mobile. This is a great advantage because they can be placed on flatbed trucks and brought to the site of the flowback, and because less untreated water is moved and handled mobile plants can reduce potential damage from wastewater spills. BCE treatment systems require fixed positions, and additional transport and handling costs. In order to simulate the potential location of off-site treatment facilities, we used ArcGIS to place candidate locations for off-site BCE treatment plants in a grid 10 miles apart along roadways (ESRI 2012).

A key parameter is the value of recycled wastewater in fracking. Our analysis uses $120 per truckload as the cost of fracking water (Dalryrmple 2012). We determined this cost from a 2012 newspaper account of the water and water trucking business in the Bakken area. It is within the range of costs presented by Stepan *et al.* (2010).

Deep injection wells are used for final storage of whatever portion of flowback water that cannot be treated and recycled. As of 2012, there were over 330 active deep injection wells in North Dakota. These wells have been in service since before fracking as a means to dispose of produced water from traditional drilling operations. Some of these are abandoned production wells and some are purposefully drilled as deep injection wells. These wells are privately owned by petroleum companies or contractors providing services to the industry and are permitted and regulated by the state (Bjorke 2011). Stepan *et al.* (2010) provide a range of prices for wastewater disposal at these wells. In general, these rates vary by contract, and are unpublished. Our analysis will use $143 per truckload, which was provided by a service provider in 2012 (Power Fuels 2012) and is within the range of rates provided by Stepan *et al.* (2010). Because it is feasible to convert production wells into deep injection wells, there is no foreseen long-term scarcity of deep injection wells (Horwath 2013).

The most critical parameter in the model is transportation cost. Roads in the Bakken are straight and flat, but many are unpaved. Trucking costs would be expected to be atypical of those nationally. A study of North Dakota trucking costs with updated parameters was used to produce an estimate of $1.01 per kilometer for a standard 8,000 gallon tanker. This figure is used by researchers at the Upper Great Plains Transportation Institute (Berwick & Dolley 1997; Dybing 2013).

We used production and deep disposal well locations provided by the North Dakota Department of Mineral Resources to identify a set of 320 wells being drilled on 24 October 2012. Of these, we designated 274 as wells that would be sources of flowback water and 46 as wells that would receive flowback water. We used ArcGIS to calculate road distances between production and disposal wells.

We considered a number of sources to estimate the environmental costs of truck transport. Forkenbrock (2001) estimates the costs of truck freight, including air pollution, noise, social costs of accidents, and unrecovered costs of road use at 13.2% of the financial costs of transportation.

Table 3 | Parameter used in analysis

Parameter	Value	Source
Trucking cost	$1.01/truckload/km	Dybing (2013)
Water replacement cost	$120/truckload	Dalryrmple (2012)
Deep well injection cost	$143/truckload	Stepan *et al.* (2010)
Fracking water quantity	142 truckloads	US Army Corps of Engineers Omaha District (2011)
Frack flowback recovered	57 truckloads	Baker *et al.* (2011)
Off-site treatment cost	$295/truckload	Baker *et al.* (2011)
On-site treatment cost	$123/truckload	Baker *et al.* (2011)
Environmental costs of transportation	33% of financial cost	Santa Cruz County Regional Transportation Commission (2010)
Well locations		ND Department of Mineral Resources undated (2013)

The Santa Cruz County Regional Transportation Commission (2010) estimated the indirect costs of standard vehicle use, including air pollution, noise, social costs of accidents, unrecovered costs of road, and congestion at 39% of direct costs. When parking is excluded from this calculation, the cost is 33% of the financial costs, which is the figure used in this analysis or $0.34 per kilometer. Table 3 summarizes parameters used in the optimization model.

RESULTS

We used the OPTMODEL procedure from SAS to solve the minimum cost-optimization model (SAS Institute 2010). When combined with ArcGIS data on road networks, this procedure can simultaneously solve for the minimum cost size and location of wastewater treatment facilities and transportation routes. At 40% of total flowback, each of the 274 wells being fracked will produce 56.8 truckloads of treatable flowback wastewater or a total of 15,561 truckloads for all 274 wells. In the base case, which uses the parameters as chosen and is presented in Table 4, 98.5% of flowback is treated in on-site mobile treatment plants and 1.5% is treated in off-site treatment plants. In the base case, the total cost of transporting and recycling 15,561 truckloads of treatable flowback was estimated to be $1,525,768. This is a savings over the simulated current cost of $3,728,544 for the 274 wells. This can be aggregated across the 1,933 production wells drilled in North Dakota during 2012 to estimate a total savings greater than $26 million (North Dakota Department of Mineral Resources undated). Thus, although suitable technology has yet to be developed and implemented, such a system would bring a substantial benefit in terms of reduced costs to the industry.

Not surprisingly, we found that on-site RO treatment was the lowest cost technology. On-site treatment implies fewer truck movements and lower transportation costs. RO also has the lowest recycling treatment cost. The only advantage of the off-site BCE system is that a higher

Table 4 | Base case results with comparison to current simulated costs

Scenario	Cost	Before treatment truckloads		After treatment truckloads	
Current	$5,254,312	15,561	To SWD	0	
Base case	$1,525,768	15,333	To small on-site plants	10,273	From on-site to reuse wells
		228	To large off-site plants	5,060	From on-site to SWD
				182	From off-site to reuse
				46	From off-site to SWD

Source: Model simulations. Parameters uses are consistent with Table 3.

percentage of the treated water becomes recycled. BCE has a recycling rate at 80% of wastewater it treats as opposed 67% for RO. This difference was not significant and on-site RO treatment is still the most cost efficient.

The base case focuses on the financial costs of a recycle and reuse system. If the environmental costs to society that are not normally absorbed by the producers are included in the analysis this could possibly modify our results. As noted, the environmental impacts of fracking include: (i) any incidence of fracking fluid leaking into groundwater sources from drilling wells or deep injection disposal wells; (ii) any spills on land of fracking fluid or chemicals; (iii) any incidence to harm to wildlife, especially birds, from contact with surface storage of fracking water or brine; (iv) the environmental costs of the water used in the fracking process; and (v) the environmental costs of transportation of fracking water and wastewater. Of these, only the transportation costs and the opportunity costs of water would be modified by a system of wastewater recycling and reuse. This environmental cost of transportation was included in the model, with an increase in per-mile transportation costs of 33%. However, the original transportation cost of $1.62 per truck mile was sufficiently high that any increase in transportation costs did not have any impact upon the model results. Thus, a simulation with increased transportation costs did not change truck use.

The results of the base-case analysis clearly demonstrate the financial incentives to recycle wastewater from on-site plants, either using membrane or thermal technologies if suitable technologies could be employed, and although RO is the globally preferred desalination technology, with the lowest costs according to Baker *et al.* (2011), this technology has yet to be proven feasible for recycling Bakken frack flowback water. Table 5 presents an analysis of the financial incentives to introduce a mobile recycling system. In this analysis, the possibility of off-site treatment was removed, and the cost of the on-site technology increases by $20 increments starting at $200 per truckload, a 40% increase over reported costs. All other parameters remain the same as the base case. As shown by the results in Table 5, there is a substantial financial incentive to develop mobile technology. However, as the costs of mobile treatment increases beyond $220 per truckload, the quantity of wastewater that would be treated declines substantially and trucking untreated flowback directly to SWDs becomes increasingly more attractive. The highest revenue available to an on-site technology is $3,267,810 at a cost of $210 per track load. This can be aggregated to match the 1933 production wells drilled in North Dakota in 2013 to reach a potential yearly revenue of nearly $24 million. As the cost of on-site treatment increases, the costs savings from recycling is reduced, and the transport of truckloads of flowback water directly to SWDs increases (see Table 5). However, in the absence of a mobile technology that can effectively treat and recycle flowback water at a cost at or below $230 per truckload, there may remain a substantial niche market for more expensive recycling technologies, due to the transportation costs to and from wells that are distant from permitted SWDs.

Table 5 | Revenue to on-site treatment plants under various prices[a]

On-site treatment cost ($/truckload)	On-site treatment truckloads	Truckloads direct to SWD	Total revenue for on-site treatment	Minimum total dollar cost of recycling and reuse
200	15,561	0	3,112,200	2,978,803
210	15,561	0	3,267,810	3,134,413
220	11,970	3,591	2,633,400	3,284,048
230	3,192	12,369	734,160	3,348,083
240	1,482	14,079	355,680	3,370,020
250	684	14,877	171,000	3,379,613
260	342	15,219	88,920	2,383,742
270	342	15,219	92,340	3,390,412
280	285	15,276	79,800	3,393,262
4800	285	15,276	1,368,000	5,163,112
7000	0	15,561	0	5,254,312

[a]No off-site treatment in model. Other parameters remain constant as base case.

CONCLUSIONS AND OBSERVATIONS

The exploitation of shale oil and gas formations will continue in North Dakota and throughout the world. It will bring both economic growth and environmental challenges. The oil boom in western North Dakota has increased economic growth, population, and private and public sector revenue to the state. It is also challenging small prairie communities with unprecedented activity, stretching the region's water resources, and congesting rural roads. Due to the geology of the Bakken region, or because of the political economy of the northern plains region, or a combination of both, the concerns that have initiated public debate about the merits of fracking in the more populated Marcellus shale region of the eastern USA have been mostly absent in North Dakota.

Truck transportation has become a big problem in the Bakken region and our research focuses on this issue. In our study, we demonstrated the financial incentives to develop a system of recycling and reuse of fracking flowback wastewater. Our base-case model results show 98.5% of flowback being treated in on-site recycling facilities under reported costs. This scenario presents substantial saving over current disposal in deep wells. The reported costs used in this analysis are speculative, because the technology suitable for widespread adoption has yet to be developed. Yet results demonstrate that on-site treatment would be used for the large majority of wastewater up to a 47% increase in reported treatment costs. Thus, there is a positive, yet limited, incentive to develop new technologies and to deliver these technologies to the Bakken region where costs may be elevated due to current labor and infrastructure shortages. Our results also demonstrate that with substantially higher costs, there is a significant niche market for recycling systems.

However, a system of recycling and reuse of fracking wastewater would only have a marginal impact upon total truck traffic in the region. At best, only 40% of fracking wastewater is suitable for treatment, and for RO, only 67% of the treated water is suitable for reuse. Thus, only 4.3% of total drilling related truck movements would be made shorter by this proposed recycling and reuse system. Investments in road, rail, and pipeline infrastructure will still be needed in the Bakken region. The estimated annual total savings from a system of recycling and reuse of $26 million is a small fraction of total estimated North Dakota petroleum revenue of $20.4 billion. This demonstrates why it is not a crucial priority to the petroleum industry, which has incentives to reduce costs and reduce truck traffic, but has a priority to frack wells and increase production.

When the environmental costs of transportation, including vehicle emissions, dust, and noise, are included in the model, the simulated truck traffic does not change. However, the reduced truck movements would marginally reduce congestion, traffic accidents, and vehicle emissions. The environmental and community benefits of reduced truck transport from a recycle and reuse system should fuel public support for research to develop desalination technologies suitable for the quality of flowback water that is produced in the Bakken region. The North Dakota Petroleum Council does support research that develops technologies suitable to the Bakken petroleum industry, and adapting recycling technologies would be an appropriate use of these public funds.

Water management is an important concern in North Dakota. The fact that surplus water created with the Lake Sakakawea reservoir is available to North Dakota alleviates much of the concern over any overuse of other water supplies. However, a change in ACE polices may require the oil industry to pay the ACE for water withdrawals. This payment is strongly opposed by the state of North Dakota. However, an increased cost of water supplies for fracking operations could add additional incentive toward the development of recycling technologies that could consequently reduce truck transport.

Although RO is currently used to treat salt and saline water to drinking water standards, the appropriate filters and membranes to treat fracking wastewater have yet to be developed and commercialized. Alternative thermal technologies might have an advantage in the Bakken because of the availability of low-cost natural gas that is now being flared. Our minimum cost-optimization model can most appropriately be used to ascertain the incentive toward developing this treatment technology.

The people of North Dakota have been generally supportive of the oil development in the Bakken region. The positive impacts of the economic boom from oil production include increased wealth, employment, and population. The negative impacts are mostly due to inadequate infrastructure available to handle the growth of activity in the region. Eventually, roads will be built or paved to meet the most pressing needs.

Fracking is a relatively new technology that has been developed to meet the increased demand for petroleum and natural gas. High petroleum prices provided economic incentive to develop this technology. Our research demonstrates the financial incentive to develop new or further develop existing technologies to meet the demand for low--cost ways of recycling fracking flowback wastewater. Similar technologies exist in the Marcellus region, and our research demonstrates incentives to develop these technologies for use in North Dakota.

Both private and public sectors have an incentive to develop and support treatment and recycling technology for the Bakken region. The negative impact of current traffic conditions and the need to conserve water resources should justify public sector investment in this research. North Dakota is a good case study to assess the incentives for developing recycling technologies. However, our modeling procedure for the Bakken region of North Dakota is appropriate for other western states and other regions. As worldwide demand for petroleum and natural gas remain high, it should be expected that fracking will expand. This expansion should increase the need to develop recycling systems for fracking flowback wastewater that are suitable for the particular needs of the region involved.

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