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Produced water reuse for irrigation of non-food biofuel crops: Effects on switchgrass and rapeseed germination, physiology and biomass yield

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ABSTRACT

High volumes of flowback and produced water are generated everyday as a byproduct of hydraulic fracturing operations and shale gas developments across the United States. Since most shale gas developments are located in semi-arid to arid U.S. regions close to agricultural production, there are many opportunities for reusing these waters as potential alternatives or supplements to fresh water resources for irrigation activities. However, the impacts of high salinity and total organic content of these types of water on crop physiological parameters and plant growth needs to be investigated to determine their utility and feasibility. The aim of the present study was to evaluate the response of switchgrass and rapeseed to treated produced water as an irrigation water source. In this greenhouse study, the influence of produced water at four total organic carbon (TOC) concentrations [1.22, 38.3, 232.2 and 1352.4 mg/l] and three total dissolved solids (TDS) levels [400,3,500, and 21,000 mg/l] on rapeseed (*Brassica napus L.)* and switchgrass (*Panicum virgatum* L.), two relatively salt-tolerant, non-food, biofuel crops, was studied. Seedling emergence, biomass yield, plant height, leaf electrolyte leakage, and plant uptake were evaluated. Irrigation water with the highest salinity and TOC concentration resulted in significantly lower growth health and physiological characteristics of both crop species. The organic content of the produced water had a negative impact on biomass yield and physiological parameters of both species. The results of this study could be valuable for regulators and stakeholders in development of treatment standards in which organic matter should be removed to less than 50 mg/l to keep leaf EL (cell damage) to less than 50% and a TOC concentration of less than 5 mg/l required to keep a sustainable biomass production rate.

1. Introduction

Large volumes of the injected water during hydraulic fracturing flows back to the surface with the extracted oil and gas (Esmaeilirad et al., 2015). This water is called flowback at the early well-life stage and produced water later during the life of a well. Approximately 90% of these kinds of water are injected back into the ground in class II wells that are regulated by EPA's *Underground Injection Control* program (Esmaeilirad et al., 2015; Boysen et al., 2011). However, this method has been linked to induced seismic activity and frequent earthquakes in Oklahoma and Texas, states that contain a large number of injection wells (Frohlich, 2012; Nicholson and Wesson, 1990; Ellsworth, 2013; Keranen et al., 2013). Moreover, drought conditions and competition for freshwater consumption, as well as environmental issues such as chemical spills, CO_2 and other greenhouse gas emissions, can result from trucking, the main water transport method for oil and gas operations (Boschee, 2012). Considering the large volume of produced water generated every day across the nation and the projected growth rate of water-intensive biofuel production (International Energy Agency, World Energy Outlook, 2012), using produced water for irrigation may provide a potential alternative to the use of only freshwater resources. High salinity, the total organic matter load, and the presence of toxic organic compounds (e.g., benzene) are the main pollutant constituents in produced water that need to be addressed when considering reuse for irrigation purposes.

In this study, we evaluated the impacts of produced water for irrigation on two non-food biofuel crops, switchgrass and rapeseed. These species can tolerate a broad range of temperature, soil pH, and water salinity conditions, and can grow under salt-stressed,

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Table 1
Organic characteristics of water samples.

Sample	TOC (mg/l)	±SE	Benzene (ug/L)	±SE	Toluene (ug/L)	±SE	Ethyl benzene (ug/L)	±SE	total xylenes (ug/L)	±SE
Irrigation water A	3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Irrigation water B	1.2	0.5	1	0.6	1.2	1.2	0.0	0.0	0.0	0.0
Irrigation water C	38.3	19.2	5.8	2.6	7.3	3.6	0.4	0.3	2.1	1.8
Irrigation water D	232.2	41.3	580	0.0	200	0.0	5.8	0.0	30.0	0.0
Irrigation water E	1352.4	108.5	1632	314.2	888	203.9	50.8	10.7	268.0	59.6

marginal soil conditions (Alexopoulou et al., 2008; Lee et al., 2007; Lynd et al.,1991; McLaughlin et al., 2002; McLaughlin and Kszos, 2005; Sanderson et al., 1996). The salinity of the soil can cause osmotic and specific ion effects (ionic stress) on plant cells that lead to nutrient imbalances affecting important physiological and biochemical processes. These can ultimately inhibit plant growth and development and reduce biomass production (Munns, 2005).

Switchgrass, a native North American, warm-season (C4 metabolism), perennial grass, is rich in natural diversity and adapted to grow over a large portion of the continent with high biomass yield potential, has been targeted for large scale lignocellulosic biomass production (Alexopoulou et al., 2008; Keshwani and Cheng, 2009; Alderson and Sharp, 1995; Chen et al., 2007; Montemayor et al., 2008). With 5–10 year average yields of 12–19 Mg/ha, switchgrass has been at the forefront of biofuel biomass research (Burkhardt et al., 2015). Switchgrass has been adopted to a range of climate and soil conditions from the northern U.S. to the Rocky Mountain regions and Mexico (Moser and Vogel, 1995; Hitchcock, 1971).

Rapeseed, an industrial oil seed crop, is relatively tolerant to stress conditions including saline soils (Ashraf and McNeilly, 1990; He and Cramer, 1992). Grewal (2010) studied the response of wheat, barley (*Hordeum vulgare, cv. Carla INTA*), rapeseed (*Hyola 42*), and chickpea (*Jimbour*) to variable levels of subsoil sodium chloride (NaCl) and determined rapeseed to be the most tolerant to Na^+ of the four crops. In rapeseed damage to plant tissues due to salt intake can appear during all developmental stages including germination, seedling establishment, vegetative growth, and seed production (Porcelli et al., 1995). Salt stress can also damage cell membranes and inhibit photosynthetic functions (Munns and Tester, 2008) in the rapeseed crop.

While the effects of salinity on many edible and non-edible crops are widely reported in the literature, the effects of the high organic content present in produced water on plant growth and physiological characteristics are not well known. The specific impact of shale-gas-produced water on plant health has not been studied. Burkhardt et al. (2015), Mullins and Hajek (1998), and Vance et al. (2008) reported different dilutions of coalbed-methane-produced water used for irrigation. Burkhardt et al. (2015) studied the effect of varying ratios of produced water and municipal water on soil characteristics, and plant biomass and secondary metabolites of sweet wormwood and switchgrass. They found increasing accumulation of Na^+ and salts in the soil with increasing concentration of the produced water. An average produced water Na^+ concentration of 1156 mg/l hampered plant growth.

Mullins and Hajek (1998) treated sorghum-sudangrass in a greenhouse study with varying dilutions of produced and deionized water up to 2000 mg/l total dissolved solids based on limits set by Alabama's Department of Environmental Management for irrigation water salinity, and reported forage yield decreased due to water logging. Vance et al. (2008) studied soil properties and vegetation responses resulting from one to four years of saline-sodic water with an EC range of 1.6–4.8 ds/m applied on native range grasslands, seeded grass hay fields, and alfalfa hay fields during two growing seasons. Biomass production was lower in fields irrigated with coal bed produced water. Zheljazkov et al. (2013) studied the effect of produced water from coal bed methane production on spearmint (*Mentha spicata L.*) and peppermint (*Mentha* × *piperita L.*). The low quality irrigation water adversely affected the soil quality and crop biomass yield by 50%. The characteristics of coal bed methane produced water were greatly different than shale gas produced water (Burkhardt et al., 2015), and the TOC concentration had not been noted.

The aim of the present study was to evaluate the response of switchgrass and rapeseed to treated produced water as an irrigation water source. Given how little is known about the effects of shale oil/gas produced water on plant growth and the growing interest to reuse produced water in irrigation, it is paramount that we understand its effects on soil accumulation and plant health.

2. Material/methods

2.1. Water treatment processes

To adjust the TDS and TOC concentrations of produced water to the four treatment levels, dilution with CSU (Colorado State University) tap water and/or chemical treatment processes was used. Treatment processes. Water quality of CSU tap water is derived from the surface water and is given in Tables 1–3 . Oxidation of Fe^{+2} to Fe^{+3}, electrocoagulation (Water Tectonic, Everett, WA), solid-liquid separation process (dissolved air flotation followed by hollow fiber membrane ultrafiltration (Mann + Hummel, Germany), granular activated carbon for organic matter removal were used to treat the produced water samples.

2.2. Water characteristics

The produced water used in this study was taken from a commercial central processing facility that serves over 500 wells in the Denver-Julesburg Basin. Typically these water samples have high TOC concentrations (>2000 mg/l) and TDS values in the range of 20,000–25,000 mg/l. In order to study the individual effects of these parameters on plants, best and worst case scenarios were defined representing high TDS-TOC and low TDS-TOC, respectively. Also,

Table 2
Cationic characteristics of water samples.

Sample	Na (mg/l)	±SE	K (mg/l)	±SE	Ca (mg/l)	±SE	Mg (mg/l)	±SE	SAR (mg/l)	±SE	Sr (mg/l)	±SE
Irrigation water A	3.6	0.0	0.8	0.0	14.4	0.0	1.8	0.0	1.8	0.0	<0.1	0.0
Irrigation water B	50.0	9.8	5.3	0.4	10.5	0.4	2.1	0.1	5.2	0.9	NA	NA
Irrigation water C	1275.0	246.6	119.0	42.1	13.0	0.8	13.1	2.1	84.2	15.4	0.3	0.1
Irrigation water D	1500.0	408.3	21.0	5.7	61.0	11.4	9.1	1.6	65.6	12.2	NA	NA
Irrigation water E	5175.0	1379.5	100.0	4.1	207.5	8.7	27.8	1.3	127.6	34.9	37.0	0.8