

Coal-Bed Methane Water Effects on Dill and Its Essential Oils

Shital Poudyal, Valtcho D. Zheljzkov,* Charles L. Cantrell, and Thijs Kelleners

Abstract

Pumping water from coal seams decreases the pressure in the seam and in turn releases trapped methane; this is the most common and economic method of methane extraction. The water that is pumped out is known as “coal-bed methane water” (CBMW), which is high in sodium and other salts. In the past 25 yr, the United States has seen a 16-fold increase in the production of coal bed methane gas, and trillions of cubic meters are yet to be extracted. There is no sustainable disposal method for CBMW, and there are very few studies investigating the effects of this water on plants and their secondary metabolites and on soil properties. This study was conducted to determine the effects of CBMW on soil chemical properties and on the biomass and essential oil yield and composition of dill (*Anethum graveolens* L.). This crop was grown in a greenhouse and was subjected to different levels of CBMW treatment: tap water only; 25% CBMW, 75% tap water; 50% CBMW, 50% tap water; 75% CBMW, 25% tap water; and 100% CBMW. The major dill oil constituents, limonene and α -phellandrene, were not affected by the treatments; however, the concentration of dill ether increased with increasing CBMW levels, whereas the concentration of carvone decreased. In soil, sodium level significantly increased with increasing level of treatment, but pH and cation exchange capacity were not much affected. Coal bed methane water could be used for irrigation of dill for one growing season, but longer-term studies may be needed to clarify the long-term effects on soil and plant.

Core Ideas

- Coal-bed methane production results in coproduced waste water, also called CBMW.
- Sustainable disposal of CBMW is a challenge.
- We determined the effect CBMW on soil and on the biomass and essential oil composition of dill.
- CBMW increased dill ether but reduced carvone in the oil; biomass and oil yields were not affected.
- CBMW increased electrical conductivity and Na but not pH or cation exchange capacity.

METHANE is a natural gas that is mainly extracted from coal seams. Pumping water out of coal seams decreases pressure, which in turn releases trapped methane gas from the seam along with the water being pumped out (Mary and Gurney, 2001). This water, also called “coproduced water” or “coal-bed methane water” (CBMW), contains high amounts of sodium, bicarbonate, and other salts and is considered waste water by the USEPA; therefore, it is considered to be unsuitable for agricultural purposes (Stearns et al., 2005; Huang and Natrajan, 2006). In the United States, production of coal-bed methane gas rose from 2.57 billion m³ in 1989 to 41.529 billion m³ in 2013. The probability for greater production of methane and the associated greater discharge of CBMW exists because the United States still holds 1.5 trillion m³ of unreleased methane gas. An average coal-bed methane well discharges about 45 L CBMW min⁻¹ (Young, 2005; Energy Information Administration, 2015), and usually there are many wells operating at a single site. Coal-bed methane water is generally disposed of by evaporation ponds or by direct discharge into streams, both of which are unsustainable. Coal-bed methane water degrades soil structure, depletes microorganisms and their action in soil, reduces vegetation density, and pollutes ground water. Apart from these detrimental effects, there is evidence suggesting an increase of salt-tolerant vegetation around CBMW-affected areas (Stearns et al., 2005; Sowder et al., 2010). The latter increases the possibility for sustainable disposal of CBMW through irrigation of some salt-tolerant crops.

There are grower-reported statements of CBMW use to irrigate different species of forage in Wyoming and Montana, but these lack documentation. High sodicity and salinity, the major attributes of CBMW, affect plants by increasing osmotic stress, which in turn causes hormonal imbalance and retards the growth of plants (Parida and Das, 2005), but there is very little evidence of the effects of manipulating this water before irrigating plants. Zheljzkov et al. (2013) studied the impact of different levels of CBMW (0% CBMW [tap water only], 25% [25% CBMW, 75% tap water], 50% [50% CBMW, 50% tap water], 75% [75% CBMW, 25% tap water], and 100% CBMW) on spearmint

Copyright © American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. 5585 Guilford Rd., Madison, WI 53711 USA. All rights reserved.

J. Environ. Qual. 45:728–733 (2016)

doi:10.2134/jeq2015.05.0215

Freely available online through the author-supported open-access option.

Received 4 May 2015.

Accepted 6 Nov. 2015.

*Corresponding author (Valtcho.Jeljzkov@oregonstate.edu; Valtcho.pubs@gmail.com).

S. Poudyal, Plant Sciences Dep., Univ. of Wyoming, 1000 University Ave., Laramie, WY 82071; V.D. Zheljzkov, Oregon State Univ., Columbia Basin Agricultural Research Center, Oregon State Univ., 48037 Tubbs Ranch Rd., P.O. Box 370, Pendleton, OR 97801; C.L. Cantrell, USDA–ARS, NPURU, University, MS 38677; T. Kelleners, Univ. Wyoming, Ecosyst. Sci. & Manag. Dep., Univ. of Wyoming, 1000 University Ave., Laramie, WY 82071. Assigned to Associate Editor Tsutomu Ohno.

Abbreviations: CBMW, coal-bed methane water; FID, flame ionization detector.

(*Mentha spicata* L.) and peppermint (*Mentha × piperita* L.) growth and secondary metabolites. The authors found that these treatments did not change peppermint total phenols, total flavonoids, or antioxidant activity, but herbage yield was affected at higher CBMW rates. Similarly, in spearmint, different levels of CBMW treatment had no significant impact on oil content, oil yield, or antioxidant activity, but there were significant differences in herbage yields. In a 2-yr field study, Burkhardt et al. (2015) compared irrigation with CBMW and municipal (tap) water on yields and ethanol production from corn (*Zea mays* L.), switchgrass (*Panicum virgatum* L.), spearmint (*Mentha spicata* L.), Japanese cornmint (*Mentha canadensis* L.), lemongrass [*Cymbopogon flexuosus* (Nees ex Steud.) J.F. Watson], and common wormwood (*Artemisia vulgaris* L.). The authors found that the accumulation of plant chemicals (essential oil) in lemongrass and in spearmint was affected by the use of CBMW. In 2012, CBMW increased the concentration of limonene in Japanese cornmint essential oil and the concentration of α -pinene in common wormwood essential oil, whereas in 2013, CBMW decreased the concentration of citral in lemongrass essential oil. Overall, the authors concluded that CBMW can be used for short-period (2 yr) irrigation of field crops. For longer periods, CBMW may need to be diluted with good-quality water to avoid deleterious effects on soil and crops (Burkhardt et al., 2015).

Dill biomass and essential oil are used in food, beverage, and pharmaceutical products (Larijani et al., 2012; Tian et al., 2012). Previous research suggests that as soil salinity increased to 12 dS m⁻¹, the yield of dill essential oil also increased, possibly because of secretion of secondary metabolites at higher rates during stress (Ghassemi-Golezani et al., 2011). The effect of CBMW alone and with different combinations of tap water on oil content, oil constituents, and fresh biomass of dill has not been studied. Therefore, the objective of this study was to determine the effect of various combinations of CBMW and tap water on the biomass, essential oil yields, essential oil composition, and effect on soil properties of dill grown in a greenhouse, where all parameters can be manipulated.

Materials and Methods

Plant Materials and Growing Conditions

This experiment was conducted in a greenhouse at the University of Wyoming Sheridan Research and Extension Center. The temperature for the entire period of growth (70 d) was maintained at around 18°C during the night and around 26°C during the daytime; these temperatures are known to be the best growing conditions for dill (Wright, 2005). Humidity was maintained around 50 to 60% for the entire growth period. Dill seeds ('Bouquet') were from Ferry Morse Seed Company. Seeds were planted in pots (volume, 11.4 L; diameter, 28 cm) on 19 July 2014. Before planting, drain holes in the bottom of the pots were covered with a double layer of filter paper to prevent soil seepage, and pots were filled with normal field soil (10 kg per pot) from the Sheridan Research and Extension Center at Wyarno site. Fresh and untreated CBMW was hauled weekly from the CBMW treatment site of BeneTerra in Sheridan, WY (Table 1), and irrigation treatments began on 30 July. There were five different water treatments in six replications. The water

Table 1. Properties of coal-bed methane water used in the greenhouse study with dill.

General parameters	CBMW†	Method used
pH	8.83	SM 4500 H B
Electrical conductivity, $\mu\text{mhos cm}^{-1}$	2183	SM 2510B
Total dissolved solids (180), mg L ⁻¹	1300	SM 2540
Alkalinity, total (as CaCO ₃), mg L ⁻¹	1193	SM 2320B
Hardness, Ca/Mg (as CaCO ₃), mg L ⁻¹	16.3	SM 2340B
Nitrogen, ammonia (as N), mg L ⁻¹	ND‡	EPA 350.1
Sodium adsorption ratio	59.8	calculation
Anions, mg L ⁻¹		
Alkalinity, bicarbonate as HCO ₃	1280	SM 2320B
Alkalinity, carbonate as CO ₃	86	SM 2320B
Chloride	7	EPA 300.0
Nitrate + nitrite as N	ND	EPA 300.0
Sulfate	ND	EPA 300.0
Cations, mg L ⁻¹		
Calcium	4	EPA 200.7
Magnesium	1.3	EPA 200.7
Sodium	555	EPA 200.7
Cation/anion-milliequivalents, meq L ⁻¹		
Bicarbonate as HCO ₃	21	SM 1030E
Carbonate as CO ₃	2.873	SM 1030E
Hydroxide as OH	ND	SM 1030E
Chloride	0.196	SM 1030E
Fluoride	ND	SM 1030E
Nitrate + nitrite as N	ND	SM 1030E
Sulfate	ND	SM 1030E
Calcium	0.19	SM 1030E
Magnesium	0.12	SM 1030E
Sodium	24.2	SM 1030E
Cation/anion balance		
Cation sum, meq L ⁻¹	24.5	SM 1030E
Anion sum, meq L ⁻¹	24.1	SM 1030E
Cation-anion balance, %	0.87	SM 1030E
Radiochemistry		
Radium 226 (dissolved), pCi L ⁻¹	0.3 ± 0.2	SM 7500-Ra B
Dissolved metals, mg L ⁻¹		
Aluminum	ND	EPA 200.7
Antimony	ND	EPA 200.8
Arsenic	ND	EPA 200.8
Barium	0.33	EPA 200.8
Beryllium	ND	EPA 200.7
Boron	0.2	EPA 200.7
Cadmium	ND	EPA 200.8
Chromium	ND	EPA 200.7
Copper	ND	EPA 200.8
Iron	ND	EPA 200.7
Lead	ND	EPA 200.8
Manganese	ND	EPA 200.7
Mercury	ND	EPA 245.1
Nickel	ND	EPA 200.7
Phosphorus	ND	EPA 200.7
Selenium	ND	EPA 200.8
Zinc	ND	EPA 200.7

† Coal-bed methane water.

‡ Not detected.

treatments were as follows: 0% CBMW (tap water only), 25% CBMW (25% CBMW plus 75% tap water), 50% CBMW (50% CBMW plus 50% tap water), 75% CBMW (75% CBMW plus 25% tap water) and 100% CBMW. The soil was a sandy loam with 71% sand, 20% silt, and 9% clay). On the top, 1 to 1.5 cm of commercial growth medium (Sunshine Mix, Sun Gro Horticulture Canada Ltd.) was applied to retain moisture for the germination of dill seeds. Tap water was applied to all of the pots until emergence of dill seedlings; once all pots showed sufficient emergence, seedlings were thinned to 10 vigorous plants per container. At the beginning of the experiment, 600 mL of water was applied every other day. After 1 mo, 600 mL of water was applied daily, but the amount was adjusted during high evaporation or cloudy days to maintain the desired moisture in the soil. For fertilization, urea for nitrogen, murate of potash for potassium, and phosphate for phosphorus were mixed (20–20–20 N–P–K) and applied every 2 wk, maintaining 0.3 g of total mixture per pot. Fertilization was stopped 2 wk before harvest (Joseph and Stephen, 2012). Containers in the greenhouse were moved every 10 to 12 d to achieve complete randomization in the experiment. Dill plants were grown for a total of 70 d. Insecticidal soap (a.i., potassium salt of fatty acid; 10 mL L⁻¹) and malathion (a.i., organophosphate; 10 mL L⁻¹) were used to control aphids on plants.

Harvesting and Extraction

Harvesting was done when most of the plants reached flowering stage by hand harvesting of all the plants using secateurs at 4 to 5 cm above the soil surface. Fresh biomass yield was recorded at harvest. Due to insufficient biomass for extraction of essential oil, Rep1 and Rep2, Rep3 and Rep4, and Rep5 and Rep6 of each treatment were combined to form three replications in total. All analyses were performed on these three replications. Essential oil was extracted by cutting the entire dill plants from the combined replications into small pieces (3–4 cm), mixing the pieces in a dishpan, and then selecting 400 g of a biomass sample for distillation. To extract the essential oil, the fresh biomass samples were subjected to steam distillation in a 2-L steam distillation unit (Heartmagic) (Gawde et al., 2009) for 45 min. The essential oil was collected in vials and measured on an analytical scale (model SI64, Denver Instrument Co.).

Soil Sample Analysis

After completion of the study and immediately after harvest, three replications from each treatment were randomly selected for soil sample analysis. The soil samples were taken from 15 cm depth, dried, and sent to American Agriculture Laboratory Inc., McCook, NE, for analysis. All of the analysis were performed following the procedures as described in Brown (1998). Specifically, soil pH was measured in soil slurry potentiometrically using an electron pH meter (Watson and Brown, 1998), and soil electrical conductivity was measured using 1:1 soil/water dilution method (Whitney, 1998). Soil organic matter was determined using the loss of weight on ignition method (Combs and Nathan, 1998). Potassium was determined by the NCR-13–exchangeable K procedure (Warncke and Brown, 1998), Ca and Mg were determined by atomic absorption, Na was determined by emission (Warncke and Brown, 1998), and cation exchange capacity was calculated using those values.

Gas Chromatography Flame Ionization Detection: Essential Oil Quantitative Analysis

Nine constituents were identified and quantified in dill herb essential oil. Essential oil samples were analyzed by gas chromatography flame ionization detection on an Agilent 7890A GC system equipped with an Agilent 5975C inert XL MSD with triple axis detector and an Agilent 7693 autosampler (Agilent Technologies, 2010). A DB-5 fused silica capillary column (30 m × 0.25 mm; film thickness, 0.25 μm) was used and operated using the following conditions: injector temperature, 240°C; column temperature, 60 to 120°C at 3°C min⁻¹, then held at 240°C at 20°C min⁻¹ for 5 min (helium was used as carrier); injection volume, 1 μL (split ratio 50:1); flame ionization detector (FID) temperature, 300°C. Postcolumn splitting was performed so that 50% of sample would proceed to FID and 50% to mass spectrometry detection.

The compounds D-limonene, α-pinene, myrcene, α-phellandrene, p-cymene, dill ether, cis-dihydrocarvone, trans-dihydrocarvone, and carvone were identified in the essential oil samples by Kovat analysis (Alencar et al., 1990) and comparison of mass spectra with those reported in the NIST mass spectra database from NIST mass spectral library. Compounds were quantified by performing area percentage calculations based on the total combined FID area. For example, the area for each reported peak was divided by the total integrated area from the FID chromatogram from all reported peaks and multiplied by 100 to arrive at a percentage. The percentage of a peak is a percentage relative to all other constituents integrated in the FID chromatogram.

Statistical Analysis

The effects of the different levels of CBMW (0, 25, 50, 75, or 100%) on plant height, plant weight, essential oil yield (weight and percent of total oil), essential oil constituents, and various soil properties were analyzed using the GLM procedure of SAS 9.4 (SAS Institute, 2013) for three combined replicates. A completely randomized design was followed. Equality of variances was checked using Hartley's Table at α 0.05 level of significance, and residuals were verified for normality. Multiple means comparison was performed using Duncan's multiple range tests at a 5% level of significance. Some values that did not meet equality of variances were transformed to squared root to achieve equality of variances and normality of residuals. To report the results after the analyses, these transformed values were back transformed to the original values by squaring the means of the transformed values.

Results

The studied levels of CBMW had varying effects on soil properties and oil constituents. Some of the essential oil constituents (α-pinene, myrcene, α-phellandrene, p-cymene, and cis-dihydrocarvone) and one of the major oil constituents (limonene) were unaffected by the treatment and showed no significant rise or decline in their content. Two other major essential oil constituents, dill ether and carvone, including trans-dihydrocarvone, were influenced by the treatments. Dill ether content was statistically similar at 0 and 25% CBMW and increased at 50% CBMW; there was a slight decrease at 75% CBMW and another increase at 100% CBMW. In contrast, carvone and

trans-dihydrocarvone concentrations were initially high and gradually decreased with increasing levels of CBMW; their levels were lowest at 100% CBMW (Table 2).

Among the analyzed soil variables, only soil pH, cation exchange capacity (which is determined mainly by the soil texture and soil minerals), and base saturation did not change with treatment; all other parameters either increased or decreased with the treatment. Concentration of soluble salts gradually increased with increasing levels of CBMW. In contrast, organic matter content, K, Ca, and Mg concentrations slowly declined with increasing CBMW levels. Base saturation percentages of K, Ca, and Mg followed a similar pattern. Sodium concentration, which is high in CBMW, seemed to increase drastically in soils from the treatments with increased levels of CBMW (Table 3).

Plant height, plant weight, essential oil yield, and essential oil content did not seem to be affected by the treatments. Although essential oil yield and content seemed to decrease with increasing levels of CBMW, they were statistically similar (Table 4).

Discussion

Although the CBMW had a high pH (8.83), pH of the soil (6.93–7.26) remained within the best range for plant growth throughout the growing period (Horneck et al., 2011) possibly because of factors such as the short application period of the CBMW treatments (5–6 wk), the use of ammonium and phosphate fertilizers (Frank and Knudsen, 1992; Schroder et al., 2011), and the buffering capacity of soil. Cation exchange capacity and base saturation percentage also did not show significant change with different levels of CBMW and were in the medium range for plants growth (Hill Laboratories, 2010). Soluble salts increased with increasing levels of CBMW and were highest (4.55 mmhos cm⁻¹) at 100% CBMW due to the presence of different soluble salts and salt-forming ions (Table 1). Organic matter, K, Ca, and Mg showed a slight decrease with increasing levels of CBMW and were lowest at 100% CBMW. There typically was no organic matter and only trace amounts of Ca and Mg present in the CBMW used in this study (Table 1). The major component of CBMW is Na, and that is why the Na concentration in the soil increased considerably with increasing

Table 2. Percentage of constituents in dill essential oil at various levels of coal-bed methane water treatment.

CBMW†	α -pinene	Myrcene	α -Phellandrene	p-Cymene	Limonene	Dill ether	cis-dihydrocarvone	Trans-dihydrocarvone	Carvone
% total oil yield									
0	0.99	0.49	39.9	2.6	22.4	15.2b‡	0.19	0.79a	17.4a
25	1.24	0.53	40.4	4.1	23.1	17.3b	0.14	0.58ab	12.4ab
50	1.17	0.54	41.3	4.6	22.4	20.3a	0.15	0.5ab	9.0ab
75	1.14	0.52	39.4	4.1	22.4	17.7b	0.20	0.64ab	12.9ab
100	1.33	0.57	45.0	5.0	21.8	20.4a	0.05	0.29b	5.2b

† Coal-bed methane water.

‡ Within each column, different lowercase letters denote statistically different values at the 0.05 level of significance (Duncan's multiple range test).

Table 3. Soil properties of dill grown at different levels of coal-bed methane water treatments.

CBMW†	pH	EC‡	OMS§	CEC¶	K	Ca	Mg	Na
		mmhos cm ⁻¹	%	meq 100 g ⁻¹	mg kg ⁻¹			
Initial soil	7.20	1.31c#	2.3a	14.66	250a	2257ab	311a	32e
0%	6.93	2.35bc	2.16ab	15.70	172b	2357a	314a	41e
25%	6.90	3.52ab	2.06ab	16.23	179b	2283a	299ab	194d
50%	7.10	3.49ab	2.03b	16.63	168b	2360a	298ab	367c
75%	7.26	3.33ab	2.16ab	16.00	166b	2147ab	278bc	501b
100%	7.16	4.55a	2.06ab	15.53	174b	2020b	264c	646a

† Coal-bed methane water.

‡ Electrical conductivity.

§ Organic matter.

¶ Cation exchange capacity.

Within each column, different lowercase letters denote statistically different values at the 0.05 level of significance (Duncan's multiple range test).

Table 4. Plant biomass and oil yield of dill on five coalbed methane water treatments.

CBMW†	Plant height	Plant weight	Oil yield	Oil content
	cm	g per combined replication	g per 400 g of fresh biomass	% of fresh wt. (g of oil per 100 g of fresh biomass)
0%	77.0ab‡	441.6	0.833	0.208
25%	84.7a	430.0	0.799	0.199
50%	85.3a	460.0	0.641	0.160
75%	77.0a	438.3	0.767	0.191
100%	85.9a	450.0	0.647	0.161

† Coal-bed methane water.

‡ Within each column, different lowercase letters denote statistically different values at the 0.05 level of significance (Duncan's multiple range test).

levels of CBMW in the treatments. Similar results were observed by Zheljzkov et al. (2013) in a study on spearmint and peppermint; however, their study was conducted using horticultural-grade growth medium (75% Canadian sphagnum peat moss, the rest being horticultural-grade perlite and dolomitic limestone), whereas this study used real field soil.

In this study, the essential oil yield, reported as grams of essential oil per 400 g of fresh biomass, did not change significantly with the application of the different levels of CBMW. In this study, the essential oil content in dill ranged from 0.16 to 0.2%; these values are usually observed in dill, as evident from a study by Porter et al. (1983) where the values for whole-plant oil content of dill ranged from 0.15 to 0.37%. Plant height (77.0–85.9 cm in this study) was similar to the range of 63 to 86 cm found by Zheljzkov and Warman (2004), and fresh herbage yield (21.5–22.5 g per plant) did not change with the different levels of CBMW. This may be because the level of salts and Na in the soil did not suppress the performance of dill, which is regarded as a crop highly tolerant to soil salinity, and in some cases the dill oil yield seems to increase as salinity stress increases (Ghassemi-Golezani et al., 2011). Similarly, other soil conditions (e.g., pH, cation exchange capacity, and organic matter) were in the optimum range for the plants. Other possible explanations include a relatively short growing cycle (70 d) that minimized CBMW application and good control of other limiting factors, such as disease and pest infestation, irrigation timing, temperature, humidity, and other environmental conditions on which the dill plant depends (Bailer et al., 2001; Sangwan and Farooqi, 2001; Tajpoor et al., 2013).

The concentrations of the various essential oil constituents, such as α -pinene (0.99–1.3%), myrcene (0.48–0.57%), α -phellandrene (39.4–45%), limonene (21.8–23.1%), and p-cymene (2.6–5.03%) also did not change among treatments. Similar results (no change) were found for total phenols, total flavonoids, and the antioxidant capacity of peppermint receiving different levels of CBMW (Zheljzkov et al., 2013). The concentrations of the oil constituents in the total essential oil in this study were within the range (wherever available) of those in the study conducted by Callan et al. (2007). Dill ether, one of the major oil constituents of dill essential oil that imparts its characteristic flavor (Blank et al., 1992), seemed to increase with increasing levels of CBMW, with highest ether levels achieved at 50 and 100% CBMW. Other studies have shown increases in secondary metabolite secretions by plants in stressful environments as a defense strategy against various factors. Dill ether, being a major and distinctive oil constituent of dill, is possibly synthesized and accumulated more in stressed environments (Ezz El-Din et al., 2009; Ghassemi-Golezani et al., 2011). Carvone content decreased from 17.4% at 0% CBMW to 5.2% at 100% CBMW, and trans-dihydrocarvone decreased from 0.79% at 0% CBMW to 0.29% at 100% CBMW. A similar response by carvone was observed in peppermint (Zheljzkov et al., 2013). In other studies, anethole and carvone, both of which are antimicrobial compounds (Esfandyari-Manesh et al., 2013), were observed to decrease with increasing stress levels in soil and the environment. The concentration of carvacrol in oregano and thyme followed a similar decreasing trend with increasing the levels of stress and salinity in soil (Ahl et al., 2009; Ezz El-Din et al., 2009).

The CBMW used in this study contained some Ra (0.3 \pm 0.2 pCi L⁻¹), but the concentration of Ra was found to be

considerably lower than the USEPA standard for drinking water (≤ 5 pCi L⁻¹) (Patil et al., 2013) and hence is not a problem in our study. The CBMW also possessed high amounts of Na and some Ba (Table 1), but heavy metals usually remain in plant tissues and do not translocate in essential oils recovered through steam distillation (Scora and Chang, 1997; Zheljzkov and Nielsen, 1996; Zheljzkov et al., 2006). Other reports demonstrated that essential oil extracted via steam distillation from dill plants remained Cu free even when the soil contained high concentrations of Cu (Zheljzkov and Nielsen, 1996; Scora and Chang, 1997). There are also reports demonstrating that essential oil extracted via steam distillation from dill plants remained unaffected even if the soil had high concentration of some elements, such as Cu (Zheljzkov and Warman, 2004). In this study we found the same pattern (i.e., that high amounts of Na and some Ra and Ba did not seem to affect the oil content). Considering the elevated salts and Na concentrations in the soil treated by different levels of CBMW, soil and plant tissues (residue from steam distillation) may contain high amounts of Na (Zheljzkov and Warman, 2004) and should be disposed of accordingly.

Conclusions

Coal-bed methane water treatments resulted in an increase of dill ether content in the essential oil of dill with increasing the level of CBMW; in contrast, trans-dihydrocarvone and carvone content of the essential oil decreased. Fresh herbage yield and essential oil yield of this plant remained unchanged with different CBMW treatments, so adjustments can be made in the irrigation of this crop to achieve different concentrations of the desired components. However, irrigation with CBMW changes the natural properties of soil. This research only covers the effect of irrigating dill with CBMW on soil that has not previously been exposed to CBMW; further research is needed to ascertain the impact of CBMW irrigation on dill grown in soil previously exposed to CBMW.

Acknowledgments

This research was supported by the University of Wyoming School of Energy funds awarded to Dr. Valtcho D. Zheljzkov (Jeliakov). The authors thank Derek Lowe of BeneTerra LLC, in Sheridan, WY, for providing access to coal-bed methane water and Dan Smith and Jeremiah Vardiman, farm manager and research associate, respectively, at the University of Wyoming's Sheridan Research and Extension Center, Sheridan, who helped with the field trial management.

References

- Agilent Technologies. 2010. Agilent 7890A gas chromatograph operating guide. Agilent Technologies, Wilmington, DE.
- Ahl, H.S.A., E. Omer, and N. Naguib. 2009. Effect of water stress and nitrogen fertilizer on herb and essential oil of oregano. *Int. Agrophys.* 23:269–275.
- Alencar, J.W., A.A. Craveiro, F.J.A. Matos, and M.I.L. Machado. 1990. Kovats indices simulation in essential oil analysis. *Quim. Nova* 13:282–284.
- Bailer, J., T. Aichinger, G. Hackl, K. De Hueber, and M. Dachler. 2001. Essential oil content and composition in commercially available dill cultivars in comparison to caraway. *Ind. Crops Prod.* 14:229–239. doi:10.1016/S0926-6690(01)00088-7
- Blank, I., A. Sen, and W. Grosch. 1992. Sensory study on the character-impact flavour compounds of dill herb (*Anethum graveolens* L.). *Food Chem.* 43:337–343. doi:10.1016/0308-8146(92)90305-L
- Brown, J., editor. 1998. Recommended chemical soil test procedures for the North Central Region. Missouri Agricultural Experiment Station SB 1001, Columbia, MO.

- Burkhardt, A., A. Gawde, C.L. Cantrell, H.L. Baxter, B.L. Joyce, C.N. Stewart, Jr., and V.D. Zheljzakov. 2015. Effect of produced water on soil characteristics, plant biomass, and secondary metabolites. *J. Environ. Qual.* 44:1938–1947. doi:10.2134/jeq2015.06.0299
- Callan, N.W., D.L. Johnson, M.P. Westcott, and L.E. Welty. 2007. Herb and oil composition of dill (*Anethum graveolens* L.): Effects of crop maturity and plant density. *Ind. Crops Prod.* 25:282–287. doi:10.1016/j.indcrop.2006.12.007
- Combs, S., and M.V. Nathan. 1998. Soil organic matter. In: J. Brown, editor, Recommended chemical soil test procedures for the north central region. Missouri Agricultural Experiment Station SB 1001, Columbia, MO.
- Energy Information Administration. 2015. US Energy information administration: Natural gas. USEPA, Washington, DC.
- Esfandyari-Manesh, M., Z. Ghaedi, M. Asemi, and M. Khanavi. 2013. Study of antimicrobial activity of anethole and carvone loaded PLGA nanoparticles. *J. Pharm. Res.* 7:290–295. doi:10.1016/j.jopr.2013.04.019
- Ezz El-Din, A.A., E.E. Aziz, S.F. Hendawy, and E.A. Omer. 2009. Response of *Thymus vulgaris* L. to salt stress and Alar (B9) in newly reclaimed soil. *J. Appl. Sci. Res.* 5:2165–2170.
- Frank, K.D., and D. Knudsen. 1992. Understand your soil test: PH-excess lime-Lime needs. Univ. Nebraska-Lincoln Ext., Lincoln, NE.
- Ghassemi-Golezani, K., S. Zehrab-salmasi, and S. Dastborhan. 2011. Changes in essential oil content of dill (*Anethum graveolens* L.) organs under salinity stress. *J. Med. Plants Res.* 5:3142–3145.
- Gawde, A.J., C.L. Cantrell, and V.D. Zheljzakov. 2009. Dual extraction for secondary metabolites from *Juniperus virginiana*. *Ind. Crops Prod.* 30:276–280. doi:10.1016/j.indcrop.2009.05.005
- Hill Laboratories. 2010. Soil tests and interpretation: Technical note. Hill Laboratories, Hamilton, NZ.
- Horneck, D.A., D.M. Sullivan, J.S. Owen, and J.M. Hart. 2011. Soil test interpretation guide. Oregon State Univ. Ext. Serv. EC 1478:1–12.
- Huang, F., and P. Natrajan. 2006. Feasibility of using natural zeolites to remove sodium from coal bed methane-produced water. *J. Environ. Eng.* 132:1644–1650. doi:10.1061/(ASCE)0733-9372(2006)132:12(1644)
- Joseph, M., and K. Stephen. 2012. Easy gardening. Texas A&M Ext., College Station, TX.
- Larijani, K., J.J. Shakouri, N. Pishbin, S. Mansourbahmani, and A.A. Heidari. 2012. The essential oils of dill (*Anethum graveolens* L.) collected from Gilan, Iran. *Ann. Biol. Res.* 3:1010–1013.
- Mary, M., and B. Gurney. 2001. Coal bed methane. *Mont. Bus. Q.* 39:10–17.
- Parida, A.K., and A.B. Das. 2005. Salt tolerance and salinity effects on plants: A review. *Ecotoxicol. Environ. Saf.* 60:324–349. doi:10.1016/j.ecoenv.2004.06.010
- Patil, A., G. Hatch, C. Michaud, M. Brotman, P. Regunathan, and R. Tallon. 2013. Radium fact sheet. Water Qual. Assoc., Naperville, IL.
- Porter, N.G., M.L. Shaw, G.J. Shaw, and P.J. Ellingham. 1983. Content and composition of dill herb oil in the whole plant and the different plant parts during crop development. *N. Z. J. Agric. Res.* 26:119–127. doi:10.1080/0288233.1983.10420961
- Sangwan, N., and A. Farooqi. 2001. Regulation of essential oil production in plants. *Plant Growth Regul.* 34:3–21. doi:10.1023/A:1013386921596
- SAS Institute. 2013. What's new in SAS 9.4. SAS Inst., Cary, NC.
- Schroder, J.L., H. Zhang, K. Girma, W.R. Raun, C.J. Penn, and M.E. Payton. 2011. Soil acidification from long-term use of nitrogen fertilizers on winter wheat. *Soil Sci. Soc. Am. J.* 75:957–964. doi:10.2136/sssaj2010.0187
- Scora, R.W., and A.C. Chang. 1997. Essential oil quality and heavy metal concentrations of peppermint grown on a municipal sludge-amended soil. *J. Environ. Qual.* 26:975–979. doi:10.2134/jeq1997.00472425002600040007x
- Sowder, J.T., T.J. Kelleners, and K.J. Reddy. 2010. The origin and fate of arsenic in coalbed natural gas-produced water ponds. *J. Environ. Qual.* 39:1604–1615. doi:10.2134/jeq2009.0428
- Stearns, M., J.A. Tindall, G. Cronin, M.J. Friedel, and E. Bergquist. 2005. Effects of coal-bed methane discharge waters on vegetation and soil ecosystem in powder River Basin, Wyoming. *Water Air Soil Pollut.* 168:33–57. doi:10.1007/s11270-005-0588-z
- Tajpoor, N., R. Moradi, and A.N. Zaeim. 2013. Effects of various fertilizers on quantity and quality of dill (*Anethum graveolens* L.) essential oil. *Int. J. Agric. Crop Sci.* 6:1334–1342.
- Tian, J., X. Ban, H. Zeng, J. He, Y. Chen, and Y. Wang. 2012. The mechanism of antifungal action of essential oil from dill (*Anethum graveolens* L.) on *Aspergillus flavus*. *PLoS One* 7(1):e30147.
- Wright, J. 2005. The Herb Society of America's essential guide to dill. Herb Society of America, Willoughby, OH.
- Warncke, D., and J.R. Brown. 1998. Potassium and other basic cations. In: J. Brown, editor, Recommended chemical soil test procedures for the north central region. Missouri Agricultural Experiment Station SB 1001, Columbia, MO. p. 7.1–7.3.
- Watson, M.E., and J.R. Brown. 1998. pH and lime requirement. In: J. Brown, editor, Recommended chemical soil test procedures for the north central region. Missouri Agricultural Experiment Station SB 1001, Columbia, MO. p. 4.1–4.7.
- Whitney, D.A. 1998. Soil salinity. In: J. Brown, editor, Recommended chemical soil test procedures for the north central region. Missouri Agricultural Experiment Station SB 1001, Columbia, MO. p. 13.1–13.2.
- Young, A.L. 2005. Coalbed methane: A new source of energy and environmental challenges. *Environ. Sci. Pollut. Res.* 12:318–321. doi:10.1065/espr2005.11.002
- Zheljzakov, V.D., C.L. Cantrell, T. Astatkie, V. Schlegel, E. Jeliakova, and D. Lowe. 2013. The effect of coal-bed methane water on spearmint and peppermint. *J. Environ. Qual.* 42:1815–1821. doi:10.2134/jeq2013.05.0211
- Zheljzakov, V.D., L.E. Craker, and B. Xing. 2006. Effects of Cd, Pb, and Cu on growth and essential oil contents in dill, peppermint, and basil. *Environ. Exp. Bot.* 58:9–16. doi:10.1016/j.envexpbot.2005.06.008
- Zheljzakov, V.D., and N.E. Nielsen. 1996. Effect of heavy metals on peppermint and cornmint. *Plant Soil* 178:59–66. doi:10.1007/BF00011163
- Zheljzakov, V.D., and P.R. Warman. 2004. Application of high-Cu compost to dill and peppermint. *J. Agric. Food Chem.* 52:2615–2622. doi:10.1021/jf035137y