Irrig Sci
DOI 10.1007/s00271-011-0282-4

ORIGINAL PAPER

Impact of sustained deficit irrigation on spearmint (*Mentha spicata* L.) biomass production, oil yield, and oil quality

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Received: 15 December 2010 / Accepted: 6 March 2011

Abstract Crop response to deficit irrigation is an important consideration for establishing irrigation management strategies when water supplies are limited. This study evaluated the response of native spearmint to water deficits applied using overhead sprinklers in eastern Washington, US. Five levels of irrigation were applied ranging from full irrigation (100%) to 5% of weekly averaged full crop water needs. Soil water monitoring with soil water balance was used to estimate soil water deficits for irrigation scheduling and soil water use. Mint oil yields, oil components, dry matter production, and the water-use efficiency of the spearmint were assessed. There was significant reduction in fresh mint hay (harvested biomass) yield with increasing water deficit. However, spearmint oil yields remained generally uniform across irrigation treatments at the first cutting but decreased at the driest plots during the second harvest due to a loss of plant stand. The wet harvest index and water-use efficiency improved significantly for both harvests with increasing water deficit. Hay yield, oil yield, wet harvest index, and water-use efficiency are pooled across sides and replicate blocks to provide trends with changes in maximum evapotranspiration. The three major monoterpenes show changes suggesting less mature oil yields. The study demonstrates the feasibility of sustaining native spearmint yields under managed deficit irrigations for deficits not lower than 0.5 ETc.

Introduction

There is increasing demand from agriculture, municipalities, industries, and for wildlife habitat rehabilitation for the limited fresh water resources. In many parts of the world, agricultural production is limited by water rather than land availability. Consequently, farmers are shifting from striving for maximum land productivity to striving for maximum water productivity. Many studies have shown that deficit irrigation practices can lead to increased water productivity, not only in terms of output per volume of applied water, but in many cases crop quality, and/or economic returns (Fereres and Soriano 2007; Kijne et al. 2003; Zwart and Bastiaanssen 2004; English 1990; English and Raja 1996). Deficit irrigation shows promise as a tool to not only stretch water resources, but also in some cases to increase a grower's profits through crop quality management. However, deficit irrigation usually entails a risk of negative impacts to crop yield and quality. Consequently, this has to be balanced against the benefits from the alternate uses for the saved water as well as an understanding of the yield and quality trade-offs to

Communicated by A. Kassam.

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optimize productivity and economic returns to the grower rather than maximizing yields (Geerts and Raes 2009; Pereira et al. 2002; Zhang and Oweis 1999; Molden 2003). An understanding of crop and particular varietal response to water stress is key to the beneficial use of deficit irrigation.

Spearmint (*Mentha Spicata* L.) is a perennial crop cultivated for its aromatic oils that are used primarily in flavoring gum and dental hygiene products. The United States is the largest producer of mint (spearmint and peppermint), and most US production is in the Pacific Northwest. Previous studies of spearmint production under deficit irrigation (Delfine et al. 2005; Mitchell and Yang 1998; Charles et al. 1990; Okwany et al. 2009) have shown that it is sensitive to water stress. Although spearmint biomass (hay) production is highly sensitive to water stress, oil yields were only marginally affected (Okwany et al. 2009). Furthermore, the essential oil components in the spearmint were shown to change positively with increased water stress (Delfine et al. 2005). Pollack (1995) has noted the use of oil quality as a possible criterion for price determination for spearmint oil by brokers. The objective of this study was to determine the responses of spearmint biomass yields, oil yields, and oil quality parameters to deficit irrigation.

Materials and methods

Site description and timeline

Research field studies were conducted for two years (2008–2009) at the Washington State University, Irrigated Agriculture Research and Extension Center (IAREC) in Prosser, WA (46.29°N, 119.75°W; 350 m above sea level). The climate is semiarid with an annual average precipitation of 195 mm and an average annual alfalfa reference ET of 895 mm. The soil (0–100 cm) at the experimental site is a Warden Silt Loam. The volumetric soil water content at field capacity (FC) in the crop root zone was observed to be approximately 22.5%, and the wilting point (WP) was about 7.0% water content. The soil has a saturated hydraulic conductivity of 3.24 cm/h and a bulk density of 1.37 g/cm^3. Plots of native spearmint (*M. spicata* L.) were planted during the spring of 2007, and during the 2007 growing season, all plots were irrigated adequately to establish uniform stands across all plots. Deficit irrigation management procedures were implemented on these plots during the 2008 and 2009 growing seasons. All plots were approximately 6 m × 3 m (20 feet × 10 feet). The research plots were designed following the line-source experimental procedure by Hanks et al. (1976, 1980) using hand line sprinkler heads spaced at approximately 6 m (20 feet) apart. Five different plots representing different irrigation treatment levels were delineated on both sides with increasing distance from the line source. The plots were planted and managed following typical agronomic management practices (WSCPR 2008) in the Mid-Columbia River Basin growing areas, except for the treatment factor (irrigation). The design was a split-plot with randomized complete block in three replications. The study design consisted of five irrigation levels, two fixed treatments on both sides of the line source and three randomized blocks (replications).

Irrigation requirement

Irrigation was scheduled based on the soil water balance with the plots adjacent to the line source receiving the maximum (100%) potential field evapotranspiration (ET) water requirement while those further from the line source received increasingly less water. The potential crop water-use requirements (evapotranspiration) were determined by monitoring the total soil water balance components of precipitation, irrigation, soil water storage, drainage, and surface runoff based on the soil water balance equation:

$$ETc = P + I - \Delta S - D + R$$

where P is precipitation, I is irrigation, ΔS is the change in soil water storage over the irrigation cycle, D is drainage below root zone, and R is runoff. Drainage was determined to be zero because the soil water content below the root zone was well below field capacity and an increase was not measured over the season. Irrigation amounts were scheduled at rates below the infiltration rate to control runoff. Neutron probe access tubes were installed in the center of each plot, and irrigations were scheduled to replace the soil water deficit in the fully irrigated plots (100%) as determined by a neutron probe soil moisture meter (Neutron probe Model 503, CPN Corp., Martinez, CA) on a weekly basis. To ensure no losses to deep percolation or runoff, water was sometimes applied up to 2–3 times per week depending on the level of soil water depletion. The actual applied irrigation amounts were measured using catch cans placed near the center of the test plots and were read after each irrigation event. The line-source water-stress treatments were applied starting early spring (early April) and continued throughout the season (ending mid-October).

Dry matter and oil yield measurements

Two harvests were taken each year. At each harvest, a 1 m × 6 m swath was harvested from the middle of each plot and weighed to determine total green hay yield. From this, a 9.5 kg sample of green mint hay was separated and put in burlap sacks. These were air-dried and individually distilled in the laboratory to determine oil content.

The distilled oil was subsequently analyzed using a gas chromatography–mass spectrometer (GC–MS) to evaluate the relative monoterpene contents (oil quality parameters). In this process, the distilled oil was diluted in pentane and analyzed for terpene content using an Agilent 6,890 N gas chromatograph with an FID detector and HP-5MS, 5% phenyl methyl siloxane (30 m × 0.25 mm ID, Agilent 19011S-433). Carrier gas (helium) flow rate was 1 ml/min. The oven temperature was programmed to start at 40°C and then, increased to 200°C at a rate of 10°C/min. Terpenes were identified by comparison of retention times and mass spectra to those of authentic standards purchased from Sigma–Aldrich (St. Louis, MO). An evaluation of the relative composition of the spearmint oil was performed with nine of the main spearmint oil monoterpenes (carvone, limonene, β-myrcene, cineole, terpineol, β-bourbonene, caryophylene, β-Farnesene, and cubebene) being tested. The primary oil components that were compared were limonene, carvone, and myrcene.

Wet harvest index and water-use efficiency

Wet Harvest Index (*WHI;* dimensionless) is a ratio of the marketable oil yield to the harvested green spearmint hay (wet mass basis). It is an indication of the oil concentration in the harvested green mint hay. It is defined as follows:

$$WHI = \frac{OY}{GHY_{ac}}$$

where OY is the oil yield (kg/ha), and GHY_{ac} is the green hay yield (kg/ha).

Water-use efficiency (*WUE*, kg oil per m^3 water use) indicates the seasonal increase in marketable yield from an unit increase in consumed water. It is calculated as follows:

$$WUE = \frac{OY}{TW}$$

where OY is the oil yield (kg/ha), and TW is the seasonal total water use (m^3/ha).

Statistical analysis

Analysis of variance (ANOVA) was used to differentiate the effect of irrigation treatments on hay and oil yields as well as oil quality components with reference to the evapotranspiration levels. Regression analyses were also performed to evaluate yield factors and relationships. Statistical analysis to test the treatment effects was conducted using the generalized linear models (GLM) procedures of the statistical package SAS (SAS Inc. version 9.1). Treatment means were compared using Fisher's least squares difference procedure and were considered significantly different at $P \leq 0.05$.

Results

Soil moisture content

The study was initiated in 2008 (Y1) with all plots starting with about the same soil water content from the previous winter precipitation. However, from the second harvest (H2) in 2008 and at subsequent harvests in 2009 (Y2), there were residual soil water deficiencies in the water-stressed plots. During both of the 2008 and 2009 growing season, precipitation was minimal (38 and 29 mm, respectively) and evapotranspiration was mainly from soil water storage and irrigation water applied.

The soil water balance scheduling system based on neutron probe measurements provided an appropriate scheduling method, and the soil profile water contents in the 100% plots stayed fairly constant throughout both seasons. The system was managed to maintain the soil water content within the top 1.2 m of the soil profile within a management allowable depletion of 75% as shown in Fig. 1. The test plots were harvested on July 1, 2008, and September 22, 2008, in the first year and July 6, 2009, and September 21, 2009, for second year for Harvests 1 and 2, respectively.

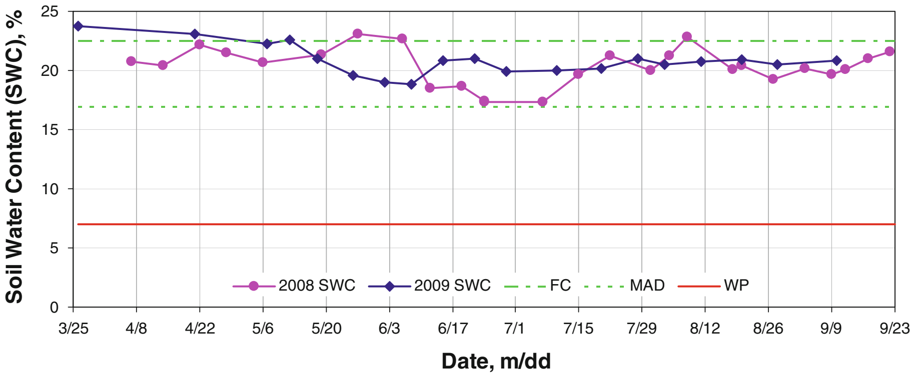

Fig. 1 Soil water content (SWC) averaged within the top 1.2-m profile across the two growing seasons

In both years, there was a substantial increase in total irrigation water applied to the second cutting compared with the first cutting with the greatest difference occurring in 2008. This is attributable to higher evapotranspirative demand after the first harvest due to hotter weather and longer days and the availability of residual soil water storage (Fig. 2). During the first harvest of both years, the water-stressed plots were able to utilize soil water from winter recharge.

The line-source irrigation system provided an uniformly decreasing application depth across the plots as was desired (Fig. 2) with applications varying from full irrigation at the center plots, reducing gradually to about 5% irrigation on the outermost plots. The applied irrigation water between the east and west sides are significantly different due to the prevailing NE–SW winds, which tended to apply more water to the western plots. Due to the groundwater storage supply and precipitation, irrigation supplied about 75% of the yearly total crop evapotranspirative requirements.

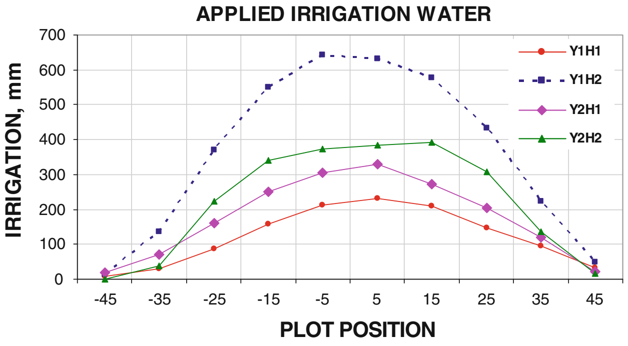

Fig. 2 Applied irrigation water for each of the harvests at each irrigation level for 2008–2009 with plot position being the distance of the plot midpoint from the *line source*

Significant differences in yields were measured across years, the two cuttings in each season and for the irrigation treatment factor (Table 1). Likewise, there were significant differences in the oil quality parameters, harvest index, and irrigation water-use efficiency as caused by water stress.

Hay and oil yields

The mean green hay yields (Fig. 3) and oil yields (Fig. 4) show significant decreases with increased water stress across both years. The decrease in hay yield with water stress was, however, much greater than with oil yield (Table 1). Total oil yields showed a low sensitivity to water stress at moderate stress levels. Over time, the driest plots were observed to have significant stand thinning and very little regrowth. These drier plots were able to utilize the winter-stored soil moisture for limited regrowth but after the first harvest there was not enough harvestable regrowth

Table 1 Quantity and quality parameters of spearmint crop under water stress treatments

	Soil moisture depletion (mm)	Irrigation applied (mm)	Total water use (mm)	Percentage of max ETc.†	Hay yield (kg/ha)	Oil yield (kg/ha)	WHI ($\times 10^3$)‡	WUE (kg/m^3)§	Percentage of limonene	Percentage of carvone	Percentage of myrcene
Year											
1	64 a	242 a	325 a	70 a	26,004 a	55.5 a	2.3 b	0.021 a	14.38 a	62.59 b	6.40 a
2	41 b	198 b	253 b	60 b	18,650 b	53.9 a	4.0 a	0.018 b	15.22 a	68.11 a	4.89 b
Harvest											
1	90 a	148 b	263 b	71 a	23,236 a	65.1 a	3.9 a	0.025 a	15.82 a	64.24 b	5.35 b
2	15 b	292 a	315 a	58 b	21,663 a	40.1 b	2.0 b	0.011 b	13.18 b	65.64 a	6.41 a
Side											
E	52 a	199 b	268 b	60 b	21,196 b	56.3 a	3.3 a	0.020 a	14.80 a	64.74 a	5.70 a
W	52 a	241 a	310 a	68 a	23,941 a	53.2 a	2.9 b	0.018 a	14.65 a	64.90 a	5.87 a
Irrigation level											
1	80 a	20 d	117 d	29 e	11,167 d	46.0 b	6.0 a	0.027 a	17.15 a	59.01 c	6.01 a, b
2	75 a	106 c	197 c	44 d	12,692 d	45.1 b	4.4 b	0.021 b	18.19 a	61.56 b	5.38 c
3	71 a	241 b	328 b	73 c	20,962 c	60.4 a	3.0 c	0.020 b	15.22 b	64.99 a	5.63 b, c
4	13 b	344 a	374 b	82 b	28,011 b	55.5 a, b	2.0 d	0.018 b	13.28 c	66.67 a	5.83 a, b
5	23 b	389 a	428 a	94 a	31,421 a	59.4 a	1.9 d	0.016 b	12.67 c	66.53 a	6.14 a

Mean separation in rows within each treatment by LSD. Different letters in columns indicate statistically significant difference at $P \leq 0.05$. Data are means for all harvest periods. Differences between treatments for blocks/replications were not significantly different

† The reduced ETc. percentage represents the level of deficit irrigation implemented

‡ Wet hay based harvest index (WHI) indicates the ratio of oil yield to wet hay biomass yield generated

§ Water-use efficiency indicates the ratio of marketable oil produced to total water consumed by the crop evapotranspiration

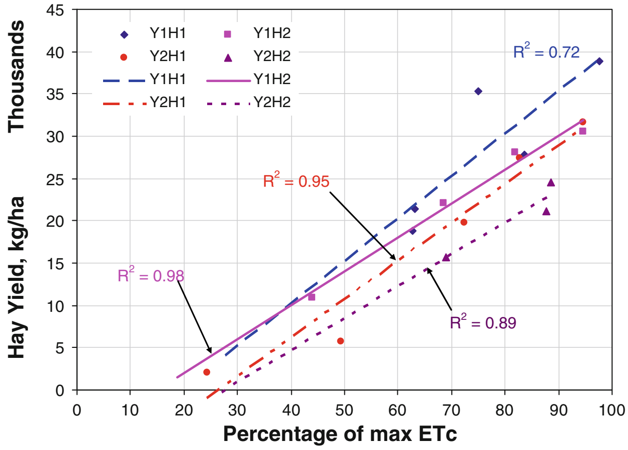

Fig. 3 Green hay yield variation under water stress conditions grouped by harvest

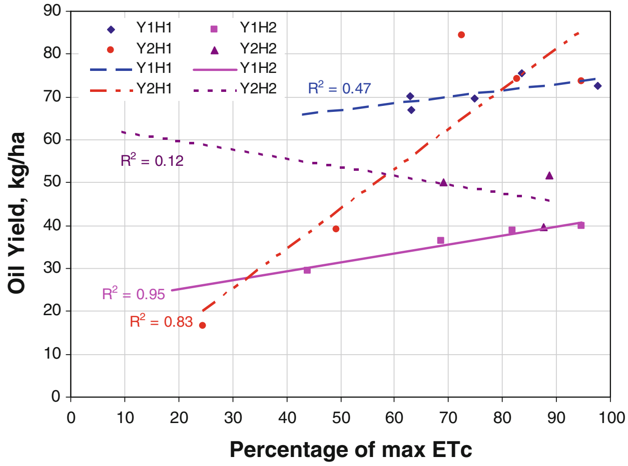

Fig. 4 Oil yield variation under water stress treatment conditions grouped by harvest

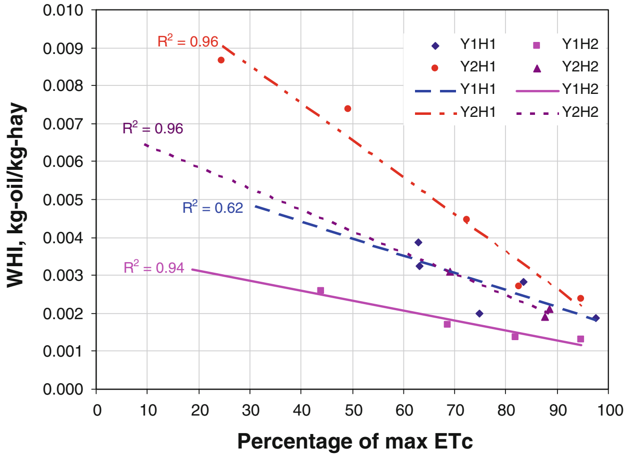

Fig. 5 Harvest indices (*wet hay*) at the various deficit irrigation levels for the growing seasons 2008–2009 grouped by harvest

to collect for harvest sampling, and therefore, there was no data for these plots on the second harvest. In the first harvest of the second year, the severely water-stressed plots had barely enough plants to take hay and oil yield samples from. These very unhealthy plants resulted in both very low hay and oil yields. In general, below 50% of full ETc., the growth and plant population was seriously curtailed and therefore cannot be recommended for spearmint production.

Wet harvest index

WHI, or oil concentration, increased substantially with increasing water stress for all harvests (Fig. 5). Water-stressing native spearmint clearly increases the amount of mint oil per ton of harvested green hay. This indicates a possibility for decreased grower costs through deficit irrigating by cutting costs for water, pumping energy, harvesting, transportation, and distilling mint hay, and for increasing profits if the oil yield and quality remain fairly constant. The significantly higher slope on the WHI at higher deficit levels in the first harvest of the second year (Fig. 5) is attributable to the use of higher residual soil moisture contents and to precipitation received later in the growth period that helped sustain the crop at these higher deficits. The unregulated availability of moisture from these sources provided an advantage that was not available for the other harvests.

Water-use efficiency

WUE shows a trend of linear increase with decrease in water use. The drastic increase in WUE in the first cutting of the first year is most likely due to the ample availability of groundwater storage that was exhaustively utilized by the crop. The year–year differences are likely due to climatic and seasonal differences between 2008 and 2009. The increases in water-use efficiency with increased deficit irrigation are attributable to the reduced ET and relatively constant oil yields under water-stress conditions. The atypical trend of the water-use efficiency for the first harvest of the second year is probably due to the uncontrolled availability of soil moisture from winter recharge that tended to equilibrate the moisture across the treatments Fig. 6.

Oil components

The three major monoterpenes (carvone, limonene and myrcene) that comprise over 80% of the significant monoterpenes are presented in Fig. 7. The result shows a 7.5% decrease in the carvone and 0.5% decrease in the myrcene

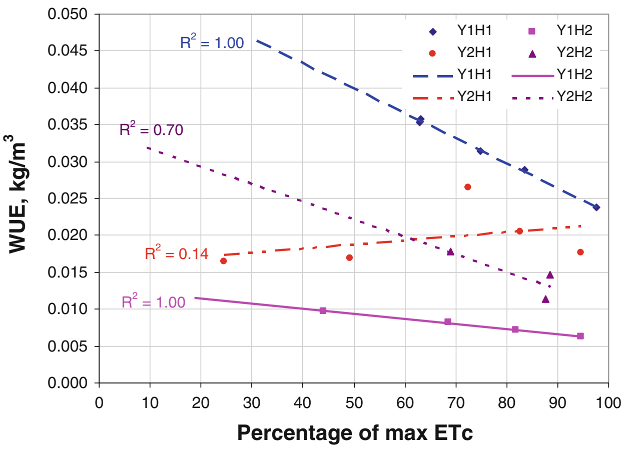

Fig. 6 Water-use efficiencies (WUE) (oil yield basis) at the various ETc. levels for the growing seasons 2008–2009 grouped by harvest

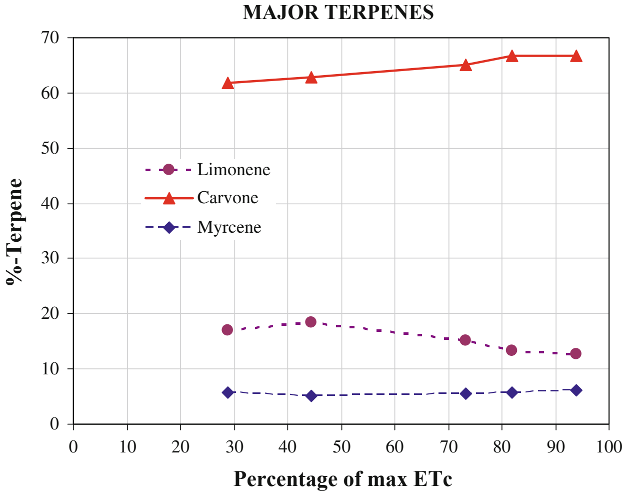

Fig. 7 Percentage composition of the major spearmint oil monoterpenes under water stress across years

contents and a 5% increase in limonene content with increased water stress (Table 1) over the ranges of applied deficit irrigation. This indicates that water-stressed plants may be less mature as limonene is a precursor to carvone.

Conclusion

All sectors of modern development (municipal, agricultural, domestic, and industrial) are facing water scarcity. Irrigated agriculture as the major user of fresh water will likely experience greater pressure for improved irrigation water-use efficiency in the future. Deficit irrigation will be an important management technique to cope with the water scarcity. In native spearmint, sustained deficit irrigation clearly decreased mint hay yields. However, oil yields remained relatively stable across the large water stresses applied in all but the first harvest of 2009. Deficit irrigation clearly resulted in increased oil concentration in the spearmint hay under sprinkle irrigation. Oil yields in the most stressed plots decreased over time due to severe plant population decreases. Oil component analysis showed later oil maturity in water-stressed spearmint. We hypothesize that water-stressed spearmint may require the full growing season to reach full oil maturity even though this would impact the adopted practice of double cutting (two harvests) in the Mid-Columbia basin.

There is potential to use deficit irrigation to increase spearmint grower's profits. Lower spearmint hay yields with comparable oil yields would mean faster harvesting, lower transportation costs, and lower oil distillation costs. Lower water use would also translate into savings in lower pumping energy costs and less wear and tear on pumps and irrigation machinery. Moderate deficit irrigation of spearmint may therefore be profitable as the oil yield level is maintained with little impact on oil quality. Water deficits over 40–50% of full water demands (maximum ETc.) are not recommended, however, as severe plant depopulation results. Soil salinization problems may also arise due to decreased deep percolation and leaching (Ragab 1996; Sarwar and Bastiaanssen 2001; Schoups et al. 2005; Kaman et al. 2006; Hsiao et al. 2007; Geerts et al. 2008). Therefore, special long-term soil quality management steps must also be considered. It must also be noted that crop water production functions are generally non-linear, crop-specific and quite often differ by physiological stage, genotype, and location (Geerts and Raes 2009). The data from this study are not adequate to define the water response relationships and differential impacts of water stress under different growth stages; thus, for greater certainty, further studies are recommended to address these factors. The plots presented are considered to offer a first step toward a better understanding of the response of native spearmint to water stress under deficit irrigation. Linear plots are subjectively used in this study to illustrate trends rather than firm yield dependencies due to limited data from some plots.

The use of sustained deficit irrigation is thus noted to offer a possible management option to farmers to address instances of water shortages. This study provides a general guideline by which native spearmint farmers can predict the yield and quality impacts of implementing given levels of water stress to their crops, thereby allowing for decisions regarding land following or limited irrigation. It is imperative to note that this conclusion is not exhaustively sufficient as it assumes implementation of the decision over the season, a fact which may not be true especially for surface water sources where water availability may be low for only part of the season. It is also recommended that the implementation of a water-stress regime allows for at least

50% of full ETc. to ensure inter-season minimum sustainability of crop stand.

Acknowledgments The authors would like to thank the Washington Mint Commission for its financial support to the project. Special acknowledgments to Ray Baker and Dr. Moumita Chakraborty for their assistance with fieldwork and lab-work respectively.

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