Cannabis (Cannabis sativa L.) legislation in North America continues to move rapidly toward liberalization and in some instances legalization, shifting cultivation from a largely illicit practice to one that is not only legal, but in high demand. In the United States, with only a handful of states having legalized recreational cannabis as of 2017, the market for legal cannabis was estimated at $2.7 billion USD in 2014, and it is expected to reach $11 billion by 2019 (ArcView Market Research and New Frontier, 2014). The current Canadian government has pledged to follow suit and pass legislation to legalize cannabis for recreational purposes beginning in spring of 2017. Until then, current legislation allows a limited number of private, licensed facilities to produce and distribute cannabis for medicinal purposes as well as conduct scientific research (Canada Gazette, 2016).

Cannabis is an annual dioecious species, producing separate male and female plants. Archeological evidence of cultivation dates to 10,000 BCE in China where cannabis was used primarily for fiber. Later, the medicinal use of cannabis became widespread, with evidence of cultivation and use in ancient Egypt around 2800 BCE and in China around 2000 BCE (Russo, 2007). The medicinal value of cannabis is attributed primarily to a group of secondary metabolites called cannabinoids which are concentrated mostly in the essential oils of unfertilized female flowers (Potter, 2014).

More than 100 unique cannabinoïds have been identified (Ahmed et al., 2008, 2015; ElSohly and Slade, 2005), although Δ⁹-THC and cannabidiol (CBD) are considered the primary psychoactive and medicinal components (Elzinga et al., 2015; Mechoulam et al., 1970). In live plants, cannabinoids exist primarily as carboxylic acids such as Δ²-THCA and cannabidiolic acid (CBDa) (Muntendam et al., 2012). These acids undergo decarboxylation during storage (Ross and ElSohly, 1997; Taschner and Schmid, 2015) and upon heating (Kimura and Okamoto, 1970) to become neutral cannabinoids such as THC and CBD. Varieties of cannabis with low THC and high CBD are termed hemp or fiber-type cannabis, whereas those with high THC and low CBD are termed marijuana or drug-type cannabis, hereafter referred to as cannabis (van Bakel et al., 2011; Vollen et al., 1986). Selective breeding has produced hundreds of varieties of cannabis with varying chemical compositions and growth characteristics (Vollen et al., 1986). Selection has mostly been for high floral THC concentration, but the medicinal effects of CBD have recently been identified (Russo, 2011) leading some breeders to select for high CBD. Most indoor production of cannabis occurs in two growth stages, vegetative and flowering, which are controlled by photoperiod (Farag and Kayser, 2015). Modern day cultivation of cannabis takes place almost exclusively indoors under artificial lighting using either solution culture systems or soilless growing substrates (Leggett, 2006; Potter, 2014). In addition, many cannabis growers favor organic production practices because consumers and regulating bodies often demand pesticide-free cannabis (Canada Gazette, 2016).

Online horticultural resources are available for cannabis production; however, limited information is available in peer-reviewed scientific literature. Furthermore, there is scant published scientific research on any aspect of organic cannabis production. Because of a lack of systematic horticultural research, current cannabis producers rely on cultivation methods derived largely from anecdotal information. Information on fiber-type cannabis cultivation techniques allows for some parallels to be drawn; however, fiber-type cannabis is field-grown and has been selectively bred for fiber production rather than for essential oil content (Amaducci et al., 2015). A chemotaxonomic study found low gene flow between drug- and fiber-type cannabis (Hillig and Mahlberg, 2004) and was supported by a recent genomic study comparing fiber and drug-type cannabis (van Bakel et al., 2011). This makes it difficult to relate cultivation techniques between the two crops (Amaducci et al., 2015).

Fertilization is one of the most important factors for indoor organic cannabis production. For fiber-type cannabis, the suggested fertilization rate is around 50–200 kg N/ha (Aubin et al., 2015; Ehrensing, 1998; Vera et al., 2004), which is similar to other high-yielding field crops such as wheat (Triticum spp.; Baxter and Scheifele, 2008). It is difficult, however, to estimate fertilizer requirements of drug-type cannabis based on fiber-type cannabis or other crops because of the differences in species and growing conditions (Wright and Niemiera, 1987). Furthermore, it is well-known that different growth stages of the same species have varying nutrient demand; when the demand is met, plant performance is improved (Raviv and Lieth, 2007; Wang, 2000). Most studies on fertilizer application in other crops have been conducted using conventional fertilizers, and there are few on the use of organic fertilizers for container crops. Fertilization rates of 190–400 mg N/L have been reported for container production of organic greenhouse-grown tomatoes (Solanum lycopersicum L.; Surraje et al., 2010; Zhai et al., 2009). To our knowledge, neither organic nor conventional fertilizer application rates have been published for indoor cannabis production in scientific literature. Appropriate choice of a growing substrate is essential for soilless crop production because it directly affects root zone water, air,
and nutrient availability and balance (Zheng, 2016). While there are no experimental data on growing substrates for cannabis, the information we collected from the industry indicates that many North American cannabis producers are using either coir- or peat-based substrates, or inert substrates such as rockwool. Different substrates have different physical and chemical properties; therefore, it is essential to fertigate plants accordingly to ensure an adequate root zone environment (Zheng, 2016).

The objective of this study was to determine the optimal organic fertilizer rates for growing vegetative-stage cannabis plants in two coir-based organic growing substrates in a controlled environment growth chamber.

**Materials and Methods**

**Plant culture and treatments.** Seventeen-day-old rooted cuttings (≈10 cm high with ≈6 leaves) of cannabis 'OG Kush × Girlz' were transplanted into round peat-based pots (9.5 cm diameter × 10.2 cm high) with one plant per pot. Pots were filled with one of two growing substrates, ABcann UNIMIX 1-HP (U1-HP) or ABcann UNIMIX 1 (U1) (Physical and chemical properties presented in Tables 1 and 2, respectively; ABcann Medicinals Inc., Nanaimo, Canada). The two organic substrates were coir-based and with two distinct WHCs: U1-HP with lower WHC and more drainage than U1.

Pots were randomly arranged in a growth chamber at a density of 97 plants/m². The growth chamber was set at 22 °C, 85% RH, 500 ppm CO₂ (day and night), and a photosynthetically active radiation (PAR) of 250 ± 50 μmol m⁻² s⁻¹ at canopy level with an 18-h photoperiod under fluorescent lighting. Beginning 3 d after transplant, plants were hand-fertigated with corresponding fertilizer, and their interaction on substrate EC and pH as well as growth index, leaf number, and branch number over time. Differences among means were tested with Tukey’s multiple means comparison test. Two-way ANOVA was used to determine the effects of substrate, fertilizer, and their interaction on substrate EC and pH as well as growth index, leaf number, and branch number over time. Differences among means were tested with Tukey’s multiple means comparison test. Two-way ANOVA was used to determine the effects of substrate, fertilizer, and their interaction on yield and the effects of fertilizer on cannabinoid concentrations.

Pearson correlation coefficients were calculated to determine if there is a relationship between growth attributes and final yield. Orthogonal partition and regression analysis (Bowler, 1999) were used to relate substrate EC, pH, plant growth yield, and cannabinoid concentrations with fertilizer rate and/or yield. If the partitioning variance analysis indicated a significant treatment effect, then the treatment effects were partitioned into one or more regression effects followed by an estimation of regression parameters for the best-fit regression. In all analyses, if there

| Growing substrate | Total porosity* (%) | CC* (%) | Air space* (%) | Bulk density* (g cm⁻³) |
|--------------------|---------------------|---------|----------------|------------------------|
| U1-HP              | 93 ± 0.4            | 61 ± 1.2| 31 ± 1.3       | 0.09 ± 0.001           |
| U1                 | 91 ± 0.3            | 72 ± 0.2| 19 ± 0.3       | 0.10 ± 0.001           |

*Data are means ± se (n = 3). CC = container capacity.
Table 2. EC, pH, and nutrient content measured using the saturated paste method for growing substrates ABcann UNIMIX 1-HP (U1-HP) and ABcann UNIMIX 1 (U1).

| Growing substrate | EC* (mS·cm⁻¹) | pH* | Nitrate N (mg·L⁻¹) | P | K | Ca | Mg | SO₄²⁻ | Na | Cl⁻ | Zn | Mn | Cu | Fe | B | Mo |
|-------------------|--------------|-----|-------------------|---|---|----|----|--------|----|-----|----|----|----|----|---|---|
| U1-HP             | 1.8 ± 0.07   | 6.30 ± 0.01 | 5               | 9.2 | 338.1 | < 1 | 2.7 | 31.2 | 104.5 | 413 | < 0.01 | < 0.01 | < 0.01 | 0.12 | 0.09 | < 0.01 |
| U1                | 2.3 ± 0.12   | 6.28 ± 0.01 | 8               | 10.4 | 431.2 | 2.3 | 5.3 | 41.3 | 136.3 | 724 | < 0.01 | < 0.01 | < 0.01 | 0.84 | 0.13 | < 0.01 |

*Data are means ± se (n = 3).

EC = electrical conductivity; N = nitrogen; P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; SO₄²⁻ = sulfate; Na = sodium; Cl⁻ = chloride; Zn = zinc; Mn = manganese; Cu = cupper; Fe = iron; B = boron; Mo = molybdenum.

Yield. There was no yield difference between substrates, and no substrate × fertilizer rate effect on yield. Based on the pooled data from both substrates, yield responded to fertilizer rate quadratically with the highest yield at a rate that supplied 389 mg N/L (Fig. 2). Yield at this fertilizer rate was interpolated to be 41.6 g/plant which is 1.8 times higher than that at the lowest which supplied 117 mg N/L. The yield was positively correlated with growth index (r = 0.45, P < 0.001), leaf number (r = 0.39, P = 0.0027), and branch number (r = 0.53, P < 0.0001) measured at the end of the vegetative stage (19 DAT; n = 58).

Cannabinoids. Of the analyzed cannabinoids, only THC, THCA, and CBN were above the detection limit (0.05%). Floral THC concentration responded quadratically to increasing fertilizer rate, reaching a maximum of 0.31% a rate supplying 418 mg N/L (Fig. 3). There was no fertilizer rate effect on the floral THCA concentration (mean ± se of 0.16% ± 0.031%) or CBN concentration (mean ± se of 0.08% ± 0.018%). Cannabinoid concentrations also varied with yield. THC and CBN were positively correlated with yield, whereas THCA was not correlated with yield (Fig. 4).

Substrate EC and pH. Substrate pH decreased over time for all fertilizer rates during the vegetative stage (Fig. 5), decreasing linearly or responding quadratically to increasing fertilizer rate. The lowest mean pH was 6.19 at the 351 mg N/L rate, measured at 17 DAT. Substrate EC, measured at 5, 13, and 17 DAT, increased linearly over time and with increasing fertilizer rate. Mean EC ranged from 0.9 to 3.9 mS·cm⁻¹ from the lowest to the highest fertilizer rate at 17 DAT. In the flowering stage, pH (measured at 47 and 59 DAT) increased linearly with increasing vegetative-stage fertilizer rate with means ranging from 6.74 to 7.16 (Fig. 6). No difference was observed in EC among vegetative stage fertilizer rates during the vegetative stage fertilizer rate linearly at 13 DAT and quadratically at 19 DAT, and leaf number responded to fertilizer rate quadratically at 13 and 19 DAT. At 19 DAT, maximum leaf number was 42 at a rate that supplied 117 mg N/L and maximum growth index was 51 at a rate that supplied 477 mg N/L. Growth effects carried forward into the flowering stage in which branch number responded quadratically to vegetative-stage fertilizer rate (maximum of 17.6 at a rate that supplied 403 mg N/L) and growth index increased linearly with increasing vegetative-stage fertilizer rate.
flowering stage with substrate EC at 1.3 ± 0.03 mS·cm⁻¹ and 1.6 ± 0.02 mS·cm⁻¹ (mean ± se) at 47 and 59 DAT, respectively. No differences in substrate EC or pH were observed between the two tested substrates in both the vegetative and flowering stages.

**Discussion**

No visual signs of nutrient disorders were observed in this trial which suggests that the fertilizers used had nutrient elements and ratios within an acceptable range. Both growth attributes and yield of the cannabis plants exhibited a typical response to varying fertilizer application rates. Yield increased with increasing fertilizer until reaching a maximum at a rate supplying 389 mg N/L. Optimal organic fertilizer application rates in this experiment were higher than synthetic fertilizer recommendations for most conventional crops (Raviv and Lieth, 2007).

Organic fertilizers contain slower releasing and less soluble forms of nitrogen and phosphorus compared with most synthetic fertilizers and may release only 25% to 60% of their nitrogen content (Prasad et al., 2004). Therefore, it is important to establish optimal organic fertilizer application rates. Yield increased, so did the concentration of THC and CBN. In fact, as concentration of THC and CBN. In fact, as

Substrate EC increased over time during the vegetative stage, and the increase was more apparent at higher fertilizer rates. Sub-optimal yields were seen at fertilizer rates that supplied 468 and 585 mg N/L under which substrate EC was 3.0 ± 0.13 and 3.8 ± 0.13 mS·cm⁻¹, respectively. These yield reductions may have been caused by high substrate salinity. High salinity can damage crops through increased ψs, depressing the external water potential in the root zone. In greenhouse-grown flowering crops, salinity thresholds vary dramatically among species, ranging in EC from of 1.0 to >4.2 mS·cm⁻¹ (Sonneveld et al., 1999). In the current study, cannabis tolerated substrate EC up to 3.0 mS·cm⁻¹ without reduction in yield.

In all fertilizer rates, pH decreased gradually during the vegetative stage; and the highest yielding rates, which supplied 234, 351 and 468 mg N/L, exhibited the lowest pH values. In most organic fertilizers, nitrogen exists primarily as NH₃ (i.e., high NH₃/N-NO₃/N ratio; Gil et al., 2007) and can be taken up by plants directly or as other forms after being converted by microorganisms in the substrate via ammonification and nitrification (Shimohara et al., 2011). Reductions in pH under organic fertilization can be caused by NH₃ nitrification and the excretion of protons by the roots after NH₄⁺ uptake (Johnson et al., 2011; Silber et al., 2004). It is possible that larger plants, those fertilized at rates identified as, or close to, optimal in this study, had higher rates of NH₄⁺ uptake which decreased root zone pH. There are no experimental data in the literature on ideal growing substrate pH range for cannabis in soilless production system; however, information we collected from the industry and gray resources (Cervantes, 2006) suggest a range of 5.8–6.8 to avoid causing nutrient disorders. In the current study, there were no visual signs of pH-induced disorder in plants within the pH ranges measured (means of 6.2 to 7.1 in the vegetative stage and 6.7 and 7.2 in the flowering stage) suggesting that these ranges are suitable for container production of organic cannabis. More research is needed to determine the optimal growing substrate pH ranges for cannabis.

Around the optimal fertilizer rate, both growing substrates tested in the current study demonstrated acceptable qualities for the growth of cannabis in the vegetative stage. There were no growth or yield differences observed between plants grown in the lower WHC (drier) substrate (U1-HP) and the higher WHC (wetter) substrate (U1) with fertigation administered when substrate moisture content dropped to 30%. This indicated that both substrates were appropriate for container production of organic cannabis. The positive correlations between growth attributes in the vegetative stage and final yield may indicate that growing larger plants during the vegetative stage will increase yield. Because larger plants, those fertilized at rates around the optimal fertilizer rate, had increased THC concentration in floral material (maximized at the rate supplying 418 mg N/L) and the concentrations of other cannabinoids were unaffected, it may be concluded that to optimize the yield and total THC content, cultivation techniques to increase vegetative growth, specifically branching, should be used. Besides fertigation, other cultural practices such as topping (Tanaka and Fujita, 1974) may also be used to increase branching.

The highest yielding plants, those fertilized around the optimal rate, had higher concentrations of THC and CBN. In fact, as yield increased, so did the concentration of

**Fig. 3. Relationship between Δ⁹-tetrahydrocannabinol (THC) concentration in dry floral material of cannabis and organic fertilizer (4.0N–1.3P–1.7K) rate [indicated by nitrogen (N) concentration] applied during the vegetative stage. Values are means ± se. The curve is the best fit regression relationship with \(P < 0.05 \) (\( n = 3 \)).**

**Fig. 4. Relationships between cannabinoid concentrations in dry floral material of cannabis and dry floral weight. Values are means ± se (\( n = 15 \) for THCA and THC; \( n = 13 \) for CBN). Lines are the best fit regression relationships with \( P < 0.05 \). THCA = Δ⁹-tetrahydrocannabinolic acid; THC = Δ⁹-tetrahydrocannabinol; CBN = cannabinol.**

**Fig. 5. Response of substrate pH and electrical conductivity to organic fertilizer (4.0N–1.3P–1.7K) rate [indicated by nitrogen (N) concentration] applied during the vegetative stage. Data are means ± se (\( n = 5 \) for pH at the 585 mg N/L rate on day 17 and \( n = 10 \) for all other means) and lines are the best fit regression relationships with \( P < 0.05 \).**

**Fig. 6. Response of substrate pH during the flowering stage to organic fertilizer (4.0N–1.3P–1.7K) rate [indicated by nitrogen (N) concentration] applied during the vegetative stage. Data are means ± se (\( n = 8 \)), and lines are the best fit regression relationships with \( P < 0.05 \).**

**Fig. 7. Relationship between cannabinoid concentrations in dry floral material of cannabis and flowering stage.**
these neutral cannabinoids. During the flowering stage, THCA transcription in floral material slows between weeks 1 and 3 whereas total cannabinoid concentration continues to increase until weeks 3 and 4, as THCA breaks down into neutral cannabinoids such as THC and CBN (Muntendam et al., 2012). This leads to an accumulation of neutral cannabinoids as plants mature through the flowering stage. It is estimated that higher concentrations of neutral cannabinoids, as seen in plants fertilized around the optimal rate, would be observed in plants which mature early. Optimal fertilization during the vegetative stage may, therefore, reduce maturation time in cannabis. Early maturation is desirable as it could decrease time to harvest and result in more frequent crop turnover. To evaluate whether fertilization can, in fact, reduce maturation time, further study is required with cannabinoid analyses throughout the flowering stage.

In the current study, treatments were applied only in the vegetative stage whereas cannabinoid production occurs primarily during flowering because of an increase in glandular trichome development in the flowering stage (Muntendam et al., 2012; Vogelmann et al., 1988). Treatment effects carried forward to some final floral cannabinoid concentrations; however, effects may have been more apparent with variable fertilizer treatments during the flowering stage. Further research is needed to evaluate the effects of fertilizer rate on flowering-stage cannabis.

Yields in the current study were slightly lower than industry standards and reports from recent horticultural studies on cannabis (Potter and Duncombe, 2012; Vanhove et al., 2011, 2012). The 47-d flowering period in the current study was relatively short, compared with the 7–9-week range in these cited studies. A shorter flowering period is known to reduce yields (Potter, 2014). Other factors including cannabis variety and the use of organic fertilizer may have also played a role.

Conclusions

Our results demonstrated that to produce high-yielding, cannabinoid-rich plants, the optimal fertilizer rate was that supplying about 389 mg N/L, for Nutri Plus Organic Grow liquid organic fertilizer (4.0N–1.3P–1.7K) in the vegetative stage of cannabis using coir-based organic substrates. These recommendations should be acceptable for similar organic fertilizer and substrates; however, different cannabis varieties may have different fertilization requirements. To provide variety-specific fertilization requirements, further study may be needed. Both organic substrates ABcann UNIMIX 1-HP and ABCann UNIMIX 1 maintained suitable pH (between 6.2 and 7.1 in the vegetative stage and between 6.7 and 7.2 in the flowering stage) and were effective for vegetative-stage cannabis growth; however, U1-HP may require more frequent fertilization than U1. Growing substrate EC of up to 3.0 mS·cm⁻¹ was tolerated without yield reductions. Furthermore, larger plants (e.g., higher growth index, branching and leaf number) generally had higher yield and floral THC concentrations which may indicate that plants should be grown as large as possible during the vegetative stage.

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