ORGANIC MANAGEMENT OF SOIL AND NUTRIENTS FOR PRIMOCANE FRUITING RASPBERRIES IN HIGH TUNNELS

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ABSTRACT

ORGANIC SOIL AND NUTRIENT MANAGEMENT OF PRIMOCANE FRUITING RASPBERRIES IN HIGH TUNNELS

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Trials were conducted over three years to determine the effects of spring applications of compost and a soy and blood meal based organic fertilizer on soil fertility and production of three varieties of primocane fruiting raspberries in multi-bay high tunnels. In the first year, compost and fertilizer were incorporated into the rows at two rates prior to planting. All treatments resulted in initially high levels of total inorganic nitrogen (N) ($\geq$80 mg kg^{-1}), and levels appeared consistent with initial application rates. Soil salinity in the top soil of the high compost treatment was excessive after the first season, with an EC of 1.22 dS m^{-1} directly beneath the drip irrigation line. Removing the plastic during winter and exposing the soil to precipitation significantly reduced soil salinity. In the second and third seasons, compost and fertilizer were top dressed over the row in spring, about a month before the tunnels were covered with plastic. This resulted in much lower levels of total inorganic-N than in year one when the compost and fertilizer were incorporated. There were significant differences in total soil inorganic-N and leaf nutrient levels between treatments when they were top dressed, with the high rate of organic fertilizer supplying more soil N and increasing leaf N levels. However, berry yields were not affected by treatments, possibly because plants were deficient in other nutrients. Results indicate that top dressing with solid organic fertilizers does not supply adequate nutrition to raspberries in high tunnels since nutrients appear to remain on the surface instead of being leached into the root zone by early-spring precipitation or drip irrigation.

Dedicated to my late grandfather, Henry Gluck.

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CHAPTER 1

REVIEW OF THE LITERAURE

The Red Raspberry

The red raspberry (*Rubus idaeus* L.) is a perennial woody shrub that has been cultivated for its small, sweet and soft red berries. The species belongs to the Rosacea, or rose family, and is a prominent member of the *Rubus* genus, which also includes several blackberry species (*R. fruticosa*), black raspberries (*R. occidentalis*) and many other wild species that are pervasive throughout the world. The red raspberry is a plant of temperate regions. Cultivation of the European red raspberry (*Rubus idaeus*) began in the 1500s, and crosses between the North American red raspberry (*Rubus strigosus*) and European red raspberry occurred in the nineteenth century in America as growers sought to improve upon wild selections (Ourecky, 1975).

The raspberry plant produces biennial shoots called canes on a perennial root system. Canes can reach heights between 1 and 3 m (Keep 1988). On wild plants, the two-year-old canes called floricanes bear the majority of fruit. However, breeding efforts in the mid-twentieth century produced cultivars that also bear fruit on new canes, called primocanes. Primocanes emerge each spring and grow vigorously through summer, typically elongating in a sigmoid growth curve (Williams, 1959; Jennings and Dale, 1982; Wright and Waister, 1982). Elongation of primocanes ceases with the formation of an apical flower bud in mid to late summer, which then initiates several distal axillary buds to form fruiting lateral branches. The fruit bearing end of the primocane is called the primocane fruiting zone (Dale, 2007).

In floricane fruiting types, axillary buds along the primocanes develop into flower buds in fall and remain dormant until the following spring. These buds produce fruiting lateral branches basipetally (Keep, 1988), and finish producing fruit by midsummer. Fruit maturation is followed by senescence of the entire floricane. A raspberry plantation may bear fruit for 20 years or longer (Demchak et al., 2001)

Raspberry Production in the United States

Red raspberries are planted on about 6600 ha in the United States (USDA, 2012a), with the majority located in either Washington, Oregon or California. Small plantings are also found in Colorado, the Midwest and the Northeast (Demchak et al., 2001). In 2011, raspberries in Oregon and Washington had a combined value of $50,736,000, of which about 94% was processed (USDA, 2012a). California is the major domestic supplier of fresh raspberries (Gaskell, 2004). Between 2000 and 2009, California raspberry acreage tripled, standing around 2185 acres (Goodue et al., 2011; USDA, 2012a). This generated revenue of $223,200,000 in 2011 (USDA, 2012a).

Prices for fresh raspberries are between three and four times greater than prices for processed raspberries (USDA, 2012a), and per capita consumption of fresh raspberries has more than tripled since the early 1990s (USDA, 2009). Demand for organic raspberries also appears moderately strong. Organic berries account for one-third of all organic fruit sales and between 2006 and 2010, weekly sales of organic berries grew 193% with retail price 33 % higher than conventional berries (The Perishables Group, 2011). In 2011, about 15% of the fresh raspberries shipped from California were organic, and retail prices in the Midwest were 24% higher than conventional prices (USDA, 2012b). Organic raspberry production was valued at 12.8 million dollars in 2008, with only 265 ha of production on 538 farms in the United States (USDA, 2008).

Productivity of red raspberries varies considerably amongst regions and production systems. In the Midwest and Northeast, farmers grow both primocane and floricane fruiting varieties in hedgerows that are 30-45 cm wide and spaced 2.7-3 m apart. Plantings tend to be just a couple hectares in size and berries are sold locally (Hanson et al., 2011). Yields can be 5700 kg per ha (Demchak et al., 2001), but maintaining consistent volumes and quality is difficult due to short growing seasons, cold winters, and prevalence fruit rots and other pests and diseases (Hanson et al., 2011).

More suitable climates for commercial raspberry production can be found along the west coast of the United States where the majority of production occurs for both processing and fresh markets. In Oregon and Washington, where raspberries are grown primarily for processing, growers use a cultural method known as the hill system with floricane fruiting varieties. Canes are trained in bundles spaced 75 cm apart and are attached to a trellis system. The hill system permits more vegetative growth than a hedgerow system and therefore results in higher yields, around 7000 kg per ha (Barney and Miles, 2007).

The most productive region of the U.S. is California, where average yield was 22,800 kg per ha in 2012 (USDA, 2012a). In contrast with the Pacific Northwest, growers plant primocane fruiting varieties in hedgerows and sell the berries on the fresh market. In the 1990s, growers in California began using high tunnels to facilitate off-season production (Gaskell, 2004) and increase fruit yields and quality (University of California, 2009). High tunnels have since become standard in California and have helped establish the region as the premier producer of fresh raspberries in the United States.

Soil and Nutrient Requirements of Red Raspberries

Soil Requirements

Raspberries grow best in soils with a medium loam texture that are well drained, high in organic matter, and slightly acid in reaction (Ljones, 1966). Among other factors, these properties are favorable for root growth and development, which directly influence above-ground productivity, yield, and longevity (Hoffman, 1928). Raspberries also are sensitive to soil pH and salinity (Ljones, 1966). Generally, soil pH should remain below 7.0 (Ljones, 1966). In Michigan, productive and vigorous plants can grow in soils with a pH range of 5.1 to 7.0 (Hoffman, 1928). Sites with even moderate salinity should be avoided since cane fruits are very susceptible to injury from excess soil salts (Baker et al., 1951).

Mineral Nutrition

Tissue nutrient concentrations are a useful guide for monitoring raspberry nutrition in the field and for comparing different fertilization and soil management strategies (Clark, 1945; Kowlenko, 1981; Kowalenko, 1994; Buskiene and Uselis, 2008; Hargreaves et al., 2008a; Warman, 2009). However, interpretation of nutrient concentrations in specific raspberry plant parts is difficult because of variations in the type of tissue sampled, when the tissue was sampled during the plant growth cycle, the position of sampling along the plant, the specific cultivar examined, and variation in mineral element content due to the environmental conditions (Bould, 1968; Hughes et al., 1979; Kowalenko, 2005; Privé and Sullivan, 1994; Ramig and Vandecaveye, 1950; Vandecaveye, 1947). For instance, John and Daubney (1972) and John et al. (1976) found that leaf elemental concentration varied significantly by sampling time, variety, and cane age. Hughes et al. (1979) sampled leaves from 'Meeker' primocanes and found that N, P, and K concentrations increased towards the growing tip, while Ca, Mn, Fe and B were lower in new, young growth than in older leaves near the base of the cane. The optimum sampling position was determined to be within the 5-12 leaves beneath the terminal 15 cm of the primocane, since these leaves exhibited the least amount of variability in elemental content. Under their experimental conditions, the optimum sampling time was during the last half of August when primocanes form terminal buds and nutrients fluctuate little (Hughes et al., 1979).

When Ramig and Vendecaveye (1950) quantified deficiency levels of N, P, K and Ca for primocanes of 'Washington' using hydroponic culture, the first six physiologically mature leaves beginning at the third or fourth leaf down from the growing tip were sampled at the first sign of deficiency. Deficiency levels were determined to be 2.9%, 0.3%, 1.0% and 0.2% for N, P, K and Ca, respectively. Whereas these canes were in a state of active vegetative growth, Bould (1968) sampled leaves from the middle position of floricanes in 'Lloyd George' during the flowering stage. Cane length increased curvilinearly as leaf N increased from 1.5% to 3% dry weight but the effect of N could be limited by low levels of P and K. Bould (1968) therefore concluded that optimum N levels for growth hadn't been reached in that study. Despite the different sampling strategies in their studies, the results of Ramig and Vandecaveye (1950) and Bould (1968) both suggest that N deficiency may occur when leaf content is below 3%. However, these results may not be applicable to primocane fruiting varieties that experience a different pattern of vegetative and reproductive growth.

Himelrick (1994) showed that optimum leaf N levels for the primocane fruiting 'Red Wing' grown in hydroponic culture were 2.2%, and that higher rates and tissue concentrations didn't increase growth or flowering. Privé and Sullivan (1994) sampled leaves of 'Red Wing' and three other primocane fruiting varieties in six different environments. They found a positive correlation between leaf N and yield, total number of harvested berries, berry size and flower number per cane, and determined that proper leaf N concentrations were between 2-3% dry weight, and an N:K ratio of less than 1.5 should also be maintained. Significant genotype x environment interactions were seen for P, Ca, Mg, Fe, and Zn, suggesting a significant role of both genetics and environment in the leaf content of these nutrients.

Leaf analysis can be useful for diagnosing nutrient deficiencies, but it may not be ideal for determining fertilizer requirements. Alternatively, some have measured the elemental contents in canes and berries to estimate the total removal of nutrients from the soil on a per area basis (Dean et al., 2000; Kowalenko, 1994; Rempel et al., 2004). Kowalenko (1994) found that total above-ground N, P, K, Ca and Mg accumulation in the floricane fruiting variety ‘Meeker’ in British Columbia was 107, 11, 102, 48 and 20 kg ha^{-1}, respectively. Dean (2000) found that ‘Meeker’ had a total above-ground N uptake of 90 to 97 kg ha^{-1} at the end of the growing season which was partitioned equally between primocanes and floricanes. In Oregon, ‘Meeker’ took up between 88 and 96 kg N ha^{-1} (Rempel et al., 2004). Significant amounts of nutrients are exported from fields in harvested berries. A crop of ‘Willamette’ berries contained 24, 3, 13, 2, and 2 kg of N, P, K, Ca, and Mg ha^{-1}, respectively (Kowalenko, 2005).

According to Kowalenko (1994), season accumulation of macro elements in raspberries, especially N, follows the same pattern as dry matter accumulation. Therefore under conditions in British Columbia, N accumulation in floricanes is most rapid in May and June and peaks in July, whereas primocanes accumulate N most rapidly in July and August, reaching a maximum in October. However, macro element accumulation of primocane fruiting raspberries has yet to be examined.

Response of Raspberries to N Fertilization in the Field

Nitrogen is often the most limiting nutrient in raspberry production (Bushway et al., 2008), but the response to N fertilization has been variable and difficult to predict. Several studies have measured yield and growth responses and uptake and partitioning of N at different fertilization rates without finding significant differences or consistent responses (Chaplin and

Marting, 1980; Kowalenko, 1981; Dean et al., 2000; Kowalenko et al., 2000). Differing environmental and cultural conditions between studies such as initial soil fertility levels (Kowalenko, 1987; Kowalenko, 1994; Dean et al., 2000; Rempel et al., 2004; Zebarth et al., 2007), the age of the raspberry plantation (Lawson and Waister, 1972) and pruning practices (Kowalenko et al., 2000) could explain the inconsistencies in fertilization trials.

The need for fertilizers can be offset by high initial fertility. Using labeled-N in ammonium sulfate, Rempel et al. (2004) showed that plants fertilized with 40 kg N ha^{-1} and 80 kg N ha^{-1} took up the same amount of total N over the season and showed no difference in yield in one of two years of the study. The % N derived from fertilizer (NDFF), however, was higher in the 80 kg N treatments (31% vs. 16%). Dean et al. (2000) found no difference in yields between control plots (0 kg N) and plots receiving high rates of poultry manure. Even though background N levels were high in the control plots, fertilized plants took up more total N. Some authors (Dean, 2000; Rempel, 2004; Strick, 2008) described this effect as “luxury” N uptake.

In British Columbia, fertilization with 134 kg N ha^{-1} increased yield 11%, delayed ripening and increased berry size compared to the unfertilized control (Kowalenko, 1981). The same N rate increased berry size but not yield in Oregon (Chaplin and Martin, 1980). Therefore, N fertilization rates up to 134 kg N ha^{-1} may improve fruit quality and occasionally improve yield, but adequate productivity could be maintained with as little as 40 kg N ha^{-1} using conventional fertilizers under Pacific Northwest conditions (Rempel et al., 2004).

Organic fertilizers in raspberry production

In raspberry production, organic fertilizers and soil amendments are useful in the establishment of new plants (Black, 2003) and are used to organically and conventionally manage fertility (Hargreaves et al., 2008; Kuepper et al., 2003; Warman, 2009; Dean et al., 2000). Organic fertilizers and amendments are derived from waste by-products of animals, animal processing and plant materials (Hammermiester et al., 2005). While inorganic fertilizers can supply nutrients precisely and in plant-available forms, portions of the macro- and micro-nutrients in organic fertilizers become available more gradually during decomposition (Cooke, 1967).

Organic amendments suitable for raspberry production may include raw or composted animal manures, blood meal and seed meal (Kuepper et al., 2003). Besides supplying plant nutrients, composts and manures may also have positive effects on soil chemical, physical and biological properties. Compost and manure increase soil organic matter (Celik and Ortas, 2004; Zebarth et al., 2007), decrease bulk density (Celik et al., 2004; Zebarth et al., 2007), increase soil aggregation (Ekwue, 1992) and stability (ShengGao, 2001; Jiang-Toa, 2007), and protect against soil erosion (Bazzoffi, 1998) and plant pathogens (Alvarez and Antoun, 1995; Stone and Hoitink., 2001).

Although organic amendments can contain large quantities of N and other nutrients, they may be released gradually through mineralization and availability may not coincide with periods of crop demand, which can limit productivity (Berry et al., 2002). Some types of compost are also high in salts, such as municipal solid waste (MSWC) (Hargreaves et al., 2008a; Herrera et al., 2009) and sewage sludge (Roca-Perez et al., 2009). Raw or un-composted animal manures may increase risks of crop contamination with human pathogens (Cieslak et al., 1993; Nelson, 1997).

Poultry manure usually has an N content between 20 and 80 g N kg^{-1} on a dry weight basis (Bitzer and Sims, 1988), of which 50% is expected to become available in the year of application (Castellanos and Pratt, 1981). Dean et al. (2000) applied poultry manure to floricane fruiting 'Skeena' at a rate of 0, 100 and 200 kg N ha^{-1}, and compared this to 55 kg N ha^{-1} as $NH_4 NO_3$. Manure and fertilizer were broadcast and incorporated into the row middles between Feb. 25 and Mar. 10. According to the results, mineralization of manure N occurred rapidly, as did nitrification which is indicated by a decrease in soil NH_4^+-N and corresponding increase in soil NO_3^--N. This is consistent with previous studies that showed rapid mineralization of organic N in poultry manures (Pratt et al., 1973; Castellanos and Pratt, 1981; Sims, 1986; Bitzer and Sims, 1988). In this study there was no effect of treatment on raspberry yields, which suggests that under the experimental conditions, existing soil organic N contributed substantially to the total N supply. It was estimated that mineralization of soil N supplied 166 to 177 kg N ha^{-1}, while crop uptake was only 90 to 100 kg N ha^{-1}.

Compost releases considerably less available N than fresh manure (Castellanos and Pratt, 1981). Up to 51% of the initial total-N in cattle manure can be lost through ammonia-N volatilization during the composting process (Parkinson et al., 2004). Composting also creates stable N compounds that resist leaching and aren't immediately available to plants (Bernal et al., 2009). Raspberries receiving MSWC and ruminant compost applied over the row at a rate of 135 kg N ha^{-1} for three consecutive years were borderline deficient in N and P and deficient in K (Hargreaves et al., 2008b). In another study, floricane leaf N levels in plants receiving MSWC were lower than plants receiving a comparable amount of N from a chemical fertilizer (Warman, 2009). These results suggest that much of the N, and perhaps P and K in surface-applied compost remained unavailable to raspberries, resulting in nutrient deficiency.

It is unclear whether raspberry nutrition could be optimized with compost formulated with a different process or used under different cultural and climatic conditions. Strategies for organic fertility and nutrition management remain elusive since research on this topic is incomprehensive, yet, nutrition management will be a critical facet of future organic production systems, such as high tunnels.

High Tunnels

Overview

High tunnels, also called hoop houses, are simple structures that are used to protect horticultural crops and improve production (Lamont, 2009; Carey et al., 2009). They consist of a metal frame covered in a single or double layer of greenhouse plastic, but may vary in size and shape. Crops are usually grown in the soil inside high tunnels, as opposed to conventional greenhouses in which crops are grown in pots, trays or on benches. Another distinguishing feature is the lack of supplemental heating (usually), cooling or lighting. The climate inside high tunnels is instead managed through ventilation. High tunnels also lack a permanent foundation and are usually considered to be non-permanent structures.

Depending on the climate and structure design, high tunnels can be used year round (4-season) or seasonally (3-season tunnels) (Giacomelli, 2009). This difference is most apparent in snowy climates where the structural ability to support a snow load determines if a high tunnel is suitable for 4-season or 3-season use. Four-season tunnels are stand-alone structures that usually have a peaked frame complete with trusses, perlins, and closely spaced legs to improve structural rigidity. The added materials contribute to a higher cost per area covered compared to a 3-season design, which by contrast has a simpler and less rigid construction. Some-stand alone tunnels are considered 3-season structures because they are not adequately strong to be covered year round.

A common 3-season tunnel consists of bays of interconnected tunnels that span large areas. The plastic is placed over the tunnel(s) in spring when the danger of snow has passed, and is removed from the structure and stored at the end of the growing season.

Raspberry Production in High Tunnels

Raspberries are grown commercially in both types of high tunnels. Large scale high tunnel production in California and elsewhere uses multi-bay or 3-season types (Carey et al., 2009; Bolda et al., 2012). Over 1619 ha of raspberries are under multi-bay tunnels in California (Carey et al., 2009), which accounts for a large portion of the total raspberry acreage (2185 ha) in that state (USDA, 2012a). Small plantings of high tunnel raspberries also can be found in Florida, Maine, Maryland, Michigan, New Jersey, Utah, Pennsylvania and Washington. These plantings tend to be in 4-season high tunnels and are primarily used for direct, fresh market production (Carey et al., 2009; Demchak, 2009).

High tunnel production of raspberries offers numerous advantages over open field culture, especially in humid northern climates like the Midwest and Northeast where growing seasons are short and humid, and management is complicated by difficult pests and diseases. Research in these regions has demonstrated that high tunnels may permit more consistent production of high quality fruit with a longer shelf life and harvest season, and may even facilitate organic production (Demchak, 2009; Hanson et al., 2011; Lang, 2009; Pogliano, 2010; Yao and Rosen, 2011). This is because high tunnels suppress several fungal diseases that are prevalent in humid climates and also accommodate alternatives to chemical control of insects. An important example is grey mold (*Botrytis cinerea*), a fungal disease that infects flowers, canes and leaves during wet weather and produces moldy berries with a poor shelf life (Bushway et al., 2008).

In multi-bay high tunnels in Michigan, for instance, no fungicides were required to keep incidence of grey mold (*Botrytis cinerea*) on fruit below 4%, whereas nearby open field plots had incidences as high as 41% when no fungicides were applied (Hanson et al., 2011). These results are similar to those of Demchak (2009) in Pennsylvania where occurrence of grey mold on high tunnel-grown berries remained very low when no fungicides were used. Suppression of grey mold in high tunnels is likely a result of excluding rainfall, depriving the pathogen of the moisture needed to cause infection (Hanson et al., 2011; Jarvis, 1962). High tunnels also prevent leaf spot (*Sphaerulina rubi* Demaree & M. S. Wilcox) anthracnose (*Elsinoe veneta* [Burkholder] Jenk.), and spur blight (*Didymella applanata* [Niessl] Sacc.) (Hanson et al., 2011).

High tunnels alter the presence and severity of insect pests as well through environmental alterations and physical exclusion. Plastic films used on high tunnels can quantitatively and qualitatively alter the solar radiation (Kittas and Baile, 1998) which can disrupt movement of insect pests that use UV light for orientation, navigation and host location (Johansen et al., 2011; Nguyen et al., 2009; Raviv and Antignus, 2004). This may explain why japanese beetle (*Popillia japonica*) numbers and damage are lower in high tunnels than open fields (Lang, 2009; Hanson et al., 2011). Plastic greenhouse films can also help exclude leafhoppers (*Empoasca fabae*) (Doukas and Payne, 2007), aphids (*Bemisia argentifolii*) (Costa and Robb, 1999) and thrips (*Frankliniella occidentalis*) (Antignus et al., 1996; Doukas and Payne, 2007). Furthermore, high tunnels can improve efficacy of biological control agents (Potorff and Panter, 2009) such as predatory mites (*Neoseiulus californicus and N. fallacis*) to control two spotted spider mites (*Tetranychus urticae*) on raspberries (Demchak, 2009; Yao and Rosen, 2011).

The plastic covering can also add significant length to the growing season. A principle advantage of season extension is the potential to market berries when either local or non-local supply is low and prices are higher (Von Weihe, 2010). Research suggests that 4-season tunnels extend the raspberry growing season longer than 3-season tunnels. In a 4-season tunnel in Pennsylvania, raspberries began fruiting 3-4 weeks earlier than in the field, and continued fruiting 3-4 weeks later (Demchak, 2009). Similarly in northern Minnesota, fruiting was extended for four 4 weeks in the fall but required some supplemental heating to prevent frost (Yao and Rosen, 2011). Multi-bay tunnels in Michigan only lengthened the harvest season by two weeks (Hanson et al., 2011), but yields were still comparable to 4-season tunnels in other areas.

Hanson et al. (2011) reported that yields from both floricane and primocane raspberries in 3-season tunnels in Michigan were between two and three times greater than what is typically produced in open-field production. In Pennsylvania, yields from ‘Heritage’ grown in a 4-season tunnel were more than 2.5 times greater than typical open-field yields for that region (Demchak, 2009). In a 4-season tunnel in northern Minnesota, average yield across five primocane fruiting varieties was 12.5 $t \cdot ha^{-1}$, more than five times the yield from the same varieties in adjacent open field plots (Yao and Rosen, 2011), but some supplemental heating was used to maintain fall fruiting. Berry size may also be greater in high tunnel production; although not statistically comparable, floricane fruiting raspberries had higher mean berry weights when grown in 3-season tunnels than when grown in open-field conditions (Hanson et al., 2011), as did primocane fruiting raspberries in a 4-season tunnel (Yao and Rosen, 2011)

Soil and Nutrient Management

The majority of high tunnel crops are grown directly in the soil, similar to open field production. However, different economic and environmental conditions of high tunnel production usually warrant more intensive management of soil, water and nutrients (Blomgren and Frisch, 2007; Montri and Biernbaum, 2009). High tunnel producers have an economic incentive to maximize production as a result of the large investment, so more resources are often expended on soil amendments. Crops may also demand more nutrition inside high tunnels through increased plant vigor and longer growing seasons. Higher air temperatures and a lack of precipitation results in elevated soil temperatures and/or dry soil conditions that may negatively impact soil and plant health (Demchak, 2009). Soil and nutrient management strategies for high tunnels vary with the crop, climate, and tunnel type, as do the potential difficulties related to soil quality and health.

The majority of high tunnel growers in the United States use them for annual crops such as vegetables and cut flowers (Carey, 2009; Knewston et al., 2010a; Conner et al., 2010). High tunnels permit several annual crop cycles per year and as such, growers have modified soil management strategies to accommodate multiple cycles. For instance, cover crops are infrequently used in high tunnels with annual crop production due to the opportunity cost of producing a cash crop. Alternatively, many growers apply compost between annual crop cycles to supply nutrients, organic matter, improve soil quality and maintain soil health (Blomgren et al, 2007; Montri and Biernbaum, 2009; Knewston et al., 2010a,b). Frequent additions of compost are viewed as a necessary practice to prevent decline in soil tilth and soil organic matter, and to prevent the buildup of soil pathogens and pests (Coleman, 1999; Montri and Biernbaum, 2009). Compost is used by both conventional and organic growers (Blomgren and Frisch, 2007; Knewston et al., 2010a) and can be as effective as fertigation with soluble fertilizers (Rosen et al., 2009) or solid mineral fertilizers (Reeve and Drost, 2011) when it is incorporated into the soil prior to an annual crop cycle. However, frequent compost additions in high tunnels can result in excessive P levels (Reeve and Drost, 2011). Therefore, organic or mineral fertilizers with a more favorable balance of nutrients are recommended after sufficient compost or organic matter has been incorporated into the soil (Blomgren and Frisch, 2007; Reeve and Drost, 2011).

High tunnel growers are advised to perform soil tests periodically to avoid nutrient imbalances and excessive salinity, which inhibits plant growth by mimicking drought conditions (Blomgren and Frisch, 2007). Soils inside high tunnels are susceptible to salinization when compost or fertilizers are applied and leaching is limited (Montri and Biernbaum, 2009). Soils are considered saline if the electrical conductivity (EC) is greater than 4 dS m^{-1} (Brady and Weil, 1999), but yield reductions in lettuce and raspberries may occur at levels of 1 dS m^{-1} (Kotuby-Amacher et al., 2000) or 2 dS m^{-1} (Bernstien, 1964). Salts have a tendency to stratify with depth in high tunnels, with highest concentrations near the surface (Wenquing et al., 2001; Ju et al., 2007; Huan et al., 2007). A survey of high tunnels in Kansas showed that 25% had a soil EC greater than 2 dS m^{-1} in the upper 5 cm of soil, and that more than half had an EC of greater than 1 dS m^{-1} in the upper 15 cm of soil. Salts may be remediated by removing the top layer of soil, flooding the soil with irrigation water (Blomgren and Frisch, 2007), or uncovering the tunnel and exposing the soil to precipitation (Coleman, 1999). Annual cropping systems facilitate soil remediation and nutrient management quite readily since the soil can be worked and amended between cycles.

Perennial crops, by contrast, present more difficulty in managing the soil environment inside high tunnels. Once in place, perennial crops cannot be removed and re-planted due to the high cost of plant material and the time needed to establish them. Salinization may also pose a greater threat to perennials as there is potential for chronic plant health effects. It is also more difficult to increase soil organic matter and add nutrients to soils in perennial crop production since amendments cannot be mechanically incorporated into the plant row. Furthermore, high tunnels prevent rainfall from leaching nutrients on the surface down to the rootzone. Conventional tunnel growers can manage the nutrition of perennial crops by injecting soluble inorganic fertilizers through drip irrigation lines, which has so far been successful for sweet cherries (Lang, pers. comm.) and raspberries (Yao and Rosen, 2011; Bolda et al., 2012), although raspberries may be somewhat susceptible to potassium deficiency in high tunnels (Demchak, 2009; Hanson et al., 2011).

Managing nutrition organically is likely to be more difficult since soluble sources of nutrients are expensive and may clog drip irrigation systems (Hartz et al., 2010). Organic tunnel raspberry growers in California are advised to fertigate with liquid fertilizers made from fish waste, guano or plant extracts to supplement solid fertilizers that are incorporated before planting new canes every 18 to 24 months (Gaskell, pers. comm.; Bolda et al., 2012). Although nitrogen in liquid organic fertilizers may behave similarly to mineral N sources (Hartz et al., 2010) cost per kg of N in liquid organic materials ranges between $10 and $36 (Miles et al., 2012). Furthermore, raspberries in northern climates cannot be removed and replanted due to the long establishment period. Therefore, organic soil management strategies of reasonable cost capable of supplying the nutritional needs of raspberries are needed.

Summary

Organic raspberries are a high value niche crop receiving a premium price on the fresh market. In California, where the current supply of organic raspberries originates, growers are using multi-bay high tunnels to extend the growing season, increase yields and improve fruit quality. These benefits are substantiated in the Midwest, showing the potential to produce organic raspberries in proximity to large population centers in the eastern United States.

Raspberries are perennial plants requiring maintenance of sufficient nutritional status, particularly nitrogen, for optimal production and quality. Organic fertilization programs often include compost, manure, and blended organic fertilizers. Since these materials require significant soil moisture to mineralize and move nutrients towards plant roots, it is unclear whether they will be effective in a high tunnel environment without rainfall and with dry soil conditions throughout the growing season. Strategies for organic nutrition management of high tunnel raspberries in the Midwest are needed.

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CHAPTER 2

EFFECT OF COMPOST AND ORGANIC FERTILIZER ON SOIL NITROGEN AND PERFORMANCE OF PRIMOCANE FRUITING RASPBERRIES IN HIGH TUNNELS

Abstract

Three primocane fruiting red raspberry (*Rubus idaeus*) cultivars (Joan J, Polka, and Himbo Top) were grown in multi-bay high tunnels in Michigan for three years under organic management. The primary objective was to compare the effects of spring applications of compost at two rates (22,400 and 11,200 kg ha^{-1}) and meal-based organic fertilizer at two rates (2,800 and 1,400 kg ha^{-1}) on soil fertility, plant nutrition and productivity. Treatments were incorporated into the rows prior to planting in May, 2010, and top dressed over established rows in early April of 2011 and 2012. Plants were trickle irrigated and pruned to the ground each spring. Tunnels were covered with plastic from May through October. Incorporation of the treatments resulted in high inorganic soil nitrogen (N), while broadcasting resulted in much lower soil inorganic-N levels as measured by KCl extraction of soil samples taken regularly throughout each season. Plant N status was increased by the high rate of organic fertilizer but all plants were deficient in potassium (K) and sulfur (S) in late July, 2012. Across treatments, analysis of primocane N content indicated that 89 to 95 kg N ha^{-1} accumulates above ground by late summer. Fertility treatments had no effects on plant growth, fruit quality or berry yield, but significant differences were found between varieties. 'Joan J' produced the highest yields in 2011 (3.2 kg m^{-1} row), which were lower than in previous studies. Future experiments should address the effect of irrigation method on nutrient availability and use of fertigation for supplementing nutrition.

Introduction

High tunnels are plastic-covered, unheated greenhouses that enhance crop production by extending the growing season, improving crop yields and quality, and reducing key pests and diseases. High tunnels are becoming an important part of small-and medium-scale fruit and vegetable farms in the eastern U.S. that supply the expanding market for locally grown food (Low and Vogel. 2011; Carey et al., 2009; Conner et al., 2009; Lamont, 2009). They are relatively low cost, simple to construct, and available in various designs and sizes. High tunnels may be single stand-alone units or hoophouses, or multi-bay tunnels consisting of several inter connected units. Multi-bay high tunnels are called 3-season tunnels in the Midwest and Northeast regions of the U.S. since the plastic is removed each winter to avoid structural damage from snow. In contrast to hoophouses that typically are for year round-vegetable production, multi-bay high tunnels are ideally suited to perennial fruit crops which have winter dormancy.

California is the primary supplier of both organic and conventional fresh raspberries in the U.S. Multi-bay high tunnels are used extensively in California because they permit year round production in mild coastal areas and improve fresh fruit quality (Gaskell, 2004). Under conventional management, high tunnels in the Midwest and Northeast provide similar benefits, including 2-4 weeks of extended harvest season, increased plant vigor, yield and fruit quality and reduced incidence of fruit, foliar and cane diseases (Hanson et al., 2011; Yao and Rosen, 2011; Demchak, 2009). Interest in and use of high tunnels for berry production in the eastern United States is increasing in response to high prices and strong demand for locally grown berries (Milkovich, 2012; Burfield, 2011). Organic berries are also in high demand, but they are difficult to grow in humid regions. Weekly sales of organic berries grew 193% between 2006 and 2010 at an average price that was 33% higher than conventional (The Perishables Group, 2011). In 2011, the average price premium for organic raspberries in the Midwest was 24% (USDA ERS, 2012).

There are no specific recommendations for organic high tunnel raspberry production in the eastern U.S.; trials thus far have been conventionally managed and research has focused on topics like variety selection and pest incidence, and much less on specific subjects such as soil fertility and nutrition management. One area of need is fertilization practices. Raspberries have a strong nutrient demand, especially for N, that continues through the 4-month growing season (Kowalenko, 1994). For conventional culture in open fields, growers in the eastern U.S. are advised to annually apply between 56 and 112 kg N ha^{-1} (Bushway et al., 2008).

In high tunnels, nutrients often are injected through drip irrigation systems since rainfall is not available to leach nutrients into the soil. Organic tunnel raspberry growers in California inject liquid organic fertilizers made from fish waste, guano, or plant extracts to supplement solid fertilizers, like compost, that are incorporated before planting every 18 to 24 months (Gaskell, pers. comm.; Bolda et al., 2012) Nitrogen in liquid organic fertilizers, like that in mineral sources, is prone to leaching (Hartz et al., 2010). These products also are expensive. Cost per kg of N in liquid organic materials ranges between $10 and $36 (Miles et al., 2012), and some of the N may be lost during filtration in the irrigation system (Gaskell, pers. comm.).

Solid materials like compost and seed meals are an alternative to liquid materials for growers in the eastern U.S. who require fertilization only seasonally as opposed to year round. These materials are less expensive and often are readily available locally, and are useful nutrient sources in open-field raspberry culture (Kuepper et al., 2003). One concern with organic fertilizers is that N mineralization and availability may not coincide with crop demand (Gaskell and Smith., 2007). Compost tends to release N slowly (Escudero et al., 2012), while N in fertilizers, like alfalfa meal, becomes available more quickly (Agehara and Warncke, 2005). These materials could be applied to the soil in early spring where they would be exposed to rain until plastic is installed on the tunnel (usually May). However, how much N would be mineralized and moved into the soil is not known. It is also unclear whether N supplies would be adequate late in the season. The purpose of this study was to compare the soil N levels and the nutritional status and productivity of high tunnel raspberries amended with spring applications of compost and meal-based organic fertilizer.

Materials and Methods

Site Description

This study took place within a 0.45 ha range of multi-bay high tunnels (Haygrove Tunnels., Redbank, Ledbury, UK) at the Michigan State University Horticulture Teaching and Research Center (HTRC), East Lansing, Michigan (42.75°N 84.47°W, USDA plant hardiness zone 5b). The range consists of nine interconnected bays oriented north to south, each measuring 61 x 8 m and 4.9 m tall at the peak. The site has a sandy soil (mixed, mesic Psammentic Hapludalf), and had been fallow for several years prior to construction of the high tunnels in 2009. Soil tests prior to the experiment indicated a pH of 5.2, with 93 mg kg^{-1} of phosphorus (P), 89 mg kg^{-1} of potassium (K), organic matter (OM) of 2.4% and a CEC of .75 meq g^{-1}.

Experimental Design

The experiment was conducted in three adjacent bays that were bordered by neighboring tunnels to minimize environmental edge effects. The experiment used a randomized complete split block design with variety as the main plot and fertility treatment as the subplot. Each tunnel was divided into two blocks with four 7.6 m long treatment plots. The soil was prepared before planting by tilling and incorporating the treatments into the planting rows to a depth of 15-20 cm in a 0.5 m wide band on 13 Apr. 2010. The four treatments consisted of dairy compost (Morgan's Compost, Evart, Michigan) applied at 22,400 kg ha^{-1} (high compost) and 11,200 $kg \cdot ha^{-1}$ (low compost) and 8-1-1 organic fertilizer (McGeary Organics, Lancaster, Pennsylvania) applied at 2,800 kg ha^{-1} (high Fertilizer) and 1,400 kg ha^{-1} (low Fertilizer). A chemical analysis of the compost was performed in each of the three years by A & L Great Lakes Laboratories (Fort Wayne, Indiana) and is shown in Table 2.1.

Table 2.1 pH, electrical conductivity, carbon to nitrogen ratio, and element concentrations in compost applied to high tunnels in 2010, 2011,2012 East Lansing, Michigan

				% of dry weight						
Year	pH	EC ($dS \cdot m^{-1}$)	C:N ratio	N	P	K	Ca	Mg	Na	S
2010	6.9	14.1	8:1	2.9	2.4	1.8	7.5	0.7	0.4	1.4
2011	8.2	2.7	13:1	1.3	1.1	1.0	6.5	0.7	0.1	0.3
2012	7.7	5.4	11:1	1.7	0.5	1.5	2.8	0.9	0.2	0.4

Three rows of raspberries spaced 2.4 m apart were planted in each tunnel on 23 Apr. 2010, with one row each of 'Polka', 'Joan J' and 'Himbo Top'. Tunnels were covered with plastic from 7 May to 20 Oct 2010. On 10 June 2010, dolomitic lime was incorporated within 60 cm of the raspberry rows at a rate of 540 kg ha^{-1} to increase soil pH.

On 18 Apr 2011, treatments were top-dressed over the row in a 0.5 m wide band and tunnels were covered from 7 May to 21 Oct. In 2012, treatments were spread over the row on 5 Apr., and tunnels were covered from 23 Apr. to 27 Oct. Floricanes were removed by pruning to ground level in March of 2011 and 2012. Temperature inside the high tunnels was recorded with data loggers (WatchDog model 2475 Plant Growth Station, Spectrum Technologies, Inc., Plainfield, Illinois). Precipitation that accumulated prior to covering the tunnels was recorded by a Michigan Automated Weather Network (MAWN) station located on-site at the HTRC. During the growing season, each row was irrigated with a single drip irrigation tube with 2.3L hr^{-1} emitters spaced .6 m apart. Plants were generally irrigated once per day for 1-2 h during warm weather, and twice a day during hot weather, based on soil moisture levels determined by feel and occasional measurements with time domain reflectometry (Trase System I, Soil Moisture Equipment Corp., Santa Barbara, California). Irrigation amounts totaled 310 mm in 2011 and 432 mm in 2012, and were not recorded in 2010.

Soil and Plant Assessment

In all three years, soil samples were collected regularly between the beginning and end of the growing season. Samples were composites of nine 2 cm diameter cores taken from within each treatment plot to a depth of 20 cm. Soils were dried and ground to pass through a 1 mm sieve, extracted with 1 M KCl, and analyzed for nitrate-nitrogen (NO_3^- -N) using the cadmium reduction method (Gelderman and Beegle, 1998), and ammonium-N (NH_4^+-N) by the salicylate method (Nelson, 1983). Electrical conductivity and pH were measured using 1:1 soil-to-water method (Whitney, 1998). Total organic carbon (OM%) was measured by loss of weight on ignition (Storer, 1984).

Leaves were sampled on 6 Aug. 2010 and 19 Jul 2012 for nutrient analyses. Samples consisted of the youngest fully expanded primocane leaves, usually located five to seven nodes below the apex. Leaf samples were dried and ground prior to analysis. Total above-ground biomass and N content of floricanes were measured in March 2011 by removing and weighing all canes in each variety and treatment plot. Three canes were selected randomly from each variety within a treatment plot, combined, then coarsely ground with a brush chipper, and weighed. A subsample was removed, dried, finely ground and then analyzed for N content. Total N concentrations in leaf and cane samples were determined colorimetrically following a Kjeldahl digestion (Bradstreet, 1965) using a QuikChem 8500 Autoanalyzer (Lacht Instruments, Milwaukee, Wisconsin). The remaining nutrient elements in leaf samples were ashed in a muffle furnace (Theromolyne model 30400; Thermo Fisher Scientific, Waltham, Massachusetts) at 500 ^{o}C for 6 h. The ash was dissolved in 1 N nitric acid and analyzed by direct current plasma emission spectrophotometry (Beckman Instruments, Fullerton, California). Above-ground N content of floricanes (g N plot^{-1}) was calculated as the product of tissue N% and cane dry weight per plot. On 1 Nov. 2011 and 2012, cane height, internode length and number of fruiting laterals were measured on 3 randomly selected canes of each variety in each treatment plot.

The seasonal pattern of N accumulation in canes was measured in 2011 and 2012 across the entire planting, irrespective of treatment. The three rows of ‘Polka’ were used as replicates. On each date, cane density was measured by counting the number of canes in a 1 m section of each nutrition plot. Different row sections were selected on each sampling date. One cane was then randomly selected from each section, cut at the base, dried, weighed, and ground. Samples were collected on 6 dates between May and July, 2011 and 7 dates between May and Aug., 2012. Tissues were processed as described previously. The N content of canes on a hectare basis was calculated based on the number of canes m^{-1} row, dry weight per cane (g) and cane N concentration (%).

Berry Yield, Berry Quality, and Harvest Times

Berry yields, average weights, and visual appearance were measured in 2011 and 2012. Fruit were picked by hand on commercial harvest schedules (every 2-3 days) in 2011 and 2012 and yields were determined by recording the number of pints per plot. Berry quality was measured on multiple dates in 2011 and 2012. One vented plastic clamshell half pint of berries was collected from each treatment and variety on five harvest dates in 2011 and three harvest dates in 2012, enclosed in a black plastic bag, stored for 24 h at 4 ^{o}C and then stored for 24 h at 18 ^{o}C to simulate retail handling. Visual appearance of each sample was rated on a scale of 1-5, where 1 = unsalable for any use, 2 = poor, generally not salable for fresh consumption, 3 = fair, possibly salable, some significant defects, 4 = good, only minor defects, and 5 = excellent, no defects. Average berry weight (g) was then measured by dividing the total weight of the half pint by the number of berries in it.

Statistical Analysis

Soil properties, leaf element concentrations, cane growth, yield and berry quality were analyzed using the PROC Glimmix procedure in SAS version 9.1 (SAS Institute, Cary, North Carolina) to calculate analysis of variance and least-square means (LSmeans). The data were checked for model assumptions and were log transformed when necessary. All LSmeans reported are in original units. Year was treated as a repeated measure for analysis of yield, berry weight, visual berry quality and cane growth. The last soil sample from each year was used for repeated measure analysis of soil EC and pH, while OM% was analyzed on the last date in 2012. For soil nitrate, ammonium and inorganic nitrogen, years were analyzed individually and date was treated as a repeated measure. Years also were analyzed separately for leaf nutrient concentration.

Results and Discussion

Temperatures and Precipitation

The temperatures inside the high tunnels varied considerably in the two years that yield data were collected. Daily high temperatures between June and August met or exceeded 35^{O}C on 42 dates in 2012, but only on two dates in 2011 (Fig 2.1). Precipitation amounts between the dates of treatment application and tunnel covering totaled 17, 85 and 25 mm in 2010, 2011, and 2012, respectively.

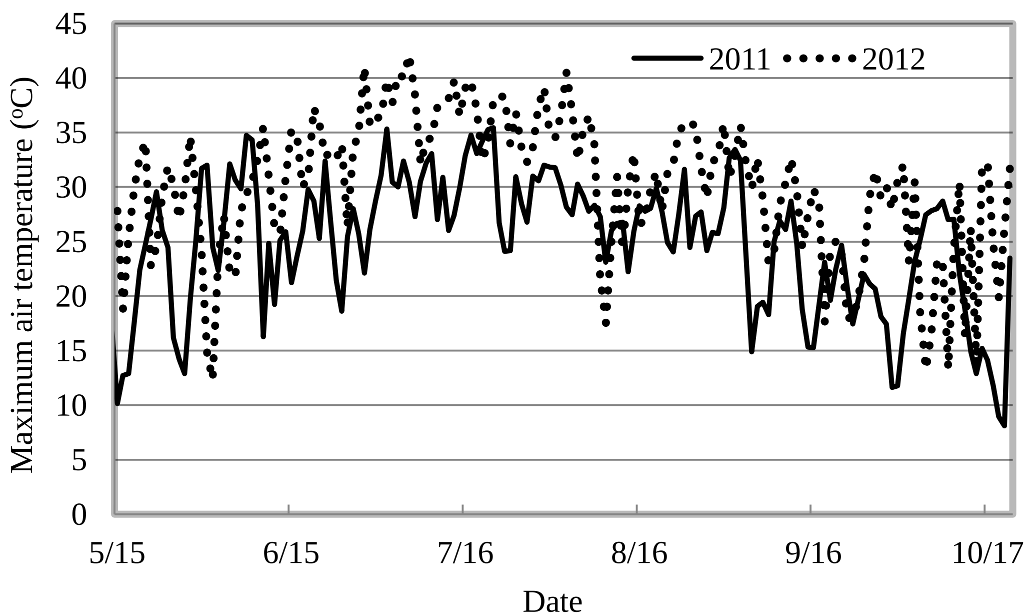

Figure 2.1. Maximum daily air temperatures in multi-bay high tunnels between May and Oct. of 2011 and 2012 in East Lansing, MI.

Soil Inorganic N

Analysis of variance was performed separately for each year since the treatments were applied differently in 2010 (incorporated) than 2011 and 2012 (top-dressed). There was a significant date x treatment interaction each year for total inorganic-N (NH_4^+-N + NO_3^--N) and NH_4^+-N. For NO_3^--N, there was a significant treatment effect in 2010, and a significant date x treatment effect in 2011 and 2012.

Total inorganic N followed a similar pattern in both the fertilizer and compost treatments when they were incorporated in 2010 (Fig. 2.2). Inorganic-N was initially high and supplied primarily by NH_4^+-N, but diminished within 6-8 weeks of incorporation. Modest amounts of inorganic-N in July and August were primarily in the NO_3^- -N form, which was statistically higher under the high compost treatment. In addition to initially high N levels in 2010, salinization appeared as a result of incorporating the high rate of compost. Plants in the high compost treatment plots initially showed marginal necrosis on developing leaves, and soil EC levels (data not shown) were above the tolerance threshold for raspberries (1.0 dS m^{-1})(Kotuby-Amacher et al.,2000). This was attributed to the high EC of the compost (Tabled 2.1), and to avoid further salinization, compost with a lower EC was used in 2011 and 2012. This resulted in a lower N application rate when compost was top dressed in 2011 and 2012 because of the lower N content of the compost (Table 2.2).

When treatments were top-dressed, levels of inorganic-N were lower compared to incorporating them in 2010. Instead of trending from initially high to low levels, inorganic-N tended to remain low but variable through the 2011 and 2012 seasons. What accounts for the regular fluctuations of inorganic-N in 2011, is unknown, but inorganic-N was significantly

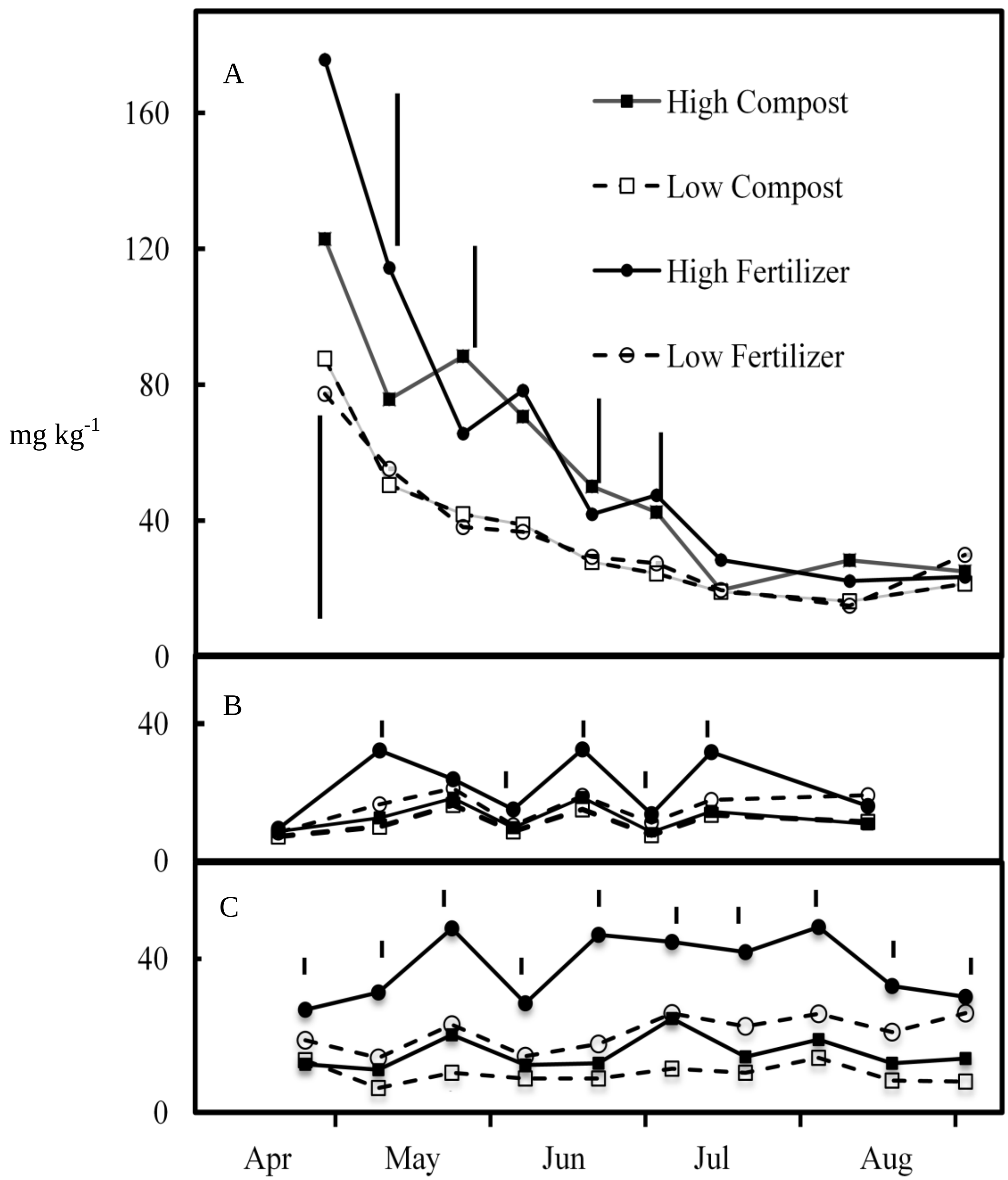

Figure 2.2. Total inorganic-N (NH_4^+-N + NO_3^- -N) in the top 20cm of soil in high tunnels in 2010 (a), 2011 (b) and 2012 (c) in East Lansing, Michigan. Bars indicate tukey-kramer's least significant difference (P≤.05).

Table 2.2. Amount of nitrogen applied (kg N ha^{-1}) across treatments in three different years in multi-bay high tunnels in East Lansing, Michigan.

Year	High Compost	Low Compost	High Fertilizer	Low Fertilizer
2010	122	61	112	56
2011	53	27	112	56
2012	71	36	112	56

Water content of the compost was estimated to be 37.5% based on data provided by the supplier (Morgan's Composting, Evert, Michigan) and mineralization rates for the compost and fertilizer were estimated at 30% and 50% per year, respectively.

higher in the high fertilizer treatment on multiple dates. Total inorganic-N was again highest in the high fertilizer treatment in 2012. Even when the N content of the compost was high in 2010, a large volume was required to match N supply from the fertilizer. In 2011 and 2012, soil inorganic-N under the high rate of compost was approximately equal to levels under the low rate of fertilizer.

One reason inorganic-N levels were generally low across treatments in 2011 and 2012 may be a lack of moisture to cause sufficient mineralization and leaching of N into the root zone. The drip irrigation system only wetted the surface soil directly beneath emitters, so much of the compost and fertilizer on the soil surface remained dry, which likely minimized N mineralization and movement. A second drip irrigation line might improve conditions by wetting a larger soil surface area.

Soil Quality

Across all years, treatments significantly affected soil EC ($p \leq .0001$) but not pH. Mean soil EC to a 20cm depth was 0.37, 0.26, .24 and 0.23 dS m^{-1} for the high and low compost and high and low fertilizer, respectively. Prior to the experiment, soil OM% averaged 2.4 $\pm$0 .4% in the three tunnels. After 3 years, soil organic matter was higher in the high compost treatment

(3.2%) than other treatments and levels in the low compost and low and high fertilizer plots did not differ (2.8, 2.6, and 2.6%, respectively). The lack of significant differences in OM% between the low compost and the fertilizer treatments suggests that high rates of compost, about 67,200 kg ha^{-1} over three years, were required to cause an increase OM% under the experimental conditions.

Leaf Nutrient Levels

Treatments affected leaf phosphorus (P) ($P \leq .01$), potassium (K) ($P \leq .01$), and Boron (B) ($P \leq .0001$) in 2010(Table 2.3). Leaf P was significantly higher in the high compost treatment compared to the low compost and low fertilizer, but levels did not differ between the high compost and high fertilizer. Leaf K was significantly increased by the high compost treatment and there was a significant trend of increasing B levels with increasing rates of compost. Across treatments, concentrations of N, calcium (Ca), magnesium (Mg), zinc (Zn), manganese (Mn), iron (Fe) and Copper (Cu) (2.99, 1.0, .49% and 44, 462, 134, 21 mg kg^{-1}, respectively) were sufficient according to Bushway et al. (2008). Despite significant treatment effects on leaf P, levels bordered on deficiency across treatments in 2010. Pre-plant testing indicated high initial P-levels, but the moderately acidic soil conditions may have limited P availability. Sulfur concentrations were much lower than the deficiency threshold of .35 mg kg^{-1} in 2010.

In 2012, treatments significantly effected on leaf levels of N ($P \leq .01$), sulfur (S), and manganese (Mn), and again on K and B. Nitrogen concentration was highest in high fertilizer while no statistical differences existed between the other treatments. Despite a lack of significant pairwise comparisons amongst leaf K levels in 2012, the analysis of variance was significant and concentrations trended upwards in the order of low fertilizer, high fertilizer, low compost and

Table 2.3 Leaf nutrient element concentration in raspberry primocane leaves in 2010 and 2012 in multi-bay high tunnels in East Lansing, MI

	N	P	K	S	Mn	B
		%			mg kg^{-1}	
			2010			
High compost	2.98	0.22a	1.8a	0.17	307	63a
Low compost	2.97	0.20b	1.66ab	0.16	317	49b
High fertilizer	3.07	0.20ab	1.6b	0.16	651	29c
Low fertilizer	2.93	0.19b	1.54b	0.16	573	30c
			2012			
High Compost	2.13a	0.26	1.41	0.12a	157a	35a
Low compost	2.06a	0.24	1.37	0.11a	112ab	29b
High Fertilizer	2.41b	0.22	1.23	0.13b	114ab	23c
Low Fertilizer	2.27a	0.23	1.13	0.13b	87b	21c

high compost. B concentrations increased significantly with increasing rates of compost, while levels remained lower in the fertilizer treatments. Sulfur was slightly but significantly increased in the high fertilizer compared to both compost treatments.

Phosphorus concentrations were nearly sufficient across treatments (0.24%) and had increased relative to 2010, which may be due to increased soil pH (data not shown) and resultant soil P availability. Leaf Ca, Mg, Zn, Fe, and Cu were sufficient across treatments in 2012 (1.1, 0.49% and 20, 160, 6.3 mg kg^{-1}, respectively) but K and S concentrations were below sufficient ranges (1.5 to 2.5% and 0 .4 to 0.6 mg kg^{-1}, respectively). Boron concentrations were below the deficiency level of 25 mg kg^{-1} in the fertilizer plots, but were adequate in both compost treatments.

After three years, the compost treatments resulted in low mean N concentrations. Open-field raspberries receiving compost at the equivalent rate of 135 kg N ha^{-1} had similar low leaf N concentrations after three years, despite the high application rate (Hargreaves et al., 2008), suggesting that surface applied compost provides little available N. Nitrogen nutrition was increased by high rates of the fertilizer in this study, which is consistent with the higher soil inorganic-N in that treatment in 2011 and 2012. However, the benefits of increased N may have been obscured by a lack of K, S and B.

Bould (1968) found that when leaf N and Mg concentrations were adequate, berry yield was significantly increased by increasing leaf K concentration. Potassium deficiency has been reported previously in high tunnel raspberries by Demchak (2009) and Hanson et al. (2011), despite fertigation with standard rates of K. It has been suggested that K deficiency can occur as a result of high Ca and Mg concentrations in irrigation water (Heidenreich et al., 2012). It has also been shown in other perennial crops including grapefruit (Swietlik, 1992) and apple (Nielson et al., 2000) that use of drip irrigation may promote K deficiency by encouraging root development around the wetted zones proximal to emitters and resulting less root proliferation and subsequent access to K than occurs with overhead irrigation.

Results of TDR measurements from this study indicate that soil moisture levels following an irrigation event were strongly influenced by proximity to the drip emitter (Fig 2.3.). Measurements taken directly beneath the emitter showed a very rapid increase in volumetric water content within the top 30 cm of soil immediately following an irrigation event. By contrast, soil moisture between the emitters showed a very slow and small response to irrigation, even after three continuous hours. Therefore, it can be concluded that under the experimental conditions, which included a sandy soil type, lateral movement of water within the top 30cm of soil was limited. It is possible that decreasing the space between emitters or adding a second

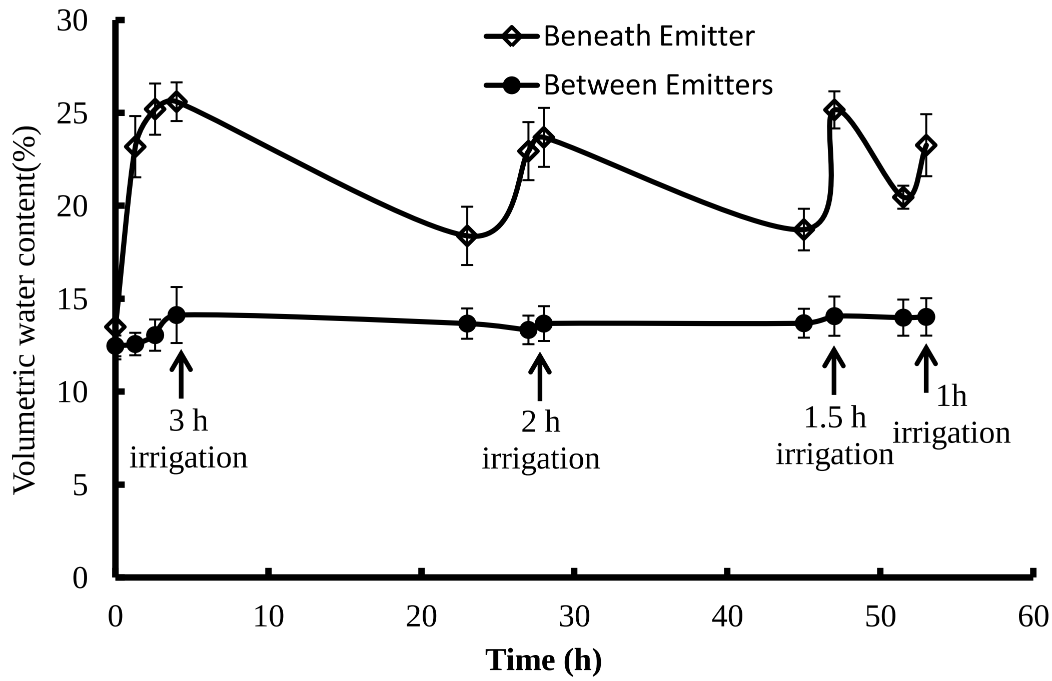

Figure 2.3. Volumetric soil water content beneath and between drip irrigation emitters over a three day period (17 Jul to 19 Jul, 2011) in a multi-bay high tunnel in East Lansing, Michigan.

irrigation line may improve K nutrition by increasing soil moisture distribution and root proliferation.

In addition to changing the irrigation design, alternative fertilization strategies are needed to improve N nutrition. One approach may be covering the tunnels later in the spring so that top-dressed fertilizers are exposed to more precipitation, increasing mineralization and movement of N to roots. This approach could increase competition from weeds and incidence of arthropod pests and diseases. In California, high tunnel organic raspberries supply N primarily through fertigation with liquid organic fertilizers (Gaskell, pers. comm.). These products mineralize quickly and supply sufficient N even under cool soil conditions, yet costs can be high, between

$10 and $36 USD per kg N, and they may complicate irrigation system maintenance (Hartz et al., 2010).

Yield, Berry Quality and Plant Growth

Berry yields in 2011 and 2012 were unaffected by treatment, but there was a significant interaction between variety and year ($P \leq .0001$) (Figure 2.5). The highest yields were obtained from ‘Joan J’ in 2011 with a mean of 3.2 kg m^{-1} row, which was significantly more than ‘Himbo Top’ and ‘Polka’, with respective yields of 2.5 and 2.7 kg m^{-1} row. In 2012, ‘Himbo Top’ yielded significantly more than ‘Polka’ but was not different from ‘Joan J’.

The highest yield was equivalent to 12,804 kg ha^{-1}, which is low compared to other studies. Yields of the primocane fruiting varieties ‘Caroline’ and ‘Heritage’ reached 20,030 kg ha^{-1} in multi-bay high tunnels (Hanson et al. 2011) and similar yields were reported in 4-season high tunnels (Demchak, 2009; Yao and Rosen, 2011). Nutrient deficiencies and insect pest pressures are two factors that could have limited yields in this study. Temperature also may have played a role in the significant difference in yields between 2011 and 2012. The daily high temperature met or exceeded 35^{o}C on 42 dates between June and August 2012, compared to just two dates during the same time period in 2011. According to Stafne et al. (2001), maximum photosynthetic rates in red raspberry occur between air temperatures of 20 and 25^{O}C, and rates may decline by 50% at 35^{O}C. Considering this, the plants may have been heat stressed often during the 2012 summer.

Average berry weight and visual appearance after a short storage period differed between varieties ($P \leq .0001$) but not treatment. Mean berry weight for ‘Himbo Top’, ‘Polka’, and ‘Joan J’

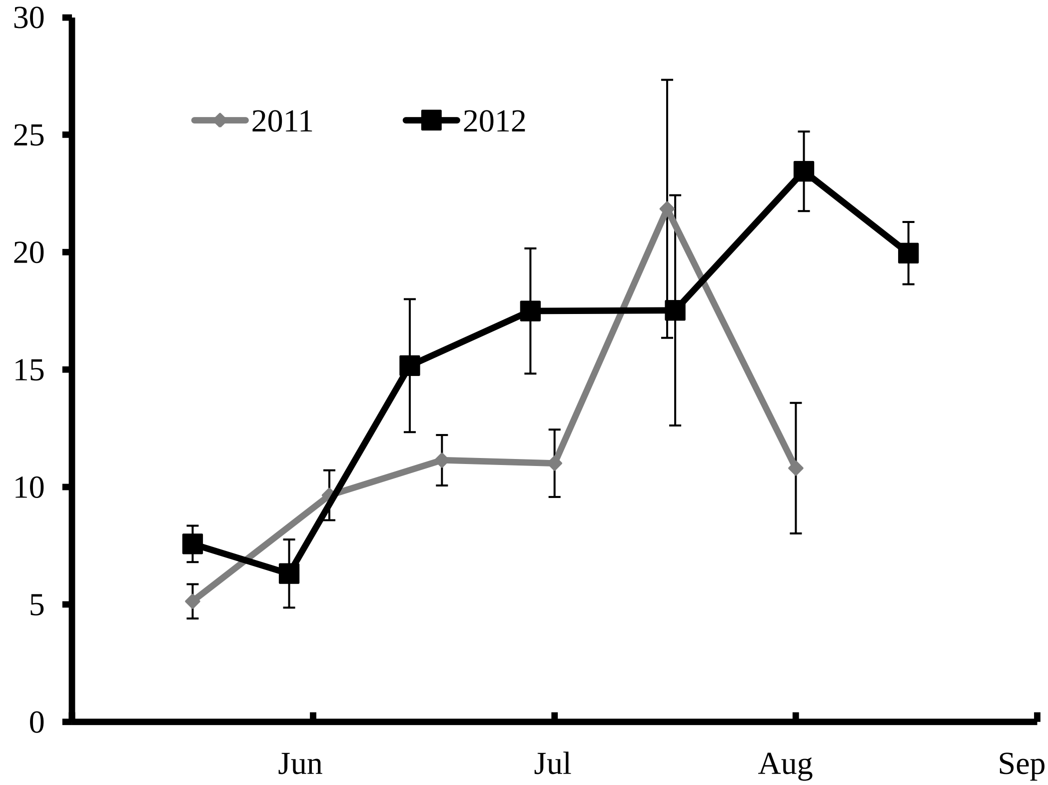

Figure 2.4. Total N content of above ground biomass of 'Polka' red raspberry in multi-bay high tunnels in 2011 and 2012 in East Lansing, Michigan. Error bars indicate standard error of the mean.

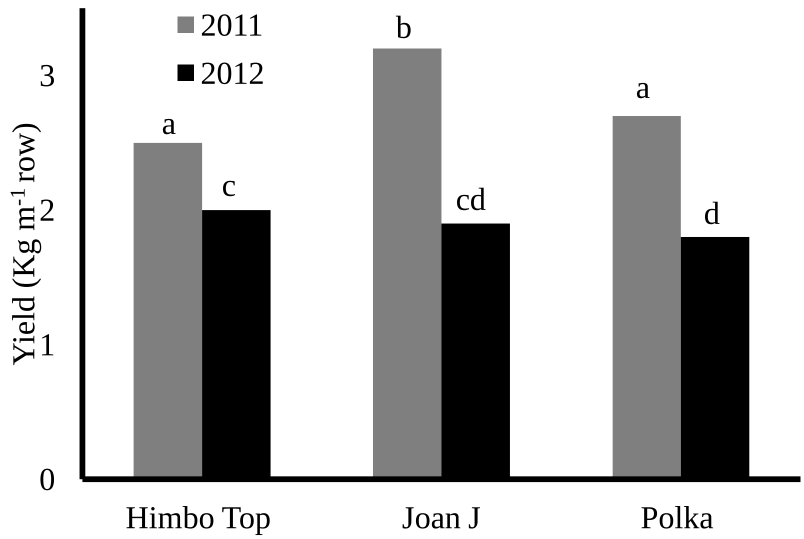

Figure 2.5. Yield of three primocane raspberry varieties grown in multi-bay high tunnels in 2011 and 2012 in East Lansing, Michigan. Means with a different letter are significantly different ($P \leq .05$)

were 3.0, 2.8, and 2.7g, respectively, and all pair wise comparisons were significant. Visual appearance was lowest for ‘Joan J’ at 3.6 , and ‘Himbo Top’ and ‘Polka’ were not statistically different from each other with respective ratings of 4.0 and 4.1.

Primocane height, internode length and number of fruiting laterals were unaffected by treatments in 2011 and 2012, but there was a significant interaction between variety and year on primocane height. While there were no differences between varieties in 2011, canes of Himbo Top (1.7 m) and Joan J (1.5 m) were significantly taller than Polka (1.35 m) in 2012. Analysis of floricanes in March 2012 indicated that treatment had no significant effects on biomass accumulation. Across treatments, mean floricane N %, biomass and N content were 0.62% , 573 and 3.5 g N m row^{-1}, respectively.

Cane N Accumulation

The pattern of N accumulation in the primocanes varied between the two years (Fig. 2.6). The abrupt decrease in total content at the last sampling date in 2011 is attributed to the random selection of small canes. Maximum accumulation was similar between 2011 and 2012, with respective values of 21.8 and 23.4 g m^{-1} row. This is roughly equivalent to 88.8 and 95.3 kg N ha^{-1}, which is consistent with N accumulation measured by Dean et al. (2000) and Rempel et al. (2004) in 'Meeker' red raspberry ranging between 88 and 97 kg N ha^{-1}.

Conclusions

The fertility treatments had significant effects on the nutritional status of the plants, but didn't affect plant growth or berry yield. Analysis of N accumulation indicates that between 89 and 95 kg N ha^{-1} may accumulate in the primocanes over the course of the season, which should be considered in N fertilization strategies. In this study, N supply from solid organic N sources was high when they were incorporated into the soil, but top dressing failed to increase N supply comparably. While the high fertilizer did result in adequate N nutrition, deficiencies in K, S and B likely obscured the benefits.

Variety was an important factor in yield, fruit quality, biomass production and cane growth. 'Himbo Top' produced the tallest canes, the largest berries, had high visual quality and the highest yields in 2012. 'Joan J' produced the most floricane biomass and had the highest yields of the study, in 2011. However, fruit quality tended to be lower than in 'Polka' and 'Himbo Top'.

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CHAPTER 3

EFFECTOF DRIP IRRIGATION AND WINTER PRECIPITATION ON DISTRIBUTION OF SOIL SALTS IN THREE SEASON HIGH TUNNELS

Abstract

High tunnels exclude rainfall and can lead to saline soil conditions that inhibit plant growth. In snow-prone regions, multi-bay tunnels are left uncovered during the winter to prevent snow damage to the structure. Exposing soils to precipitation during the winter period may leach salt from the soil profile. Red raspberries (*Rubus idaeus*) were planted in April, 2010 under multi-bay high tunnels in East Lansing, Mich., USA (42.75°N 84.47°W). Dairy-based composts were incorporated in the row before planting (2010) or spread over the row (2011). Plants were irrigated with a single drip line. Tunnels were covered with plastic from May to Oct. Soil was sampled at the end of the first season and the beginning and end of the second season, at three depths (2.5, 10, 25 cm), beneath and 40 cm to the side of the drip line. Soils were analyzed for total salt (electrical conductivity) and specific ions. Total salt was higher away from the irrigation line after the first season, but beneath the line following the second season. Total salt after the first growing season was highest at 2.5 cm depths (electrical conductivity 3.53 mS cm^{-1}), intermediate at 10 cm (1.13 mS cm^{-1}) and lowest at 25 cm (0.67 mS cm^{-1}). Salt levels the following spring after soils had been exposed to winter precipitation decreased to acceptable levels (0.14 mS cm^{-1} to 0.20 mS cm^{-1}) and were uniform with depth and distance from the trickle irrigation line (mean across depths and location 0.18 mS cm^{-1}). After the second growing season, a similar stratification pattern was present. The primary ions contributing to soil salt were Ca, K, and Mg. Results indicate that excluding precipitation with high tunnels results in salt

accumulation near the soil surface, but removing plastic and exposing soil to off-season precipitation is an effective method of alleviating salinity.

Introduction

High tunnels and greenhouses exclude precipitation and can lead to salinization, or accumulation of salts in the soil (Wenqing et al., 2001; Ju et al., 2006; Knewston et al., 2010). Greenhouse and high tunnel crops are frequently amended with high rates of fertilizer in order to maximize production, which further contributes to salt buildup if leaching is limited (Merkle et al., 1944; Ju et al., 2006). Outside of the United States in regions where passive greenhouse technologies have a longer history, some authors have suggested that secondary salinity buildup happens because growers are unfamiliar with its causes or solutions (Darwish et al., 2005; Huan et al., 2007). Since high salt levels reduce soil quality, methods are needed to prevent or correct salinization.

Salts in amended greenhouse soils have a tendency to stratify with depth, with highest concentrations close to the surface (Wenquing et al., 2001,Ju et al., 2006; Huan et al., 2007). This can happen when evapotranspiration exceeds the amount of leaching (Darwish et al., 2005). Coleman (1999) suggested one strategy for ameliorating salinity in humid regions is to remove plastic and expose soils to precipitation. In snow-prone regions, the plastic covering on multi-bay high tunnels is removed during the off-season to prevent structural damage from snow (Giacomelli, 2009). Exposure to winter precipitation may reduce soil salt levels. The goal of this study was to describe changes in soil salt levels during the growing season when high tunnels are covered, and during the winter season when the tunnel is uncovered.

Materials and Methods

Construction of a 0.45 ha range of multi-bay high tunnels (Haygrove Tunnels Ltd.) at the Michigan State University Horticulture Teaching and Research Center (HTRC), East Lansing, Michigan (42.75°N 84.47°W) was completed in April, 2010. Tunnel bays were 61m x 8 m and 4.9 m tall at the peak. Three bays were planted in red raspberry (*Rubus idaeus L)* on 23 April, 2010 with three rows spaced 2.4 m apart. The soil type is a Spinks sand (Mixed, mesic Psammentic Hapludalf). Each row was irrigated with a single drip tube (Netafim USA, Fresno, California) with emitters every 0.6 m that delivered 2.3 L hr^{-1}. In 2010, irrigation was applied weekly according to physical observations of soil moisture. Irrigation amounts were not recorded in 2010, but totaled 732 L·m^{-1} row in 2011. Ion content of the irrigation water is shown in Table 3.1. Precipitation that accumulated while the tunnels were uncovered was recorded by a Michigan Automated Weather Network (MAWN) station located on site at the HTRC.

Table 3.1 Electrical conductivity (EC) and concentrations of specific ions in irrigation water supplying high tunnels, E. Lansing, Mich.

EC (dS m^{-1})	ug·l^{-1}				
	K	Ca	Mg	Na	Cl
.6	2.2	83.6	34.8	15	43

Prior to planting, six 7.6 m long plots received a dairy manure based compost amended with feather meal and wood ash (Table 3.2) (Morgan's Compost, Evart, Michigan). Compost was applied at a rate of 22 t·ha^{-1} in a roughly 0.5 m wide band over the planting rows and incorporated with a rototiller. Tunnels were covered with Luminance THB polyethylene (BPI.Visqueen Horticultural Products, Stockton-on-Tees, United Kingdom) from 7 May 2010 to

Table 3.2 pH, electrical conductivity, carbon to nitrogen ratio, and specific element concentrations in compost applied to high tunnels in 2010 and 2011, E. Lansing, Mich.

Year	pH	EC ($dS \cdot m^{-1}$)	C:N ratio	% of dry weight						
				N	P	K	Ca	Mg	Na	S
2010	6.9	14.05	7.9:1	2.92	2.43	1.83	7.45	.69	.35	1.37
2011	8.2	2.68	13.2:1	1.27	1.14	.98	6.48	.7	.14	.25

20 Oct. 2010. In June, 2010, dolomitic lime was incorporated within 60 cm of the raspberry rows at a rate of 540 kg ha^{-1} to increase soil pH. In 2011, non-amended dairy compost (Table 3.2) was applied over the top of the rows on 18 April at a rate of 22 $t \cdot ha^{-1}$ and the tunnels were covered with plastic on 7 May.

On 15 Oct. 2010, 6 April 2011, and 20 Sep. 2011 soil samples were collected at 0-2.5, 2.5-10, and 10-25 cm depths beneath the trickle irrigation line and 40 cm to the side, from six replicated plots (two per bay). Samples from each plot were composites of nine, 2 cm-wide cores. Soils were dried and homogenized by hand.

All soils were analyzed for total salt by electrical conductivity (EC) using the 1:1 soil-to-water method (Whitney, 1998). Samples from 15 Oct. 2010, and 20 Sep. 2011, were analyzed for specific ion contents. Available K, Ca, Mg and Na, were determined following extraction with neutral 1M NH_4OA_c (Warncke and Brown, 1998). NO_3^{-1}-N was analyzed using the cadmium reduction method (Gelderman and Beegle, 1998), NH_4^+-N by the salicylate method

(Nelson, 1983), and Cl using a modified potentiometric known addition method (J. Dahl, pers comm., 2011).

Data were analyzed using the Mixed Procedure in SAS v 9.2 (SAS Institute, Cary, North Carolina) with depth treated as a repeated measure and covariance structure chosen by lowest AIC. Log transformation was used to correct normality when needed. Significance was determined as $p \leq .05$.

The number of pore volumes leached through the top 25 cm of the soil profile between 15 Oct. 2010 and 6 April 2011 was estimated by equation 1;

Eq.1 $$V = \frac{I-(D*A)}{D*P}$$

Where *V* is the number of pore volumes leached, *I* is the amount of precipitation (cm), *D* is the depth of the sampled soil profile (cm), *A* is the available water capacity (cm/cm) and *P* is the macro porosity (%), assuming the wilting point as initial soil moisture conditions. Values of *A* and were obtained from Cornell University (2010) and values of *P* were obtained Burgess Roe (1950).

Results and Discussion

On 15 October 2010, after tunnels had been covered with plastic for 166 days, mean soil EC was higher 40 cm away from the drip irrigation line (1.78 dS m^{-1}) than directly beneath the drip line (1.22 dS˙ m^{-1})(fig 3.1). EC also varied significantly with depth, but the interaction of depth and position relative to the irrigation tube was not significant. Mean EC across both positions was significantly different ($p<.0001$) at each depth (2.9, 1.02, 0.56 dS m^{-1} at 0-2.5, 2.5-10, 10-25cm depths, respectively).

On 6 April 2011, 169 days after plastic was removed from the tunnels, mean EC was much lower than during the previous October (Fig 3.1). There was no difference in EC between positions. Mean EC at 0-2.5 cm depths (0.20 $dS^{\cdot}m^{-1}$) was significantly higher than at 2.5-10 cm

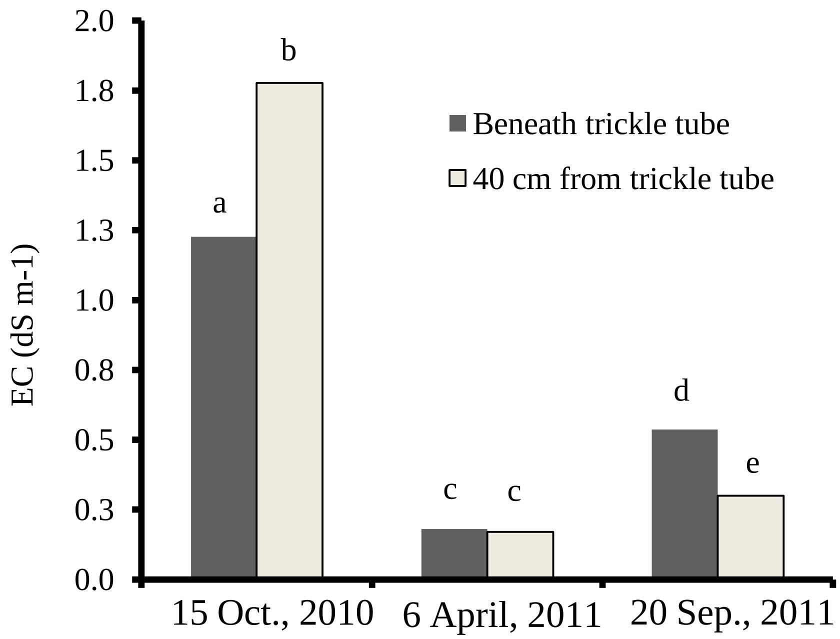

Figure 3.1. Effect of date and position relative to the trickle irrigation tube on soil salt level in high tunnels, E. Lansing, Mich. Tunnels were covered with plastic from 7 May to 20 Oct., 2010, and 7 May to Oct., 2011. Letters above bars indicate significant differences, P = 0.05.

(0.17 $dS^{\cdot}m^{-1}$) and 10-25 cm (0.15 $dS^{\cdot}m^{-1}$). Precipitation and snow amounts between Oct 15 2010 and 6 April, 2011 totaled 18.3 cm, which according to eq. 1, has the potential to leach of up to 1.6 pore volumes from the top 25 cm of soil under the experimental conditions, which include a sandy loam soil type. In and silt loam soil type and clay loam soil type, 18.3 cm of precipitation would leach approximately .91 and 1.0 pore volumes. Therefore, salts are leached more readily from sandier soil types.

By 20 Sep 2011, after a second growing season under plastic, soil EC levels had generally increased from levels at the beginning of the season in April, but were not as high as those in Oct. 2010. Directly beneath the drip line and 40 cm away from the drip irrigation soil EC values were .54 ($p<.0001$) and .30 dS m^{-1} ($p<.003$) respectively. Unlike Oct 2010, salts were higher beneath the irrigation line instead of away from the irrigation in Sep 2011. This is likely due to the fact that the compost used in 2011 was lower in salts and was top-dressed instead of incorporated into the soil. Uptake of salts by plants was also likely greater in 2011 since plants were established, and the irrigation water may have been a more significant source of salts than the compost under these conditions.

Salts applied through irrigation during 2011 totaled around 0.28 kg m^{-1} row, whereas salts applied in the compost totaled 9.3×10^{-4} kg m^{-1} row. The primary ions contributing to EC were Ca, K, and Mg (Table 3). Concentrations of Ca, Mg, Na, and NH_4^+-N were higher beneath the drip irrigation line than away from it on both dates, and Cl and K levels were higher in September (Table 3.3). Only NO_3^--N was significantly lower beneath the drip irrigation line in both years, which may have been due in part to plant uptake and leaching.

Concentrations of individual ions were all higher close to the soil surface. Others have reported that NO_3^--N and other macro-nutrients accumulate in shallow depths beneath plastic greenhouses if soils are over-fertilized (Ju et al., 2006; Huan et al., 2007). If plastic is removed, leaching may result in a loss of these nutrients and possible in water contamination by nitrate (Shi et al., 2008). In snow prone regions, optimum fertilization strategies should be optimized to limit the accumulation of excess macro nutrients in the top soil and subsequent leaching losses during winter.

Table 3.3 Effect of date (15 Oct, 2010 and 20 Sep. 2011), position relative to the trickle irrigation tube (directly beneath or 40 cm away) and depth on soil ion concentrations in a high tunnel, E. Lansing, Mich.

			mg·kg^{-1}						
Date	Position	Depth(cm)	K	Ca	Mg	Na	Cl	NO_3^--N	NH_4^+-N
Oct	Drip	0-2.5	178	1003	184	82	135	71	8.8
Oct	Drip	2.5-10	109	816	142	50	41	13	5.5
Oct	Drip	10-25	68	554	101	41	33	4	3.8
Oct	Away	0-2.5	290	965	192	92	182	212	6.2
Oct	Away	2.5-10	142	575	99	42	114	29	3.8
Oct	Away	10-25	114	419	65	32	45	7	3.9
Sep	Drip	0-2.5	275	954	164	76	168	12.4	4.5
Sep	Drip	2.5-10	199	951	166	55	96	4.8	6.8
Sep	Drip	10-25	132	762	146	44	51	1.5	5.5
Sep	Away	0-2.5	191	730	104	42	85	8.7	2.6
Sep	Away	2.5-10	153	545	83	28	48	2.5	4.0
Sep	Away	10-25	114	450	65	29	40	1.1	2.1
	Significance[z]								
	Position		ns	***	***	***	ns	ns	**
	Depth		***	***	***	***	***	***	*
	Position*Depth		ns	***	ns	ns	ns	ns	ns
	Date		ns	ns	ns	*	ns	***	*
	Position*Date		**	ns	*	**	***	**	ns
	Depth*Date		ns	***	**	**	*	**	***
	Position*Depth*Date		*	ns	ns	ns	**	ns	ns

[z]Non-significant (ns) or significant at P = 0.05 (*), 0.01 (**) or 0.001 (***).

Conclusions

In high tunnels, soil salts increased during the growing season and accumulated in the shallow depths of the soil profile. Except for NO_3^{-1}-N, concentrations of specific ions were higher beneath the drip irrigation line than away from the line. Removing tunnel plastic and exposing soils to winter precipitation reduced soil salt levels. More precipitation is needed to leach salts from loam and clay soil types compared to sandy soil types.

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