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**ABSTRACT**

Water and ground management are key production practices in sweet cherry. A field trial was conducted on bearing sweet cherry (*Prunus avium* L.) trees (Lapins/Mazzard) on a fine loam soil at The Dalles, Oregon from 2006 through 2008 to evaluate and demonstrate the impacts of using double-lateral drip irrigation (DD) and straw mulching (SM) as an integrated alternate production system on water use, fruit yield, quality, and storability of sweet cherry compared with the current micro sprinkler irrigation (MS) and no ground cover (NC) system. Two irrigation systems of MS and DD and two in-row ground cover systems of wheat straw mulch and the control (no ground cover but herbicides were used to control weeds) were evaluated in a randomized complete block split-plot design with four replicates. Double-lateral drip irrigation reduced irrigation water consumption by 47.6 to 58.2% in sweet cherry compared with MS. Straw mulch seemed to reduce irrigation water use relative to NC. Irrigation water productivity was enhanced by 69.8 to 135.4% with DD relative to MS. Fruit yields and quality of firmness, size, and sugar at harvest were not affected by DD over MS. Double-lateral drip irrigation showed a trend of increasing marketable fruit production and improving fruit quality after storage relative to MS. However, Leaf P, B, Zn, and Fe concentrations were decreased with DD over MS. Therefore, switching from MS to DD can markedly reduce irrigation water use while maintaining comparable productivity of bearing sweet cherry, but more P, B, Zn, and Fe fertilizers may be needed. Double-lateral drip irrigation is a viable alternate irrigation system for already established bearing sweet cherry orchards with limited water resources. Straw mulch seems to lower water use in addition to protecting soil from erosion. An integrated DD and SM production system is feasible for sweet cherry in areas where irrigation water is limited and soil erosion is an issue.

**Abbreviations:** Double-lateral drip irrigation (DD); micro sprinkler irrigation (MS); straw mulch (SM); no ground cover (NC).

## INTRODUCTION

Water and ground management are key production practices in sweet cherry. Impact and micro sprinkler irrigation are the major orchard irrigation systems (Fereres et al., 2003). These sprinkler irrigation systems wet the entire ground surface by providing water to both the tree rows and between-row grass alleys at a relatively high speed. Due to higher energy prices in recent years, higher production costs and lower grower profitability are observed with the current irrigation systems (Bryla et al., 2005). On the other hand, the current irrigation systems are not favorable for fruit storability (Bryla et al., 2003). Furthermore, water shortages increasingly occur in many areas for orchard irrigation or/and orchard acreage expansion. It is obvious that alternate irrigation systems with higher water use efficiency are needed for orchard crops.

Drip irrigation systems are assumed potential alternate irrigation systems to the current sprinkler irrigation systems (Shock et al., 2005, 2007). Drip irrigation is usually more efficient than impact and micro sprinkler irrigation in terms of water use since it provides water to only the tree rows with no water applied to the between-row grass alleys and irrigates at a much lower speed ( Locascio, 2005; Afolayan et al., 2007; Sokalska et al., 2009). So far, limited information is available about the transitional influences of switching from impact or micro sprinkler irrigation to drip irrigation on water use, growth, and productivity of bearing sweet cherry or other orchard trees. Instead most irrigation studies have focused on newly planted orchards (Neilsen et al., 2001; Faircloth et al., 2007), irrigation vs. non-irrigation comparisons (Valverde et al., 2006; Nuti et al., 2009), and water stress levels of deficit irrigation (Iniesta et al., 2008; García-Vila et al., 2009; Egea et al., 2010).

It has been documented that wetting only 20 to 50% root zone of bearing deciduous fruit trees is adequate to optimize yield, assumed sufficient water is available to meet the evapotranspiration requirements during critical periods of fruit development (Fereres and Goldhamer, 1990; Vieira de Azevedo et al., 2008; Spreer et al., 2009). Water use efficiency of sweet cherry is enhanced with increased water stress, but there are no significant yield reductions associated with lowering crop evapotranspiration from 100% to 75% (Dehghanisanij et al., 2007).

On the other hand, water management is found to be linked to fruit quality and storability. For instance, physiological disorders including deep suture, fruit cracking, and double fruit and fruit quality of sweet cherry are affected by irrigation regime (Engin *et al.*, 2009). Deep suture is mostly seen in fruit exposed to moderate water stress plus N application. Excessive water application can cause sweet cherry surface pitting (Patten *et al.*, 1983), which heavily influences fruit storage, marketing, and pricing.

Ground management is another key management practice in tree fruit production (Hornig and Buneman,1995; Derr, 2001; Hipps et al., 2004; Granatstein and Mullinix, 2008). Effective ground management can control weeds, conserve soil moisture, improve soil water infiltration and nutrient retention, enhance fruit quality, maintain/ improve soil organic matter and structure, and prevent soil erosion (Merwin et al., 1994; Merwin et al., 1996; Moore-Kucera et al., 2008; Sirrine et al., 2008). For decades, herbicide application in tree rows along with grass alleys between tree rows has been the standard orchard ground management practice in the United States (Shribbs and Skroch, 1986). This system aims at providing a vegetation free zone within the tree rows to minimize weed competition with trees for water and nutrients, while maintaining soil structure in the alleys (Parker and Hull, 1993). Although in-row herbicide application in orchards is effective in weed control, it is costly and adversely affects soil ecosystems and the environment. For instance, herbicide application in the row area of orchards reduces soil microbial activities (Elmore *et al.*, 1997; Glover *et al.*, 2000) and causes herbicide contamination of underground and surface water (Merwin *et al.*, 1996). Furthermore, soil organic matter and microorganisms in orchard row areas are decreased due to lack of additional organic material input except for fallen tree leaves. All these suggest that alternate in-row ground management systems need to be developed.

Using crop straw to cover the row areas beneath orchard trees is emerging as an in-row ground management alternative to the traditional practice of NC but with herbicide applications for weed control (Yin et al., 2006; Yin et al., 2007; Verdu and Mas, 2007; Granatstein and Mullinix, 2008). Mulching orchard tree rows with organic materials has been proven to offer various benefits including improved weed control, enhanced tree growth and fruit yields, soil improvement, and higher water use efficiency (Forge *et al.*, 2003; Sanchez *et al.*, 2003; Yao *et al.*, 2005). A long-term experiment on apple concluded that trunk cross-sectional area and fruit yield of apple are significantly enhanced due to in-row organic mulching compared with NC but with herbicide applications (Forge *et al.,* 2003). Soil water availability, soil organic matter, water infiltration, saturated hydraulic conductivity, and soil temperatures are also improved by organic mulching (Merwin *et al.,* 1994). In addition, the leaching and runoff of nitrate-N and benomyl fungicide are reduced due to organic mulching (Merwin *et al.,* 1996). All these results imply that orchard productivity and soil quality are improved due to straw mulching.

Soil microbial communities and nutrient availability differ significantly among ground management practices in a 10-year apple trial (Laurent et al., 2008). Soil treated with pre-emergence residual herbicides has the fewest culturable bacteria, while soil under mowed-sod treatment has the largest population of culturable fungi; root-lesion (Pratylenchus sp.) nematode populations are greater in mowed-sod than other ground management treatments ( Yao et al., 2005; Laurent et al., 2008). Ground cover affects root number and root distribution in the soil profile (Yao *et al.*, 2009).

To date, the transitional impacts of switching from impact or micro sprinkler irrigation to drip irrigation and shifting from no ground cover but with herbicide applications to straw mulch cover on productivity and water use of bearing orchard trees are largely unknown. The objectives of this study were to evaluate and demonstrate the effects of DD and SM as an integrated alternative production system on tree growth, fruit yield, quality, and storability of sweet cherry compared with the current MS and NC (but with herbicide applications) system; assess the impacts of the new integrated system on water consumption of sweet cherry; and deliver the information about the new integrated system to growers and other interested groups. Overall, the project goal was to develop and distribute accurate information about the integrated DD and SM production system in various fruit production areas in Oregon and the Pacific Northwest, and to increase the growers' awareness of the economic, social, and environmental benefits with the new integrated system, and thus encouraging growers to use straw mulching and drip irrigation as an integrated alternative production system.

## MATERIALS AND METHODS

### Experimental Conditions

A field experiment was conducted from 2006 through 2008 on bearing Lapins sweet cherry on a fine-loamy, mixed, mesic Ultic Haploxeralfs soil near The Dalles, Oregon. The Ultic Haploxeralfs series has a surface layer of very dark grayish brown silt loam and a subsoil of dark brown and dark yellowish brown silt loam, sandy clay loam, and loam. Effective root depth is about 100 to 150 m for this soil. The weather data was collected from The Dalles Downtown Weather Station, OR, which was about 3 km away from the experiment site (http://www.wunderground.com/history/airport/KDLS/2008/7/1/MonthlyHistory.html).

The orchard block used for this study was planted 5.5 m between tree rows and 4.8 m between trees in the same row in 1999. The trees were trained to central leaders. The cherry cultivar was Lapins on Gisela 6 rootstock. Micro sprinkler irrigation and no ground cover but with herbicide applications for weed control were used to manage this block prior to the initiation of this trial. Two irrigation systems of double-line drip irrigation (DD), and micro sprinkler irrigation (MS) and two ground management systems of straw mulch cover (SM, 15 cm thick and 3-m wide), and control (NC) (no mulch or fabric cover, but herbicides were used in the row areas of same width to control weeds) were evaluated in a randomized complete block split-plot design with four replications. The two irrigation systems and two ground cover systems were assigned to the main and sub plots, respectively. The traditional MS treatment had one sprinkler under each tree with a capacity of 56.8 liters per emitter per hour. Newly introduced DD had a dripper every 0.6 meter with a capacity of 1.9 liter per emitter per hour. Double-line drip irrigation had two pressure-compensating drip lines spaced 91 cm apart and located on each side of each tree row. That means each tree receives 56.8 liters of water per hour under MS but only 30.2 liter per hour under DD. Wheat straw was put on the ground surface with a thickness of 15 cm in March 2006 for SM. Roundup [N-(phosphonomethyl) glycine] at 1.4 L $ha^{-1}$ mixed with 147 L $ha^{-1}$ of water was sprayed in the control treatment of NC in early June each year. Each sub treatment plot had 7 trees; the central five trees were used for sampling and data collection.

During experimentation, soil moisture measurements were taken weekly at a soil depth of 30 cm from May to October each year. Weed, disease, and insect controls and fertilizer applications were managed using the practices that were commonly used for commercial production in the region.

**Soil Moisture Monitoring and Irrigation Scheduling**

Irrinet LLC **(**Fall City, WA**)** was contracted to monitor soil moisture status and provide irrigation schedules for the trial. Irrigation was conducted separately for each sub plot on a weekly basis from May to October according to soil moisture content; which was monitored weekly with a Campbell Pacific Nuclear neutron probe meter CPN 503DR Hydroprobe (CPN Company, Martinez, CA). The experiment called for the producing sweet cherry trees to be kept between full field capacity (100%) and 20% deficit of total soil moisture (80% full capacity) between fruit set and harvest. All treatments were irrigated as needed to stay within these bounds. One access tube was installed in each sub plot at the beginning of the trial. The tube was 3.8 cm 125 psi PVC tubing cut to 106.7 cm. The access hole was hand augured into the soil profile with an augur of exactly 3.8-cm outer diameter. The access tube was then driven in to form a tight fit with the soil. The tube protruded 10.2 cm above ground surface for the probe to rest on and has 5.1 cm extra at the bottom to allow the probe to stay off the bottom of the tube. Because these were well drained soils and no sub surface ponding occurred, the access tubes were not sealed at the bottom. Each tube was numbered and capped to keep moisture and debris out. Tubes were positioned under the canopy of the tree, at a healthy tree with buffer trees on either side to minimize lateral effects. All tubes were exactly the same distance from the tree. In the case of MS (there was one per tree), the tube was placed midway between the tree and the micro sprinkler. In the case of DD, the two lines were 91 cm apart and the access tube installed midway between the drip lines and between drip emitters (which were 61 cm) and again the same distance from the tree.

The CPN 503DR Hydroprobe was calibrated to display soil moisture in mm/m. The probe was calibrated against actual soil samples taken from the profile and tested gravimetrically. To obtain the soil sample, a thin walled aluminum cylinder of known volume was driven into undisturbed soil at least 15 cm below soil surface. The soil sample was then weighed wet before being oven dried and the weight loss (being the soil moisture) calculated. Using the relative density of the dry soil, the soil moisture was determined. An access tube was then placed close to the place where the soil sample was taken. The probe was lowered to the depth where the soil sample was taken and the probe was calibrated to give the same reading. The calibration curve was a straight line of the form Water = Ratio × A + B. The dry end of the line was determined in a large drum of oven dried soil with an access tube embedded in the middle of it.

During installation of the access tubes, soil moisture status was assessed by an experienced consultant to estimate the initial moisture status at each depth. These observations, worked back to 100% were entered into the Probe Schedule software as the full field capacity of the profile at each depth. The full level was refined over time after several cycles of wetting and drying and observing the drainage pattern within the soil and direct checking by digging in the soil.

Soil moisture readings were taken once a week on the same day and time. Readings were taken at 15, 30, 45, 60, 75, and 90 cm in the soil profile. The readings were logged on the CPN 503DR head and then downloaded to a computer for further processing. Data was stored, processed, and displayed by the Probe Schedule© irrigation scheduling software. The software makes use of daily weather data, moisture holding capacity of the soil, and crop coefficients to model the daily water use and daily water balance. The remaining time to the pre-set refill point is projected based on current rates of extraction, current weather, and water status on the day, providing the grower with a time scale and volume to irrigate (in unit of mm).

**Leaf and Soil Sampling and Analysis**

A leaf sample was taken randomly from each sub plot in August, approximately one month after fruit harvest each year. The samples were collected from the same trees and under similar weather conditions each season. Each leaf sample consisted of 30 new but fully developed mid-terminal leaves from current year shoots at 1.5-m level above the ground in the tree canopy. All leaf samples were cleaned, oven-dried at 65$^{o}$C, and ground to pass through a 1-mm sieve. Total N in leaf was determined using a combustion method with a Carlo Erba 1500 series Nitrogen/Carbon Analyzer (Gavlak *et al.*, 1994). Total P, K, Ca, Mg, and S were digested in a CEM MDS 2100 series microwave using nitric acid and hydrogen peroxide, and the digest was analyzed on a Thermo Jarrel Ash 1100 ICP (Gavlak *et al.*, 1994).

Soil sampling was conducted at the depth interval of 0 to 30 cm from each sub plot in August of each year. Ten soil cores with a 2.5-cm diameter soil probe were randomly collected from under the five central trees in each sub plot to make a composite sample after removing visible tree and weed residues from the soil surface. Each sample was placed in a soil-sampling bag, and then stored in a cold storage room at 1$^{o}$C. All samples were air dried, ground to pass through a 2-mm sieve, and thoroughly mixed. Soil available $NH_4^+$, $NO_3^-$, P, K, Ca, Mg, S, B, Zn, Mn, and Cu contents were extracted using the Mehlich III method (Mehlich, 1984). Soil amino sugar N was extracted with NaOH (Khan *et al.*, 2001). Soil total N was determined by combustion (Gavlak *et al.*, 1994) . Soil pH was determined in a 1:1 (soil:$H_2O$) solution (Watson and Brown, 1998), and organic matter was measured using the loss-on-ignition method (Combs and Nathan, 1998). Soil bulk density and sand, silt, and clay contents were determined for the samples collected at the end of experimentation in 2008. Analyses on active bacteria and fungi, total bacteria and fungi, protozoa, nematodes were conducted by Microbial Matrix Systems Inc.

(Tangent, OR) on the soil samples which were collected after fruit harvest from the SM and NC sub treatments under MS in 2007 and from all the main and sub treatments in 2008.

**Fruit Yield, Quality, and Storability Determinations**

Fruit yield was determined by harvesting five central trees from each sub plot each year. Fruit quality attributes including fruit firmness, size, and sugar were measured on a sub plot basis each season. Fruit firmness and size were assessed using 30 fruit per plot on a FirmTech 2 Fruit Firmness Tester (BioWorks Inc, Stillworks, OK). Fruit sugar was determined using a PR101α digital refractometer (Atago Co., LTD. Tokyo, Japan). Fruit skin color was determined with a Minolta CR-200 Chromameter using 50 fruit per plot. Visual evaluation of fruit surface pitting was conducted after the fruit had been stored in a cold storage room at -1$^{o}$C for three weeks. Four categories of excellent, slightly pitted, pitted, and bruised fruit were used in this evaluation. The percentage of marketable fruit consisted of the percentages of both excellent fruit and slightly pitted fruit.

**Statistical Analysis**

Analysis of variance (ANOVA) for each measurement was conducted for each year and the average of the three years according to an ANOVA procedure using SAS statistical software (SAS Institute, Cary, North Carolina, 2010). Probability levels less than 0.05 were designated as significant except for soil microbes, nematodes, and protozoa in which probability levels less than 0.10 were designated as significant. Presentation and discussion of the results in the Results and Discussion section focus on the effects of main and sub treatments themselves since few significant main treatment × sub treatment interactions were observed in the measurements in this study.

## RESULTS AND DISCUSSION

Year of 2006 (Oct. 2005 -- Sept. 2006) was wet with an annual precipitation of 47 mm, 27% higher than the 30-year average; while 2007 and 2008 were both dry and had annual precipitations 11 and 18% lower than the 30-year average, respectively (Fig. 1). Annual precipitations were not uniformly distributed all the year round at this location. Most of them occurred in the winter and spring (October to April, 86% of the yearly total according to the 30-year average data); seasonal drought was common in summer and fall. However, monthly and annual temperatures were similar for the three years of study, and were close to the 30-year averages (Fig. 1).

**Consumption and Productivity of Irrigation Water**

One of the largest benefits with DD was saving water. Irrigation water consumption was reduced by 47.6, 56.5, and 58.2% under DD compared with the current irrigation system -- MS in 2006, 2007, and 2008, respectively (Table 1). Numerical but insignificant reductions in irrigation water use were consistently observed with SM relative to NC in each of the three years (Table 1). On the average of three-year data, irrigation water consumption was significantly reduced by 9.7% with SM over NC. No correlation was observed between irrigation water consumption and annual precipitation or fruit yield. Similarly, Bryla et al. (2003) reported that drip irrigation reduced irrigation water use by over 50% compared with microjets on peach trees in central California.

Irrigation water productivity was affected by irrigation systems. Double-lateral drip irrigation increased irrigation water productivity by 69.8, 135.4, and 138.5%, respectively, relative to MS in 2006, 2007, and 2008 (Table 1). Overall, one mm of irrigation water produced 3.1 to 7.6 kg $ha^{-1}$ of fruit with DD, but grew only 1.3 to 4.5 kg $ha^{-1}$ fruit under MS during the three years. Straw mulch significantly increased irrigation water productivity by 25.0% in 2007, 17.6% in 2008, and 9.4% averaged over three-years relative to NC.

Results of this study are consistent with those of other investigations in the same region (Yin *et al.*, 2006; Yin *et al.*, 2007). Yin and Huang (2009) reported that one mm of irrigation water produced 235 to 292 kg $ha^{-1}$ of pear under single-lateral drip irrigation, but only 59 to 172 kg $ha^{-1}$ with MS. Our results suggest that switching from MS to DD is a viable approach to save irrigation water and enhance irrigation water productivity, which is supportive of the current theory and practice of partial root drying irrigation on orchards (Brocic et al., 2009; Costa et al., 2007; Savic et al., 2009).

**Fruit Yield and Quality**

Fruit yield varied substantially with year regardless of irrigation and ground cover systems (Table 1). However, Fruit yield did not differ between the two irrigation systems averaged over the two ground cover systems any season. There was no significant yield response to SM over NC. Our results suggest that switching from MS to DD and shifting from NC to SM do not reduce fruit yields even on already established bearing sweet cherry orchards.

Fruit quality at harvest is crucial in sweet cherry marketing and pricing. Key fruit quality attributes including fruit size, firmness, and sugar at harvest, were not affected by DD compared with MS or by SM relative to NC in any of the three seasons (Table 2). Our results agree with those observed in western Turkey (Demirtas *et al.*, 2008), which reported that irrigation rates did not influence fruit quality such as fruit weight, flesh/seed ratio, water soluble solids, pH, titratable acidity, or inverted as well as total sugars of sweat cherry at harvest. Our previous study on pear also found that fruit size and color did not differ between single-lateral drip irrigation and MS (Yin and Huang, 2009). Hipps et al. (2004) concluded that ground cover system did not affect apple fruit quality based on an eight-year long-term experiment.

Fruit quality after storage has been reported to be influenced by water and nutrient management. In this study, fruit sugar content after 3-week cold storage was 3.4% higher DD relative to MS in 2008 (Table 3). Straw mulch seemed to improve fruit firmness and size over NC in 2008. Our results are in agreement with those of previous studies which suggested that chemical compositions of fruit are affected by irrigation regime (Perez-Pastor et al., 2007; Zegbe *et al.*, 2008). For instance, fruit of 'Billida' apricots (Prunus armeniaca L) from both deficit irrigation signified higher values of total soluble solids and hue angle than the control during the first 10 days of the 30-day chilling storage period, and fruit weight loss and fungal attacks mainly Rhizopus sp. and Monilinia sp. were lower in deficit irrigation during a subsequent retail sale period of four days at 13$^{o}$C (Perez-Pastor et al., 2007). These improvements might be related to the differences in fruit chemical compositions, particularly the total content and its compositions of anthocyanin between the treatments (Esti *et al.*, 2002).

**Fruit Storability**

Pitting in sweet cherries are small sunken areas on fruit surface. Symptoms are primarily caused by mechanical impact or compression (Thompson, 2006). Pitting is associated with physical damage to cell near the epidermis which collapse over time. Cherry pitting becomes apparent after fruit being stored for several days at room temperatures or longer at lower temperatures. Physical damage on cherry fruit can occur during fruit picking, packing, and transportation (Patten, 2006). Overall, fruit surface pitting in sweet cherry has long been a very common and major problem in the fresh market cherry industry (Porritt et al., 1971). It is one of the leading causes of price reductions and product rejection from the fresh market.

Our results showed that marketable fruit production is related to water management. The percentage of marketable (excellent and slight pitted) fruit was enhanced by 6.3, 3.6, and 5.6% (absolute value) although insignificant, with DD compared with MS in 2006, 2007, and 2008, respectively (Table 4). However, DD significantly increased marketable fruit by 5.2% (absolute value) averaged over the three-year results. No such benefits were observed with SM relative to NC in any season. In addition, percentages of marketable fruit varied markedly with growing seasons.

It has been found that sweet cherry fruit pitting is linked to cultivar, tree condition, nutrient and water management, geographic location, micro-climate, harvest maturity, picking protocol, packingline condition, and fruit storage temperature (Patten et al., 2006). Patten et al. (2006) reported that extensive irrigation or prolonged water uptake by fruit during heavy rains promotes fruit softening, and thus increases fruit pitting of sweet cherry. Trees under DD received much less water than with MS, which may at least partially explain why trees with DD had reduced fruit surface pitting and higher marketable fruit production in this study. Similarly, the work of 'Pacific Rose (TM)' demonstrated that apple storability was enhanced under partial root zone drying treatment (Zegbe *et al.*, 2008).

**Leaf Nutrient Concentrations after Fruit Harvest**

Leaf P concentration after harvest was reduced by 23.1, 18.2, and 26.1% with DD relative to MS in 2006, 2007, and 2008, respectively (Table 5), although leaf P levels under DD were still in the normal range for sweet cherry (Heckman, 2004; Leece, 1976). Concentrations of other macro nutrients such as N, K, Ca, Mg, and S in leaf were not affected by shifting from MS to DD. Double-lateral drip irrigation decreased leaf B concentration by 6.0, 7.9, and 9.6%, respectively, in 2006, 2007, and 2008 compared with MS. Zinc concentration in leaf was lowered by 20.4% in 2006 and 15.3% in 2007 due to the switch form MS to DD. In addition, DD reduced leaf Fe concentration in 2006 and 2008, and Cu level in 2006 relative to MS. The reductions in leaf nutrient concentrations with DD might be attributed to the markedly reduced root volume receiving irrigation water. The wet ground area was only about 60% with DD over MS. Therefore, it is crucial to apply higher rates of P, B, Zn, and Fe fertilizers close to the wet ground areas if DD is used to replace MS on bearing sweet cherry orchards. The results of this study were similar to those on bearing pear (Yin and Huang, 2009), which reported decreased leaf P levels due to switching from MS to single-lateral drip irrigation.

Because leaf P levels were lower with DD, leaf N/P ratio was enhanced but P/K was lowered with DD compared with MS in all three seasons (Table 5). Other ratios like N/K, K/Ca+Mg, and P/Zn were mostly not affected under DD. The results of nutrient ratios in this study are useful for developing fertilizer recommendations based on the Diagnosis and Recommendation Integrated System (DRIS), as the concepts of DIRS are based on nutrient ratios, not on concentrations, to judge nutrient balances in the tree (Hartz et al., 1998; Jimenez et al., 2007; Mourao, 2004). However, more data about leaf nutrient ratios are needed if DIRS is going to be used on sweet cherry.

Leaf nutrient concentrations in August, approximately one month after fruit harvest, are commonly used as references to assess the nutrient management program implemented in the current season, and to make fertilizer recommendations for the following season in sweet cherry production. Sufficient range approach is one of the most common used approaches (Jones, 1993). Based on the leaf composition standards for sweet cherry (Heckman, 2004; Leece, 1976), leaf concentrations of macro nutrients including N, P, K, Ca, and Mg were in the normal range regardless of irrigation and ground cover treatments in this study, while concentrations of macronutrient S and micronutrients Fe, Cu, and Mn were a little below the normal, and micronutrient B is slightly higher than normal (Table 5).

**Soil Nutrient Levels and Soil Quality after Fruit Harvest**

Soil pH or organic matter content was not affected by DD relative to MS in any year (Table 6). Soil N parameters including $NO_3$-N, $NH_4$-N, amino sugar N, estimated N release, and total N content did not differ regardless of irrigation system. Contents of available soil P, K, Ca, Mg, S, and micro nutrients were mostly similar for the two irrigation systems. The results of this study are similar to those of another study on pear in the same region (Yin and Huang, 2009). Soil fertility did not differ with the ground cover systems in any season. Soil C, bulk density, or sand, silt, and clay contents were not affected by DD and SM relative to MS and NC, respectively (Table 7). However, soil C/N ratio was higher with SM than NC. It is interesting to note that SM did not increase soil organic matter or C after three years of mulching, possibly because the wheat straw materials were not incorporated into the soil in this study or/and the three-year test period was too short to detect the effects.

**Soil Microbial Communities after Fruit Harvest**

Active bacteria and fungi contents or total bacteria and fungi contents were not affected by DD relative to MS by the end of experimentation in 2008 (Table 8). However, the ratio of total fungi to total bacteria was higher with DD. Active fungi content and the ratio of active fungi to active bacteria were enhanced with SM relative to NC. Contents of bacteria-feeders, fungal-feeders, and total nematodes was numerically but insignificantly higher with DD and SM compared with MS and NC, respectively in 2008 (Table 9). Populations of flagellates, amoeba, and total protozoa were substantially reduced with SM over NC in 2008 (Table 10).

Active bacteria and fungi contents or total bacteria and fungi contents were not affected by SM compared with NC under MS in 2007 or 2008 (Table 11). Content of bacteria-feeders, fungal-feeders, root-feeders, predators, or total nematodes was not influenced by SM relative to NC in 2007 or 2008 or averaged over the two years (Table 12). Populations of amoeba were reduced but populations of ciliates increased with SM relative to NC in 2008 and on the averages of 2007 and 2008 (Table 13).

Double-lateral drip irrigation saved approximately 50 to 60% of irrigation water in this study, while single-lateral drip irrigation had over 70% savings of irrigation water (Yin et al., 2010), compared with the current irrigation system - MS. Because DD doubles the volume of tree root zone to receive irrigation water and applies more irrigation water relative to single-lateral drip irrigation, DD has stronger capability to help trees to endure severely drought conditions, particularly when the irrigation systems fail. However, DD systems cost more since two drip lines are needed for each tree row (Bryla et al., 2005).

## BENEFITS OR IMPACTS ON AGRICULTURE

The impacts of this project on sweet cherry productivity, economics, and the environment were significant, and will be greater. For instance, about 300 targeted sweet cherry growers along with thousands other fruit growers were educated through a variety of outreach activities during the project implementation period. The following benefits about DD and SM were delivered to growers: Double-lateral drip irrigation saves 48 to 58% of irrigation water compared with MS. Fruit yield and quality under DD are comparable to those under MS. Double-lateral drip irrigation significantly increases the percentage of marketable fruit by reducing fruit surface pitting and bruising compared with MS. There is a trend of saving water with SM relative to NC in addition to reducing soil erosion. Furthermore, the improved water use efficiency with this innovative production system will restore streamflow in streams and rivers in the region and accordingly improve the conditions for fish, and for tourism and recreation. Due to the impacts of this project, growers in Oregon and the Pacific Northwest have begun to use DD and SM on their orchards, and this trend will be continued and magnified during the next 5 to 10 years.

## REACTIONS FROM PRODUCERS

Producers with limited water rights and erosive soils on their orchards are very interested in the results of our project. They believe this project will help them to use water more efficiently, reduce soil erosion, and increase cherry storability. The following situations are favorable for utilizing DD: (1) limited water resources; (2) high electricity costs on irrigation; (3) soils with low water permeability to the root zone; (4) fertigation needed to improve nutrient uptake; and (5) production of high quality fruit. It is a common expectation that utilization of DD on newly-planted cherry orchards will be more feasible than switching from MS to DD on already established bearing orchards. Generally, DD is more suitable for high density orchards, particularly on soils of medium to heavy texture with good water holding capacity, but may be not suited for soils of coarser-texture with poor lateral movement of water.

## RECOMMENDATIONS OR NEW HYPOTHESES

In our project, we tested the double-lateral drip irrigation system, and found this system saves 48 to 58% of irrigation water compared with our current irrigation system- micro sprinkler irrigation. In this study, the between tree row grass alleys with DD dried out in July and August each year because they were not irrigated at all during the entire season. This may increase the orchard temperatures and force fruit to mature earlier, and thus may reduce fruit size, particularly during dry seasons. Therefore, a combination of DD and MS seems to be a good approach to save water but meanwhile keep the between-row grass alleys green throughout the season. Growers can use DD and MS systems alternatively on the same field by running MS during the day time and DD during the night time, or running DD in the months of May, June, September, and October and MS in the hottest months of July and August.

## OUTREACH

Outreach activities were conducted to disseminate research findings to producers, agricultural professionals, local citizens, and other interested groups via on-farm field tours, field days, conferences, and presentations. For instance:

1. Yin, X. 2006. Sustainable water and nutrient management alternatives for sweet cherry. 2006 Oregon Sweet Cherry Growers' Meeting. *Oral.* Richland, WA, Nov. 16.

2. Yin, X. 2006. Is drip irrigation an effective water management practice for sweet cherry in the Mid-Columbia region? *Poster.* Annual Meetings of Washington State Horticultural Association. Yakima, WA, Dec. 4-6.
3. Yin, X. 2006. Progress in water and nitrogen management research for pears and sweet cherries. KIHR radio show. *Oral.* Hood River, OR, Dec. 7.
4. Yin, X. 2007. Drip irrigation and straw mulch as an integrated cherry production system. Oregon Sweet Cherry Symposium. *Oral.* The Dalles, OR, Jan. 25.
5. Yin, **X.** 2007. Sustainable nutrient and water management alternatives for sweet cherry. 2007 Northwest Sweet Cherry Growers' Meeting. *Oral.* Wenatchee, WA, Nov. 15-16.
6. Yin, X. 2007. Nutrient and water management research for tree fruit. KIHR radio show. *Oral.* Hood River, OR, Dec. 10.
7. Long, L.E., and X. Yin. 2010. How Straw Mulch and Drip Irrigation Affects Productivity, Water Use and Fruit and Soil Quality. Mid-Columbia Cherry Day Meeting. *Oral.* The Dalles, OR, Feb. 2.

In addition, Lynn Long and Xinhua Yin presented the results of this project at the following national and international academic conferences.

1. Long, L.E., and X. Yin. 2009. Responses of sweet cherry water use and productivity and soil quality to alternate groundcover and irrigation systems. The 6th International Cherry Symposium. *Oral.* Chile, Nov. 12-15.
2. Yin, X., X. Huang, and L.E. Long. 2009. Responses of sweet cherry productivity and soil quality to alternate groundcover and irrigation systems. 2009 Annual Meetings of American Society of Agronomy and Soil Science Society of America. *Poster. Agronomy Abstract.* Pittsburgh, PA. Nov. 1-5.
3. Yin, X., C.F. Seavert, L.E. Long, and N. Tomasini. 2008. Impacts of double-line drip irrigation and straw mulching on sweet cherry water use and productivity. 2008 Annual Meetings of American Society for Horticultural Science. *Oral, HortSci Abstract.* Orlando, FL. Jul. 21-24.

## CONCLUSIONS

Double-lateral drip irrigation reduced irrigation water consumption by 47.6 to 58.2% in sweet cherry compared with MS. Straw mulch seemed to reduce irrigation water use relative to NC. Irrigation water productivity was enhanced by 69.8 to 135.4% with DD relative to MS. Fruit yields and quality of firmness, size, and sugar at harvest were not affected by DD over MS. Double-lateral drip irrigation showed a tendency of increasing the percentage of marketable fruit and improving fruit quality after storage relative to MS. However, Leaf P, B, Zn, and Fe concentrations were reduced with DD over MS. Switching from MS to DD can substantially reduce irrigation water use while maintaining comparable productivity of bearing sweet cherry but more P, B, Zn, and Fe fertilizers may be needed. Double-lateral drip irrigation is a viable alternate irrigation system for already established bearing sweet cherry orchards with limited water resources for irrigation. Shifting from NC to SM seems to save irrigation water in addition to the protection of soil from erosion. In conclusion, an integrated DD and SM production system is feasible on sweet cherry in areas where shortage of irrigation water and soil erosion occur.

## ACKNOWLEDGMENTS

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Fig. Monthly precipitation and temperature of the experimental period at the test site.

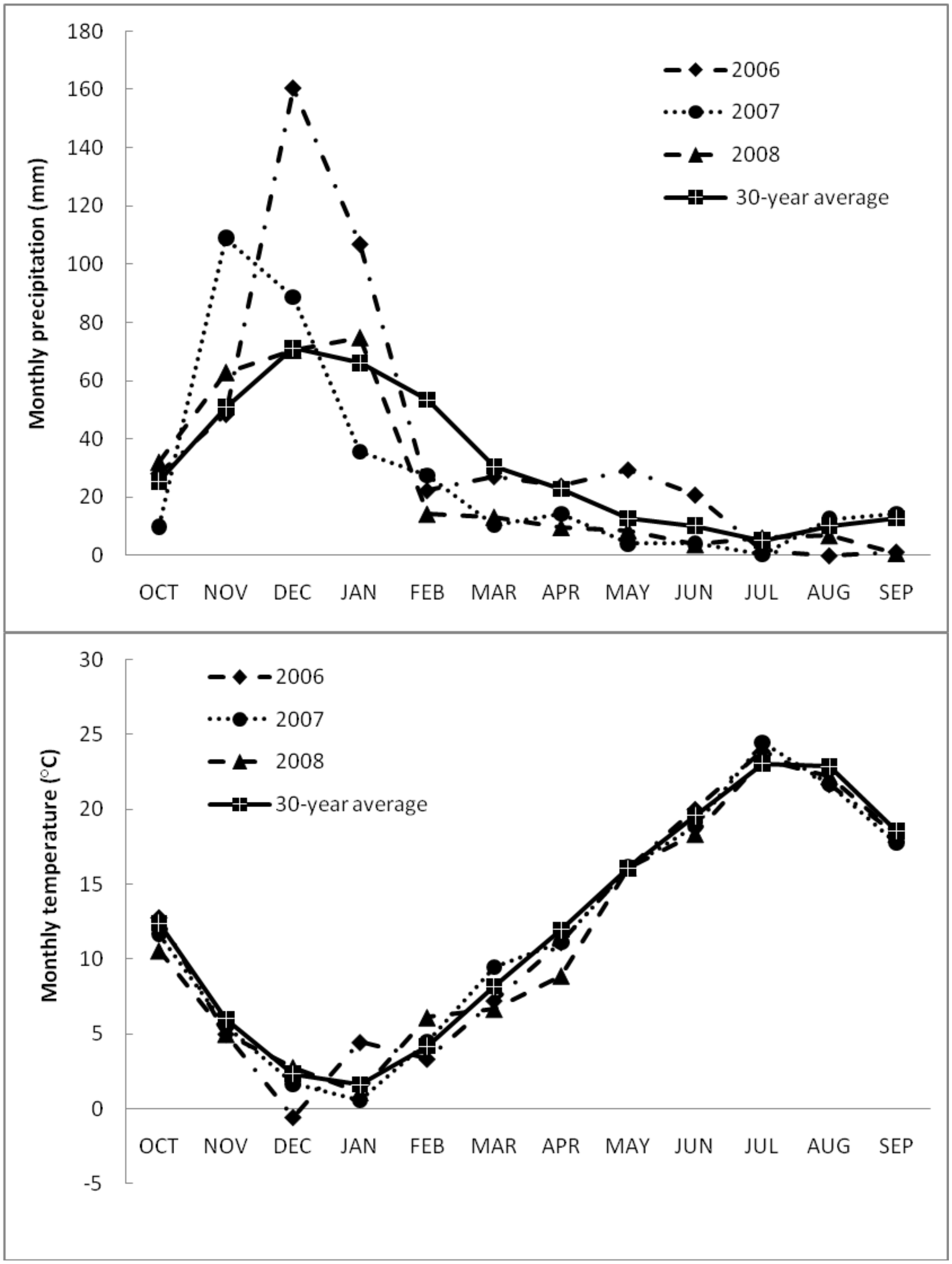

Table 1. Effects of double-lateral drip irrigation (DD) and straw mulch (SM) on irrigation water consumption, fruit yield, and irrigation water productivity.

| Treatment | Irrigated water consumption (mm) | | | | Fruit yield (Mg ha$^{-1}$) | | | | Irrigation water productivity (kg ha$^{-1}$mm$^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2006 | 2007 | 2008 | Average | 2006 | 2007 | 2008 | Average | 2006 | 2007 | 2008 | Average |
| MS | 7305 | 8512 | 7559 | 7792 | 32.7 | 16.1 | 9.9 | 19.6 | 4.5 | 1.9 | 1.3 | 2.6 |
| DD | 3828 | 3700 | 3159 | 3562 | 29.0 | 16.5 | 9.8 | 18.4 | 7.6 | 4.5 | 3.1 | 5.0 |
| Significance | *[†] | * | * | ** | ns | ns | ns | ns | * | * | * | ** |
| | | | | | | | | | | | | |
| NC | 5697 | 6628 | 5574 | 5967 | 31.2 | 15.7 | 9.3 | 18.7 | 5.5 | 2.4 | 1.7 | 3.2 |
| SM | 5436 | 5584 | 5145 | 5388 | 30.5 | 16.8 | 10.4 | 19.2 | 5.6 | 3.0 | 2.0 | 3.5 |
| Significance | ns | ns | ns | * | ns | ns | ns | ns | ns | * | * | * |

[†]Non significant effect is denoted by ns. Significant effect at 5 and 1% probability level is denoted by * and **, respectively.

Table 2. Effects of double-lateral drip irrigation (DD) and straw mulch (SM) on fruit quality at harvest.

| Year | Treatment | Firmness (g mm$^{-2}$) | Size (mm) | Sugar (g kg$^{-1}$) | Color | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | L | a | b | c | h |
| 2006 | MS | 238.2 | 27.1 | 173.0 | 27.3 | 12.5 | 2.80 | 12.8 | 12.3 |
| | DD | 240.6 | 26.6 | 175.0 | 27.2 | 12.0 | 2.63 | 12.3 | 11.9 |
| | Significance | ns[†] | ns | ns | ns | ns | ns | ns | ns |
| | NC | 244.4 | 26.4 | 174.0 | 27.3 | 12.1 | 2.68 | 12.4 | 12.0 |
| | SM | 234.4 | 27.3 | 175.0 | 27.2 | 12.4 | 2.77 | 12.7 | 12.2 |
| | Significance | ns | ns | ns | ns | ns | ns | ns | ns |
| 2007 | MS | 292.1 | 29.9 | ND[§] | 26.5 | 15.8 | 4.51 | 16.5 | 15.0 |
| | DD | 302.1 | 30.3 | ND | 26.8 | 16.9 | 4.97 | 17.6 | 15.5 |
| | Significance | ns | ns | | ns | ns | ns | ns | ns |
| | NC | 301.2 | 29.9 | ND | 26.9 | 17.6 | 5.32 | 18.4 | 15.9 |
| | SM | 292.8 | 30.3 | ND | 26.3 | 15.0 | 4.16 | 15.6 | 14.6 |
| | Significance | ns | ns | | * | * | * | * | * |
| 2008 | MS | 290.4 | 29.7 | 187.3 | ND | ND | ND | ND | ND |
| | DD | 293.8 | 29.7 | 187.1 | ND | ND | ND | ND | ND |
| | Significance | ns | ns | ns | | | | | |
| | NC | 294.6 | 29.5 | 187.0 | ND | ND | ND | ND | ND |
| | SM | 289.6 | 29.9 | 187.4 | ND | ND | ND | ND | ND |
| | Significance | ns | ns | ns | | | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Average | MS | 273.6 | 28.9 | 180.1 | 26.9 | 14.2 | 3.7 | 14.7 | 13.7 |
| | DD | 278.8 | 28.9 | 181.1 | 27.0 | 14.5 | 3.8 | 15.0 | 13.7 |
| | Significance | ns | ns | ns | ns | ns | ns | ns | ns |
| | | | | | | | | | |
| | NC | 280.1 | 28.6 | 180.5 | 27.1 | 14.9 | 4.0 | 15.4 | 14.0 |
| | SM | 272.3 | 29.2 | 181.2 | 26.8 | 13.7 | 3.5 | 14.2 | 13.4 |
| | Significance | ns | * | ns | ns | ns | ns | ns | ns |

†Non significant effect is denoted by ns. Significant effect at 5% probability level is denoted by *.

§ND, not determined due to instrument unavailability.

Table 3. Effects of double-lateral drip irrigation (DD) and straw mulch (SM) on fruit quality after cold storage (2008)

| Treatment | Firmness (g mm$^{-2}$) | Size (mm) | Sugar (g kg$^{-1}$) |
|---|---|---|---|
| DD | 339.2$^{\dagger}$ | 30.0 | 191.8 |
| MS | 327.2 | 29.9 | 185.5 |
| Significance | ns | ns | * |
| | | | |
| NC | 323.1 | 29.6 | 187.3 |
| SM | 343.3 | 30.3 | 190.0 |
| Significance | ns | ns | ns |

$^{\dagger}$Non significant effect is denoted by ns. Significant effect at 5% probability level is denoted by *.

Table 4. Effects of double-lateral drip irrigation (DD) and straw mulch (SM) on the percentage of fruit surface pitting.

| Year | Treatment | Excellent | Slightly Pitted | Marketable | Pitted | Bruised | Pitted & Bruised |
|---|---|---|---|---|---|---|---|
| 2006 | MS | 42.1 | 27.1 | 69.2 | 16.4 | 10.5 | 3.9 |
| | DD | 48 | 24.5 | 75.5 | 12 | 11.4 | 4.2 |
| | Significance | *[†] | ns | ns | * | ns | ns |
| | NC | 45.3 | 26.2 | 71.5 | 14.1 | 11.5 | 2.9 |
| | SM | 44.9 | 25.6 | 70.5 | 14.2 | 10.7 | 4.6 |
| | Significance | ns | ns | ns | ns | ns | ns |
| 2007 | MS | 22.2 | 32 | 54.2 | 24 | 14.3 | 7.5 |
| | DD | 22.6 | 35.2 | 57.8 | 21.6 | 15.4 | 5.2 |
| | Significance | ns | ns | ns | ns | ns | ns |
| | NC | 25.8 | 29.6 | 55.4 | 25 | 15.4 | 4.2 |
| | SM | 19.9 | 36 | 55.9 | 21.6 | 14.3 | 8.2 |
| | Significance | ns | * | ns | ns | ns | * |
| 2008 | MS | 8.8 | 49.9 | 58.7 | 33.0 | 3.0 | 5.3 |
| | DD | 10.8 | 53.5 | 64.3 | 21.6 | 7.2 | 6.9 |
| | Significance | ns | ns | ns | ns | ns | ns |
| | NC | 10.4 | 50.7 | 61.1 | 26.8 | 5.5 | 6.6 |
| | SM | 9.3 | 52.7 | 61.9 | 27.8 | 4.7 | 5.6 |
| | Significance | ns | ns | ns | ns | ns | ns |
| Average | MS | 24.4 | 36.3 | 60.7 | 24.5 | 9.3 | 5.6 |
| | DD | 27.1 | 37.7 | 65.9 | 18.4 | 11.3 | 5.4 |
| | Significance | ns | ns | * | * | ns | ns |
| | NC | 27.2 | 35.5 | 62.7 | 22.0 | 10.8 | 4.6 |
| | SM | 24.7 | 38.1 | 62.8 | 21.2 | 9.9 | 6.1 |
| | Significance | * | ns | ns | ns | ns | ** |

[†]Non significant effect is denoted by ns. Significant effect at 5% probability level is denoted by *.

Table 5. Effects of double-lateral drip irrigation (DD) and straw mulch (SM) on leaf nutrient concentrations after harvest.

| Year | Treatment | Macronutrient (g kg$^{-1}$) | | | | Micronutrient (mg kg$^{-1}$) | | | | | | | Molar nutrient ratio | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N | P | K | Ca | Mg | S | B | Fe | Mn | Cu | Zn | N/P | N/K | P/K | K/Ca+Mg | P/Zn |
| 2006 | MS | 22.8 | 3.9 | 25.3 | 19.5 | 4.2 | 1.6 | 77.1 | 99.1 | 41.2 | 5.5 | 19.1 | 13.14 | 2.51 | 0.19 | 1.00 | 435.1 |
| | DD | 23.1 | 3.0 | 22.4 | 18.0 | 4.1 | 1.7 | 72.5 | 88.0 | 43.6 | 4.7 | 15.2 | 17.37 | 2.90 | 0.17 | 0.93 | 423.6 |
| | Significance | ns† | * | ns | ns | ns | ns | * | * | ns | * | * | ** | * | ** | ns | ns |
| | NC | 22.7 | 3.4 | 24.1 | 17.8 | 4.2 | 1.6 | 75.1 | 90.9 | 41.9 | 4.8 | 18.9 | 15.31 | 2.65 | 0.18 | 1.00 | 376.6 |
| | SM | 23.2 | 3.5 | 23.7 | 19.7 | 4.1 | 1.7 | 73.7 | 95.6 | 43.1 | 5.2 | 15.7 | 15.19 | 2.76 | 0.19 | 0.93 | 482.2 |
| | Significance | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | * | ns | ns | ns | ns | * |
| 2007 | MS | 25.5 | 3.3 | 26.6 | 14.2 | 4.0 | 1.5 | 75.9 | 84.8 | 46.0 | 6.0 | 31.4 | 17.07 | 2.68 | 0.16 | 1.30 | 236.9 |
| | DD | 24.9 | 2.7 | 25.1 | 13.3 | 4.1 | 1.5 | 69.9 | 90.5 | 46.0 | 5.5 | 26.6 | 20.72 | 2.78 | 0.14 | 1.27 | 230.1 |
| | Significance | ns | ** | ns | ns | ns | ns | ** | ns | ns | ns | * | ** | ns | ** | ns | ns |
| | NC | 24.8 | 2.9 | 25.9 | 13.9 | 4.1 | 1.4 | 72.4 | 92.1 | 43.4 | 5.6 | 26.7 | 19.64 | 2.68 | 0.14 | 1.28 | 236.7 |
| | SM | 25.6 | 3.2 | 25.8 | 13.7 | 4.0 | 1.5 | 73.4 | 83.3 | 48.5 | 5.9 | 31.3 | 18.15 | 2.78 | 0.15 | 1.29 | 230.3 |
| | Significance | ns | * | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| 2008 | MS | 21.4 | 4.6 | 28.9 | 13.8 | 3.3 | 1.6 | 75.0 | 107.6 | 51.9 | 6.6 | 98.0 | 10.52 | 2.08 | 0.20 | 1.54 | 99.1 |
| | DD | 21.6 | 3.4 | 26.3 | 14.3 | 3.4 | 1.7 | 67.8 | 95.3 | 56.2 | 6.4 | 81.4 | 14.24 | 2.30 | 0.16 | 1.37 | 88.4 |
| | Significance | ns | ** | * | ns | ns | ns | * | * | ns | ns | ns | ** | ns | ** | ns | ns |
| | NC | 21.6 | 3.9 | 27.2 | 14.2 | 3.5 | 1.7 | 73.2 | 98.7 | 51.1 | 6.7 | 92.4 | 12.73 | 2.24 | 0.18 | 1.41 | 89.7 |
| | SM | 21.4 | 4.0 | 27.9 | 13.8 | 3.2 | 1.7 | 69.6 | 104.3 | 57.0 | 6.4 | 87.0 | 12.03 | 2.14 | 0.18 | 1.50 | 97.9 |
| | Significance | ns | ns | ns | ns | ns | ns | ns | ns | * | ns | ns | ns | ns | ns | ns | ns |
| Average | MS | 23.2 | 3.9 | 26.9 | 15.8 | 3.8 | 1.6 | 76.0 | 97.2 | 46.4 | 6.0 | 49.5 | 13.58 | 2.42 | 0.18 | 1.28 | 257.0 |
| | DD | 23.2 | 3.0 | 24.6 | 15.2 | 3.9 | 1.6 | 70.0 | 91.3 | 48.6 | 5.5 | 41.0 | 17.44 | 2.66 | 0.16 | 1.19 | 247.4 |
| | Significance | ns | ** | ** | ns | ns | ns | ** | ns | ns | * | * | ** | * | ** | ns | ns |
| | NC | 23.0 | 3.4 | 25.7 | 15.3 | 3.9 | 1.6 | 73.6 | 93.9 | 45.5 | 5.7 | 46.0 | 15.89 | 2.52 | 0.16 | 1.23 | 234.3 |
| | SM | 23.4 | 3.6 | 25.8 | 15.7 | 3.8 | 1.6 | 72.2 | 94.4 | 49.5 | 5.8 | 44.6 | 15.12 | 2.56 | 0.18 | 1.24 | 270.1 |
| | Significance | ns | * | ns | ns | ns | ns | ns | ns | * | ns | ns | ns | ns | * | ns | ns |

†Non significant effect is denoted by ns. Significant effect at 5 and 1% probability level is denoted by ** and *, respectively.

Table 6. Effects of double-lateral drip irrigation (DD) and straw mulch (SM) on the soil nutrient levels after harvest.

| Year | Treatment | pH | OM | $NO_3$ | $NH_4$ | Total N | Amino sugar N | P | K | Ca | Mg | S | B | Zn | Mn | Cu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | g $kg^{-1}$ | mg $kg^{-1}$ | mg $kg^{-1}$ | g $kg^{-1}$ | mg $kg^{-1}$ | mg $kg^{-1}$ | mg $kg^{-1}$ | mg $kg^{-1}$ | mg $kg^{-1}$ | mg $kg^{-1}$ | mg $kg^{-1}$ | mg $kg^{-1}$ | mg $kg^{-1}$ | mg $kg^{-1}$ |
| 2006 | MS | 7.35 | 13.7 | 2.91 | 2.89 | 0.7 | 84.2 | 58.0 | 443 | 1638 | 311 | 24.4 | 0.74 | 4.31 | 139.2 | 3.14 |
| | DD | 7.31 | 13.6 | 10.90 | 3.05 | 0.7 | 89.4 | 61.2 | 441 | 1622 | 298 | 30.0 | 0.75 | 3.67 | 140.8 | 3.11 |
| | Significance | ns$^{\dagger}$ | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| | NC | 7.30 | 13.6 | 8.25 | 3.02 | 0.7 | 89.2 | 61.6 | 430 | 1700 | 311 | 30.3 | 0.74 | 4.40 | 141.5 | 3.20 |
| | SM | 7.36 | 13.7 | 5.58 | 2.91 | 0.7 | 84.3 | 57.6 | 463 | 1560 | 298 | 24.0 | 0.75 | 3.59 | 138.6 | 3.04 |
| | Significance | ns | ns | ns | ns | ns | ns | ns | ns | * | ns | ns | ns | ns | ns | * |
| 2007 | MS | 7.22 | 13.0 | 1.50 | 4.02 | 0.7 | 112.7 | 42.7 | 494 | 1831 | 300 | 40.1 | 0.57 | 3.57 | 164.7 | 3.13 |
| | DD | 7.17 | 13.0 | 4.42 | 3.35 | 0.7 | 115.5 | 47.5 | 473 | 1746 | 283 | 56.2 | 0.60 | 3.53 | 172.5 | 3.19 |
| | Significance | ns | ns | ns | ns | ns | ns | ns | ns | ns | * | ns | ns | ns | ns | ns |
| | NC | 7.21 | 12.8 | 2.90 | 3.75 | 0.6 | 117.1 | 47.1 | 485 | 1865 | 300 | 50.6 | 0.61 | 3.47 | 169.6 | 3.23 |
| | SM | 7.20 | 13.1 | 2.05 | 3.85 | 0.7 | 110.1 | 41.5 | 495 | 1741 | 288 | 40.3 | 0.56 | 3.64 | 165.0 | 3.08 |
| | Significance | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| 2008 | MS | 7.14 | 8.0 | 1.41 | 2.43 | 1.0 | 103.3 | 39.4 | 481 | 1458 | 223 | 15.6 | 0.60 | 3.38 | 143.8 | 2.87 |
| | DD | 7.08 | 7.5 | 1.98 | 2.64 | 1.2 | 108.5 | 44.5 | 498 | 1569 | 211 | 25.5 | 0.76 | 3.08 | 148.6 | 2.91 |
| | Significance | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| | NC | 7.05 | 7.9 | 2.13 | 2.81 | 1.2 | 110.3 | 43.3 | 430 | 1592 | 218 | 18.1 | 0.65 | 3.52 | 151.8 | 2.98 |
| | SM | 7.16 | 7.5 | 1.26 | 2.25 | 1.1 | 101.5 | 40.6 | 549 | 1435 | 216 | 23.0 | 0.71 | 2.94 | 140.6 | 2.80 |
| | Significance | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| Average | MS | 7.24 | 11.6 | 1.94 | 3.11 | 0.8 | 100.1 | 46.7 | 472 | 1642 | 278 | 26.7 | 0.64 | 3.75 | 149.2 | 3.05 |
| | DD | 7.19 | 11.4 | 5.77 | 3.01 | 0.9 | 104.5 | 51.1 | 471 | 1646 | 264 | 37.2 | 0.70 | 3.43 | 154.0 | 3.07 |
| | Significance | ns | ns | * | ns | ns | ns | ns | ns | ns | ** | ns | * | ns | ns | ns |
| | NC | 7.19 | 11.4 | 4.43 | 3.19 | 0.8 | 105.5 | 50.7 | 449 | 1719 | 276 | 33.0 | 0.67 | 3.80 | 154.3 | 3.14 |
| | SM | 7.24 | 11.4 | 2.96 | 3.00 | 0.8 | 98.6 | 46.6 | 502 | 1579 | 267 | 29.1 | 0.67 | 3.39 | 148.1 | 2.97 |
| | Significance | * | ns | ns | ns | ns | ns | ** | ** | ** | ns | ns | ns | ns | * | ** |

[†]Non significant effect is denoted by ns.  Significant at 5 and 1% probability level is denoted by * and **, respectively.

Table 7. Effects of double-lateral drip irrigation (DD) and straw mulch (SM) on soil quality by the end of 2008.

| Treatment | C<br>g kg$^{-1}$ | N<br>g kg$^{-1}$ | C:N | Bulk density<br>g cm$^{-3}$ | Sand<br>g kg$^{-1}$ | Silt<br>g kg$^{-1}$ | Clay<br>g kg$^{-1}$ |
|---|---|---|---|---|---|---|---|
| MS | 9.9 | 1.0 | 9.9 | 1.16 | 404 | 429 | 166 |
| DD | 11.7 | 1.2 | 9.8 | 1.16 | 405 | 414 | 182 |
| Significance | ns† | ns | ns | ns | ns | ns | ns |
| | | | | | | | |
| NC | 10.9 | 1.2 | 9.1 | 1.16 | 405 | 419 | 175 |
| SM | 10.7 | 1.1 | 9.7 | 1.16 | 404 | 424 | 173 |
| Significance | ns | ns | * | ns | ns | ns | ns |

†Non significant effect is denoted by ns. Significant effect at 5% probability level is denoted by *.

Table 8. Effects of double-lateral drip irrigation (DD) and straw mulch (SM) on soil microbes by the end of 2008.

| Treatment | Active fungi (AF) $\mu g\ g^{-1}$ | Active bacteria (AB) $\mu g\ g^{-1}$ | Total fungi (TF) $\mu g\ g^{-1}$ | Total bacteria (TB) $\mu g\ g^{-1}$ | AF/ TF ratio | AB/ TB ratio | AF/AB ratio | TF/ TB ratio |
|---|---|---|---|---|---|---|---|---|
| MS | 2.8 | 4.9 | 37.9 | 467.1 | 0.10 | 0.01 | 0.64 | 0.09 |
| DD | 3.8 | 4.8 | 52.7 | 362.4 | 0.08 | 0.02 | 0.87 | 0.15 |
| Significance | ns† | ns | ns | ns | ns | ns | ns | * |
| | | | | | | | | |
| NC | 2.0 | 5.1 | 49.0 | 371.4 | 0.05 | 0.02 | 0.45 | 0.10 |
| SM | 4.5 | 4.6 | 41.6 | 458.1 | 0.13 | 0.01 | 1.05 | 0.13 |
| Significance | # | ns | ns | ns | ns | ns | # | ns |

†Non significant effect is denoted by ns. Significant effect at 10 and 5% probability level is denoted by # and *, respectively.

Table 9. Effects of double-lateral drip irrigation (DD) and straw mulch (SM) on soil nematodes by the end of 2008.

| Treatment | Bact-feeders | Fungal-feeders | Root-feeders | Predators | Total nematodes |
|---|---|---|---|---|---|
| | $\mu g\ g^{-1}$ | $\mu g\ g^{-1}$ | $\mu g\ g^{-1}$ | $\mu g\ g^{-1}$ | $\mu g\ g^{-1}$ |
| MS | 0.21 | 0.02 | 0.04 | 0.01 | 0.29 |
| DD | 0.33 | 0.05 | 0.02 | 0.00 | 0.41 |
| Significance | ns[†] | ns | ns | ns | ns |
| NC | 0.19 | 0.03 | 0.03 | 0.01 | 0.25 |
| SM | 0.36 | 0.05 | 0.04 | 0.01 | 0.45 |
| Significance | ns | ns | ns | ns | ns |

[†]Non significant effect is denoted by ns.

Table 10. Effects of double-lateral drip irrigation (DD) and straw mulch (SM) on soil protozoa by the end of 2008.

| Treatment | Flagellates counts $g^{-1}$ | Amoeba counts $g^{-1}$ | Ciliates counts $g^{-1}$ | Protozoa counts $g^{-1}$ |
|---|---|---|---|---|
| MS | 304 | 1827 | 10 | 2140 |
| DD | 165 | 1903 | 10 | 2078 |
| Significance | ns† | ns | ns | ns |
| | | | | |
| NC | 396 | 3657 | 8 | 4061 |
| SM | 72 | 73 | 11 | 156 |
| Significance | # | * | # | * |

†Non significant effect is denoted by ns. Significant effect at 10 and 5% probability level is denoted by # and *, respectively.

Table 11. Effects of straw mulch (SM) on soil microbes under micro sprinkler irrigation in 2007 and 2008.

| Year | Treatment | Active fungi (AF) μg $g^{-1}$ | Active bacteria (AB) μg $g^{-1}$ | Total fungi (TF) μg $g^{-1}$ | Total bacteria (TB) μg $g^{-1}$ | AF/ TF ratio | AB/ TB ratio | AF/AB ratio | TF/ TB ratio |
|---|---|---|---|---|---|---|---|---|---|
| 2007 | NC | 6.0 | 9.3 | 46.6 | 248.2 | 0.16 | 0.04 | 0.65 | 0.19 |
| | SM | 7.8 | 11.3 | 33.1 | 302.2 | 0.23 | 0.04 | 0.72 | 0.11 |
| | Significance | ns† | ns | ns | ns | ns | ns | ns | ns |
| 2008 | NC | 1.6 | 4.8 | 39.9 | 371.8 | 0.05 | 0.01 | 0.30 | 0.11 |
| | SM | 4.0 | 5.0 | 35.8 | 562.5 | 0.15 | 0.01 | 0.97 | 0.07 |
| | Significance | ns | ns | ns | ns | ns | ns | ns | ns |
| Average | NC | 3.8 | 7.0 | 43.2 | 310.0 | 0.10 | 0.03 | 0.47 | 0.15 |
| | SM | 5.9 | 8.1 | 34.4 | 432.3 | 0.19 | 0.03 | 0.84 | 0.09 |
| | Significance | ns | ns | ns | # | # | ns | ns | ns |

†Non significant effect is denoted by ns. Significant effect at 10% probability level is denoted by #.

Table 12. Effects of straw mulch (SM) on soil nematodes under micro sprinkler irrigation in 2007 and 2008.

| Year | Treatment | Bact-feeders $\mu g\ g^{-1}$ | Fungal-feeders $\mu g\ g^{-1}$ | Root-feeders $\mu g\ g^{-1}$ | Predators $\mu g\ g^{-1}$ | Total nematodes $\mu g\ g^{-1}$ |
|---|---|---|---|---|---|---|
| 2007 | NC | 0.86 | 0.19 | 0.03 | 0.06 | 1.13 |
| | SM | 0.68 | 0.10 | 0.14 | 0.15 | 1.07 |
| | Significance | ns | ns | ns | ns | ns |
| 2008 | NC | 0.19 | 0.02 | 0.02 | 0.01 | 0.24 |
| | SM | 0.24 | 0.02 | 0.06 | 0.01 | 0.33 |
| | Significance | ns | ns | ns | ns | ns |
| Average | NC | 0.52 | 0.11 | 0.03 | 0.03 | 0.69 |
| | SM | 0.46 | 0.06 | 0.10 | 0.08 | 0.70 |
| | Significance | ns | ns | ns | ns | ns |

[†]Non significant effect is denoted by ns.

Table 13. Effects of straw mulch (SM) on soil protozoa under micro sprinkler irrigation in 2007 and 2008.

| Year | Treatment | Flagellates | Amoeba | Ciliates | Protozoa |
|---|---|---|---|---|---|
| | | counts $g^{-1}$ | counts $g^{-1}$ | counts $g^{-1}$ | counts $g^{-1}$ |
| 2007 | NC | 338 | 23 | 9 | 370 |
| | SM | 1672 | 347 | 184 | 2203 |
| | Significance | ns | ns | ns | # |
| 2008 | NC | 542 | 3603 | 9 | 4154 |
| | SM | 65 | 51 | 12 | 128 |
| | Significance | ns | # | # | ns |
| Average | NC | 440 | 1813 | 8 | 2261 |
| | SM | 868 | 199 | 98 | 1165 |
| | Significance | ns | # | # | ns |

†Non significant effect is denoted by ns. Significant effect at 10% probability level is denoted by #.