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Effects of integrated nitrogen fertilization and irrigation systems, rootstocks, and cultivars on productivity, water and nitrogen consumption, and mineral nutrition of pear

Xinhua Yin[1*], Xiao-Lan Huang[1], Jac le Roux[2]

[1]Department of Plant Sciences, The University of Tennessee, Jackson, USA;
[*]Corresponding Author: xyin2@utk.edu
[2]IRRINET, Dalles, USA

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ABSTRACT

Water and nitrogen (N) management are key factors for sustainable pear production in many areas. Effects of integrated N fertilization and irrigation systems, rootstocks, and cultivars on pear (*Pyrus communis*) mineral nutrition, irrigation water and N consumption, and fruit productivity were investigated on a fine sandy loam soil at Hood River, Oregon from 2005 through 2007. Nitrogen application reduced to 80% of the current broadcast application rate and fertigated in five equal split applications could supply bearing pear trees with adequate N nutrition without reducing soil N reserves. Shifting from the broadcast of dry N fertilizer on soil surface and micro sprinkler irrigation system (BSS) to the split N fertigation and drip irrigation system (FDS) did not affect tree growth, fruit yield, or fruit size of pear. However, FDS produced more Bartlett fruit in color categories of 390 - 417 and 417 - 496 nm than BSS. Irrigation water consumption was reduced by 42.0% to 78.3%, but water use efficiency was enhanced by 51.0% to 264.2% with FDS relative to BSS. Split N fertigation and drip irrigation system may be used as an alternate N fertilization and irrigation system on bearing pear orchards to reduce irrigation water and N consumption in Hood River and other similar areas.

Keywords: N Fertigation; Drip Irrigation; Irrigation Water Consumption; Fruit Yield; Fruit Weight; Pear

1. INTRODUCTION

Pear production is highly dependent on N fertilization to achieve optimum yield and quality [1]. Nitrogen fertilizer is often uniformly broadcast on soil surface in a single application during April or May each year in Oregon and other Pacific Northwestern states. This practice has been used for decades because it is simple and only needs to be applied once per year. However, there are growing concerns as follows about this practice as fertilizer prices continue to rise and environmental regulations become increasingly tighter: Nitrogen fertilizer is applied on the soil surface, thus it is prone to volatilization and runoff losses. The single-time N application rate may be too high, resulting in low N use efficiency and high N losses since the root system cannot take up so much N in a short period of time. For example, water quality monitoring data in Hood River, OR have shown that Hood River tributaries draining orchard lands have excessive N levels (H. Coccoli, personal communications). Average nitrate (NO_3)/nitrite (NO_2) concentration at all 10 sites monitored in Hood River in 2001 exceeded the Oregon Department of Environmental Quality recommended N evaluation indicator value of 0.3 mg·L^{-1} NO_3/NO_2 [2] by 1.5 to 12 times. Over- or under-application of N can occur in each season since the current N application rate is recommended for normal high yields. Unlike annual crops, pear yield on a given orchard block varies considerably from year to year due to training, pruning, and weather conditions. The flexibility for applying N late during the season is low. Because there are fruit on the tree canopy late in the season, it is hard to move a fertilizer applicator around in the orchard, and it also takes labor to conduct N applications.

Water management is another key practice in pear production. Impact and micro sprinkler irrigation systems are the primary types of irrigation used on orchards [3]. These sprinkler systems have resulted in higher production costs and lower profitability in recent years due to increased energy prices [4]. There is increasing concern about the adverse impacts of sprinkler systems on fruit storability [5,6]. Furthermore, there are not adequate water resources in rivers and streams available for orchard irrigation, particularly during dry seasons, or for the expansion of acreage to tree fruit production in many regions. Therefore, alternate irrigation systems with higher water use efficiency potentials are warranted to reduce orchard water consumption.

Drip irrigation systems are considered potential alternates to replacing sprinkler irrigation systems since drip irrigation provides water to tree row areas only at a much lower flow rate and does not irrigate between-row grass alleys. Because of the significant reduction in irrigated ground area and decreased flow rate, drip irrigation is usually more efficient in water use than sprinkler irrigation [7]. Drip irrigation has been demonstrated to increase apple productivity while reducing shoot growth relative to sprinkler irrigation [8].

Nitrogen fertigation is an integrated N and irrigation management system which mixes N with irrigation water by injecting fertilizer solution into the flowing water of an irrigation system [9]. Split N fertigation under drip irrigation has the potential to reduce N losses and increase N use efficiency for the following reasons: 1) Nitrogen fertilizer is delivered into the root zone along with irrigation water; 2) N application rate for each time is substantially reduced due to split applications; 3) over- and under-applications of N are avoidable since opportunities are provided to adjust N application rates during the season; 4) flexibility for applying N late in the season is increased since no fertilizer spreader is needed to apply N via fertigation; 5) split fertigation does not take much labor due to the easily operated automatic systems; 6) split fertigation can synchronize N application with plant N uptake during the season [10]; and 7) split N fertigation reduces soil compaction due to lack of utilizing a fertilizer spreader.

Previous investigations on orchards have shown increased N use efficiency, compatible or enhanced yields, and improved weed control with split N fertigation compared with surface broadcast of N. For instance, a recent study in China reported that N fertilizer consumption by pear was reduced by 23% - 30% and N loss was lowered by 45% to 56% with N fertigation under drip irrigation [11]. Yield of tart cherry was compatible or even higher, and nitrate leaching dramatically diminished when N was fertigated at a reduced rate in Michigan [12]. Results in Israel indicated that N fertigation could supply sufficient N nutrition for pear growth, and does not reduce fruit size [9].

Little research has been documented on the responses of bearing fruit trees of different cultivars on contrasting rootstocks to the switching from surface broadcast of N fertilizer under micro sprinkler irrigation to split N fertilization with drip irrigation. The objective of this study was to evaluate the effects of integrated N fertilization and irrigation systems (BSS and FDS), pear cultivars (Bartlett and Bosc), rootstocks (OH × F87 and OH × F97), and their interactions on leaf mineral nutrition, irrigation water and N consumption, and fruit yield and quality of pear and soil nutrient reserves.

2. MATERIALS AND METHODS

2.1. Site Description and Experimental Design

A field experiment was conducted on a Van Horn fine sandy loam soil near Hood River, Oregon from 2005 through 2007. This soil series consists of well drained soils on uplands. These soils formed in stratified alluvial deposits and are moderately permeable. Weather data were collected during the experimental period from the Hood River Agricultural Weather Station, which was about 1000 m away from the experimental site (http://www.usbr.gov/pn/agrimet/aginfo/station_params.html#HOXO).

A 2 ha orchard consisting of Bartlett and Bosc pear cultivars and planted in 5.5 m (between-row) × 2.4 m (in-row) in 1996 was used for this study. Rootstocks of OH × F87 and OH × F97 were used for each cultivar. All trees were trained to central leaders. This orchard was managed under BSS since its establishment till the initiation of this study.

Two integrated N fertilization and irrigation systems (BSS and FDS), two pear cultivars (Bartlett and Bosc), and two rootstocks (OH × F87 and OH × F97) were assigned to the main, sub, and sub sub-plots, respectively, in a randomized complete block split split-plot design with four replicates. The BSS treatment had one Supernet sprinkler (Netafim USA, Fresno, CA) under each tree with a capacity of 55 dm^3 per emitter per hour, which was placed at 0.91 m west from the tree trunk. Treatment FDS used Netafim RAM pressure compensating drip tubing (Netafim USA, Fresno, CA) with a dripper every 0.6 meter and a capacity of 3.8 dm^3 per emitter per hour. Each tree received 55 dm^3 of irrigation water per hour under BSS but only 15.2 dm^3 per hour with FDS. Annual N application rate was 53.6 and 42.8 $kg \cdot ha^{-1}$ for BSS and FDS, respectively. The N rate of 53.6 $kg \cdot ha^{-1}$ for BSS was the recommended N rate by Oregon State University for pear trees of 8 to 10 years old [13]. The 42.8 $kg \cdot ha^{-1}$ rate for FDS was based on the annual N rate for BSS in this study and previous research findings about fertigation on other fruit crops [12,14]. Nitrogen fertilizer of urea (46N-0P-0K) was uniformly broadcast on the soil surface once in April with BSS, but it was fertigated once about every three weeks in five equal split applications during May to August under FDS. Each sub sub-plot contained seven trees with the center five trees for sampling and data collection.

During experimentation, 60 kg·P·ha^{-1} as triple super phosphate (0N-20P-0K) and 180 kg·K·ha^{-1} as muriate of potash (0N-0P-50K) were broadcast on the soil surface once in April regardless of treatment each year. Insects and diseases were controlled identically for all treatments with the standard practices commonly used in the region.

2.2. Soil Moisture Monitoring and Irrigation Scheduling

Irrinet LLC (The Dalles, OR) was contracted to monitor soil moisture status and provide irrigation schedules for the trial. Irrigation was conducted separately for each sub sub-plot on a weekly basis from May to September based on soil moisture content, which was monitored weekly with a Campbell Pacific Nuclear neutron probe "CPN 503DR Hydroprobe" (CPN Company, Martinez, CA). The experiment called for the moisture of soil beneath trees to be kept between full field capacity (100%) and 20% deficit (80% full capacity) of total soil moisture between fruit set and harvest. Each sub sub-plot was irrigated as needed to stay within these bounds.

A PVC access tube was installed in each sub sub-plot. Because this was a well drained soil and no sub surface ponding occurred, the access tubes were not sealed at the bottom. Each tube was capped to keep moisture and debris out. Tubes were positioned under the canopy of a healthy tree with buffer trees on either side to minimize lateral effects. All tubes were at 1.52 m west from the tree trunk. In the case of micro sprinklers, the tube was placed midway between the tree and the micro sprinkler. In the case of single-lateral drip line, the line was put near the tree trunk and the access tube installed 30.5 cm away from the drip line, equidistant between drip emitters, and again the same distance from the tree.

The probe was calibrated using actual soil samples and tested gravimetrically. Calibration of the wet end was done in the soil at a 30 cm depth. A hole was dug to a 28 cm depth of soil with the bottom leveled. A thin-walled aluminum cylinder was driven into the soil at the bottom of the hole. An undisturbed sample of in situ soil with known volume was extracted at a 30 cm depth. This sample was weighed and then dried at 100˚C for 24 hours; the loss of weight was measured. With the known volume of dry soil, relative density of the soil was calculated. With all these information, current moisture content of the soil (mm/m) was calculated. Next, a hole of exactly 3.8 cm diameter was augered in the soil near that location. An access tube was inserted into that hole. The neutron probe was lowered to read at an average depth of 30 cm. The neutron probe was then calibrated in the soil at a 30 cm depth to give the same reading as that calculated with the gravimetric method. To minimize lateral variation of soil moisture due to irrigation system non-uniformity, this procedure was performed in spring when the trees were bare and the soil profile was filled by rain water.

Because naturally occurring dry soil could not be found in the spring, a soil sample of 200 kg was taken from the orchard and dried to a moisture level below what would be found in orchard. The soil sample was packed into a barrel to simulate in situ soil, and was then used for the determination of dry end. The same process as used for the determination of wet end was utilized for determining the dry end. The calibration curve was a straight line of the form Moisture = Ratio × A + B.

During installation of the access tubes, soil moisture status was assessed by an experienced consultant to estimate the soil moisture status at each depth at the time of installation. Probe readings were then taken at each depth with the calibrated neutron probe. The full field capacity of the soil at each depth was then calculated by prorating the probe reading with the observations and working back to 100% (e.g. the assessment of the soil at a 20 cm depth was that the current moisture status was 80% of field capacity, and the neutron probe reading was 240 mm·m^{-1}, then the full capacity at 20 cm would be 240/0.8 = 300 mm·m^{-1}). In this way, the full capacity of the soil can be calculated fairly accurately even when the soil is tested while not at full capacity. These calculated full capacities were entered into the Probe Schedule software as the full field capacity of the profile at each depth. The full field capacity was refined over time after several cycles of wetting and drying by observing the drainage pattern within the soil and direct checking via digging in the soil.

Soil moisture readings were taken at 15, 30, 45, 60, 75, and 90 cm in the soil profile once a week on the same day and time. The readings were logged on the neutron probe head and then downloaded to a computer for further processing. Data were stored, processed, and displayed with the Probe Schedule© irrigation scheduling software. The software makes use of daily weather data, moisture holding capacity of the soil, and crop coefficient to model the daily water use and daily water balance. The remaining time to the pre-set refill point is projected based on the 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).

The following water balance relationship was used to determine the irrigation amount:

$$I + P - R = ETc + D + SW$$

where the terms on the left-hand side of the above equation represent the applied irrigation water (I), precipitation (P), and surface runoff (R). The sum of these three terms represents the net addition of water to the soil profile over a time period of interest. On the right side of the equation are estimated potential crop evapotranspiration under standard field conditions (ETc), drainage or deep percolation (D), and the water storage change (SW) of soil moisture profile. Each of the terms in the above equation represents water flows or storage changes over some arbitrary time intervals. All of the terms in the equation are positive except for D and SW, which may be either positive or negative depending on the direction of the water flow (upward or downward flow) [15].

The irrigation scheduling was done with the Probe Schedule© irrigation scheduling software using data collected from the local weather station to estimate daily crop water use (ETc). The Probe Schedule© program estimates crop water use (ETc) by using the modified Penman equation [16]. Surface runoff in this study was negligible due to the control of water application and the dominant rainfall rate per event lower than the amount of water required to replenish the top 90 cm of the soil profile to field capacity. Deep percolation or drainage occurred only when soil moisture in the deepest soil layer we monitored was over 100% of field capacity. Drainage was estimated by expanding the formula used for calculating ETc and only after the crop coefficient has been accurately determined. If in the formula ($I + P – R = ETc + D + SW$), there was no irrigation, rain, or runoff in a given period, then $0 = ETc + D + SW$ or $D = –SW –ETc$. In this trial, drainage formed a very small portion of the water balance because care was taken not to overfill the profile.

Irrigation water consumption (mm) per year was calculated as the product of flow rate ($mm·hour^{-1}$) of each sub sub-plot multiplied by the total time (hours) spent irrigating the sub sub-plot during the entire season. Total water consumption (mm) consisted of irrigation water consumption, rainfall, and soil water used for each sub sub-plot during the season. Water use efficiency ($kg·ha^{-1}·mm^{-1}$) was calculated as the quotient of fruit yield ($kg·ha^{-1}$) divided by total water consumption including irrigation water, rainfall, and soil water used (mm) for each year.

2.3. Soil and Plant Sampling and Analyses

Soil sampling was conducted at the depth interval of 0 to 30 cm from each sub sub-plot in October of 2005 and 2006. A 2.5 cm diameter soil probe was used to randomly collect ten soil cores from under the center five trees in each sub 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˚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 were extracted using the Mehlich III method [17]. Soil amino sugar N was extracted with NaOH. Soil total N was determined by combustion [18]. Soil pH was determined in a 1:1 (soil: H_2O) solution [19], and organic matter was measured using the loss-on-ignition method [20].

A leaf sample was taken randomly from each sub sub-plot in October of 2005, 2006, and 2007, respectively, approximately one month after fruit harvest. Each year, the sample was collected from the same center five trees. Each sample contained 30 newly but fully developed mid-terminal leaves from current year shoots at a level of 1.5 m in the tree canopy. Samples were washed with tap water for three times and then washed with deionized water for three times, oven-dried at 65˚C, and ground to pass through a 1-mm sieve. Total N was determined using a combustion method with a Carlo Erba 1500 series Nitrogen/Carbon Analyzer [18]. Total P, K, Ca, Mg, and S in leaf were extracted by digesting the sample 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 [18].

2.4. Tree Growth and Fruit Yield and Quality

Tree trunk cross-sectional area was measured at 24 cm above ground for each sub sub-plot after fruit harvest each year. Fruit yield was determined by harvesting the center five trees from each sub sub-plot in September each year. Single fruit weight and fruit color were measured by running all fruit harvested from each sub sub-plot through a Greefa MSE 2000 packing line (Greefa, Tricht, The Netherlands). The weight of single fruit was grouped into 0 - 141, 141 - 158, 158 - 174, 174 - 191, 191 - 211, 211 - 236, 236 - 268, 268 - 309 and 309 - 999 g. The fruit color of Bartlett was divided into 0 - 300, 300 - 390, 390 - 417, 417 - 496 and 496 - 1024 nm categories; whereas, the color of Bosc was grouped as 0 - 430, 430 - 460, 460 - 480, 480 - 485, and 485 - 1024 nm.

2.5. Statistical Analysis

Analysis of variance for each measurement was conducted separately for each year and three years combined as well using the GLM procedure in the SAS package (SAS Institute, Cary, North Carolina). For the analyses of each individual-year data, a randomized complete block split split-plot model was used with integrated N fertilization and irrigation systems as the main plot factor, pear cultivars as the sub-plot factor, and rootstocks as the sub sub-plot factor. The main effects of main, sub, and sub

sub-factors and all the two-way and three-way interactions of the main, sub, and sub sub-factors were included into the model. For the analyses of the three-year combined data, the same model as used for each individual-year data was used but year was added into the model as a fixed factor, and all the interactions of year with the main, sub, or/and sub sub-factors are also added into the model. Probability levels less than 0.05 and 0.01 were designated as significant and highly significant, respectively.

3. RESULTS

Presentation of the results in this section focuses on the main effects of main, sub, and sub-sub treatments because no interactions of main, sub, and sub-sub treatments for each individual year data or of main, sub, and sub-sub treatments and year for the three-year combined data were statistically significant in any measurement in this study.

Because water from snowfall in the winter is mostly stored in the soil profile after it melts, and it is critical for pear production at this site of dry climate; annual precipitation including snowfall rather than rainfall during the irrigation season is used to interpret the results of this study. The growing season of 2005 (Oct. 2004 - Sept. 2005) was dry with an annual precipitation of 417 mm, only 53% of the 30-year average; while 2006 and 2007 seasons had an annual precipitation similar to the 30-year average (**Figure 1**). Annual precipitation was not uniformly distributed all the year round at this site according to the 30-year averages. Most of it occurred in the winter and spring with seasonal drought common in the summer and fall. Average monthly temperatures from October to June were similar for all three years and were close to the 30-year averages (data not presented). Average monthly temperatures from July through September were 2˚C to 3˚C higher for all three years than the 30-year averages.

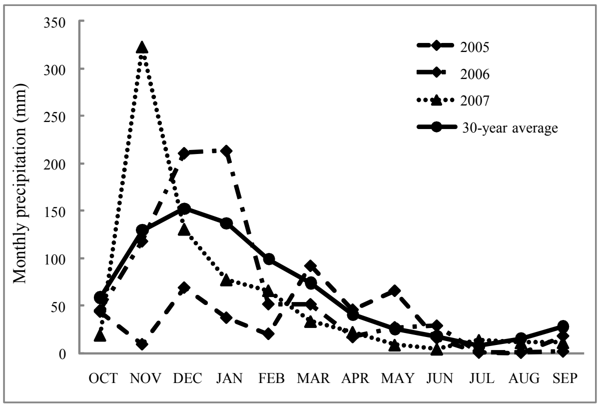

Figure 1. Monthly precipitation of the experimental period (2005-2007) at the experimental site of Hood River, OR. Note: Data were collected at the Hood River Agricultural Weather Station.

3.1. Tree Growth, Fruit Yield, Irrigation Water Consumption, Total Water Consumption, and Water Use Efficiency

Tree trunk cross-sectional area at 24 cm above ground did not differ between FDS and BSS after fruit harvest in any year or on the three-year averages regardless of cultivar and rootstock (data not presented). Fruit yields were similar for FDS and BSS in all three years averaged over the two cultivars and two rootstocks (**Table 1**).

Irrigation water consumption which was defined as the total amount of water irrigated per season (from May to September) was 152.2, 235.2, and 177.5 mm with FDS, which was reduced by 42.0%, 69.6%, and 78.3% compared with those under BSS in 2005, 2006, and 2007, respectively, on the averages of the two cultivars and two rootstocks (**Table 2**). The FDS system lowered irrigation water consumption by 69.6% averaged over the three years. The differences in irrigation water consumption between FDS and BSS seemed to gradually enlarge over the three-year period. Reponses of total water consumption to the treatments which consisted of irrigation water consumption, rainfall, and soil water used during the season showed identical trends as those of irrigation water consumption (**Table 3**).

Water use efficiency that was referred to as the fruit weight ($kg \cdot ha^{-1}$) produced with each unit (mm) of total water consumed was affected by integrated N fertilization and irrigation system (**Table 4**). Water use efficiency was enhanced by 51.0%, 192.4%, and 264.2% with FDS over BSS in 2005, 2006, and 2007, respectively, with a three-year average increment of 128.7% averaged over the cultivars and rootstocks. One mm of total water consumption produced 193 to 219 $kg \cdot ha^{-1}$ of fruit under FDS, but grew only 53 to 145 $kg \cdot ha^{-1}$ fruit with BSS during the three years. In addition, water use efficiency with Bosc was 16.4% greater than that of Bartlett, and water use efficiency under OH × F87 was 23.4% higher than that with OH × F97, averaged over the three years.

3.2. Fruit Weight and Color

Weight of single fruit and fruit skin color are key quality attributes of pear for pricing and marketing. No significant differences in fruit weight were observed between FDS and BSS in this study (data not presented) although N fertilization and irrigation are known as key management practices in pear production. Significant effects of integrated N fertilization and irrigation system on fruit color were observed in Bartlett only averaged over the three years (**Table 5**). Generally, FDS produced more fruit in color categories of 390 - 417 and 417 - 496

Table 1. Effects of integrated N and irrigation system, cultivar, and rootstock on fruit yield in each individual year (2005-2007) and on three-year averages.

Treatment		Fruit yield			
		2005	2006	2007	Average
		$Mg \cdot ha^{-1}$			
N and irrigation	FDS	41.7	56.3	46.0	48.0
	BSS	43.9	52.6	44.2	46.9
	Significance	ns	ns	ns	ns
Cultivar	Bartlett	40.0	45.1	42.6	42.6
	Bosc	45.6	63.7	47.7	52.3
	Significance	ns	ns	ns	ns
Rootstock	OH × F87	43.3	54.1	46.9	48.1
	OH × F97	42.4	54.8	43.4	46.8
	Significance	ns	ns	ns	ns

Note: Non significant effect is denoted by ns. $Mg \cdot ha^{-1}$ means megagrams per hectare.

Table 2. Effects of integrated N and irrigation system, cultivar, and rootstock on irrigation water consumption in each individual year (2005-2007) and on three-year averages.

Treatment		Irrigation water consumption			
		2005	2006	2007	Average
		mm			
N and irrigation	FDS	152.2	235.2	177.5	188.3
	BSS	262.6	774.9	819.2	618.9
	Significance	*	**	**	**
Cultivar	Bartlett	233.4	583.1	688.0	501.5
	Bosc	237.3	509.3	554.2	433.6
	Significance	ns	ns	ns	ns
Rootstock	OH × F87	217.4	513.6	591.7	440.9
	OH × F97	256.5	578.2	638.2	491.0
	Significance	ns	ns	ns	ns

Notes: Irrigation water consumption was defined as the total amount of water irrigated per season (from May to September). Significant effects at 5% and 1% probability levels are denoted by * and **, respectively. Non significant effect is denoted by ns.

nm than BSS did.

Differences in fruit weight between Bartlett and Bosc mainly lay in the two largest fruit weight categories of 268 - 309 and 309 - 999 g in terms of fruit weight and weight percentage (data not presented). Bartlett had only 5.6% and 9.1% of fruit, while Bosc having as much as 11.6% and 31.2% of fruit, respectively, in the 268 - 309 and 309 - 999 g categories. Effects of rootstocks on fruit weight were also significant (data not presented). Rootstock OH × F87 produced a higher percentage of smaller fruit than OH × F97 in the weight categories of 0 - 141, 141 - 158, and 158 - 174 g averaged over the two cultivars.

Similar to fruit weight, fruit color differed between the two cultivars (data not presented). Bartlett had more than 90% (by both weight and piece) of fruit fallen into the color categories of 300 - 390 and 390 - 417 nm, while Bosc had over 80% of fruit in the color group of 485 - 1024 nm. Significant rootstock effects on fruit color were observed in Bartlett only (data not presented). Rootstock

Table 3. Effects of integrated N and irrigation system, cultivar, and rootstock on total water consumption in each individual year (2005-2007) and on three-year averages.

Treatment		Total water consumption			
		2005	2006	2007	Average
		mm			
N and irrigation	FDS	201.5	308.4	254.2	270.3
	BSS	305.6	844.8	899.0	695.1
	Significance	*	**	**	**
Cultivar	Bartlett	279.5	652.9	766.2	557.2
	Bosc	276.0	582.0	633.4	537.1
	Significance	ns	ns	ns	ns
Rootstock	OH × F87	260.2	582.0	667.9	511.9
	OH × F97	303.0	652.9	719.6	588.4
	Significance	ns	ns	ns	ns

Notes: Total water consumption consisted of irrigation water consumption, rainfall, and soil water used during the season. Significant effects at 5% and 1% probability levels are denoted by * and **, respectively. Non significant effect is denoted by ns.

Table 4. Effects of integrated N and irrigation system, cultivar, and rootstock on water use efficiency in each individual year (2005-2007) and on three-year averages.

Treatment		Water use efficiency			
		2005	2006	2007	Average
		$kg \cdot ha^{-1} \cdot mm^{-1}$			
N and irrigation	FDS	219	193	193	199
	BSS	145	66	53	87
	Significance	*	**	**	**
Cultivar	Bartlett	159	104	79	116
	Bosc	175	134	113	135
	Significance	ns	ns	ns	*
Rootstock	OH × F87	176	126	114	137
	OH × F97	149	112	82	111
	Significance	ns	ns	**	*

Notes: Water use efficiency ($kg \cdot ha^{-1} \cdot mm^{-1}$) was calculated as the quotient of fruit yield ($kg \cdot ha^{-1}$) divided by total water consumption including irrigation water, rainfall, and soil water used (mm) for each year. Significant effects at 5% and 1% probability levels are denoted by * and **, respectively. Non significant effect is denoted by ns.

OH × F87 produced more fruit in color categories of 390 - 417 and 417 - 496 nm than OH × F97.

3.3. Leaf Nutrient Concentrations after Fruit Harvest

Effects of integrated N fertilization and irrigation system on leaf nutrient concentrations approximately one month after fruit harvest were not consistent across the three years (**Table 6**). Leaf N concentrations were similar in 2005 and 2006, but were 6.4% greater in 2007 under FDS compared with BSS, although N application rate was reduced by 20% under FDS each year. Phosphorus concentration was lowered by 9.6% and 12.7% in 2005 and 2007, respectively, with a three-year average reduction of 8.9%, under FDS over BSS. Leaf K concentrations were reduced by 8.4% and 5.9% in 2005 and 2007, respectively under FDS.

3.4. Soil Nutrient Levels after Fruit Harvest

Soil NO_3-N, NH_4-N, amino sugar N, estimated N re-

Table 5. Effects of integrated N and irrigation system on fruit skin color of Bartlett at harvest averaged over the two rootstocks and three years (2005-2007).

N and irrigation	Fruit color	Fruit distribution based on weight		Fruit distribution based on pieces	
	nm	kg·tree^{-1}	% tree^{-1}	pieces·tree^{-1}	% tree^{-1}
FDS	0 - 300	1.2	2.1	10.0	3.5
BSS		2.4	4.3	13.1	4.9
Significance		ns	ns	ns	ns
FDS	300 - 390	43.9	78.4	217.5	76.6
BSS		43.9	79.4	210.4	78.3
Significance		ns	ns	ns	ns
FDS	390 - 417	9.2	16.4	47.2	16.6
BSS		7.6	13.7	37.6	14.0
Significance		*	*	**	**
FDS	417 - 496	1.7	3.0	9.3	3.3
BSS		1.4	2.5	7.5	2.8
Significance		ns	ns	*	*
FDS	496 - 1024	0.0	0.0	0.1	0.0
BSS		0.0	0.0	0.1	0.0
Significance		ns	ns	ns	ns

Notes: Significant effects at 5% and 1% probability levels are denoted by * and **, respectively. Non significant effect is denoted by ns.

Table 6. Effects of integrated N and irrigation system on leaf N, P, K, Ca, Mg, and S concentrations one month after fruit harvest averaged over the two cultivars and two rootstocks in each individual year (2005-2007) and on three-year averages.

Year	N and irrigation	Macronutrient					
		N	P	K	Ca	Mg	S
		g·kg^{-1}					
2005	FDS	18.64	1.51	10.52	14.19	2.40	1.34
	BSS	18.43	1.67	11.48	14.33	2.23	1.35
	Significance	ns	**	**	ns	**	ns
2006	FDS	20.09	1.50	10.56	15.68	2.71	1.38
	BSS	20.57	1.53	11.08	16.04	2.60	1.43
	Significance	ns	ns	ns	ns	ns	*
2007	FDS	19.38	1.38	10.08	13.87	2.58	1.16
	BSS	18.22	1.58	10.71	13.61	2.46	1.17
	Significance	*	**	*	ns	ns	ns
Average	FDS	19.37	1.46	10.39	14.58	2.56	1.29
	BSS	19.07	1.59	11.09	14.66	2.43	1.32
	Significance	ns	**	ns	ns	ns	ns

Notes: Significant effects at 5% and 1% probability levels are denoted by * and **, respectively. Non significant effect is denoted by ns.

lease, or total N content did not differ between FDS and BSS regardless of year, cultivar, and rootstock, although the N application rate was reduced by 20% each year in FDS relative to BSS (data not presented). Soil pH, organic matter, and available P, K, and micronutrients were similar for FDS and BSS.

4. DISCUSSION

Similar fruit yields for FDS and BSS in **Table 1** indicate that split N fertigation under drip irrigation at 80% of the recommended N application rate by Oregon State University for the single broadcast application under micro sprinkler irrigation system could maintain normal growth and productivity of bearing pear trees during the first three years of transition relative to the current N fertilization and irrigation system—single broadcast application of N on the soil surface under micro sprinkler irrigation in the pear production systems in Oregon.

Our results of fruit yield (**Table 1)**, fruit quality (**Table 5**), and N consumption showed similar trends as those of previous studies on other orchard crops. Sanchez *et al.* (2003) [12] reported that yield of tart cherry was compatible or even greater, but nitrate leaching dramatically diminished, when N was fertigated at a reduced annual rate of 66 $kg \cdot N \cdot ha^{-1}$ relative to 113 $kg \cdot N \cdot ha^{-1}$ of surface broadcast N during a six-year field study in Michigan. Worley *et al.* (1995) [14] found that no reduction in yield or quality of pecan nuts occurred when 112 $kg \cdot ha^{-1}$ of N was fertigated compared with 224 $kg \cdot N \cdot ha^{-1}$ applied via surface broadcast under a drip irrigation system in a 10-year long-term study in Georgia. These preceding investigations and this study together suggest that the reductions of N fertilizer consumption through fertigation are site and management specific. Tree species, plant status, soil properties, irrigation system, fertigation and irrigation scheduling, and micro climate are all relevant to fertigated N use efficiency.

In terms of irrigation water consumption, our results suggest that switching from BSS to FDS is a viable approach to reduce irrigation water use on already established bearing pear orchards (**Table 2**), which is consistent with the findings of drip irrigation on peach trees in California [3] and partial root drying irrigation on orchards [21,22]. The differences in irrigation water consumption between FDS and BSS seemed to gradually enlarge over the three-year period; which might be related to the fact that the trees under FDS gradually became used to FDS over the three-year period. Before the initiation of this study, this orchard block had been managed under micro sprinkler irrigation for 11 years, the tree roots were able to take up irrigation water from a large irrigated ground area including both tree row areas and between-row grass alleys. After the switch to drip irrigation treatment, only the tree row areas were irrigated, and between-row areas did not receive any irrigation water; therefore the irrigated ground area was remarkably reduced, and the percentage of roots which received irrigation water was accordingly reduced under FDS. Under drip irrigation, more and more new tree roots might grow beneath the irrigated ground area each year when the treatment implementation progressed during the three-year period, and thus the uptake of irrigation water gradually became more efficient with FDS. No association was observed between irrigation water consumption and annual precipitation or between irrigation water consumption and fruit yield in any season.

Similar or even greater leaf N concentrations with FDS relative to BSS in **Table 6** have confirmed that split N fertigation under drip irrigation at 80% of the recommended N application rate could provide adequate N nutrition for bearing pear trees relative to the current N fertilization and irrigation system—single broadcast application of N on the soil surface under micro sprinkler irrigation. This agrees with those of prior studies on other fruit trees about N fertigation. No reduction in leaf N concentrations of pecans occurred when 112 $kg \cdot ha^{-1}$ of N was fertigated compared with 224 $kg \cdot N \cdot ha^{-1}$ applied via broadcast application under drip irrigation in Georgia [14]. Similar findings were reported by Klein *et al.* (1999) [9] on N fertigation for apple trees. Improved N use efficiency of fruit trees under FDS might be partially attributed to the following facts: Firstly, the fertilizer is delivered directly into the root zone; and secondly, the N rate in each application is substantially lowered due to split applications.

Leaf N, P, K, Ca, Mg, and S concentrations of pear are designated as deficient when they are below 18.0, 0.9, 7.0, 8.0, 1.3, and 1.0 $g \cdot kg^{-1}$, respectively [23]. According to the above standards, our leaf nutrient results (**Table 6**) showed that similar to BSS, FDS could provide sufficient N, P, K, Ca, Mg, and S nutrition for Bartlett and Bosc on OH × F87 and OH × F97 at a reduced N application rate.

Content of soil NO_3^--N, NH_4^+-N, amino sugar N, estimated N release, or total N after fruit harvest did not differ between FDS and BSS regardless of cultivar and rootstock (data not presented), which suggests that FDS at a reduced N rate does not cause any depletion in soil N reserves. Our soil N results further implies that split fertigation of N under drip irrigation at 80% of the recommended normal N rate, could supply adequate N nutrition to bearing pear trees compared with broadcast application under micro sprinkler irrigation. It is obvious that FDS offers the potential for reducing N fertilizer consumption and increasing N use efficiency on orchards compared with BSS being used in Oregon and other Pacific Northwestern states.

Since leaf P and K concentrations were usually lower with FDS (**Table 6**), it might be needed to apply higher rates of P and K fertilizers if FDS is used to replace BSS on producing pear orchards, particularly during the first several years of transition. It might be more efficient to apply P and K fertilizers in the irrigated ground areas only under FDS. On the other side, P and K fertilizers for FDS might also be applied into the root zone via fertigation that might increase P and K use efficiencies.

The utilization of FDS is feasible to reduce irrigation water and N consumptions, soil compaction, and water and N losses in pear production. The economic returns would be greater under FDS relative to BSS owing to the marked reductions of N fertilizer and irrigation costs and N application costs.

5. CONCLUSIONS

Nitrogen application reduced to 80% of the current broadcast application rate and fertigated in five equal split applications each season could supply bearing pear trees with adequate N nutrition without resulting in reduction of soil N reserves. Shifting from the current BSS to FDS does not affect tree growth and fruit yield and weight of pears regardless of cultivar and rootstock. Significant effects of the integrated N and irrigation management systems on fruit color were observed in Bartlett with FDS having more fruit in color categories of 390 - 417 and 417 - 496 nm than BSS. Irrigation water consumption was reduced by 42.0% to 78.3%, but water use efficiency was enhanced by 51.0% to 264.2% with FDS relative to BSS. Therefore, FDS may be used as a viable N fertilization and irrigation replacement on bearing pear orchards. However, it may be needed to apply higher rates of P and K fertilizers in the irrigated ground areas if FDS is used to replace BSS on producing pear orchards, particularly during the transitional period.

Differences of single fruit weight between Bartlett and Bosc mainly lay in that Bartlett had only 5.6% and 9.1% of fruit, while Bosc having 11.6% and 31.2% of fruit, respectively, in the 268 - 309 and 309 - 999 g categories. Rootstock OH × F87 produced more smaller fruit than OH × F97 in the weight categories of 0 - 141, 141 - 158, and 158 - 174 g. Rootstock OH × F87 produced more fruit in color categories of 390 - 417 and 417 - 496 nm than OH × F97.

Leaf concentrations of N, P, K, Ca, Mg, and S differed considerably between Bartlett and Bosc. Therefore, plant nutritional diagnoses and fertilizer recommendations based on leaf nutrient analysis may be improved if the differences in leaf nutrient concentrations between cultivars are taken into account.

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ABBREVIATIONS

Bosc, golden Russet Bosc;
BSS, broadcast of dry N fertilizer on soil surface and micro sprinkler irrigation system;
FDS, split N fertigation and drip irrigation system.

