Yield of Leafy Greens in High Tunnel Winter Production in the Northwest United States

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Abstract. Season extension structures like high tunnels make it possible to produce cold-tolerant crops during winter months for both a longer cropping season and a winter market season. The effects of location and planting date on the fresh yield of several cultivars of Asian greens (*Brassica rapa* L.), lettuce (*Lactuca sativa* L.), and spinach (*Spinacia oleracea* L.) were examined at Moscow, ID/Pullman, WA, and Vancouver, WA, a cold temperate climate and a mild marine climate, respectively. In Winter 2005–06, 20 cultivars were evaluated and in Winter 2006–07 a subset of 12 cultivars were evaluated. Location impacted yield, and higher yields overall were attained at Vancouver than at Moscow/Pullman, likely as a result of more consistent, warmer soil and air temperatures as well as increasing irradiance in February and March at Vancouver. Asian green cultivars had the highest overall yield resulting from faster growth compared with spinach and lettuce cultivars at both locations. Although most lettuce cultivars grew throughout the winter, further research is needed to identify the most suitable cultivars, seeding dates, and planting densities to optimize winter production of this crop and for Asian greens and spinach. Planting date influenced yields with the highest yields obtained for the third planting date for all trials except at Moscow/Pullman in the second year. Overall, this research suggests that it is possible to grow many cold-tolerant cultivars of Asian greens, spinach, and lettuce in a high tunnel during the winter months in both mild and cold temperate northern climates.

High tunnels, also called hoophouses, are used worldwide to provide environmental control for raising horticultural crops (Lamont, 2009; Waterer, 2003; Wells and Loy, 1993). Protected cultivation with high tunnels is not as prevalent in the United States as it is in other parts of the world, but interest is growing rapidly for small-scale producers wanting earlier crop maturity and a longer season for sales at local markets (Carey et al., 2009). High tunnels are used primarily to minimize environmental effects on crop production

either by extending the growing season in both spring and fall or providing protection from wind and rain in warmer months or climates (Lamont et al., 2003; Lang, 2009; Panter, 2007; Wein, 2006). High tunnels can modify the climate sufficiently to lengthen the growing season from 1 to 4 weeks in the spring and 2 to 8 weeks in the fall (Wells and Loy, 1993). Unlike traditional greenhouses, high tunnels do not have power for heat, lights, or fans, and crops are planted directly into the soil. Giacomelli (2009) describes thoroughly high tunnel design, construction, and environmental control.

Many crops have been successfully cultivated in the United States and throughout the world in high tunnels, including vegetable crops (Carey et al., 2009; Lamont, 2009; Lamont et al., 2003; Waterer, 2003), small fruit (Demchak, 2009; Lamont et al., 2003), cut flowers (Lamont, 2009; Wien, 2009), and small-statured fruit trees (Lang, 2009). Benefits that high tunnels provide to horticultural crops include soil warming, reduced soil compaction, and often reduced diseases and insect pests (Demchak, 2009; Lamont et al., 2003; Lang, 2009). As a result, crop yield and quality can be improved when crops are grown in a high tunnel (Carey et al., 2009; Demchak, 2009; Lang, 2009; Waterer, 2003).

Cultivar selection is an important consideration for winter production because crops must have tolerance to cold temperatures and freezing even in protected structures. Maynard and Hochmuth (2006) have classified many leafy green vegetables as cool season-hardy (cabbage, kale, mustard, spinach) or half-hardy (Chinese cabbage, lettuce). Information on optimum growing conditions is not available for all Asian greens (*Brassica rapa* L.) but Chinese cabbage grows best in moderate to cool temperatures (13 to 24 °C; Bennett et al., 2010) and can tolerate frost (Cramer et al., 2006). The optimum temperature range for lettuce (*Lactuca sativa* L.) is 13 to 16 °C but it can tolerate temperatures as low as –2 °C without damage (Mansour and Raab, 1996). The optimum temperature is ≈17 °C for spinach (*Spinacia oleracea* L.), but it can tolerate temperatures as low as –9 °C without injury (Koike et al., 2011). Spinach may be grown in the open field where winters are mild by seeding in mid to late September (Mansour and Raab, 1996). The cold hardiness of Asian greens, lettuce, and spinach suggest they may be ideal for winter high tunnel cultivation in Washington State and may expand the market for leafy greens in the region and other areas with similar climatic conditions.

The purpose of this study was to assess the yield of leafy green vegetables grown for a salad mix in a high tunnel during the winter in two climatically different locations in Washington and to characterize several environmental factors that may affect their yield. The specific objective was to examine the effects of location, crop type, and time of harvest on yield of cultivars included in this study. This information could provide growers an affordable opportunity to attain year-long local production.

Materials and Methods

Study locations. This experiment was conducted at two climatically different locations, with similar latitudes, east and west of the Cascade Mountains in Washington State. In 2005–06, the eastern field site was at Moscow, ID [lat. 46.73 °N, long. 116.99 °W; elevation 792 m (National Oceanic and Atmospheric Administration, 2009)], which was only 13 km away from the 2006–07 field site at Pullman, WA [lat. 46.73 °N, long. 117.17 °W; elevation 779 m (National Oceanic and Atmospheric Administration, 2009)]. The two field sites have similar winter weather and environmental conditions with an average temperature of –0.3 °C, an average maximum temperature of 3.3 °C, and an average minimum temperature of –3.8 °C (December to February, 1960 to 2006; Office of the Washington State Climatologist, 2009). The soil type at the Moscow site is a Naff Fine-Silty, Mixed, Superactive, Mesic Typic Agriixeroll and at the Pullman site a Palouse Fine-Silty, Mixed, Superactive, Mesic Pachic Ultic Haploxeroll. The western field site was at Vancouver, WA [lat. 45.63 °N, long. 122.67 °W; elevation 50 m (National Oceanic and Atmospheric

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Administration, 2009)] both years. The average winter temperature was 4.4 °C, the average maximum temperature was 8.5 °C, and the average minimum temperature was 0.4 °C (December to February, 1960 to 2006; Office of the Washington State Climatologist, 2009). The soil type at the Vancouver location is a Hillsboro Fine-Silty, Mixed, Superactive, Mesic Ultic Agriixeroll.

High tunnel structure. The high tunnels were 5 m wide and 15 m long (75 m²) at Moscow, 6 m wide and 15 m long (90 m²) at Pullman, and 5 m wide and 20 m long (100 m²) at Vancouver. Each was covered with a single layer of 0.15-mm ultraviolet-treated greenhouse plastic and planting was directly in the soil. The end doors were opened during the daytime to ventilate the high tunnels on warm, sunny days and closed again at night when temperatures became cool.

Trial dates and crop cultivars. Both years, all cultivars were started from seed in a greenhouse, and seeding dates were 2 weeks apart each year. Seedlings were transplanted at 6 weeks into the high tunnel (Table 1). In 2005–06, a total of 20 cultivars were seeded: eight Asian greens, 10 lettuce, and two spinach. ‘Mizuna’ was not included in the first planting at either location as a result of late arrival of seed, whereas Tat Soi and ‘Cardinale’ were not included at Vancouver as a result of lack of seed availability. In 2006–07, a subset of 12 cultivars was selected based on plant growth: four Asian greens, six lettuce, and two spinach.

Each planting was in a separate bed in a high tunnel with four replicates arranged in a randomized complete block design. Each bed measured 1 m wide and 15 m long (15 m²), and beds were spaced 1.5 m apart. In 2005–06, two plants of each cultivar were transplanted into an area of 20 cm × 25 cm (500 cm²) and in 2006–07, four plants of each cultivar were transplanted into an area of 40 cm × 25 cm (1000 cm²). Both years plant density was 40 plants/m².

Fertility management. At all locations, compost was added to the beds at 10 kg·m⁻² wet weight and incorporated to a depth of 10 cm; incorporation was 3 to 4 weeks before the first planting the first year and 2 weeks before the first planting the second year. At Moscow, compost was 1.2% to 1.4% total nitrogen (N) with 25 carbon (C):1 N on a dry weight basis

and at Pullman compost was 1.4% total N with 20 C:1 N. At Vancouver, compost was 0.9% to 1.1% total N with 22 to 30 C:1 N in 2005–06 and was 1.1% total N with a 19 C:1 N in 2006–07. All compost samples were analyzed for C/N ratios by the University of Idaho Analytical Sciences Laboratory in Moscow, ID.

At all locations in 2005–06, BioGro™ fish-fertilizer (7N–3.1P–1.7K; Bio-gro, Inc., Mabton, WA) was applied at a rate of 118 to 236 mL/plant and Acadian Seaplants™ seaweed extract (1N–0.44P–16.6K with trace minerals; Acadian Seaplants Limited, Nova Scotia, Canada) was applied at a rate of 12.5 mL/plant at transplanting and every 3 weeks thereafter. In 2006–07, BioLink™ (5N–2.3P–4.2K; Westbridge Agricultural Products, Vista, CA) and Acadian Seaplants™ seaweed extract were applied at the same fertilizer rates as the first year. Drip irrigation was provided at each location both years at 3 cm·ha⁻¹ per week.

Temperature and light measurements. Soil and air temperatures inside and outside the high tunnel were measured hourly using HOBO® H8 Outdoor/Industrial External data loggers (Onset Computer Corporation, Bourne, MA), and mean values were calculated for each 4-h period for the duration of the experiment (November to March) except for Vancouver in 2005–06 where air temperature was measured outside the high tunnel by the Washington State University Agriculture Weather Network located ≈200 m from the high tunnel. Soil temperature was measured at a depth of 5 cm, and air temperature was measured 1 m above the soil surface at Moscow/Pullman in 2005–07 and at Vancouver in 2006–07. Growing degree-days (GDD) were calculated from daily outdoor and indoor air temperature readings at both locations with a base temperature of 4 °C for Asian greens, lettuce, and spinach.

In 2006–07, light intensity was measured twice a week at the same time of day using a Quantum PPF Meter (Spectrum Technologies, Inc., Plainfield, IL) at Pullman and Vancouver. For each measurement, readings were taken at each of three points inside the high tunnel: facing south at the north end, in the center, and at the south end. Eight readings were taken outside the high tunnel: facing south at each corner and at the center of each end and side.

Harvest. Each cultivar was harvested when the outermost leaves of the plants were ≈10 to 15 cm long, a size suitable for salad mix. At harvest, each plant was cut at the soil. Both plants of each cultivar were harvested in 2005–06 and all four plants in 2006–07. Whole plant weight was measured and averaged for each plot both years.

Statistical analysis. Data were analyzed using the PROC GLM procedure in SAS (SAS Inst., Cary, NC). All statistical analyses of fresh weight yield were conducted at the 95% confidence level of significance. Analyses were performed for all data collected at both locations in both years as a factorial design with year, location, harvest date, and cultivar as factors. Data were analyzed separately by year.

Significant three-way interactions among location, harvest date, and cultivar were found and each cultivar and harvest date was analyzed individually using Tukey’s method of comparison with 95% confidence. Data were separated by location and analyzed for cultivar by harvest date and for harvest date by cultivar.

Results

Temperature and light. Because air and soil temperatures were similar between years at all locations, temperature means across both years were presented (Fig. 1). Mean air temperatures were 1.9 °C warmer inside (2.7 °C at Moscow/Pullman and 7.6 °C at Vancouver) than outside (0.8 °C at Moscow/Pullman and 5.7 °C at Vancouver) the high tunnel at all locations. At Moscow/Pullman, optimum growing temperatures (13 to 24 °C) for the three crop types were only attained inside the high tunnels (Fig. 1A) throughout the growing season. At Vancouver, however, optimum temperatures for the crops occurred periodically outside the high tunnel (Fig. 1B) beginning in December and continuing through late February but were only high enough inside the high tunnel in early December. Air temperatures at Moscow/Pullman were often below the base temperature for Asian greens, lettuce, and spinach for the majority of the season, inside as well as outside the high tunnel (Fig. 1A), whereas at Vancouver, air temperatures were often above the base temperature, inside and outside (Fig. 1B). Mean soil temperatures were 3.1 °C warmer inside (4.2 °C) than outside (1.2 °C) the high tunnel at Moscow/Pullman and 1.4 °C warmer inside (7.9 °C) than outside (6.6 °C) the high tunnel in Vancouver. Mean air temperatures inside and outside the high tunnel were 4.9 °C warmer at Vancouver than Moscow/Pullman. Similarly, mean soil temperatures were 5.3 °C warmer outside and 3.6 °C warmer inside the high tunnel at Vancouver than Moscow/Pullman.

In Winter 2006–07, light intensity outside the high tunnel was lowest at both locations in January (322 μmol·m⁻²·sec⁻¹ and 206 μmol·m⁻²·sec⁻¹ at Pullman and Vancouver, respectively; Fig. 2) and highest in February (388 μmol·m⁻²·sec⁻¹ and 399 μmol·m⁻²·sec⁻¹ at Pullman and Vancouver, respectively). Inside the high tunnel, light intensity was also lowest in January at both locations (222 μmol·m⁻²·sec⁻¹ and 129 μmol·m⁻²·sec⁻¹ at Pullman and Vancouver, respectively), but at Pullman was highest in December (303 μmol·m⁻²·sec⁻¹), whereas at Vancouver it was highest in February (264 μmol·m⁻²·sec⁻¹). Average light intensity inside the high tunnel was 27% lower than outside the high tunnel at Pullman (260 and 356 μmol·m⁻²·sec⁻¹, respectively) and 36% lower at Vancouver (291 and 186 μmol·m⁻²·sec⁻¹, respectively).

In 2005–06, GDD began to accumulate in late January outside the high tunnel at Vancouver and continued to increase from February through late March (Fig. 3A). Inside the high tunnel, GDD accumulation also began in

Table 1. Dates for seeding, transplanting, and harvesting three plantings of leafy green crops at Moscow and Vancouver in Winter 2005–06 and Pullman and Vancouver in Winter 2006–07.

Yr	Planting no.	Seeding date	Transplant date	Harvest date
2005–06	1	9 Nov.	14 Dec.	15 Mar.
	2	23 Nov.	4 Jan.	28 Feb. ^z
	3	7 Dec.	18 Jan.	30 Mar.
2006–07	1	3 Oct.	15 Nov.	25 Jan.
	2	17 Oct.	1 Dec.	15 Feb.
	3	31 Oct.	12 Dec.	1 Mar.

^zHarsh winter conditions slowed growth of plants transplanted on the first date (14 Dec.) so that they were harvested after those transplanted on the second date (4 Jan.).

Fig. 1. Mean monthly temperatures (°C) collected at 4-h intervals for winter/spring in 2005–06 and 2006–07 inside and outside the high tunnel for air (A) and soil (C) at Moscow/Pullman and air (B) and soil (D) at Vancouver, WA. The solid lines (—) in A and B indicate the optimum temperature range for growing Asian greens, lettuce, and spinach, and the dotted line (---) indicates the base temperature for these crops (4 °C). At Moscow/Pullman in 2005–07 and Vancouver in 2006–07, air temperature was measured 1 m above the soil surface inside and outside the high tunnel; at Vancouver in 2005–06, air temperature outside the high tunnel was measured by the Washington State University Agriculture Weather Network. Soil temperatures were measured at a depth of 5 cm inside and outside the high tunnel at Moscow/Pullman and Vancouver in 2005–07.

Fig. 2. Average light intensity (μmol·m⁻²·sec⁻¹) inside and outside the high tunnel in 2006–07 at Pullman and Vancouver.

late January but was more rapid and 214 GDD accumulated inside compared with 79 GDD outside by the final harvest date (30 Mar.). At Moscow, GDD did not begin to

accumulate outside the high tunnel until mid-February (Fig. 3A) and remained low (33 GDD) outside the high tunnel by the final harvest date. Inside the high tunnel, however,

GDD began to accumulate in late December and increased rapidly throughout the growing season and 400 GDD had accumulated by late March. In 2006–07, GDD again began to accumulate earlier and more rapidly outside the high tunnel at Vancouver (early December) than at Pullman (mid-December; Fig. 3B). In mid-January, GDD accumulation was briefly higher at Pullman than Vancouver until early February. More GDD accumulated more rapidly inside the high tunnel (155 GDD) compared with outside (92 GDD) at Vancouver by the final harvest date (1 Mar.). At Pullman, GDD accumulated earlier (early December; Fig. 3B) and were higher (419 GDD) inside the high tunnel compared with outside (87 GDD) on the final harvest date.

Yield 2005–06. Data were analyzed separately by year, and a significant three-way interaction was found for location, harvest date, and cultivar ($P < 0.0001$) and data were separated again and analyzed by location. At Moscow, statistical analysis showed a significant interaction between harvest date and cultivar ($P < 0.0001$) and the effect of cultivar was analyzed by harvest date and the effect of harvest date analyzed by cultivar. Many cultivars had the highest yield on the third harvest date (Table 2). Overall means demonstrated

Fig. 3. Cumulative growing degree-days for Asian greens, lettuce and spinach inside and outside the high tunnel at base temperature 4 °C during winter months at Moscow/Pullman and Vancouver, WA, in 2005–06 (A) and 2006–07 (B).

that Asian green cultivars had the highest yield for all three harvest dates (29 g/plant, 31 g/plant, and 70 g/plant, respectively) followed by spinach (14 g/plant, 18 g/plant, and 21 g/plant, respectively), and then lettuce cultivars (11 g/plant, 11 g/plant, and 18 g/plant, respectively).

Individual cultivar yield was variable within each harvest date, but several cultivars within each crop type were consistently larger than others. Among the Asian greens, ‘Shanghi’ pak choy, ‘Mizuna’, tat soi, ‘Komatsuna’, and ‘China Jade’ baby bok choy were the largest. Both spinach cultivars were consistently high-yielding and did not differ from each other. Although most of the lettuce cultivars did not have high yields compared with Asian green and spinach cultivars, ‘Cracoviensis’, ‘Jackice’, ‘Oscarde’, ‘Brown Golding’, and ‘Cardinale’ were the most consistent.

At Vancouver, a significant interaction occurred between cultivar and harvest date ($P < 0.0001$) and the effect of cultivar was analyzed by harvest date and the effect of harvest date analyzed by cultivar. Crops in the first and second plantings suffered substantial pest damage (mice and slugs) and

many plants were not considered marketable. On the third harvest date, Asian green cultivars had the highest average yield (233 g/plant) followed by lettuce cultivars (54 g/plant) and then spinach cultivars (46 g/plant; Table 3). Cultivars that had the greatest yields were ‘Komatsuna’, ‘China Jade’ baby bok choy, and ‘Arctic Circle’ Tah Choy for Asian greens; ‘Cracoviensis’, ‘Bronze Arrowhead’, and ‘Kwiek’ lettuce; and ‘Tyee’ spinach.

Cultivars took an average of 10 weeks after transplanting to reach marketable size at both locations. As a result of harsh winter conditions at Moscow, plants transplanted on the first date (14 Dec.) took longer to develop and were harvested 2 weeks after those transplanted on the second date (4 Jan.). Mean yield was significantly higher at Vancouver (43 g/plant) than Moscow (26 g/plant) across all cultivars and harvest dates.

Yield 2006–07. At Pullman, there was a significant interaction between harvest date and cultivar ($P = 0.0006$) and the effect of cultivar was analyzed by harvest date and the effect of harvest date analyzed by cultivar (Table 4). On each of the three harvest dates,

Asian green cultivars had the highest overall mean yield (19 g/plant, 23 g/plant, and 14 g/plant, respectively) followed by spinach cultivars (13 g/plant, 10 g/plant, and 12 g/plant, respectively), whereas lettuce cultivars had the lowest overall mean yield (8 g/plant, 8 g/plant, and 8 g/plant, respectively). Asian green cultivars ‘Ching-Chiang’ pac choy, ‘Komatsuna’, tat soi, and ‘Mizuna’ had consistently high yields. Among lettuce cultivars, ‘Cracoviensis’ consistently had the highest yield followed by ‘Bronze Arrowhead’, ‘Yugoslavian Red’, and ‘Cardinale’. ‘Tyee’ and ‘Giant Winter’ spinach cultivars both had similarly high yields except for the first harvest date when ‘Tyee’ was greater.

At Vancouver, there was a significant interaction between cultivar and harvest date ($P < 0.0001$) and the effects of cultivar were analyzed by harvest date and the effects of harvest date were analyzed by cultivar (Table 4). Mean yield was greatest for Asian green cultivars at each harvest date (7 g/plant, 114 g/plant, and 148 g/plant, respectively) followed by lettuce cultivars (11 g/plant, 22 g/plant, and 31 g/plant, respectively) and spinach cultivars (5 g/plant, 13 g/plant, and 22 g/plant, respectively). All cultivars had the highest yield on the third harvest date. Asian green cultivars ‘Komatsuna’ and ‘Mizuna’ had the highest yields overall followed by tat soi and ‘Ching-Chiang’ pac choy. ‘Cracoviensis’, ‘Bronze Arrowhead’, and ‘Cardinale’ had the highest yields of the lettuce cultivars followed by ‘Brown Golding’ and ‘Yugoslavian Red’. ‘Tyee’ and ‘Giant Winter’ spinach cultivars both had similarly high yields.

At both locations in 2006–07, cultivars took an average of 11 weeks after transplanting to reach marketable size. Mean plant yield was again higher at Vancouver (43 g/plant) than at Pullman (12 g/plant).

Discussion

Winter production of leafy greens was successful in both the cold temperate climate of Moscow/Pullman and the mild marine climate of Vancouver. Higher air and soil temperatures and accumulated GDD demonstrate that it is necessary to grow leafy green crops inside high tunnels at both locations during winter months. Considerably higher rates and accumulated GDD inside a high tunnel at Moscow/Pullman suggest that leafy green crops would have higher yields at this location compared with Vancouver. However, overall yields were higher at Vancouver than at Moscow/Pullman, likely as a result of more constant, favorable temperatures in western Washington. Greater fluctuations of air temperatures at Moscow/Pullman resulted in large daily temperature extremes and more accumulated GDD. At Vancouver, differences between daily maximum and minimum temperatures were less, and fewer GDD accumulated. Similarly, soil temperatures were warmer and more consistent at Vancouver than Moscow/Pullman (Figs. 1C–D). Extreme high temperatures likely occurred in the high tunnel at the arid Moscow/Pullman sites under clear,

Table 2. Mean fresh weight (g/plant) for leafy green crops grown in three trials at Moscow in Winter 2005–06.

Cultivar	Harvest Date 1			Harvest Date 2			Harvest Date 3		
Asian greens	(g/plant)								
Komatsuna	40	x ^z	a ^y	38	x	a–c	68	x	a–d
Shanghi Pak Choy	35	x	ab	58	x	a	77	x	ab
Ching-Chiang	21	y	b–d	27	y	a–d	96	x	a
Mizuno	14	y	cd	7	y	cd	54	x	a–e
China Jade	30	y	ab	24	y	b–d	71	x	a–c
Arctic Circle Tah Choy	26	y	bc	47	x	ab	40	xy	b–e
Tat Soi	33	x	ab	13	x	cd	77	x	ab
Mizuna	35	x	ab	N/A ^x	—	—	77	x	ab
Lettuce									
Cracoviensis	11	y	d	17	xy	b–d	19	x	e
Emerald Oak	12	xy	cd	5	y	d	17	x	e
Jackice	12	x	d	16	x	b–d	17	x	e
Oscarde	12	y	d	9	y	cd	25	x	c–e
Bronze Arrowhead	14	x	cd	16	x	b–d	23	x	de
Brown Golding	9	x	d	14	x	cd	9	x	e
Blushed Butter Oak	10	x	d	6	x	cd	17	x	e
Yugoslavian Red	11	y	d	6	y	cd	20	x	e
Kwiek	8	y	d	5	y	d	14	x	e
Cardinale	13	x	cd	12	x	cd	19	x	e
Spinach									
Tyee	14	x	cd	20	x	b–d	13	x	e
Giant Winter	13	x	cd	15	x	b–d	29	x	c–e

^zHarvest date means for the same cultivar followed by the same letter, x–y, are not significantly different at the 5% level according to a Tukey's standardized range test.

^yCultivar means for the same harvest date followed by the same letter, a–e, are not significantly different at the 5% level according to a Tukey's standardized range test.

^xCultivar not included in harvest date as a result of pest damage.

Table 3. Mean fresh weight (g/plant) for leafy green crops grown in three trials at Vancouver in Winter 2005–06.

Cultivar	Harvest Date 1			Harvest Date 2			Harvest Date 3		
Asian greens	(g/plant)								
Komatsuna	4	y ^z	a ^y	N/A ^x	—	—	584	x	a
Shanghi Pak Choy	N/A	—	—	N/A	—	—	81	—	cd
Ching-Chiang	1	y	a	N/A	—	—	157	x	bc
Mizuno	5	y	a	N/A	—	—	130	x	b–d
China Jade	13	y	a	3	y	a	238	x	b
Arctic Circle Tah Choy	8	y	a	3	y	a	207	x	b
Tat Soi ^w	N/A	—	—	N/A	—	—	N/A	—	—
Mizuna	N/A	—	—	N/A	—	—	N/A	—	—
Lettuce									
Cracoviensis	4	y	a	4	y	a	63	x	cd
Emerald Oak	N/A	—	—	N/A	—	—	N/A	—	—
Jackice	N/A	—	—	N/A	—	—	56	—	cd
Oscarde	14	x	a	2	x	a	47	x	cd
Bronze Arrowhead	9	y	a	3	y	a	70	x	cd
Brown Golding	8	x	a	N/A	—	—	53	x	cd
Blushed Butter Oak	N/A	—	—	N/A	—	—	25	—	d
Yugoslavian Red	N/A	—	—	N/A	—	—	46	—	cd
Kwiek	N/A	—	—	N/A	—	—	72	—	cd
Cardinale	N/A	—	—	N/A	—	—	N/A	—	—
Spinach									
Tyee	5	y	a	N/A	—	—	57	x	cd
Giant Winter	2	y	a	2	y	a	35	x	d

^zHarvest date means for the same cultivar followed by the same letter, x–y, are not significantly different at the 5% level according to a Tukey's standardized range test.

^yCultivar means for the same harvest date followed by the same letter, a–e, are not significantly different at the 5% level according to a Tukey's standardized range test.

^xCultivar not included in harvest date as a result of pest damage.

^wTat soi, Mizuna, and Cardinale were not included at Vancouver as a result of lack of seed availability.

dry conditions when sunlight levels were high but dropped quickly at nightfall or under cloudy conditions, whereas at the maritime Vancouver site, more consistent cloud cover regulated extremes in temperature and kept temperatures relatively warm all winter. The more consistently warmer growing conditions at Vancouver may be more critical than the

higher light intensities or accumulated GDD at Moscow/Pullman for yield production.

Yields of Harvests 1 and 2 in 2005–06 at Vancouver were reduced as a result of slug and mice damage; however, by the third harvest, pests were well managed and yields for all cultivars and crop types were in many cases higher than at Moscow. Waterer (2003)

observed fewer disease and insect pests in the short, cool, dry growing season of the Canadian prairies compared with high tunnels in warm and humid regions as noted by Wells and Loy (1993). The drier, cooler climate of Moscow/Pullman compared with Vancouver appears to have lessened the impact of pests, particularly slugs, on leafy green crops.

For all locations, the highest yields for all cultivars tended to occur on the third harvest date followed by second and first harvest dates. Earlier seeding and transplanting dates in the second year as compared with the first year resulted in higher yields, but earlier seeding dates did not reduce the number of days from transplant until harvest (10 weeks on average the first year, 11 weeks the second year). The crop types in this study appeared to mature at different times and Asian greens grew to a suitable size for salad mix earlier than spinach or lettuce. Certain leafy green cultivars may have slower growth than others when temperatures are below optimal levels (Mansour and Raab, 1996; Rader and Karlsson, 2006; Smith et al., 2011). As a result, the mixed stand of leafy green vegetables grown in this experiment made it difficult to harvest all cultivars at their optimal market maturity. Although all crop types were well suited for winter production, we recommend that producers plant crops separately to ensure that the quality of each cultivar is optimized at harvest. Waterer (2003) also describes different maturation times of three different crop types grown in a single high tunnel.

The majority of leafy green cultivars grown in this study had good vigor and showed promise for high tunnel production during the winter in Washington. At both locations when temperatures were below freezing, plants would also freeze and often would develop ice crystals. However, after temperatures increased above freezing, the plants continued to grow with minimal apparent leaf damage. Overall, yield of Asian green cultivars was higher than spinach cultivars, and lettuce cultivars tended to have the lowest overall yield regardless of planting and harvest dates. In this study, the Asian green cultivars 'Shanghi' pak choy, 'Ching-Chiang' pac choi, China Jade baby bok choy, 'Komatsuna', 'Mizuna', and tat soi had consistently high yields. Both spinach cultivars had relatively high yields under all conditions in this study and appear suitable for winter production. Lettuce cultivar 'Cracoviensis' consistently produced the highest yield followed by 'Brown Golding', 'Bronze Arrowhead', 'Cardinale', and 'Yugoslavian Red'.

Winter production of leafy greens should be further explored as an opportunity for growers to extend their season using unheated, unlit high tunnel structures. Yield was variable, but in general, Asian green and spinach cultivars grew well under a variety of light and temperature conditions. Research should be continued to identify best management practices and suitable planting and harvest dates for all cultivars for winter production, whereas more work is needed to

Table 4. Mean fresh weight (g/plant) for leafy green crops grown in three trials at Pullman and Vancouver in Winter 2006–07.

	Pullman									Vancouver								
Cultivar	Harvest Date 1			Harvest Date 2			Harvest Date 3			Harvest Date 1			Harvest Date 2			Harvest Date 3		
Asian greens	(g/plant)									(g/plant)								
Komatsuna	21	x ^z	a ^y	23	x	ab	20	x	a	9	z ^z	ab ^y	168	y	a	248	x	a
Ching-Chiang	18	xy	ab	23	x	ab	7	y	ab	8	y	ab	58	x	bc	70	x	cd
Tat Soi	19	x	ab	17	x	a–c	15	x	ab	6	z	ab	69	y	b	105	x	c
Mizuna	16	x	a–c	27	x	a	N/A ^x	—	—	6	y	ab	160	x	a	169	x	b
Lettuce																		
Cracoviensis	13	x	b–d	12	x	b–d	15	x	ab	12	x	ab	27	x	b–d	29	x	de
Oscarde	6	x	d	3	x	d	6	x	ab	7	y	ab	10	y	d	24	x	de
Bronze Arrowhead	5	x	d	10	x	cd	9	x	ab	13	y	a	22	xy	cd	40	x	de
Brown Golding	8	x	cd	6	x	cd	3	z	b	11	y	ab	23	x	cd	15	xy	e
Yugoslavian Red	9	x	cd	7	x	cd	9	x	ab	10	y	ab	18	y	cd	44	x	de
Cardinale	9	x	cd	7	x	cd	4	y	b	13	x	a	31	x	b–d	33	x	de
Spinach																		
Tyee	19	x	ab	7	y	cd	14	xy	ab	6	y	ab	13	y	d	21	x	de
Giant Winter	7	x	d	13	x	b–d	9	x	ab	3	y	b	12	xy	d	23	x	de

^aHarvest date means for the same cultivar followed by the same letter, x–y, are not significantly different at the 5% level according to a Tukey's standardized range test.

^bCultivar means for the same harvest date followed by the same letter, a–d, are not significantly different at the 5% level according to a Tukey's standardized range test.

^cData missing for Mizuna in Harvest 3 as a result of crop loss.

identify lettuce cultivars that are especially well suited to winter production. An earlier planting date will not reduce the length of time it takes to reach marketable size; however, establishing transplants before the onset of low winter light intensities and temperatures resulted in larger plants in the spring. Non-destructive, “cut and regrow” harvest methods may also be considered by managers; however, removal of damaged leaves from marketable salad mix may be difficult and weeds would need to be controlled over time. It is also recommended to regulate extreme temperature fluctuations and to maintain consistent, warmer growing conditions for crops throughout the winter. Low tunnels, also called rowcovers, are often used inside high tunnels to enhance crop growth when additional warmth or insulation is necessary (Lamont, 2009; Waterer, 2003; Wein, 2006). Because crop types and cultivars can reach optimum market maturity at different times, different crops should be cultivated in separate plantings to help producers harvest each crop at its optimum maturity. More work is also needed to better understand growth rates for each cultivar under winter conditions so as to create recommended planting mixes and densities.

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