Canadian Journal of Plant Science

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Journal:	<i>Canadian Journal of Plant Science</i>
Manuscript ID	CJPS-2021-0138.R1
Manuscript Type:	Article
Date Submitted by the Author:	08-Jul-2021
Complete List of Authors:	Leisso, Rachel; Montana State University Bozeman, Department of Research Centers Jarrett, Bridgid; Montana State University Bozeman, Department of Research Centers Richter, Rebecca; Montana State University Bozeman, Department of Research Centers Miller, Zachariah; Montana State University Bozeman, Department of Research Centers
Is the invited manuscript for consideration in a Special Issue?_:	Canadian Horticulture Special Issue
Keywords:	blue honeysuckle, haskap, honeyberry, postharvest

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Fresh haskap berry postharvest quality characteristics and storage life

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For Review Only

Abstract

Haskap (*Lonicera caerulea* L.) is a relatively new berry crop in North America, and little research exists regarding its postharvest storage characteristics or storage life. Postharvest changes in berry quality and principal factors limiting storage life at 1.1 °C and 95% relative humidity were evaluated up to 14 d for three cultivars in 2019 and up to 28 d for six cultivars in 2020. Containerized berries were periodically assessed for soluble solids content, skin rupture force (both 2019 and 2020) and flesh firmness, titratable acidity, and Brix/acid ratio (2020 only). External appearance was also evaluated both years, revealing berry shrivel as the primary factor negatively impacting visual appeal, followed distantly by low incidence of spoilage later in storage. All cultivars exhibited relatively constant postharvest soluble solid contents and decreasing skin rupture force, flesh firmness, and titratable acidity (resulting in increasing Brix/acid ratio). Postharvest quality differed slightly between years; relative skin rupture force was consistent among cultivars while soluble solids content was not. Some cultivars had a portion of shriveled berries at harvest, pointing to a need for cultivar-specific harvest indices. Mean days to the slight shrivel for individual berries varied among cultivars evaluated, ranging from 7.5 - 21.9 d postharvest and varied among cultivars evaluated, with mean weight loss ranging from 1.2 - 1.6% at this stage. Combined with group marketability estimates—set at threshold of 10% severely shriveled berries—we estimate a storage life of 7-10 d for fresh haskaps. Additional research is needed to delineate maturation physiology and optimize harvest timing.

Keywords: blue honeysuckle, haskap, honeyberry, postharvest

Introduction

Haskap (*Lonicera caerulea* L.) is a shrub in the honeysuckle family (Caprifoliaceae) with blue berries that are exceptionally high in antioxidants and have numerous documented health benefits, including anti-inflammatory and anti-diabetic properties (De Silva and Rupasinghe 2020; Rupasinghe et al. 2018; Rupasinghe et al. 2012; Viljoen et al. 2012). The flavor of preferred cultivars has been described as a cross between a blueberry and a raspberry (Bors et al. 2015). Favorable characteristics of the haskap plant include high tolerance to a wide range of soil pH, exceptional cold hardiness (Bors et al. 2012; Bors et al. 2015; Gerbrandt 2014; Plekhanova 1996), and the ability of the blossoms to withstand freezing temperatures (Gasic et al. 2018).

Haskap production is increasing in Canada, where orchards of up to 40 acres have been planted (Statistics Canada 2020). Haskap production is not currently tracked by government entities in the United States, although a western-region survey indicated that respondents' orchards were typically less than 5 acres (Kuo and Garg, unpublished, 2020). Both commercial plantings and nursery stock available for retail purchase include North American varieties bred in the last 20 years by breeding programs led by Dr. Maxine Thompson and Dr. Bob Bors (University of Saskatchewan) (Bors et al. 2015; Bors et al. 2009; Bors et al. 2012; Thompson and Barney 2007; Thompson 2006, 2016a, 2016b, 2016c, 2016d, 2017a, 2017b; Thompson and Chaovanalikit 2003), with the germplasm sourced for their programs originating from Japan, the Kuril Islands, Russia, and Canada. Haskap germplasm characteristics—including parameters influencing location-specific suitability—are available through studies published by Gerbrandt (2014) and Gerbrandt et al. (2017, 2018a, 2018b, 2020). Due to the recent introduction of these cultivars, detailed or cultivar-specific horticultural management guidance is limited.

In addition to adaptation to cold climates, interest in haskap is partly driven by the early harvest season relative to other berry crops. Haskaps ripen earlier than either raspberries or blueberries and earlier or concurrent with strawberries (Gerbrandt et al. 2018a). The fresh haskap season for the range of cultivars available in Canada spans two months (Bors et al. 2015). In the United States, published information on harvest season is sparse, although harvests for 18 cultivars in western Montana typically begin in mid-June and finish near the end of July (Miller and Jarrett, personal communication, 2021).

Information on postharvest quality and storage life of fresh haskap berries under conditions of commercial refrigeration is very limited, especially for cultivars that are widely available in North America. Storage life can be defined as the period over which fruit retains ideal eating qualities. Measures for establishing and evaluating storage life generally include assessments of blemishes, texture (firmness), and flavor (acidity and sweetness) at intervals over a defined period of storage (Kader 1983).

Since appearance is a primary driver for consumer decisions to purchase produce (Cook 2002; Kays 1991), we examined postharvest berry quality characteristics and external visual factors influencing storage life of haskaps. We also measured fruit weight loss over time in relation to shrivel, as weight loss (attributed largely to water loss) is one of the principal factors limiting berry storage life (Thompson et al. 2008). The aim of our research was to 1) compare postharvest fruit quality characteristics for several haskap cultivars, 2) determine factors of haskap berry external appearance limiting storage life, and 3) estimate haskap berry marketable storage life based on these factors when stored under commercial refrigeration.

Materials and Methods

Plant materials and growing conditions

Experiments were conducted at Montana State University Western Agricultural Research Center (MSU-WARC) in Corvallis, MT, United States (lat. 46°19'45.5 N, long. 114°5'7.4 W) in the summers of 2019 and 2020. Cultivars tested include Aurora, Indigo Gem, and Tana in 2019. These three cultivars were also used for 2020 experiments, along with Sugar Mountain Blue, 85-19 (Dr. Maxine Thompson line), and Kapu (Solo™). Haskap plants used in the present trial were planted in 2015 in a field trial where each cultivar is represented by nine total plants at 0.91 and 3.6 m in-row and between-row spacing, respectively. The shrubs are not mulched, and during the 2019 and 2020 growing seasons, plants were irrigated at a rate of 53 L per week, with additional irrigation during weeks when temperatures surpassed 32.2 °C. Weed management included hand weeding and spot spraying with glyphosate in the first year. After the first growing season, dormant applications of granular pre-emergent herbicide (Casoron 4G; active ingredient: dichlobenil, 112 kg·ha⁻¹) were made. Fertility management followed standard

recommendations for macronutrients (N-P-K) in bush and cane berries (Miller et al. 2021). Plants were protected with bird netting beginning the first week of June, prior to blue color development for berries for any haskap cultivars.

Berry harvest and storage

Harvest indices utilized to determine harvest dates were: 1) exterior blue color for all fruits on the shrub, 2) bulk fruit SSC ($n = \sim 27$ berries, at least three from each plant in the trial) near 14% (bulk SSC continues to increase after the exteriors of the berries are all fully blue), and 3) full flavor development (subjective evaluation). Harvest dates varied according to cultivar and are indicated in Table 1. All berries for experiments in both years were harvested by hand (with workers wearing latex or nitrile gloves), except 'Indigo Gem' in 2019, which was harvested with a low-tech mechanical harvest method that we term "shake-and-catch". This method begins by placing paired stainless-steel harvest bins (Indigo Waxwing Harvester) tightly together on the ground beneath the canopy of an individual shrub. A battery-operated reciprocating saw equipped with a custom U-shaped attachment is used to vibrate the main woody branches of the shrub, causing berries to shake loose and drop into collection bins. In 2019, we harvested between 8 AM and 2 PM. In 2020, we harvested fruit between 6 AM and 7 AM.

For both years of the study, fruit to be evaluated were stored in a walk-in cooler ("cold room" or "cold storage") maintained at 1.1 °C and 95% relative humidity (RH). The berries were either placed in vented polyethylene terephthalate (PET) produce/berry containers ("plastic clamshells") (item #434H160; Webstaurant Store, Las Vegas, NV, United States), which have an enclosed volume of 177 cm³, or on uncovered cellularized trays with 10 shallow depressions that separated individual fruit from one another. Randomized containers or trays of berries were stored a single layer on cold room shelves.

Berry quality measures

Berry weights were recorded to the nearest 0.001 g on an analytical balance (Model PR323N/E; Ohaus Corporation, Parsippany, NJ, United States). Destructive fruit assessments including skin rupture force (N) and flesh firmness (N) were collected using a manual fruit firmness tester (FR-5120 Digital Fruit Firmness Tester; QA Supplies, Norfolk, VA, United States) equipped with a 2 mm probe mounted on a

stand. Measurements were collected with the penetrometer settings at “fast” (instrument reading update time of 0.2 s) and “Peak H” (instrument displays peak value of force). To the extent possible, the same person measured berry skin rupture force (SRF) and flesh firmness throughout the trial. Skin rupture force (N) was tested by placing fruit on its flattest side and depressing the penetrometer until the skin was punctured. Flesh firmness (N) was measured on a different set of fruit by placing fruit on its non-flat side (so that one side of the two ovaries enclosed by the copula would be facing up to the penetrometer as depicted in Fig. 1), removing the smallest amount of skin possible to expose berry flesh of the up-facing ovary, and depressing the penetrometer. Readings were collected for SSC—or Brix, in the Brix/acid (B/A) ratio— from juice expressed from individual fruit following penetrometer measurements with a hand-held digital refractometer (HI 96822; HANNA Instruments, Smithfield, RI, United States). Sufficient juice volume for measuring titratable acidity (TA) and pH was achieved by pooling ten fruit per cultivar for each test for SRF or flesh firmness. The pooled fruit were placed in small polyethylene bags and macerated by hand to release the juice. A corner of the bag was removed for draining juice into several 2 mL centrifuge tubes and centrifuging at 13,000 x *g* to deposit sediment. The supernatant was decanted and used to measure pH and TA using a potentiometric titrator (Model AT1102; Hach Inc., Loveland, CO, United States) equipped with an autosampler (AS1000; Hach Inc.) and an electrode (pH IntelliCAL™ PHC281 pH Ultra Refillable pH electrode; Hach Inc.). Samples of juice were titrated to pH 8.2 with 0.25 M NaOH (sodium hydroxide). Results are expressed in g citric acid L⁻¹ of solution, as citric acid is the predominant acid in haskaps (Rupasinghe al. 2018), according the following calculation, adapted from the manufacturer’s guide (Hach Inc. 2019):

$$\text{Acidity (g/L)} = \frac{C_{\text{titrant}} \times V_{\text{titrant}}(\text{mL})}{n_{e-\text{citric acid}} \times n_{e-\text{titrant}} \times V_{\text{sample}}(\text{mL})} \times M_{\text{citric acid}}(\text{g/mol})$$

Where C_{titrant} is the concentration of the titrant (NaOH), in eq/L (0.25); V_{titrant} is the volume of titrant used, $n_{e-\text{chosen acid}}$ is the number of exchanged electrons for the predominant acid (3 [citric acid]), $n_{e-\text{titrant}}$ is the number of exchanged electrons for the titrant (1 [sodium hydroxide]), and $M_{\text{chosen acid}}$ is the molar weight of

the predominant acid (192.1 g mol^{-1} [citric acid]), and V_{sample} is the volume of the sample; note, for conversion to percent, $1 \text{ g/L} = 0.1\%$.

We calculated the B/A ratio by adapting definitions from citrus per definitions in United States Electronic Code of Federal Regulations (eCFR) 7 CFR § 93.2 (Processed...2021) defined as degrees Brix of the juice to the grams of anhydrous citric acid per 100 grams juice.

Postharvest berry quality characteristics and periodic evaluations of shrivel and spoilage (experiments 2019, 2020A)

In 2019, berries from six 'Indigo Gem' plants were mechanically harvested, and a portion of the harvest was gently transferred to fill one plastic clamshell per plant. Berries from six plants of each cultivar Aurora and Tana were hand-harvested from all sides and canopy positions to fill a plastic clamshell from each plant (approximately 160 berries per container). These clamshells were refrigerated as described above, and ten berries from each plastic clamshell were removed for each assessment, for a total of 60 berries per cultivar per evaluation. Berry assessments included weight, SSC, SRF, and external appearance evaluations for defects after 1 h at room temperature. Based on preliminary data, fruit bruising or skin abrasion were occasional defects but the primary postharvest issues for external berry appearance were shrivel (desiccation) and spoilage (external visual evidence of postharvest pathogens, i.e., mold), and these were the two principal external characteristics visually evaluated for berries. Berry assessments were made for cultivars Indigo Gem and Aurora on 0, 7, and 14 d in 2019. Since little external spoilage-based deterioration was observed in 'Indigo Gem' and 'Aurora' berries through 14 d storage, we further assessed 'Tana' berries at 27 d to examine this characteristic for a longer storage duration. Fruit remaining in containers were not returned to storage after evaluation.

In 2020, three experiments were conducted on a total of six cultivars. For experiment 2020A, a total of ~250 fruit were hand-harvested for each cultivar, representing ~27 fruit from each of nine shrubs of each Indigo Gem, Aurora, Kapu, and Tana. Berries of each cultivar were pooled together; 180 fruit were arbitrarily selected from each pool and distributed in groups of 10 among clamshells, for a total of 18 clamshells per cultivar. Berries in six clamshells per cultivar were evaluated and subsequently discarded

at storage durations of 0, 14, and 28 d. Berry assessments included weight, SSC, SRF, flesh firmness, pH, and TA. Shriveled incidence was rated as either absent, slight (fruit would still be acceptable for fresh market), or severe (fruit would be unmarketable). Spoilage incidence was recorded based on the visual observation of mold on the fruit exterior. A subset of berries with spoilage were shared with colleagues for microscopic identification in 2019 (MSU Schutter Diagnostic Laboratory, Bozeman, MT, United States) and microscopic/molecular identification in 2020 (E. Boyd and M. Burgess, MSU Department of Plant Sciences, Bozeman, MT).

Shriveled, weight loss, and marketability (experiments 2020B and 2020C)

For experiment 2020B, approximately 45 fruit (5 fruit from each plant in the trial) were harvested from each of the cultivars Aurora, 85-19, Sugar Mountain Blue, and Kapu. Extra attention was given to fruit quality at harvest, ensuring no shriveled was apparent and that fruit were evenly firm based on gentle tactile palpation. Berry samples were randomly selected from harvested fruit, divided among three plastic cellularized trays, and placed in the cold room. Trays were transferred to the laboratory for a short time (less than 1 min) daily to weigh and rate individual fruit for marketability. Fruit were deemed unmarketable if they appeared severely shriveled or moldy; these berries were discarded after being weighed and evaluated. For follow-up experiment 2020C, we placed ten fruit into each of 12 clamshells for each of the cultivars 'Indigo Gem', 'Aurora', and 'Tana' and then weighed them weekly through 35 d of cold storage.

Statistics

The SAS Statistical Package (Version 9.4; SAS Institute, Cary, NC) was used for data analysis. Data for postharvest berry quality characteristics and periodic evaluations of spoilage and shriveled (experiments 2019, 2020A) were analyzed using analysis of variance (ANOVA) with cultivar and storage duration as factors using PROC GLM; fruit were destructively sampled each time (data are independent sub-samples). Time was considered a factor and not a regression variable in these models. Exploratory data gathered at 27 d for 'Tana' in 2019 were additionally analyzed separately in comparison to data from 0, 7, and 14 d. Cumulative weight loss for individual fruit for experiment 2020B were first analyzed with an analysis of covariance (ANCOVA) in PROC MIXED with cultivar as a class variable and storage duration

as the independent variable. Based on the significant interaction of cultivar and storage duration in ANCOVA, linear regression analysis was performed on cultivars separately with PROC REG. Weight loss was subjected to *post hoc* comparisons of least square means at $P < 0.05$. We created plots with a linear regression line via ggplot2 (Wickham, 2009) in R (R Core Team, 2021). Data for marketability, shrivel, and weight loss in individual fruit, as well as tray storage-life (the number of days at which 10% or more of fruit were considered “severely” shriveled), were analyzed using ANOVA via PROC GLM. Prior to analysis, these data were summarized for individual fruit as “days to first shrivel”, “days to severe shrivel”, “cumulative weight loss to first shrivel (%)”, and “cumulative weight loss to severe shrivel (%)”. For the follow-up weight loss experiment on fruit in plastic clamshells (experiment 2020C), repeated measures were specified as random effects in the model with the RANDOM statement. In all analyses, *post hoc* Fisher’s Least Significant Difference test was used to separate means where the overall model was significant ($P < 0.05$).

Results

Postharvest berry quality characteristics and periodic evaluations of shrivel and spoilage

In the initial storage-life trial in 2019, there were only minor changes in fruit quality over 14 d of storage and almost no spoilage (Table 2), although mechanically-harvested ‘Indigo Gem’ did exhibit high rates of shrivel by 7 d. Soluble solids content ranged from 14.4% to 16.7% and only increased significantly during storage for ‘Indigo Gem’ (14.6% at harvest vs 16.7% at 14 d harvest). Soluble solids content was not altered during storage for the other two cultivars. Skin rupture force varied among cultivars, with Aurora having the highest SRF (0.97 N) at harvest, versus 0.42 N for Indigo Gem, and 0.80 N for Tana. Skin rupture force changed significantly during storage for ‘Aurora’, decreasing to 0.80 N at 14 d, and increasing for ‘Indigo Gem’ to 0.55 N at 14 d. In 2019, shrivel ratings did not differentiate between slight (marketable fruit) and severe (unmarketable fruit). Shrivel was significantly higher (60% of fruit affected) for mechanically harvested ‘Indigo Gem’ by 7 d storage, relative to both ‘Aurora’ and ‘Tana’ as well as in comparison to initial levels (0%) at harvest for ‘Indigo Gem’. For ‘Aurora’, shrivel incidence was not significantly different at 7 and 14 d of storage (mean=5%). Shrivel was present in ‘Tana’ berries at harvest (Table 2), suggesting harvesting occurred after optimal maturity, but shrivel incidence increased only on

day 27 of storage, with an average of 30% of fruit exhibiting shrivel (data not shown). *Penicillium* spp. was identified on spoiled berries in 2019.

In 2020, results of periodic postharvest fruit quality (Table 3) show that individual fruit weight varied among cultivars, with Aurora berries averaging 1.49 g at harvest, followed by Tana at 1.39 g, Kapu at 1.13 g, and Indigo Gem at 1.02 g. The “increase” in berry weight between harvest and 14 d is likely due to differences in individual berry weights (berries were destructively sampled at each evaluation date) combined with slow weight loss and may indicate a need for greater numbers of berries in experimentation. Mean berry weight decreased in storage for ‘Aurora’ between 14 d and 28 d; weights varied between storage dates for ‘Kapu’ but did not exhibit a trend in relation to storage. Mean berry weights did not differ according to storage for ‘Indigo Gem’ or ‘Tana’. Cultivar type and storage duration influenced pH, which increased between harvest and 28 d for all cultivars except Kapu. Titratable acidity differed among cultivars and the effects of storage varied among cultivars. ‘Kapu’ had the highest TA at 30 g L⁻¹ citric acid equivalents (CAE) at harvest. ‘Tana’ had the lowest TA, at 17.9 g L⁻¹ CAE. Titratable acidity decreased in storage for all cultivars, although means separations suggest rates vary within a cultivar. Tana was the only cultivar without a significant change in TA between harvest and 14 d, and Aurora was the only cultivar without a significant change between 14 and 28 d. Brix/acid ratio varied among cultivars, with ‘Aurora’ having the highest at harvest at 9.1, and Kapu, the lowest, at 6.9. Brix/acid ratio increased significantly in storage for all cultivars. Although SSC differed among cultivars, with Kapu having the highest average SSC, the effects of storage on SSC varied among cultivars, with most cultivars exhibiting similar SSC between 0 and 28 d. In ‘Indigo Gem’, soluble solids increased from 0 to 28 d. Soluble solids content was nominally higher for ‘Indigo Gem’ in 2020 than in 2019, while ‘Aurora’ and ‘Tana’ appeared similar across years. Skin rupture force differed among the cultivars, with Kapu having the highest SRF. Effects of storage on SRF varied among cultivars with most cultivars having consistent SRF over four weeks but the skins of Kapu weakened during storage. There was a similar SRF order for the same cultivars evaluated in 2019 and 2020, with ‘Aurora’ having the highest SRF, followed by ‘Tana’ and ‘Indigo Gem’. Flesh firmness varied among cultivars, with ‘Aurora’ having the highest flesh firmness of 0.35 N at harvest, followed by ‘Kapu’ at 0.30 N, ‘Tana’ at 0.25 N, and ‘Indigo Gem’ at 0.12 N. Flesh firmness significantly decreased in storage only for ‘Tana’. In 2020, 20% of berries from ‘Indigo

Gem' had slight shrivel at harvest (Table 4), indicating that harvest occurred after optimal maturity. All cultivars had a significantly higher incidence of slight shrivel by 14 d of storage than at harvest. 'Aurora' and 'Indigo Gem' did not have significantly higher levels of severe shrivel (5 and 0%) at 14 days of storage than at harvest, and percent of fruit affected by shrivel was lower than Kapu and 'Tana', for which 25% of fruit in a container had severe shrivel. Two percent of 'Indigo Gem' berries exhibited postharvest spoilage at 14 d; 5% was documented at 28 d for 'Aurora', 17% for 'Kapu', and no spoilage for 'Tana'. In 2019, 'Indigo Gem' was also the only cultivar with spoilage documented at 14 d, but mechanical harvest was likely a confounding factor. Both *Penicillium* spp. and *Botrytis* spp. were noted in spoiled berries in 2020.

Shrivel, weight loss, and marketability

Cumulative weight loss rates for individual fruit differed among cultivars (ANCOVA, $p < 0.0001$). Linear regression lines and fit indicators for cumulative weight loss $\times$ day for each cultivar are shown in Fig. 2. Per regression equations, weight loss rates ranged from 0.0014 to 0.0022 g^{-1} per day per berry among the four cultivars, with the regression equations for 85-19 having the highest R^2 value (0.77) and the lowest weight loss rate of 0.0014 g^{-1} day, although weight loss recorded at first incidence of severe shrivel was significantly lower for 85-19 (1.8%) relative to the other cultivars (Table 5). The shortest storage duration until the appearance of slight shrivel was 7.5 d for 'Sugar Mountain Blue'; the highest was 21.9 d for 'Aurora'—even though 'Aurora' had the highest rate of weight loss (Fig. 2). The lowest average number of days until severe shrivel was 14.5 d for 'Indigo Gem'; the highest average days until severe shrivel was 24.9 for 'Aurora'. We estimated tray marketable life as number of days until 10% or more of fruit were considered unmarketable according to the presence of severe shrivel. Market life varied among cultivars, with 'Aurora' having the longest marketable life, and 'Sugar Mountain Blue' having the shortest marketable life. Since berries are not commercially stored or sold individually, we followed up by evaluating weight loss rates for berries stored in clamshells ($n = 10$ per container). Weight loss differed among cultivars, with 'Aurora' and 'Tana' remaining below 1% weight loss at 7 days of storage, while 'Indigo Gem' lost nearly 1.5%, which was inconsistent with what was documented with individual fruit,

where 'Aurora' had a higher rate of weight loss. By day 35 of storage, 'Indigo Gem' had lost nearly 10% of its initial weight, while 'Aurora' and 'Tana' weight loss remained below 5% (Table 6).

Discussion

Although information comparing fruit quality of haskap germplasm or cultivars is available and increasing (e.g. Bors et al. 2012, Gerbrandt et al. 2020, Ochmian et al. 2012, Tanaka and Tanaka 1998), readily available published research on haskap postharvest storage characteristics and storage life, especially for new North American cultivars is minimal. MacKenzie et al. (2018) reported significant loss of marketability in less than 7 d of storage for several cultivars, although the only cultivar in common with the present experiments was Indigo Gem. In the same study, marketable fruit storage duration also varied year to year, with 60 to 70% of fruit marketable after one week in the first year of the study and 30% marketable after a week of storage the following year. The more rapid postharvest quality loss in the second year was attributed to rain events immediately preceding harvest, potentially resulting in high-moisture fruit that were more prone to degradation. The authors (MacKenzie et al. 2018) noted a relatively long storage-life for haskaps compared to raspberries and strawberries, which—at optimal storage conditions—keep for 7-10 d and 3-6 d, respectively (Thompson et al. 2008). Patents for 'Tana' and 'Kapu' indicate storage potential of up to 1 month (Thompson 2016a, 2016d), but information on storage conditions and fruit quality characteristics for these results is not readily available. Anticipating a potentially short storage life for haskaps, in the first year of the present study (2019), periodic storage life evaluations were performed only up to 14 d for 'Aurora' and 'Indigo Gem'. Although we noted shrivel in storage, we documented very little postharvest spoilage—even for 'Indigo Gem' whose berries were damaged by mechanical harvest and for 'Tana', whose storage was extended to enable evaluation at 27 d. Based on limited spoilage noted in 2019, in the following season (2020), we performed destructive postharvest fruit quality assessments at longer storage intervals (14 d and 28 d for four cultivars, including the three assessed in 2019) and—since shrivel was the primary defect clearly limiting berry storage-life in 2019—conducted a separate experiment in 2020 assessing cultivar-specific weight loss rates and cumulative weight loss to first incidence of shrivel for four cultivars.

Although direct statistical comparison was not performed due to differing environmental conditions and storage durations, year-to-year comparison of postharvest fruit quality indicates fruit physiochemical characteristics at harvest and in storage (14 d) can nominally vary year-to-year within a cultivar. However, year-to-year, the relative order of SRF levels were consistent cultivar-to-cultivar, with 'Aurora' exhibiting the highest SRF, followed by 'Tana', and 'Indigo Gem' having the lowest SRF. Soluble solids content was less consistent year-to-year, with 'Indigo Gem' and 'Aurora' having higher levels in the second year; levels were relatively unchanged both years for all cultivars during postharvest storage.

At-harvest fruit quality characteristics further indicated significant cultivar variability in berry size, SSC, TA, the B/A ratio, SRF, and flesh firmness. Berry weights were overall lower than those reported for elite breeding lines in Bors et al. (2012), although direct cultivar comparison is not possible. Average 'Indigo Gem' weights were similar to those reported in Gerbrandt et al. (2018a). Overall, SSC in for berries the present study are higher than reported by Thompson and Barney (2007), De Silva and Rupasinghe (2020), and Gerbrandt et al. (2020), slightly higher than MacKenzie et al. (2018), but lower than those reported by Bors et al. (2012). As noted in Gerbrandt et al. (2020), both cultivar pedigree and environmental differences among geographic locations can influence fruit quality characteristics. Titratable acidity in the present study was lower than values reported by Gerbrandt et al. (2020), except for Kapu, a cultivar originating from Japanese germplasm (Thompson, 2016a), which had TA values similar to other Japanese lines (Gerbrandt et al. 2020). Little information is readily available in previous studies on haskaps regarding SRF and flesh firmness. Although parameters involved in measuring SRF and flesh firmness are not standardized for haskaps, present results may suggest haskap berries are less firm than other familiar small fruit or berries. Note, however, that in other small fruits, firmness measures are influenced by instrumentation, including probe shape and diameter; instrumental parameters, e.g. puncture speed, puncture depth; and force measured, e.g. force curve, compression, or tension; see Døving et al. [2005]; in addition, many studies simply report one value [firmness] and do not separate skin rupture force from flesh firmness. However, with similar focus on skin resistance to puncture, haskap SRF was lower than that reported for table grapes (Sabir and Sabir 2019; however, their probe diameter is not noted) and blueberries (Ordóñez et al. 2020; same probe diameter). Regarding flesh firmness, the interior

of ripe haskap berries can be extremely soft, reminiscent of the locular jelly of fruit like tomatoes, and this is reflected by extremely low values (less than 0.5 N).

Postharvest cold storage influenced the fruit quality measures TA, SSC, and B/A, with some potentially useful implications for aspects of flavor. Titratable acidity decreased in storage, but since in the present study this was measured at relatively long intervals (minimum 14 d), the rate of TA decrease in storage remains to be determined. With postharvest decrease in TA and the relatively constant SSC, the increase in B/A ratio during storage suggests potentially favorable changes in consumer perception, as higher B/A can be linked to greater consumer preference in other fruits (Harker et al. 2002; Jayasena and Cameron, 2008). In related research, a consumer study of 'Aurora' haskaps conducted in 2020 using berries harvested from the same plants and stored in nearly the same conditions (differing in type of plastic containers) as the present study received the same consumer acceptance ranking at two weeks postharvest (7.6 on the hedonic scale of food acceptability [ranging from 1 to 9]) (Garg et al., 2021) as at harvest, even though both SRF and TA had decreased significantly at two weeks storage.

Daily evaluation of individual berries in cold storage suggests that the average storage duration to first incidence of slight shrivel can be as low as 7.5 d ('Indigo Gem') or as high as 21.9 d ('Aurora'). We considered 'Indigo Gem' fruit to be unmarketable as a group at ~10 d postharvest due to 10% or more of fruit being affected by severe shrivel. This is a conservative shrivel incidence threshold; other studies use 25% - 50% unacceptable fruit as the marketability threshold (Crisosto and Crisosto 2005; Hancock et al. 2008). However, high incidence of slight shrivel (greater than 50% of berries in a container) was documented at 14 d of storage for plastic clamshells of all cultivars assessed in 2020, suggesting overall inferior condition of containerized fruit relative to individual fruit in a similar time frame. This could be due to the extra care taken to harvest high quality (firm and shrivel-free) fruit for individual berry evaluations, while containerized fruit were simply harvested to represent total fruit on the shrub at harvest maturity per indices described. In our studies, shrivel ratings of berries stored in plastic clamshells differed year-to-year within a cultivar, although results are confounded by mechanical harvest of 'Indigo Gem' in 2019, as well as by implementing a more detailed shrivel rating scale in 2020. Alternatively, it is possible that storing berries together in a plastic clamshell negatively influences storability, although typically fruit

stored in similar containers have longer shelf-lives, due to higher humidity within the container (Ikegaya et al. 2020). Finally, for some fruit, flavor-based marketable storage life is shorter than appearance-based marketable storage life (Pelayo et al. 2003).

Haskap weight loss rates were slow relative to blueberries, for which research has documented 5.3% and 7.6% weight loss at 14 days when stored at 0 °C or 5 °C, respectively (Sanford et al. 1991), and 10% when stored for 21 days at 0 °C (Paniagua et al. 2013a). In contrast, haskap weight loss in similar conditions was below 3% for 'Aurora' and 'Tana' at 21 d and below 5% for 'Indigo Gem'. Even at 35 d postharvest, all three cultivars had weight loss less than 10%. We speculate that the lower weight loss rate could be due to the unique anatomy of haskap berries—which have two ovaries enclosed in the skin of the copula (Gerbrandt E. 2014; Rehder 1909)—resulting in a fruit with a double layer of skin enclosing the soft flesh. However, haskap cumulative weight loss present at both first incidence of slight shrivel (1.2% to 2.6% weight loss, relative to initial) and severe shrivel (1.8 to 4.9% weight loss relative to initial) was lower than for blueberries, where studies have indicated that up to 8% water loss is acceptable (Paniagua et al. 2013b), which could point to physiological processes beyond water loss (e.g. changes in cellular structure) contributing to shrivel in haskap. For haskaps harvested per indices described in the present study, after 1-2% weight loss, berries may be unmarketable or more appropriate for processing or discounting, if unspoiled. As noted, maturity at harvest may influence shrivel, with less mature berries less prone to shriveling quickly.

Spoilage incidence was negligible in individually stored fruit and typically occurred much later and at lower incidence rates than shrivel for containerized fruit. *Penicillium* spp. and *Botrytis* spp. were identified on spoiled fruit, but Koch's postulates are needed to confirm pathogenicity (Boyd et. al., unpublished, 2020). However, both genera are known postharvest pathogens in other small fruits (Horvitz 2017; Xiao and Saito 2017).

To our knowledge, since haskap is a relatively new fruit crop, harvest indices for specific cultivars and regions are not established, and, in addition, information on postharvest physiology (e.g. ripening competence) is limited (see further discussion of Yamamoto et al. [2014], below). Therefore, cultivars in the present study may not have been harvested at optimal maturity for fresh market/postharvest storage,

and cultivar comparison of storage outcomes should be considered cautiously, as maturity could influence storage outcomes. Based on the information that many growers currently harvest haskaps mechanically and move fruit immediately to processing, our approach to determining harvest timing has been to require full blue color for all berries on a shrub, optimize flavor (subjective), as well as require a minimum mean SSC of ~14 in bulked pre-harvest samples ($n = \sim 27$ berries). However, present results suggest that harvest indices for fresh market should be considered separately from requirements for processed fruit, in addition to being cultivar-specific: requiring a mean SSC of 14 or greater in pre-harvest samples led to harvesting at least one cultivar each year past optimal fresh-eating quality and maturity as indicated by shrivel observed at the time of harvest; 'Tana' had 13% shrivel incidence at harvest in 2019, and 'Indigo Gem' had 20% shrivel incidence at harvest in 2020. This emphasizes the need for distinct harvest indices for each cultivar for fresh market harvest, as shrivel was not noted at harvest for all cultivars based on the present harvest indices. For future consideration in determining fresh market harvest indices and timing, work by Yamamoto et al. (2014) involving immature berries indicated color can further develop and TA as well as firmness can decrease postharvest. They suggested that harvesting slightly prior to horticultural maturity (optimal palatability) may be possible, but more research is needed, as postharvest SSC remained relatively constant for immature berries in their trial and never attained SSC of fruit harvested at maturity.

Conclusions

We compare postharvest fruit quality for several haskap cultivars during extended cold storage, with results indicating cultivar-specific differences in measures of SSC, SRF, flesh firmness, TA, and B/A, suggesting cultivar-specific differences in flavor and storability. Shrivel was the primary postharvest defect limiting haskap berry storage life, followed by spoilage, which was tentatively attributed to *Penicillium* spp. and *Botrytis* spp. We noted berry shrivel incidence in certain cultivars at the time of harvest, which points to need to optimize harvest indices for haskap on a cultivar-specific basis. Additionally, improving upon packaging and storage conditions (i.e., lowering temperature and raising humidity) (Kader 2003) could increase haskap berry storage life. Since we observed no chilling injury when berries were stored at 1.1 °C, longer storage duration may be possible at the ideal commercial berry storage temperatures of -0.6 to

0 °C (Thompson et al. 2008), and supplemental treatments could also be tested for aiding in reduction of haskap berry desiccation and spoilage (Kader 2003).

Acknowledgements

We would like to thank Montana State University (MSU)-Bozeman and MSU-Western Agricultural Research Center staff Amy Darling, Haydon Davis, Kyrstan Hubbel, Ashley Kapus, Katrina Mendrey, Kierstin Schmitt, Alex Hooglund, Shawna Medlar, Frances Rafferty, Olivia Soller, and Andrea Ziolkowski for administrative or technical support. We also thank the anonymous reviewers whose comments greatly improved the presentation of these results.

Competing interests: The authors declare there are no competing interests.

Contributors' statement

R. Leisso: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – Original Draft, Supervision, Project administration, Funding acquisition. **B. Jarrett:** Investigation, Writing – Reviewing and Editing, Supervision, Resources. **R. Richter:** Investigation, Writing – Reviewing and Editing, Visualization. **Z. Miller:** Writing – Reviewing and Editing, Formal analysis, Resources, Funding acquisition.

Funding statement

This project was funded by the Montana Specialty Crop Block Grant AM200100XXXXG026 and the Northwest Center for Small Fruits Research, Corvallis, OR, United States.

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Data availability statement

Data are available upon request.

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Table 1. Harvest dates and experiments for haskap cultivars in the trial. One postharvest storage experiment was performed in 2019 (2019); two principal experiments (2020A, 2020B) plus a follow-up (2020C) were performed in 2020.

Cultivar	Harvest date	Harvest date	Experiment code
	2019	2020	
'Sugar Mountain Blue'		16 June 2020	2020B
'Indigo Gem'	2 July 2019	22 June 2020	2019; 2020A, B, C
'Aurora'	11 July 2019	2 July 2020	2019; 2020A, B C
85-19		9 July 2020	2020B
'Tana'	29 July 2019	20 July 2020	2019, 2020 A, C
'Kapu' ^a		23 July 2020	2020A

^aSolo™

Table 2. Postharvest quality and incidence of shrivel and spoilage of haskap berries stored at 1.1 °C and 95% relative humidity in polyethylene clamshell containers in 2019. Ten fruit were selected at random from each of six full containers of fruit (volume of ~177 cm³, ~160 fruit per container) for a total of 60 fruit per mean, except for weights, where n = 6 (six weights of 10 fruit together). Containers were destructively sampled; each evaluation is independent. Means followed by different letters in a column are statistically different according to Fisher's least significant difference ($P < 0.05$) for the interaction of factors cultivar*storage, except where noted. Abbreviations: soluble solids content (SSC), skin rupture force (SRF), ns (not significant).

Cultivar	Storage	mean ± SE				
	days	Wt. of 10 berries(g) ^a	SSC (°Brix)	SRF (N)	Shrivel (%) ^b	Spoilage (%) ^c
'Aurora'	0	19.6 ± 0.50a	14.4 ± 0.25c	0.97 ± 0.04a	0 ± 0.0e	0 ± 0ns
	7	18.2 ± 0.47a	15.0 ± 0.14bc	0.81 ± 0.03b	2 ± 0.1e	0 ± 0ns
	14	18.9 ± 0.28b	14.7 ± 0.49c	0.80 ± 0.04bc	8 ± 0.1de	0 ± 0ns
'Indigo Gem' ^d	0	11.1 ± 0.43ns	14.6 ± 0.15c	0.42 ± 0.02e	0 ± 0.0e	0 ± 0ns
	7	10.6 ± 0.24ns	15.9 ± 0.16ab	0.51 ± 0.03de	60 ± 0.2b	0 ± 0ns
	14	9.7 ± 0.34ns	16.7 ± 0.37a	0.55 ± 0.04d	82 ± 0.2a	1.7 ± 0.1ns
'Tana'	0	16.3 ± 0.32ns	14.9 ± 0.21bc	0.80 ± 0.04bc	13 ± 0.1cd	0 ± 0ns
	7	17.1 ± 0.48ns	14.8 ± 0.59c	0.75 ± 0.04c	5 ± 0.1de	0 ± 0ns
	14	15.4 ± 0.33n	15.0 ± 0.28bc	0.75 ± 0.04c	20 ± 0.2c	0 ± 0ns

<i>P</i>					
cultivar	<0.0001	0.0015	<0.0001	<0.0001	0.3686
storage	0.0485	0.0096	0.0083	<0.0001	0.3686
cultivar*storage	0.0930	0.0425	0.0010	<0.0001	0.4170

^aCultivar*storage was not significant; means comparisons were performed at the level of cultivar (indicated by capital letters) and within cultivars (indicated by small letters).

^bShrivel incidence was visually evaluated as shrivel absent/present.

^cSpoilage incidence was visually evaluated as spoilage absent/present (mycelia visible).

^d'Indigo Gem' was harvested mechanically via the small-scale 'shake-and-catch' method.

Table 3. Postharvest quality for haskap berries stored in groups of 10 in polyethylene clamshell containers and stored at 1.1 °C and 95% relative humidity in 2020 (experiment 2020A). Abbreviations: Titratable acidity (TA), Brix/acid (B/A), soluble solids content (SSC), skin rupture force (SRF). For pH, TA, and B/A, each mean represents six samples of sap (ten fruit contributed to each sample). For SSC, SRF, and flesh firmness, each mean represents 60 fruit (10 berries per container for 6 containers). Containers were destructively sampled; each evaluation is independent. Means followed by different letters in a column are statistically different according to Fisher's least significant difference ($P < 0.05$) for the interaction of factors cultivar*storage.

Cultivar	Storage days	mean $\pm$ SE							
		Wt individual berry (g)	pH	TA (g•L ⁻¹) ^a	B/A ^b	SSC (°Brix)	SRF (N)	Flesh firmness (N) ^c	
'Aurora'	0	1.49 $\pm$ 0.03a	3.38 $\pm$ 0.03de	18.7 $\pm$ 1.06e	9.1 $\pm$ 0.52cd	15.5 $\pm$ 0.37d	1.05 $\pm$ 0.08ab	0.35 $\pm$ 0.07	ns
	14	1.55 $\pm$ 0.04a	3.44 $\pm$ 0.04cd	14.6 $\pm$ 0.81hi	11.1 $\pm$ 0.56a	14.5 $\pm$ 0.34e	1.17 $\pm$ 0.06a	0.33 $\pm$ 0.05	A ns
	28	1.39 $\pm$ 0.04b	3.51 $\pm$ 0.03ab	13.4 $\pm$ 0.55i	12.4 $\pm$ 0.75a	15.0 $\pm$ 0.40de	0.95 $\pm$ 0.05bc	0.25 $\pm$ 0.08	ns
'Indigo Gem'	0	1.02 $\pm$ 0.03ef	3.48 $\pm$ 0.06c	22.0 $\pm$ 0.94d	8.1 $\pm$ 0.44f	16.6 $\pm$ 0.44c	0.64 $\pm$ 0.06fg	0.12 $\pm$ 0.03	b
	14	0.94 $\pm$ 0.03fg	3.38 $\pm$ 0.03e	18.9 $\pm$ 0.61e	9.4 $\pm$ 0.44c	16.8 $\pm$ 0.50c	0.83 $\pm$ 0.07cde	0.11 $\pm$ 0.02	B b
	28	0.91 $\pm$ 0.03g	3.53 $\pm$ 0.02a	15.8 $\pm$ 0.55gh	12.0 $\pm$ 0.64a	17.4 $\pm$ 0.54b	0.72 $\pm$ 0.06ef	0.19 $\pm$ 0.04	a
'Kapu'	0	1.13 $\pm$ 0.04d	3.19 $\pm$ 0.02h	30.4 $\pm$ 2.32a	6.9 $\pm$ 0.42f	18.4 $\pm$ 0.54a	1.17 $\pm$ 0.06a	0.30 $\pm$ 0.07	ns
	14	1.26 $\pm$ 0.03c	3.13 $\pm$ 0.03i	28.4 $\pm$ 0.84b	6.4 $\pm$ 0.18f	17.3 $\pm$ 0.42b	0.89 $\pm$ 0.07bcd	0.26 $\pm$ 0.05	A ns
	28	1.08 $\pm$ 0.04de	3.25 $\pm$ 0.03g	24.1 $\pm$ 1.63c	9.2 $\pm$ 0.60de	18.5 $\pm$ 0.48a	0.33 $\pm$ 0.03g	.	

'Tana'	0	1.39 ± 0.03b	3.31 ± 0.02f	17.8 ± 0.18ef	8.6 ± 0.18de	14.5 ± 0.31e	0.86 ± 0.07cde	0.25 ± 0.05	a
	14	1.40 ± 0.03b	3.39 ± 0.02cd	16.3 ± 0.53fg	10.0 ± 0.44c	14.7 ± 0.37e	0.85 ± 0.06cde	0.18 ± 0.04	B b
	28	1.38 ± 0.03b	3.48 ± 0.02b	14.3 ± 0.37i	10.6 ± 0.29b	14.6 ± 0.31e	0.73 ± 0.04def	0.12 ± 0.03	b
<i>P</i>									
cultivar		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		<0.0001 ^c
storage		0.0002	<0.0001	<0.0001	<0.0001	0.0008	<0.0001		
cultivar x storage		0.0170	<0.0001	0.0060	0.0070	0.0007	<0.0001		

^aTitrateable acidity is in terms of citric acid; 1 g•L⁻¹ = 0.1%.

^bBrix/acid ratio defined as degrees Brix of the sap to the grams of anhydrous citric acid per 100 g sap (adapted from citrus in 7 CFR § 93.2 – Definitions in Electronic Code of United States Federal Regulations (2021). Citric acid is the dominant organic acid in haskaps.

^cMissing data for 'Kapu'; initial comparison performed at the cultivar-level only followed by ANOVA within each cultivar with storage as a factor.

Table 4. Postharvest incidence of shrivel and spoilage for haskap berries stored in polyethylene clamshell containers in 2020 (experiment 2020A). Shrivel incidence was categorized in terms of marketability as absent, slight (fruit still marketable), or severe (fruit unmarketable). Evaluations of postharvest spoilage (mold) were based on visual observation of the fruit exterior and with rating criteria of “absent” or “present”. Each mean represents percent incidence for 60 fruit (10 berries per container for 6 containers). Fruit were not submitted to repeated evaluations; each evaluation is independent. Means followed by different letters in a column are statistically different according to Fisher’s least significant difference ($P < 0.05$) for the interaction of factors cultivar*storage.

Cultivar	Storage	mean $\pm$ SE		
	days	Slight shrivel (%)	Severe shrivel (%)	Spoilage (%)
‘Aurora’	0	0 $\pm$ 0.0e	0 $\pm$ 0.0d	0 $\pm$ 0.0b
	14	43 $\pm$ 7.7cd	0 $\pm$ 0.0d	0 $\pm$ 0.0b
	28	33 $\pm$ 8.2abc	35 $\pm$ 6.2ab	5 $\pm$ 2.2b
‘Indigo Gem’	0	20 $\pm$ 9.0de	0 $\pm$ 0.0d	0 $\pm$ 0.0b
	14	68 $\pm$ 6.1ab	5 $\pm$ 2.2d	2 $\pm$ 1.7b
	28	28 $\pm$ 4.3a	57 $\pm$ 8.0a	20 $\pm$ 3.7a
‘Kapu’	0	0 $\pm$ 0.0e	0 $\pm$ 0.0d	0 $\pm$ 0.0b
	14	48 $\pm$ 7.2ab	25 $\pm$ 7.2bc	0 $\pm$ 0.0b
	28	42 $\pm$ 7.7a	45 $\pm$ 7.6ab	17 $\pm$ 6.7a

'Tana'	0	0 ± 0.0e	0 ± 0.0d	0 ± 0.0b
	14	28 ± 8.5bc	25 ± 3.4bc	0 ± 0.0b
	28	48 ± 7.7ab	28 ± 5.4b	0 ± 0.0b
<i>P</i>				
cultivar		0.0058	0.0087	0.0002
storage		<0.0001	<0.0001	<0.001
cultivar*storage		<0.0001	<0.0001	<0.0001

Table 5. Storage days to first shrivel, severe shrivel, and associated weight loss for individual fruit and marketable life for berries as a group based on the percent incidence of severe shrivel. Berries were stored on cellularized trays at 1.1 °C and 95% relative humidity (n = 30 fruit per cultivar) (experiment 2020B). Means in a column followed by a different letter are different according to Fisher's least significant difference ($P < 0.05$).

Cultivar	mean $\pm$ SE individual berries				Tray marketable life (mean $\pm$ SE [days]) ^a
	Days to first shrivel	Days to severe shrivel	Wt. loss to first shrivel (%)	Wt. loss to severe shrivel (%)	
85-19	12.9 $\pm$ 0.77b	17.1 $\pm$ 16b	1.2 $\pm$ 0.10b	1.8 $\pm$ 0.11c	14 $\pm$ 1.0b
'Aurora'	21.9 $\pm$ 0.79a	24.9 $\pm$ 25a	2.6 $\pm$ 0.19a	3.3 $\pm$ 0.28b	20 $\pm$ 0.6a
'Indigo Gem'	8.2 $\pm$ 0.89c	14.5 $\pm$ 13b	1.6 $\pm$ 0.19b	3.4 $\pm$ 0.30b	10 $\pm$ 0.3c
'Sugar Mtn. Blue'	7.5 $\pm$ 0.67c	17.2 $\pm$ 10b	1.6 $\pm$ 0.18b	4.9 $\pm$ 0.28a	13 $\pm$ 0.3b
<i>P</i>					
cultivar	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
tray	0.1445	0.2354	0.9583	0.4481	0.1696
cultivar x tray	0.2019	0.6929	0.0982	0.4794	0.5232

^aShelf-life based on severe shrivel affecting 10% or more of berries on a tray.

Table 6. Weight loss for groups of 10 fruit (n = 6) stored in polyethylene clamshell containers at 1.1 °C and 95% relative humidity (experiment 2020C). Means followed by different lowercase letters in a column are different according to cultivar and uppercase letters in a row are statistically within a cultivar different according to Fisher’s least significant difference.

	wt. loss (mean ± SE [%])				
Cultivar	7 d	14 d	21 d	28 d	35 d
‘Aurora’	0.39 ± 0.03c, E	1.23 ± 0.05b, D	2.09 ± 0.18b, C	3.12 ± 0.12b, B	4.24 ± 0.18b, A
‘Indigo Gem’	1.53 ± 0.09a, E	2.82 ± 0.14a, D	4.72 ± 0.22a, C	6.95 ± 0.36a, B	9.69 ± 0.57a, A
‘Tana’	0.68 ±0.10b, D	1.49 ± 0.13b, CD	2.47 ± 0.23b, C	3.28 ± 0.23b, B	4.30 ± 0.30b, A
<i>P^a</i>					
cultivar	<0.0001				
cultivar x container	<0.0001				
<i>P^b</i>					
trial (day)	<0.0001				
trial x container x cultivar	<0.0001				

^arepeated measures ANOVA between subjects

^brepeated measures ANOVA within subjects

1 **Figure captions**

2 **Fig. 1.** Berry anatomy and preparation for flesh firmness testing. All haskap berries have two
3 ovaries inside an outer layer of skin called the copula. Although most berries develop with the
4 exterior copula closed, we share a photo of an atypical “open” berry showing the two interior
5 ovaries for diagrammatic purposes (A). In B, the black line indicates where the berry was sliced
6 to remove a small portion of both skin layers for flesh firmness assessment.

7 **Fig. 2.** Cumulative water loss in 2020 for individual fruit of four haskap cultivars stored on
8 cellularized trays at commercial refrigeration conditions until fruit were deemed unmarketable
9 (due to severe shrivel) and discarded (experiment 2020B). Cultivars differed in weight loss rates
10 at $P < 0.05$.

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165x109mm (220 x 220 DPI)

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210x117mm (87 x 87 DPI)

Fig. 2. Cumulative water loss in 2020 for individual fruit of four haskap cultivars stored on cellularized trays at commercial refrigeration conditions until fruit were deemed unmarketable (due to severe shrivel) and discarded (experiment 2020B). Cultivars differed in weight loss rates at $P < 0.05$.

365x307mm (59 x 59 DPI)