

Maintaining Cranberry Fruit Quality during Storage and Marketing

Charles F. Forney*

Atlantic Food and Horticulture Research Centre, Agriculture and Agri-Food Canada, 32 Main St., Kentville, Nova Scotia, B0P 1T0 Canada

Correspondence: * Charles.Forney@agr.gc.ca

ABSTRACT

The American Cranberry (*Vaccinium macrocarpon* Ait.) produces a tart red fruit and is native to northeastern and north central North America. In recent years its popularity has increased due to claims of potential health benefits. While most fruit are processed into juice, sauce or other products, a growing market for fresh fruit exists. To expand fresh market opportunities, fruit must be stored for extended periods of time. During storage, substantial losses of fresh cranberries can result from decay and physiological breakdown. Incidence of both decay and physiological breakdown are influenced by cultural practices, harvest methods, and storage conditions. Plant cultivar, age and vigor, soil fertility, water availability, and the presence of both abiotic and biotic stresses can influence fruit quality and market life. Bruising that occurs during harvest and postharvest handling can induce physiological breakdown and substantially reduce market life. Proper management of relative humidity (RH) and temperature during storage are also critical to maximize storage life. High RH can increase rates of decay and physiological breakdown; optimum storage humidities are around 80%. Cranberry fruit have been reported to be chilling sensitive and fruit stored at 0°C often have greater quality loss than fruit stored at 2 to 7°C. However, greater losses at low temperatures could be a result of high RH rather than low temperature. A variety of postharvest technologies have been tested to extend cranberry storage life, including controlled atmospheres, heat treatments, irradiation, and fumigation, but none have been shown to provide consistent benefits.

Keywords: decay, physiological breakdown, relative humidity, temperature, *Vaccinium macrocarpon*

Abbreviations: ABA, abscisic acid; FW, fresh weight; IAA, indole-3-acetic acid; LPE, lysophosphatidylethanolamine; RH, relative humidity; UV, ultraviolet

CONTENTS

INTRODUCTION.....	67
FRUIT BIOLOGY	68
CAUSES OF QUALITY LOSS	68
Decay.....	68
Physiological breakdown.....	69
CULTURAL FACTORS AFFECTING MARKET LIFE	69
Cultivar.....	69
Fertility.....	69
Bog management.....	69
Fruit maturity.....	70
HARVEST METHOD.....	70
STORAGE CONDITIONS	71
Humidity.....	71
Temperature.....	72
Atmosphere modification	72
POSTHARVEST TREATMENTS	73
Heat	73
Irradiation	73
Fumigation.....	73
Coatings.....	74
CONCLUSIONS.....	74
ACKNOWLEDGEMENTS	74
REFERENCES.....	74

INTRODUCTION

The American or large-fruited cranberry (*Vaccinium macrocarpon* Ait.) has been growing in popularity in North America for the past century and has been a traditional part of many Thanksgiving and Christmas meals. The cranberry is

native to northeastern and north central North America where it grows in peat bogs and marshes (Roper and Vorsa 1997). Wild stands of the fruit were originally harvested and consumed by Native Americans and later European colonists. In the early 1800's cranberries were first cultivated in Massachusetts and New Jersey (Caruso *et al.* 2000). Over

the years production has increased and spread to other areas of North America and the world. In recent years, increasing evidence has demonstrated health benefits due to the consumption of cranberry and cranberry products. Much of this focus has been on the benefits of cranberry in preventing urinary tract infections (Cimolai and Cimolai 2007; Jepson and Craig 2007) with some evidence suggesting possible reductions in cardiovascular diseases (Ruel and Couillard 2007) and cancer (Neto 2007). This increasing interest in the health benefits of cranberries has further stimulated the demand for cranberry fruit and products.

While about 95% of cranberries are processed into juice, sauce, sweetened dried cranberries, and other processed products (Roper and Vorsa 1997), there is a potential growing market for fresh fruit. While cranberries are normally not consumed without some form of processing, the interest in fresh and natural foods is driving the increased consumption of fresh fruit. In addition, cranberry consumption has been growing beyond the traditional holiday meals creating new demand for fresh fruit in the late winter and spring months. In order to supply this growing demand, improved technologies are needed to maintain fruit quality and minimize storage losses.

Factors determining fresh fruit quality and storage life were recently reviewed (Forney 2003a). Since the publication of that review, additional research has been conducted to reassess optimum storage conditions and evaluate the effects of various technologies on the storage life of fresh cranberries. This paper reviews factors that determine fruit quality and storage life of fresh cranberries in light of this recent research.

FRUIT BIOLOGY

Cranberry fruit are true berries that are borne on short vertical uprights from the trailing stems of the cranberry plant. Fruit set occurs in late June and fruit reach maturity by mid-September through early November depending on cultivar, season, and location. While up to seven flowers may be pollinated on each upright, generally only 1 to 3 fruit will successfully develop to full maturity (Hawker and Stang 1985; Brown and McNeil 2006). Fruit growth, when determined as an average of a population of fruit, was linear (Forsyth and Hall 1967; Hawker and Stang 1985) and driven by days at optimum growing temperatures of 16 to 30°C (DeMoranville *et al.* 1996).

Fruit ripening is primarily determined by anthocyanin formation that gives the fruit a dark red color. Ripening appears to be initiated by a combination of environmental factors including accumulation of growing degree days, photoperiod, and light exposure (Hawker and Stang 1985). As fruit turn from white to red, there is an increase in anthocyanin content (Forney *et al.* 2009). During this transition, the relative proportion of proanthocyanidins, flavonols, and anthocyanins shifts from 80, 20, and <1%, respectively, in white fruit to 50, 15, and 30% in red fruit (Vvedenskaya and Vorsa 2004), with anthocyanin concentration reaching 45 mg kg⁻¹ in red fruit (Özgen *et al.* 2002). Soluble solids of 'Stevens' fruit were also higher in red fruit (9.2%) compared to white fruit (7.2%) (Özgen *et al.* 2002). Concentrations of glucose, fructose, and sucrose were 70, 12 and 2.3 mg g⁻¹ fresh weight (FW), respectively in red fruit compared to 45, 3.8, and 0.9 mg g⁻¹ FW in white fruit (Forney *et al.* 2009). Similarly, the concentration of the dominant organic acids quinic, malic, and shikimic were 0.82, 0.36, and 0.01 mg g⁻¹ FW, respectively, in red fruit compared to 0.50, 0.18, and 0.005 mg g⁻¹ FW in white fruit (Forney *et al.* 2009). Cuticle thickness was greater in dark red fruit (11.7 µm) compared to white fruit (8.2 µm) and red fruit had a greater resistance to puncture (Özgen *et al.* 2002). As cranberry fruit develop, fruit respiration rates measured as O₂ consumption (Forsyth and Hall 1967) or CO₂ production (Forsyth and Hall 1969; Abdallah and Palta 1989) declined substantially. When CO₂ production was measured in fruit with different degrees of color development, rates decreased from about 28 mg kg⁻¹

h⁻¹ in white fruit to 17 mg kg⁻¹ h⁻¹ in red fruit with rates of light red and pink fruit being intermediate (Özgen *et al.* 2002). No rise in respiration rate has been associated with the initiation of color formation in the fruit (Forsyth and Hall 1967; Abdallah and Palta 1989).

A rise in ethylene production precedes the onset of anthocyanin formation in cranberry fruit and appears to persist during color development (Forsyth and Hall 1967, 1969; Hawker and Stang 1985; Abdallah and Palta 1989). Application of (2-chloroethyl) phosphonic acid (ethephon), an ethylene-releasing compound, to cranberry fruit about 2 weeks prior to harvest can increase anthocyanin content and fruit color (Bramlage *et al.* 1972; Shawa 1979; Farag *et al.* 1992). Ethephon treatments were most effective in stimulating color development in immature berries, especially uncolored berries deep in the foliage that received little light (Rigby *et al.* 1972). While ethephon treatments stimulated color formation in cranberry fruit, it had no effect on fruit soluble solids, acidity or size (Shawa 1979). Application of the phospholipid lysophosphatidylethanolamine (LPE) to fruit 4 weeks prior to commercial harvest also was reported to increase fruit anthocyanin content 9 to 27% compared to untreated fruit and it was suggested this effect may be the result of stimulation of ethylene production (Özgen *et al.* 2005). In addition, the preharvest application of the insecticide malathion (Eck 1968; Devlin *et al.* 1969) and the preemergence herbicide dichlorobenzonitrile (dichlobenil) (Devlin and Demoranville 1968) can stimulate color development. If fruit are harvested prior to obtaining optimum color, exposure of fruit to ethylene causes a slight stimulation of color formation (Craker 1971). However, exposure of fruit to light is more effective to stimulate post-harvest color formation (Craker 1971; Zhou and Singh 2004; Forney *et al.* 2009). Neither preharvest treatments with indole-3-acetic acid (IAA) (Devlin *et al.* 1969) nor treatment of white harvested fruit with abscisic acid (ABA) (Forney *et al.* 2009) stimulated color formation in cranberry fruit.

CAUSES OF QUALITY LOSS

Fruit quality loss during the postharvest storage and marketing of cranberry fruit is primarily the result of decay, physiological breakdown, and mechanical damage. Fruit for the fresh market are typically stored after harvest, and then graded to remove any defective fruit prior to packaging for the market (Hancock 1995). During storage, fruit losses can vary dramatically (Olatinwo *et al.* 2004) depending on a wide variety of known and unknown factors that affect rates of decay and/or physiological breakdown.

Decay

The decay of cranberry fruit in the field as well as during storage is caused by a complex of fungal organisms. Multiple fungi are often associated with the development of storage rot in cranberry (Olatinwo *et al.* 2004). The dynamic disease complex found in cranberry fruit can be composed of multiple fungal species, which vary in composition and abundance depending on location and season (Oudemans *et al.* 1998; Stiles and Oudemans 1999). As a result of this disease complex, the visual symptoms of fruit decay often cannot be associated with specific pathogens (Olatinwo *et al.* 2003). Fungal organisms contributing to storage rot can vary substantially in different growing location and regions (Gourley 1969; Oudemans *et al.* 1998; Stiles and Oudemans 1999; Olatinwo *et al.* 2004). Fungal pathogens commonly contributing to postharvest cranberry fruit decay and resulting diseases include *Allantophomopsis lycopodina* (Hohn.) Carris (black rot), *Allantophomopsis cytisporea* (Fr.:Fr.) Petr. (black rot), *Strasseria geniculata* (Berk. & Br.) Höhnel (black rot), *Coleophoma empetri* (Rostr.) Petr. (ripe rot), *Fusicoccum putrefaciens* Shear. (end rot), *Phyllosticta elongata* G.J. Weidemann (berry speckle), *Physalospora vaccinii* (Shear) Arx & E. Müller (blotch rot), and *Botrytis* spp.

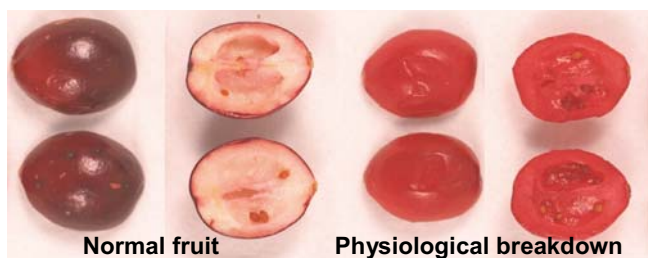


Fig. 1 External and internal appearance of a cranberry fruit affected by physiological breakdown. The picture includes a normal unaffected fruit for comparison.

(yellow rot) (Boone 1995a, 1995b; Carris 1995; Caruso 1995; Pepin and Boone 1995; Oudemans *et al.* 1998). In Michigan, *Colletotrichum acutatum* Simmonds, which is a major cause of blueberry fruit rot, also contributed to cranberry fruit decay (Olatinwo *et al.* 2004). Many additional fungi have been isolated from cranberry fruit that do not appear to contribute to decay (Oudemans *et al.* 1998). As well, no bacterial diseases have been reported to occur in cranberry fruit (Oudemans *et al.* 1998).

Infection of the fruit by these diverse fungi is believed to occur during bloom, early fruit set, or during harvest (Oudemans *et al.* 1998). When cranberry bogs are flooded during a wet harvest, large numbers of spores can be found in the water, which can infect fruit wound sites that occur during harvest (Stretch and Ceponis 1983; Shwartz 1985). Decay normally is characterized by discoloration and softening of the fruit. Rotted cranberries generally have external lesions and part or all of the internal flesh becomes discolored. Unlike many postharvest decays in other crops, there is little spread of disease from infected to healthy fruit in storage (Oudemans *et al.* 1998).

Physiological breakdown

Physiological breakdown, also referred to as sterile breakdown, is characterized by a dull appearance, rubbery texture, and red discoloration of the fruit flesh that renders the fruit unmarketable (Fig. 1) (Terry *et al.* 2009). The cause of physiological breakdown is not well understood, but it is not caused by a fungal organism as seen in storage rots. Its development during storage has been associated with numerous factors including over-mature fruit (Doughty *et al.* 1967), bruising (Patterson *et al.* 1967), chilling injury (Hruschka 1970), freezing (Bristow and Patten 1995), extended water immersion (Ceponis and Stretch 1983), and anoxia (Stark *et al.* 1974). The occurrence of physiological breakdown increases with storage duration (Forney 2008), but is highly variable depending on cultural and environmental factors.

CULTURAL FACTORS AFFECTING MARKET LIFE

Cultivar

While fruit size, color, and other characteristics are dependent on cultivar (Eck 1990; Trehane 2004), cultivar effects on fruit storage life are less defined. Cultivars, compared within one season and location, have shown significant differences in rates of postharvest deterioration. When different cultivars were grown in Wisconsin and stored at 4°C, 'Stevens' and 'McFarlin' had the greatest storage life compared with 'Howes', 'Searles', 'Black Veil', and 'Metallic Belle' (Swanson and Weckel 1975). Similarly, when New Jersey-grown cranberries were stored for 12 weeks at 3°C plus 4-d at 21°C, 'Franklin' and 'Pilgram' were superior to 'Early Black', while 'Ben Lear', 'Wilcox', and 'Stevens' were intermediate (Stretch and Ceponis 1986). More recently Wang and Wang (2009) evaluated 9 cultivars stored for 3 to 4 months at temperatures ranging from 0 to 15°C and found 'Crowly', 'Howes', and 'Pilgram' had the least

amount of decay and physiological breakdown, while 'Ben Lear', 'Cropper', 'Early Black', and 'Stevens' had the most following storage at 0°C. However, when differences in rates of storage rot among 8 cultivars produced at 8 locations over 2 seasons were evaluated in Michigan following storage at 5°C for 2 months, considerable variability in storage life was observed and differences among cultivars were not significant (Olatinwo *et al.* 2004). In a more extensive study in Wisconsin, Boone (1994) evaluated 69 cultivars grown at one location over 10 seasons for development of storage rot following 4 months of refrigerated storage. He found cultivars with the poorest storage life to include 'Prolific', 'Stankovich' and 'Pilgrim', while those with the best storage life included 'Howes', 'Early Black', and 'Rezin McFarlin'.

The variability in storage rot among cultivars could reflect possible variability in resistance of cultivars to specific pathogens. When fruit were assayed for fungal infections in Michigan, some cultivars yielded significantly more *Colletotrichum acutatum* or *Phomopsis vaccinii* than others (Olatinwo *et al.* 2004). Differences among cultivars in the incidence of fruit-rotting fungi were also found in Massachusetts (Oudemans *et al.* 1998). However, Stiles and Oudemans (1999) reported that rot resistance among 11 different cranberry cultivars grown in New Jersey was nonspecific since they had similar fungal profiles. To further complicate matters, cultivars were reported to vary in susceptibility to infection by specific fungi from one growing region to another (Olatinwo *et al.* 2004), suggesting interactions between genetic and environmental factors.

Fruit characteristics of different cultivars may influence potential storage life. Fruit size has been suggested to affect storage life since larger fruit could be more prone to mechanical damage during harvest and postharvest handling. When fruit size was correlated with storage rot using data from the 69 cultivars evaluated by Boone (1994), a correlation coefficient of 0.41 was calculated suggested that fruit size may influence storage life. Cultivars having fruit with high total acid content have better keeping quality than those with low acid content, but benzoic acid concentration had no effect on storage life (Clague and Fellers 1934). Fruit cuticle thickness has also been reported not to correlate with storage life (Stevens 1932b).

Fertility

Cranberry bog fertility can affect fruit quality and storage life. Increasing nitrogen fertility can stimulate plant growth, but may reduce fruit storage life. Enhanced vegetative growth can limit air movement, solar penetration, and pesticide penetration in the plant canopy. This may result in reduced fruit color development and increased fruit decay. In a limited study, Swanson and Weckel (1975) found that applications of 18.7 to 37.5 kg·ha⁻¹ of nitrogen (N) did not affect the quality of cranberry fruit following storage at 4 or 20°C. However, in a more extensive multiple year study across North America, fruit from cranberry bogs fertilized with 0, 22.0, or 44.0 kg·ha⁻¹ of N developed more storage rots with increasing N application following storage at 4°C (Davenport 1996). Application of calcium in foliar sprays during the growing season had no effect on incidence of storage rots, fruit Ca content, or resistance of the epidermis to puncture (Blodgett *et al.* 2002).

Bog management

Cultural management of cranberry bogs can affect fruit quality and decay in storage. Cultural practices, including pruning, that reduce vine overgrowth and increase air circulation and solar penetration in the cranberry canopy can reduce fruit rot (Oudemans *et al.* 1998). Removal of plant debris from the bog and good sanitation practices are also advised to minimize fungal inoculum (Oudemans *et al.* 1998). Management of flooding may also be a tool to reduce fruit decay and promote fruit ripening. Draining bogs

in early March for a month and then reflooding for a month, which is referred to as “late water”, is effective in reducing some disease and insect problems and improving fruit storage life in Massachusetts (Zuckerman 1958). However, this practice has not been beneficial in other growing areas. The practice of sanding, which entails the even distribution of 1.3 to 2.5 cm of sand over the bog during the winter every 2 to 5 years, improves vine vigor by burying runners and stimulating new root growth. Sanding can also reduce fruit decay by burying inoculum sources and thus reducing the amount of pathogen inoculum present (Oudemans *et al.* 1998).

Application of fungicides during bloom and early fruit set may reduce latent infections and fruit decay during storage, but its effectiveness is dependent on the fungicide used and timing of application (Jeffers 1991; Oudemans *et al.* 1998). Due to the diverse nature of the fungal pathogens affecting cranberry fruit, broad spectrum fungicides are most effective. Many of the newer fungicides that are more specific in their action are not effective in controlling fruit rot (Caruso 1990; Jeffers 1991). In a study assessing fruit from cranberry bogs throughout Michigan, the incidence of storage rot was not related to fungicide use (Olatinwo *et al.* 2004). Oudemans *et al.* (1998) suggest that many of the fungal organisms responsible for decay of cranberries take several years to complete an infection cycle and therefore the build up of inoculum and infection in the field may take years to develop. When fungicide applications were stopped, fruit rot increased progressively reaching about 50% after 3 years compared with an incidence of 2 to 10% in plots receiving fungicides (Oudemans *et al.* 1998).

Environmental factors during the growing season also affect cranberry fruit storage potential. Stevens (1932a) first suggested that factors such as temperature and rainfall impact fruit keeping quality, possibly by affecting rates of fungal infection and fruit physiology. Using weather data and storage records, he developed a model to predict fruit keeping quality. This predictive model was further refined by Franklin and Cross (1948), who also considered hours of sunlight. This model is still used in Massachusetts to predict the keeping quality of the current year's cranberry crop.

Fruit maturity

Cranberry fruit maturity at the time of harvest can affect storage life. The thickening of the cuticle and slowing of respiration as the fruit ripens has been associated with longer storage life (Özgen *et al.* 2002). Özgen *et al.* (2002) observed that dark-red ‘Stevens’ fruit maintained more marketable fruit than light-red, bluish, or white fruit following storage. Ceponis and Stretch (1981, 1983) also found that within a harvest highly colored ‘Early Black’ fruit had less physiological breakdown than less colored fruit during storage, but when harvest was delayed, greater amounts of physiological breakdown occurred. They suggested that there may be a subtle distinction between color and maturity and that higher concentrations of fruit soluble solids may be associated with reduced physiological breakdown. Swanson and Weckel (1975) also found that green and white immature ‘McFarlin’ fruit break down more rapidly than mature fruit during storage at 4°C. In another study, ‘McFarlin’ fruit grown in Washington had less physiological breakdown and pathological rot when harvested 2 weeks prior to commercial maturity (11 weeks past full bloom) than when harvested at commercial maturity (13 weeks past full bloom) (Doughty *et al.* 1967). However, the method of harvest used for each fruit maturity was not reported. As discussed below, differences in physical abuse that could have occurred during the harvest process could have negated maturity effects in this study.

HARVEST METHOD

Methods for harvesting cranberry fruit have evolved over the years with continued efforts to improve efficiency and

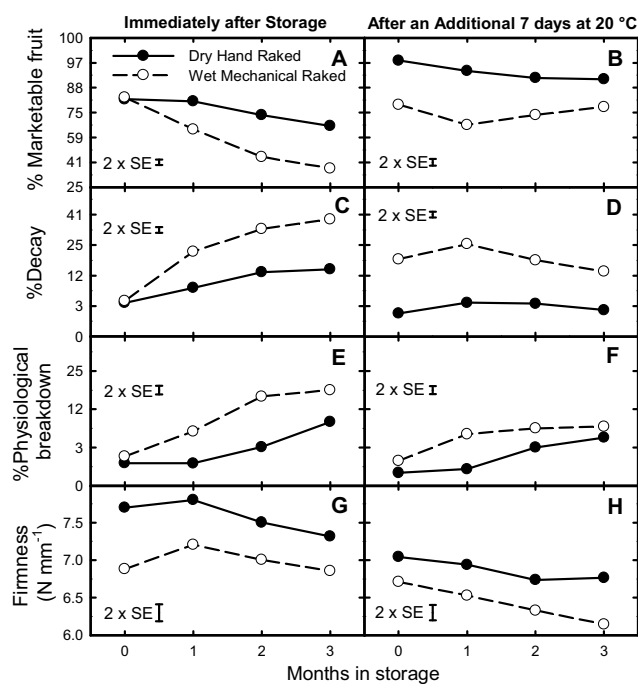


Fig. 2 Effect of harvest method on cranberry fruit quality following storage. Percentage of marketable fruit (A, B), decay (C, D), physiological breakdown (E, F) and firmness (G, H) of ‘Stevens’ and ‘Bergman’ cranberry fruit measured immediately following storage at 3 or 7°C or after marketable fruit were held an additional 7 days at 20°C. Points represent fruit samples from 6 bogs harvested dry with a hand rake or wet with a mechanical rake. Modified from Forney (2005).

reduce injury to the fruit (Eck 1990). Harvest methods have progressed from hand picking and scooping to dry and wet mechanical harvesting. Mechanical harvesting, which dominates the industry today, includes dry harvesting with machines using raking or scooping mechanisms. Since cranberry fruit float, they also can be harvested wet by flooding the bog and removing fruit from the plant with a water rake or a water reel harvesting machine. Wet harvesting can improve harvest efficiency, but water must be cool, immersion time limited and fruit dried after harvest to limit storage rot and physiological breakdown (Eck 1990). The harvesting process can cause significant damage to the fruit, which may result in increased rates of decay and physiological breakdown during storage and marketing. When 6 bogs containing ‘Stevens’ or ‘Bergman’ cranberry fruit were harvested by hand raking or mechanically by wet raking, mechanically harvested fruit had a reduced storage life (Forney 2005). After 1 month of storage, mechanically harvested fruit had 21% less marketable fruit than hand raked fruit, and this difference increased to 44% after 3 months (Fig. 2A). Mechanical harvesting increased both decay and physiological breakdown while reducing fruit firmness during storage (Fig. 2C, 2E, 2G). When marketable fruit were held an additional week at 20°C, mechanically harvested fruit continued to have greater amounts of decay and physiological breakdown (Fig. 2D, 2F). Similarly, when cranberry fruit were harvested dry with a Furford Dry Harvester, 55% of the fruit were injured or developed breakdown compared to only 3% for hand raked fruit (Davis and Shawa 1983). Modifications of the Furford harvester to reduce damage improved fruit storage life. ‘McFarlin’ cranberries harvested with a water reel harvester also had several fold greater rates of spoilage during storage than fruit harvested by wet or dry raking (Swanson and Weckel 1975). Similarly, fruit losses during storage of 6 cultivars harvested with a water reel harvester were 2- to 4.6-fold greater than with hand picked fruit (Stretch and Ceponis 1986). The incidence of black rot during storage was greater in wet than dry harvested fruit (Stretch and Ceponis 1983, 1986). Prolonging water immersion during

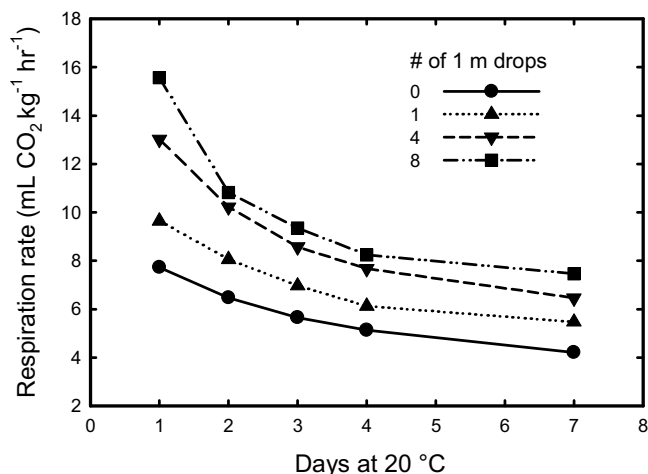


Fig. 3 Dropping effects on respiration of cranberry fruit. ‘Stevens’ cranberry fruit were dropped 1 meter 0, 1, 2, 4, or 8 times. Following the drop treatment, fruit were sealed in 1 L glass jars, held at 20°C, and CO₂ evolution was monitored continuously for 90 minutes using a GM70 Carbon Dioxide Meter with a GMP221 probe (Vaisala, Helsinki, Finland). Modified from Forney (2005).

wet harvest increased both decay and physiological breakdown during storage (Ceponis and Stretch 1981, 1983).

Bruising and other physical damage that occurs during harvest and postharvest handling may not be immediately apparent visually, but is expressed by increased fruit respiration, and subsequent softening, physiological breakdown, and decay of cranberry fruit (Forney 2005). Increasing numbers of 1-m drops to simulate commercial damage, increased respiration rates of cranberry fruit after 1 day. Respiration rate of fruit dropped 8 times doubled while that of fruit dropped only once increased 25% when compared to respiration rates of fruit that was not dropped (Fig. 3). Respiration rates remained elevated even after 7 days. Following 3 months of storage at 3°C, fruit dropped 1 m had 13% fewer marketable fruit, which declined a further 5% after an additional 7 days at 20°C when compared to fruit that was not dropped (Forney 2005). When ‘McFarlin’ cranberries were bruised by dropping a 100 g weight onto individual berries from a height of 23 cm, 90% of the bruised fruit softened during 60 d of storage while < 15% of unbruised berries softened (Graham *et al.* 1967). Bruise-induced softening was primarily a result of physiological breakdown, but fungi were associated with 9 and 39% of the fruit stored at 2 or 20°C, respectively. Fruit damage that occurs during harvesting, screening, grading and packaging of fruit may not be immediately apparent and can take hours to develop depending on the severity of the bruising (Massey *et al.* 1981). Fruit subjected to commercial screening, grading, and packaging had 39% of the fruit unmarketable due to heavy bruising or breakdown after 12 weeks of storage at 2.2°C compared to 27% unmarketable fruit in unhandled stored fruit (Massey *et al.* 1981). In observations made over 5 seasons, Norton (1982) reported that bruised fruit stored for several months had about 5 times more rot than unbruised fruit. Fruit softening that occurred with bruise-induced physiological breakdown was associated with induced polygalacturonase activity in the bruised fruit (Patterson *et al.* 1967). Impact bruising is cumulative and repeated small impacts are detrimental to storage life (Massey *et al.* 1981). Therefore, minimizing handling of fruit can result in improved performance during storage.

STORAGE CONDITIONS

Humidity

During extended periods of storage, the RH of the storage environment can have a greater effect on fruit storage life than temperature, with the greatest losses of marketable

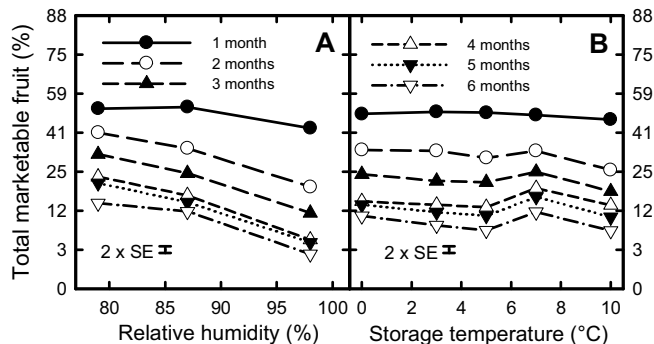


Fig. 4 Effects of temperature (A) and relative humidity (B) on total marketable cranberry fruit. Fruit were stored for up to 6 months plus an additional week at 20°C. Points are means of fruit from 12 bogs harvested over 3 seasons and stored at 5 temperatures (A) or 3 levels of humidity (B). Note the y axis scale represents the angular transformation. Data presented in this figure was taken from the paper by Forney (2008a).

fruit occurring in high RH. In a 3-year study, Forney (2008) reported that after 2 months or longer storage, fruit losses were lower in low RH (75%) than in medium (82 to 88%) or high (~98%) RH, regardless of the storage temperature that ranged from 0 to 10°C (Fig. 4A). After 5 months, fruit stored in low RH had 45 and 244% more marketable fruit than those stored in medium or high RH, respectively. Even after marketable fruit were removed from storage and held an additional week at 20°C, fruit previously held in high RH continued to have the highest loss of marketability. These losses were the result of increases in both decay and physiological breakdown. In storage studies with ‘Early Black’ and ‘Howes’ cranberry fruit, Wright *et al.* (1937) concluded that a storage humidity of 70 to 75% RH favored better fruit storage life than 90 to 95% RH. Cranberry fruit stored under a 100% nitrogen atmosphere were also reported to have lower rates of decay when the humidity was maintained at 65 to 70% RH compared to 95 to 100% RH (Stark *et al.* 1974). Similarly, fruit stored in polyethylene bags that maintained a high RH had more decay and physiological breakdown than fruit stored in boxes, well-ventilated bags, or unlined cartons (Anderson *et al.* 1963; Hruschka 1970).

Adequate ventilation to maintain lower RH is beneficial to extend cranberry fruit storage life. Norton (1982) reported that fruit stored in unventilated bins for several months had over 40% rot compared to <20% in ventilated bins. Following a series of additional commercial-scale experiments, he found that storage rot was reduced when adequate ventilation was supplied through storage containers and RH was held near 70%. He concluded that proper air circulation removes moisture and other products of respiration that may be detrimental to fruit storage life.

Storing fruit in low RH with high ventilation increases fruit fresh weight loss. Norton (1982) reported weight loss of 1% every 12 days when fruit were stored in 70% RH with forced air ventilation, but he concluded that the resulting dehydration was an acceptable sacrifice to maintain satisfactory fruit quality. In another report, fruit held in 75% RH had twice the rate of fresh weight loss than fruit held in 98% RH (Forney 2008). While fruit firmness decreased during storage, the RH of the storage environment did not affect firmness. After 6 months of storage, firmness of marketable fruit was not significantly different among different storage humidities (Forney 2008). Interestingly, the cranberry fruit is able to maintain fruit firmness even with the potential loss of turgor in the low humidity storage.

Contrary to these results showing that cranberry fruit store longer under conditions of low RH and good ventilation, many published recommendations for cranberry storage call for storage RH levels to be >90% (Hardenburg *et al.* 1986; Spayd *et al.* 1990; Kader 1997). It appears that these recommendations are based on the typical benefits of

high RH, which can reduce weight loss, minimize water stress, and slow senescence in many fresh fruits and vegetables. Consideration of the atypical response of fresh cranberry fruit to high RH reported in the literature may not have been fully considered.

Temperature

There are various recommendations for the optimum storage temperature for cranberry fruit, which may be due to the confounding factors previously discussed influencing the apparent response to temperature. Cranberry fruit have been considered to be chilling sensitive based on reports of their response to storage temperature (Wright *et al.* 1937; Levine *et al.* 1941; Anderson *et al.* 1963; Hruschka 1970). As a result, various handbooks recommend temperatures for storage of fresh cranberries between 2 to 7°C (Hardenburg *et al.* 1986; Lidster *et al.* 1988; Spayd *et al.* 1990; Kasmire and Thompson 1992; Kader 1997). However, a recent re-evaluation of the effects of storage temperature, in which RH was controlled, brings into question the classification of cranberry as a chilling sensitive fruit (Forney 2008). In this 3-year study that looked primarily at 'Stevens' but also included 'Pilgram' and 'Bergman', the loss of marketable fruit during 6 months of storage was greatest at 10°C and least at 0, 3, or 5°C, which were not significantly different. Greater losses in marketable fruit stored at 7 and 10°C were the result of increases in physiological breakdown, but temperature had no significant effect on decay among fruit stored at 0 to 10°C throughout the 6 month storage period. When fruit were held an additional week at 20°C, there was no significant difference in total marketable fruit among fruit stored at 0 to 10°C within each monthly evaluation (Fig. 4B).

The classification of cranberries as chilling sensitive originates from several studies, including Wright *et al.* (1937) where large amounts of "sterile breakdown" (physiological breakdown) occurred when 'Early Black' and 'Howes' fruit were held at -1.1°C and to a lesser extent at 0°C. Since the freezing point of cranberries ranges from -1.4 to -0.9°C (Whiteman 1957), the physiological breakdown that occurred at -1.1°C was most likely freezing rather than chilling injury. In fact, they describe the fruit as having "the taste and appearance of frozen berries". The cause of physiological breakdown that occurred at 0°C may also have been induced by high RH or freezing if temperature fluctuations in the refrigeration system occurred. The next coldest temperature tested was 2.2°C, at which the greatest percentage of marketable cranberries were found. Levine *et al.* (1941) also reported low temperature breakdown when 'Early Black' and 'Howes' fruit were stored at -1.1°C, which again was likely a result of freezing injury. They concluded that the best storage temperature was 1.7°C although rates of spoilage did not differ greatly in fruit stored at 1.7 to 7.2°C following 7 to 18 weeks of storage. Anderson *et al.* (1963) reported little difference in the spoilage of 'Howes' cranberries stored at 0 or 3.3°C in storage trials conducted during the 1959 season but the following season decay and breakdown was less in fruit stored at 3.3 than 0°C, which suggested chilling injury. In addition to these observations, Hruschka (1970) reported an increase in physiological breakdown of 'Early Black' cranberries stored at 0.6°C after 12 to 20 weeks compared to fruit stored at 3.3°C after an additional week at 21.1°C. However, effects of humidity were not considered.

The apparent chilling sensitivity of cranberries in these past studies could be a response to RH rather than temperature. With the exception of the study by Wright *et al.* (1937), RH was not controlled in these studies. Since the water holding capacity of air decreases as temperature decreases, lower storage temperatures would tend to give rise to high RH. In addition, rates of air circulation, which affects the actual humidity surrounding the stored fruit, are not reported, but were likely low. Therefore, greater rates of physiological breakdown and/or decay that were attributed to

chilling injury could have been a response to high RH at the reported chilling temperature.

In addition to humidity, other factors could affect the response of cranberries to storage temperature. Cultivar differences could contribute to apparent differences in chilling sensitivity. Wang and Wang (2009) compared the effects of storage at 0, 5, 10, and 15°C on the decay and physiological breakdown of 9 cranberry cultivars. After 3 or 4 months of storage at 0°C they reported high amounts of physiological breakdown and decay in 'Ben Lear', 'Cropper', 'Early Black'; and 'Stevens', moderate amounts in 'Franklin' and 'Wilcox' and little in 'Crowley', 'Howes', and 'Pilgram'. However, the confounding effects of humidity were not considered. Many preharvest environmental factors discussed earlier, including bog location, management practices, and weather conditions, can affect fruit storage life, but also may affect the response of the fruit to storage temperature. Fungal disease organisms responsible for storage decay can vary substantially among bogs (Olatinwo *et al.* 2004) and their impact on fruit decay may be determined by the fruit's postharvest environment. In addition, the effects of fruit maturity, method of harvest, and postharvest handling on fruit storage life may each be modified by the storage environment. The potential complex interaction of factors that affect fruit decay and physiological breakdown with conditions of the storage environment could explain some of the reported variable responses to storage temperature and merit further investigation.

Many cranberries are stored in unrefrigerated buildings where fruit temperatures vary during storage depending on ambient conditions. However, using refrigeration to maintain a constant storage temperature can reduce storage losses. When 'Howes' cranberries were stored at a constant 4.4°C, 96% of the fruit were good after 6 weeks, 95% after 12 weeks, and 88% after 19 weeks (Ringel *et al.* 1959). This was superior to a simulated common storage, which was held at 15.6°C for 4 weeks, followed by 10.0°C for 5 weeks and 4.4°C for 10 weeks in which 93, 89, and 76% of the fruit were good after 6, 12, and 19 weeks of storage, respectively.

Precooling is the rapid removal of heat from freshly harvested produce to reduce respiration, retain fruit quality, and slow decay development. This process is commonly conducted on perishable fresh fruits and vegetables to maximize market life (Hardenburg *et al.* 1986). However, since cranberries are harvested late in the year when field temperatures are normally low, precooling is normally not done. Precooling of cranberries can be performed using cold air (forced-air) or water (hydrocooling). If significant field heat is present at the time of harvest, fruit may benefit from its rapid removal (Kaufman *et al.* 1958). If good air circulation is maintained through and around the fruit, room cooling can cool fruit to room temperature in 24 to 48 h.

In addition to the effect temperature can have on slowing decay and physiological breakdown, temperature also affects fruit color development during storage. At 2.2°C and above color tends to darken. At 10°C and above berries may become a solid red color, which may be darker than some markets desire (Wright *et al.* 1937). Color can be improved in early harvested fruit by storing at 7.2 to 10°C for several weeks (Levine *et al.* 1941).

Atmosphere modification

Controlled atmosphere (CA) storage of cranberry fruit does not provide extension of fruit storage life. In CA storage trials conducted with 'Stevens' fruit, no reduction of decay or physiological breakdown was observed in fruit stored in 0, 5, 10 or 15 kPa CO₂ in combination with 1 or 15 kPa O₂ at 5°C (Forney 2009). Similarly, 'Howes' cranberries stored in combinations of 0, 5, or 10 kPa CO₂ with 3, 10 or 21 kPa O₂ at 0 or 3.3°C had fruit losses greater than the air control (Anderson *et al.* 1963). If humidity was lowered in the CA chambers, some atmospheres gave results similar to the air controls, but no benefits were found. Stark *et al.* (1969a,

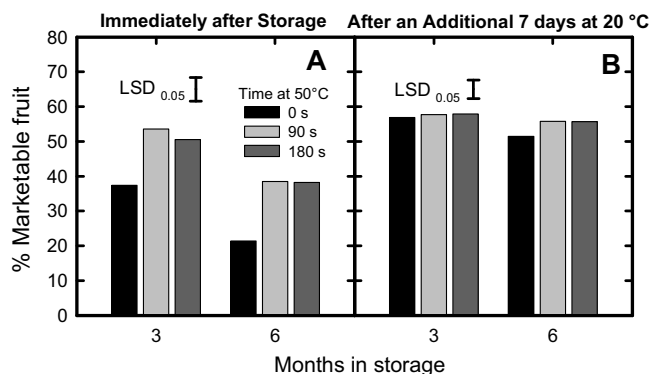


Fig. 5 Hot water treatments of ‘Stevens’ cranberry fruit. Percentage of marketable fruit following a 50°C water dip for 0, 90, or 180 seconds and storage for 3 or 6 months at 3 or 7°C. Fruit were evaluated immediately after removal from storage or after marketable fruit were held an additional 7 days at 20°C. Bars represent the mean of 8 fruit samples representing 4 commercial bogs stored at 3 or 7°C. Modified from Forney *et al.* (2003).

1969b) found that cranberries stored at 22°C for 3 weeks in atmospheres of 5 or 10 kPa CO₂ with 3 kPa O₂ had the same levels of decay as air stored fruit. Fruit held in 100 kPa N₂ became dull and water soaked in appearance and had a fermented odor (Stark 1969a, 1969b; Lockhart *et al.* 1971).

Recent attempts to use more extreme CO₂ and O₂ concentrations in the atmosphere have also had limited success. Concentrations of 70 kPa O₂ had no beneficial effect in reducing decay or physiological breakdown and induced production of acetaldehyde, ethanol, and ethyl acetate in cranberry fruit stored at 3°C (Gunes *et al.* 2002). However, Gunes *et al.* (2002) found atmospheres of 30 kPa CO₂ and 21 kPa O₂ reduced decay and breakdown of ‘Pilgrim’ and ‘Stevens’ fruit when stored for 2 months at 3°C, but after 4 months these benefits were no longer apparent due to extensive breakdown (>97%) in all atmospheres tested. In addition, the beneficial effect of the 30 kPa CO₂ atmospheres was diminished with late-harvested fruit. The high RH (>95%) may have contributed to the extensive breakdown observed in this study. The benefits of 30 kPa CO₂ should be further evaluated in atmospheres with reduced RH.

POSTHARVEST TREATMENTS

Heat

Short treatments using hot water or hot air can reduce decay and spoilage of fresh commodities during storage by killing pathogens or altering the physiology of the product. Hot water treatments of ‘Stevens’ cranberries that were conducted over 2 seasons reduced the loss of marketable fruit following 2 to 6 months of storage at 3 or 7°C and 86% RH (Forney *et al.* 2003, 2004). In the first season, treatments consisting of 50°C for 90 or 180 seconds increased marketable fruit about 40 and 80% following 3 and 6 months of storage, respectively (Fig. 5A). Decay was reduced by about 20% by the heat treatments, while physiological breakdown was reduced by 13 to 36% after 3 months and 6 to 13% after 6 months. In the second season, where overall fruit loss during storage was higher, a 50°C treatment for 90 or 180 seconds increased marketable fruit 58 and 32% respectively, only after 6 months of storage. Heat treatments had no significant effect on marketability after 2 or 4 months of storage. When marketable fruit were held an additional 7 days at 20°C following storage, quality retention of heat treated fruit was not significantly different from controls in the 2003 season (Fig. 5B) as well as the 2004 season (Forney *et al.* 2004). A steam treatment of 50°C for 90 seconds also was effective in reducing decay of ‘Stevens’ cranberry fruit 34% and physiological breakdown 21% following sto-

rage for 4 months at 7°C (Forney *et al.* 2004). Anderson and Smith (1971) reported that hot water treatments of 49°C for 150 or 300 seconds and 52°C for 150 seconds had some benefits in prolonging cranberry storage life. However, treatments were less effective on late harvested fruit, where heat treatments increased physiological breakdown.

Irradiation

Ultraviolet (UV) radiation kills microorganisms and can induce resistance to decay in some fresh fruits and vegetables. ‘Howes’ cranberry fruit irradiated with 0.50 -1.25 KJ m⁻² of UV-C radiation and then stored in the dark at 9 °C and 95% RH for 16 weeks had up to 30% less spoilage than untreated fruit (Desjardins *et al.* 2000). The UV treatments caused a linear decrease in anthocyanin concentration as UV dose increased up to 5.25 KJ m⁻², but had little effect on soluble solids and titratable acids. However in a similar study, when ‘Stevens’ cranberry fruit were exposed to 0.5 to 2.0 KJ m⁻² of UV-C light prior to storage, no significant effects on fruit decay, physiological breakdown, marketability, firmness, or weight loss were observed following storage at 7°C for 3 or 6 months (Kalt *et al.* 2006). In addition, no effects of UV-C treatments were observed on phenolic or anthocyanin content or antioxidant capacity of the fruit.

Irradiation of cranberry fruit with 150 or 300 krad using a cobalt-60 source stimulated anthocyanin and flavonol production in red fruit during 1 to 2 months of storage (Lees and Francis 1972). Red pigment formation of the white flesh was observed during storage. Pigment formation in half-red fruit was less than that of red fruit as a result of irradiation, while pigment formation in pink fruit was inhibited. Irradiation caused some softening of the fruit, but it was not considered to be detrimental. No storage life enhancement by gamma radiation treatments was reported.

Exposure of cranberry fruit to high voltage electric fields of 2 to 8 kV cm⁻¹ for 30 to 120 minutes reduced the rise of respiration observed during storage at 23°C and 65% RH for 3 weeks (Palanimuthu *et al.* 2009). Treatments did not significantly affect weight loss, total soluble solids, L*, a* or b* color values, or fruit firmness during the 3 weeks of storage. The authors suggest the lower rates of respiration could extend fruit storage life but this is yet to be tested.

Fumigation

Fumigation treatments have not been effective in prolonging cranberry storage life. Ozone has strong antimicrobial properties and has been reported to reduce decay of some fruits and vegetables (Forney 2003b), however fumigation with gaseous ozone was not effective in maintaining cranberry fruit quality. Decay was not reduced in ‘Early Black’ fruit stored for 2 months at 4.4°C in a 0.27 μL L⁻¹ ozone atmosphere (Norton *et al.* 1968), while concentrations of 0.60 μL L⁻¹ ozone causes physiological damage in ‘Howes’ fruit after 5 weeks at 15.6°C, resulting in 2-fold more rot than in the controls. Cranberry fruit held in 0.60 μL L⁻¹ ozone had 25% less surface lipids compared to control fruit resulting in 3 times more weight loss than air-stored fruit. Ozone also induced a faint but pleasant flower-like aroma (Norton *et al.* 1968).

Fumigation with the natural volatile hexanal is reported to reduce decay in some whole and fresh cut fruit and has antifungal properties (Song *et al.* 2007). However, in studies conducted over 2 seasons where cranberry fruit were treated with 900 or 2000 μL L⁻¹ hexanal vapors prior to storage in air, treatments had no benefit in extending storage life (Forney *et al.* 2003, 2004). After 2, 4, or 6 months of storage at 3 or 7°C, the hexanal treatments had no significant effect on decay, physiological breakdown, marketability, weight loss, or fruit firmness.

Coatings

Cranberry fruit are normally not subjected to wax or other coatings prior to storage or marketing. However, one study suggests that coatings could extend fruit storage life. When cranberry fruit were coated with formulations of carnauba wax with or without the biological fungicide Biosave® (EcoScience Produce Systems Division, Orlando, Fla.) prior to storage for 16 weeks at 13°C, fruit decay was reduced (Chen *et al.* 1999). After 16 weeks, carnauba wax alone reduced decay by 25%, while in combination with Biosave 110®, decay was reduced by about 33%.

CONCLUSIONS

The storage life of fresh cranberry fruit is influenced by many pre- and post-harvest factors. The quality of fruit obtained from cranberry cultivars is influenced by a variety of abiotic and biotic factors such as temperature, water, light, soil fertility, cultural practices and the presence of fungal pathogens. These factors affect the physiology and pathology of the fruit that ultimately determines its response to the postharvest environment and the expression of physiological breakdown and decay. The effects of physical handling of the fruit during harvest and postharvest handling are often not considered when conducting storage experiments or commercial storage of fruit. Bruising caused by handling can stimulate respiration and increase the susceptibility of the fruit to physiological breakdown or decay during storage. The RH of the storage environment has a strong effect on fruit with high RH accelerating the rate of decay and physiological breakdown, while low RH (70 to 80%) preserving fruit quality. The mechanisms by which RH affects fruit storage life need to be determined. Storage temperatures in the range of 0 to 10°C do not have strong and consistent effects on fruit quality and temperature effects may be confounded by RH, which brings into question the classification of cranberry as a chilling sensitive fruit. None of the postharvest technologies that have been tested including controlled atmospheres, heat treatments, irradiation, fumigation, or coatings have proven to be practical to apply or consistent in their benefit. Understanding the physiology and pathology of the cranberry fruit and how these aspects interact with the pre- and postharvest environment, provide many challenges for optimizing fruit market life.

ACKNOWLEDGEMENTS

Contribution no. 2371 of the Atlantic Food and Horticulture Research Centre, Agriculture and Agri-Food Canada. The author thanks Mr. Blake Johnston of Bezanson & Chase Cranberry Co Ltd., Aylesford, Nova Scotia for supplying fruit and financial support, Carol Domytrak, Stephanie Bishop, Michele Elliot, Vivian Agar, and Jan Dick for providing technical support and Drs. Wilhelmina Kalt and Paul D. Hildebrand for their critical review of this manuscript.

REFERENCES

- Abdallah AY, Palta JP (1989) Changes in biophysical and biochemical properties of cranberry (*Vaccinium macrocarpon* Ait.) fruit during growth and development. *Acta Horticulturae* **241**, 360-365
- Anderson RE, Hardenburg RE, Vaught HC (1963) Controlled-atmosphere storage studies with cranberries. *Journal of the American Society for Horticultural Science* **83**, 416-422
- Anderson RE, Smith WL, Jr. (1971) Effect of postharvest hot-water treatments on spoilage of cranberries in storage. *USDA Market Research Report* 928
- Blodgett AB, Caldwell RW, McManus PS (2002) Effects of calcium salts on the cranberry fruit rot disease complex. *Plant Disease* **86**, 747-752
- Boone DM (1994) Cranberry Cultivar Evaluation. University of Wisconsin-Madison, Available online: http://www.hort.wisc.edu/cran/pubs_archive/proceedings/1994/craboo.pdf
- Boone DM (1995a) Blotch rot. In: Caruso FL, Ramsdell DC (Eds) *Compendium of Blueberry and Cranberry Diseases*, APS Press, Saint Paul, MN, pp 32
- Boone DM (1995b) Yellow rot. In: Caruso FL, Ramsdell DC (Eds) *Compendium of Blueberry and Cranberry Diseases*, APS Press, Saint Paul, Minn., pp 42
- Bramlage WJ, Devlin RM, Smagula JM (1972) Effects of preharvest application of ethephon on 'Early Black' cranberries. *Journal of the American Society for Horticultural Science* **97**, 625-628
- Bristow PR, Patten KD (1995) Physiological (sterile) breakdown. In: Caruso FL, Ramsdell DC (Eds) *Compendium of Blueberry and Cranberry Diseases*, APS Press, Saint Paul, MN, pp 68-69
- Brown AO, McNeil JN (2006) Fruit production in cranberry (Ericaceae: *Vaccinium macrocarpon*): A bet-hedging strategy to optimize reproductive effort. *American Journal of Botany* **93**, 910-916
- Carris LM (1995) Black rot. In: Caruso FL, Ramsdell DC (Eds) *Compendium of Blueberry and Cranberry Diseases*, APS Press, Saint Paul, MN, pp 31-32
- Caruso FL (1990) Evaluation of fungicides for control of field and storage rot of cranberries. *Fungicide and Nematicide Tests* **45**, 65
- Caruso FL (1995) Botryosphaeria fruit rot and berry speckle. In: Caruso FL, Ramsdell DC (Eds) *Compendium of Blueberry and Cranberry Diseases*, APS Press, Saint Paul, MN, pp 32-33
- Caruso FL, Bristow PR, Oudemans PV (2000) Cranberries: The most intriguing native North American fruit, American Phytopathological Society. Available online: <http://www.apsnet.org/online/feature/cranberry/>
- Ceponis MJ, Stretch AW (1981) The influence of water immersion times at harvest on physiological breakdown of 'Early Black' cranberries in storage. *HortScience* **16**, 60-61
- Ceponis MJ, Stretch AW (1983) Berry color, water-immersion time, rot, and physiological breakdown of cold-stored cranberry fruits. *HortScience* **18**, 484-485
- Chen X, Grant LA, Caruso F (1999) Effect of Biosave® and carnauba wax on decay of cranberry. *Proceedings of the Florida State Horticulture Society* **112**, 116-117
- Cimolai N, Cimolai T (2007) The cranberry and the urinary tract. *European Journal of Clinical Microbiology and Infectious Diseases* **26**, 767-776
- Clague JA, Fellers CR (1934) Relation of benzoic acid content and other constituents of cranberries to keeping quality. *Plant Physiology* **9**, 631-636
- Craker LE (1971) Postharvest color promotion in cranberry with ethylene. *HortScience* **6**, 137-139
- Davenport JR (1996) The effect of nitrogen fertilizer rates and timing on cranberry yield and fruit quality. *Journal of the American Society for Horticultural Science* **121**, 1089-1094
- Davis DC, Shawa AY (1983) Reducing injury during mechanical harvesting of cranberries. *Journal of the American Society for Horticultural Science* **108**, 444-447
- DeMoranville CJ, Davenport JR, Patten K, Roper TR, Strik BC, Vorsa N, Poole AP (1996) Fruit mass development in three cranberry cultivars and five production regions. *Journal of the American Society for Horticultural Science* **121**, 680-685
- Desjardins Y, Makhlof J, Arul J, Guerero K, Constantin A, Corcuff R, Labarre L (2000) Évaluation des méthodes pré- et post-récolte afin d'accroître la valeur nutraceutique de la canneberge, Sainte-Foy (Québec), 4 pp
- Devlin RM, Demoranville IE (1968) Influence of dichlobenil on yield, size, and pigmentation of cranberries. *Weed Science* **16**, 38-39
- Devlin RM, Zuckerman BM, Demoranville IE (1969) Influence of preharvest applications of malathion and indole-3-acetic acid on anthocyanin development in *Vaccinium macrocarpon*, var. 'Early Black'. *Journal of the American Society for Horticultural Science* **94**, 52-55
- Doughty CC, Patterson ME, Shawa AY (1967) Storage longevity of the 'McFarlin' cranberry as influenced by certain growth retardants and stage of maturity. *Proceedings of the American Society for Horticultural Science* **91**, 192-204
- Eck P (1968) Chemical color enhancement of cranberry fruit. *HortScience* **3**, 70-72
- Eck P (1990) *The American Cranberry*, Rutgers University Press, New Brunswick, NJ, 420 pp
- Farag KM, Palta JP, Stang EJ (1992) Ethanol enhances the effectiveness of ethephon on anthocyanin production in cranberry fruits in the field. *HortScience* **27**, 411-412
- Forney CF (2003a) Postharvest handling and storage of fresh cranberries. *HortTechnology* **13**, 267-272
- Forney CF (2003b) Postharvest responses of horticultural products to ozone. In: Hodges DM (Ed) *Postharvest Oxidative Stress in Horticultural Crops*, Food Products Press, Binghamton, NY, pp 13-54
- Forney CF (2005) Effects of harvest method on cranberry fruit storage life, AAFC Technical Report, Atlantic Food and Horticulture Research Centre, Kentville, NS, 11 pp
- Forney CF (2008) Optimizing the storage temperature and humidity for fresh cranberries: A reassessment of chilling sensitivity. *HortScience* **43**, 439-446
- Forney CF (2009) Postharvest issues in blueberry and cranberry and methods to improve market-life. *Acta Horticulturae* **810**, 785-798
- Forney CF, Hildebrand P, Bishop S, Elliot M, Agar V (2004) Improvement of the storage-life of fresh cranberry fruit 2003/2004 season, AAFC Technical Report, Atlantic Food and Horticulture Research Centre, Kentville, NS, 29 pp
- Forney CF, Hildebrand P, Elliot M (2003) Improvement of the storage-life of fresh cranberry fruit 2002/2003 season, AAFC Technical Report, Atlantic

- Food and Horticulture Research Centre, Kentville, NS, 31 pp
- Forney CF, Kalt W, Abrams SR, Owens SJ** (2009) Effects of postharvest light and ABA treatments on the composition of late-harvested white cranberry fruit. *Acta Horticulturae* **810**, 799-806
- Forsyth FR, Hall IV** (1967) Oxygen absorption and ethylene production by developing cranberry fruit. *Canadian Journal of Plant Science* **47**, 153-156
- Forsyth FR, Hall IV** (1969) Ethylene production with accompanying respiration rates from the time of blossoming to fruit maturity in three *Vaccinium* species. *Le Naturaliste Canadien* **96**, 257-259
- Franklin HJ, Cross CE** (1948) Weather in relation to cranberry production and condition. *University of Massachusetts Bulletin* **450**
- Gourley** (1969) Observations on cranberry fruit rots in Nova Scotia, 1945--55. *Canadian Plant Disease Survey* **49**, 22-26
- Graham SO, Patterson ME, Allen B** (1967) Bruising as a predisposing factor in the decay of stored cranberries. *Phytopathology* **57**, 497-501
- Gunes G, Liu RH, Watkins CB** (2002) Controlled-atmosphere effects on post-harvest quality and antioxidant activity of cranberry fruits. *Journal of Agricultural and Food Chemistry* **50**, 5932-5938
- Hancock JF** (1995) Introduction: The taxonomy, botany and culture of *Vaccinium*. In: Caruso FL, Ramsdell DC (Eds) *Compendium of Blueberry and Cranberry Diseases*, APS Press, Saint Paul, MN, pp 1-5
- Hardenburg RE, Watada AE, Wang CY** (1986) The commercial storage of fruits, vegetables, and florist and nursery stocks, USDA Agricultural Handbook 66, 130 pp
- Hawker GM, Stang EJ** (1985) Characterizing vegetative growth and fruit development in cranberry (*Vaccinium macrocarpon* Ait.) by thermal summation. *Acta Horticulturae* **165**, 311-324
- Hruschka HW** (1970) Physiological breakdown in cranberries - Inhibition by intermittent warming during cold storage. *Plant Disease Reporter* **54**, 219-222
- Jeffers SN** (1991) Effects of fungicides applied during bloom on yield, yield components, and storage rots of cranberry. *Plant Disease* **75**, 244-250
- Jepson RG, Craig JC** (2007) A systematic review of the evidence for cranberries and blueberries in UTI prevention. *Molecular Nutrition and Food Research* **51**, 738-745
- Kader AA** (1997) A summary of CA requirements and recommendations for fruits other than apples and pears. *Proceedings of CA '97* **3**, 1-34
- Kalt W, Rimando AM, Elliot ML, Forney CF** (2006) Effects of postharvest storage and UV-C irradiation on the phenolic content and antioxidant capacity of cranberries. *HortScience* **41**, 978
- Kasmire RF, Thompson JF** (1992) Selecting a cooling method. In: Kader AA (Ed) *Postharvest Technology of Horticultural Crops*, University of California, Davis, CA, pp 63-68
- Kaufman J, Ringel SM, Hamer AA, Atrops EP, Ramsey GB** (1958) Effect of precooling on market quality of cranberries shipped by rail or truck. *USDA Marketing Research Report* **287**
- Lees DH, Francis FJ** (1972) Effect of gamma radiation on anthocyanin and flavonol pigments in cranberries (*Vaccinium macrocarpon* Ait.). *Journal of the American Society for Horticultural Science* **97**, 128-132
- Levine AS, Fellers CR, Guinness CI** (1941) Carbon dioxide-oxygen and storage relationships in cranberries. *Proceedings of the American Society for Horticultural Science* **38**, 239-242
- Lidster PD, Hildebrand PD, Bérard LS, Porritt SW** (1988) *Commercial Storage of Fruits and Vegetables 1523/E*, Agriculture Canada, Ottawa, ON 88 pp
- Lockhart CL, Forsyth FR, Stark R, Hall IV** (1971) Nitrogen gas suppresses microorganisms on cranberries in short-term storage. *Phytopathology* **61**, 335
- Massey LM Jr., Chase BR, Starr MS** (1981) Impact-induced breakdown in commercially screened 'Howes' cranberries. *Journal of the American Society for Horticultural Science* **106**, 200-203
- Neto CC** (2007) Cranberry and blueberry: Evidence for protective effects against cancer and vascular diseases. *Molecular Nutrition and Food Research* **51**, 652-664
- Norton JS** (1982) Bulk storage of cranberries *Modern Cranberry Cultivation*, Cooperative Extension Service, University of Massachusetts, Amherst, Mass, pp 117-133
- Norton JS, Charig AJ, Demoranville IE** (1968) The effect of ozone on storage of cranberries. *Proceedings of the American Society for Horticultural Science* **93**, 792-796
- Olatinwo RO, Hanson EJ, Schilder AMC** (2003) A first assessment of the cranberry fruit rot complex in Michigan. *Plant Disease* **87**, 550-556
- Olatinwo RO, Schilder AMC, Kravchenko AN** (2004) Incidence and causes of postharvest fruit rot in stored Michigan cranberries. *Plant Disease* **88**, 1277-1282
- Oudemans PV, Caruso FL, Stretch AW** (1998) Cranberry fruit rot in the Northeast: A complex disease. *Plant Disease* **82**, 1176-1784
- Özgen M, Farag KM, Ozgen S, Palta JP** (2005) Lysophosphatidylethanolamine accelerates color development and promotes shelf life of cranberries. *HortScience* **40**, 127-130
- Özgen M, Palta JP, Smith JD** (2002) Ripeness stage at harvest influences postharvest life of cranberry fruit: Physiological and anatomical explanations. *Postharvest Biology and Technology* **24**, 291-299
- Palanimuthu V, Rajkumar P, Orsat V, Gariépy Y, Raghavan GSV** (2009) Improving cranberry shelf-life using high voltage electric field treatment. *Journal of Food Engineering* **90**, 365-371
- Patterson ME, Doughty CC, Graham SO, Allan B** (1967) Effect of bruising on postharvest softening, color changes and detection of polygalacturonase enzyme in cranberries. *Proceedings of the American Society for Horticultural Science* **90**, 498-514
- Pepin HS, Boone DM** (1995) End rot. In: Caruso FL, Ramsdell DC (Eds) *Compendium of Blueberry and Cranberry Diseases*, APS Press, Saint Paul, MN, pp 36-37
- Rigby B, Dana MN, Binning LK** (1972) Ethephon sprays and cranberry fruit color. *HortScience* **7**, 82-83
- Ringel SM, Kaufman J, Jaffe MJ** (1959) Refrigerated storage of cranberries. *USDA Marketing Research Report* **312**
- Roper TR, Vorsa N** (1997) Cranberry: Botany and horticulture. *Horticultural Reviews* **21**, 215-249
- Ruel G, Couillard C** (2007) Evidences of the cardioprotective potential of fruits: The case of cranberries. *Molecular Nutrition and Food Research* **51**, 692-701
- Shawa AY** (1979) Effect of ethephon on color, abscission, and keeping quality of 'McFarlin' cranberry. *HortScience* **14**, 168-169
- Shwartz MR** (1985) Effect of wounding on incidence of black rot on cranberry in Wisconsin. *Plant Disease* **69**, 225-227
- Song J, Hildebrand PD, Fan L, Forney CF, Renderos WE, Campbell-Palmer L, Doucette C** (2007) Effect of hexanal vapor on the growth of postharvest pathogens and fruit decay. *Journal of Food Science* **72**, M108-M112
- Spayd SE, Morris JR, Ballinger WE, Himelrick DG** (1990) Maturity standards, harvesting, postharvest handling and storage. In: Galletta J, Himelrick DG (Eds) *Small Fruit Crop Management*, Prentice Hall, Englewood Cliffs, NJ, pp 504-531
- Stark R, Forsyth FR, Lockhart CL, Hall IV** (1974) Processing quality of cranberries after extended storage in N₂ atmosphere with low and high relative humidities. *Canadian Institute of Food Science and Technology Journal* **7**, 9-10
- Stark R, Hall IV, Forsyth FR, Dean PR** (1969a) Cranberries, evaluated for fresh fruit and processing quality, after reduced oxygen storage Part I. *Cranberries* **37** (6), 14, 16
- Stark R, Hall IV, Forsyth FR, Dean PR** (1969b) Cranberries, evaluated for fresh fruit and processing quality, after reduced oxygen storage Part II. *Cranberries* **34** (7), 14, 16
- Stevens NE** (1932a) Notable outbreaks of cranberry fruit rots in Massachusetts. *Phytopathology* **22**, 911-916
- Stevens NE** (1932b) Thickness of Cuticle in Cranberry Fruits. *American Journal of Botany* **19**, 432-435
- Stiles CM, Oudemans PV** (1999) Distribution of cranberry fruit-rotting fungi in New Jersey and evidence for nonspecific host resistance. *Phytopathology* **89**, 218-225
- Stretch AW, Ceponis MJ** (1983) Influence of water immersion time and storage period on black rot development in cold-stored, water harvested cranberries. *Plant Disease* **67**, 21-23
- Stretch AW, Ceponis MJ** (1986) Fungal and physiological breakdown in six cranberry cultivars following water harvesting and cold storage. *HortScience* **21**, 265-267
- Swanson BG, Weckel KG** (1975) Refrigerated storage of fresh cranberries. *Journal of Food Science* **40**, 259-261
- Terry LA, Cristosto CH, Forney CF** (2009) Small Fruits. In: Yahia EM (Ed) *Modified and Controlled Atmospheres for the Storage, Transportation, and Packaging of Horticultural Commodities*, CRC Press, Boca Raton, pp 363-395
- Trehane J** (2004) *Blueberries, Cranberries, and Other Vacciniums*, Timber Press, Inc., Portland, OR 256 pp
- Vvedenskaya IO, Vorsa N** (2004) Flavonoid composition over fruit development and maturation in American cranberry, *Vaccinium macrocarpon* Ait. *Plant Science* **167**, 1043-1054
- Wang CY, Wang SY** (2009) Effect of storage temperatures on fruit quality of various cranberry cultivars. *Acta Horticulturae* **810**, 853-862
- Whiteman TM** (1957) Freezing points of fruits, vegetables and florist stocks. *USDA Marketing Research Report* **196**
- Wright RC, Demaree JB, Wilcox MS** (1937) Some effects of different storage temperatures on the keeping of cranberries. *Proceedings of the American Society for Horticultural Science* **34**, 397-401
- Zhou Y, Singh BR** (2004) Effect of light on anthocyanin levels in submerged, harvested cranberry fruit. *Journal of Biomedicine and Biotechnology* **5**, 259-263
- Zuckerman BM** (1958) Relative importance of cranberry fruit rot fungi during the storage and harvest seasons in Massachusetts, 1956-1957. *Plant Disease Reporter* **42**, 1214-1221