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Potential for Modelling Postharvest Quality of Fresh Fruit and Vegetables

**Clément Vigneault[1*] • Gaétan Bourgeois[1] • Vicky Toussaint[1] •
Denis Charlebois[1] • Denyse I. LeBlanc[2]**

[1] Horticulture Research and Development Centre, Agriculture and Agri-Food Canada, 430 Gouin Blvd, St-Jean-sur-Richelieu, Quebec, J3B 3E6 Canada
[2] Atlantic Food and Horticulture Research Centre, Agriculture and Agri-Food Canada, c/o Université de Moncton, Moncton, New Brunswick, E1A 3E9 Canada

Corresponding author: * clement.vigneault@agr.gc.ca

ABSTRACT

For fresh fruit and vegetables, models that use temperature and relative humidity data measured throughout the cold chain and quality parameters measured at specific steps need to be developed to predict the produce quality that can be expected subsequently based on the environmental conditions. The development of such models requires data on physiological and microbial quality changes and on disease development in a wide variety of fresh fruit and vegetables as a function of time, temperature and relative humidity. Unfortunately, the availability of this type of data is relatively limited. One of the challenges in developing such models is defining the parameters that best describe the overall quality of fresh produce, given that the ideal parameters probably vary considerably depending on the type of produce. Associated with this is the challenge of finding the best tool for measuring the various aspects (physiological, microbial, pathological, etc.) of horticultural produce quality at any point along the field-to-fork continuum. Once these challenges have been resolved, systems could be developed to record ambient conditions (temperature and relative humidity) for each load of fresh produce and to use models to predict produce quality at various steps in the cold chain. Such systems could be used by producers, shippers, wholesalers and retailers to identify the optimum market for a particular load of fresh produce.

Keywords: horticulture, prediction, pathology, physiology, quality measurement

Abbreviations: ATP, adenosine triphosphate; **C_2H_4**, ethylene; **CCD**, charge-coupled device; **CO_2**, carbon dioxide; **GC/MS**, gas chromatography/mass spectrometry; **IR**, infrared radiation; **MIR**, mid-infrared radiation; **MRI**, magnetic resonance imaging; **NIR**, near-infrared radiation; **NMR**, nuclear magnetic resonance; **O_2**, oxygen; **RFID**, radio frequency identification; **RH**, relative humidity; **SSC**, soluble solids content; **UV**, ultraviolet light; **Vis**, visible light

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INTRODUCTION

An estimated 200 million tons of fruit were produced worldwide in 1992 (IIR 1995). In 2002, the domestic and international trade in fresh produce exceeded US$70 billion (Vigneault *et al*. 2009). The number of people consuming fresh fruit and vegetables has continuously increased in recent decades, and people are buying fresh produce even out of season (Garcia and Barrett 2004). Along with their increased demand for fruit and vegetables, consumers are expecting improved produce quality from their retailers (Garcia and Barrett 2004) as well as a wider variety of fresh fruit and vegetables. The globalization of the fresh produce trade is creating a need for better long-distance transportation systems and handling methods to preserve produce quality.

Between harvest and retail display or merchandising, fresh produce undergoes a number of handling steps, including cooling, transportation and storage, under various environmental conditions. The time between harvest and retail display can be less than a week for locally grown fruit and vegetables, such as berries and lettuce, or may be several months for long-life fresh produce, such as carrots, cabbages, pears and apples. During postharvest handling, fresh produce is susceptible to physical damage and deterioration. Produce losses vary widely depending on the type, storage life and production region of the produce. Approximately 40% of vegetables never make it to supermarket shelves because of damage during transit (Anonymous 2006), since produce is rarely held under optimum environmental conditions during transport. Other studies report horticultural produce losses as high as 50% in developing countries due

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to inefficient postharvest procedures (Camargo and Perdas 2002; Kader 2002) compared to 5 to 25% in developed countries (Kader 2002). Loss data vary significantly depending on the measuring method and, unfortunately, these methods are rarely reported (Camargo and Perdas 2002; Kader 2002; Anonymous 2006). About half of the losses are due to physical injuries and improper handling during storage and distribution (Cortez *et al*. 2002). The remaining losses are attributed to rodents, insects, and microorganisms (Sholberg 2008), although the proportion resulting from each of these is not known.

Among all environmental conditions, temperature is the main factor influencing produce quality. Excessively low temperature causes chilling or freezing injury (Tanner and Smale 2005), while high temperature increases the respiration rate and water loss, causes shrivelling and premature softening, and decreases internal flesh quality. Other factors affecting produce quality are initial quality, environmental humidity and water loss, atmospheric gas concentration, physical injury and stress, transport conditions (mixed loads, surface road conditions, time of day, etc.), and plant pathogen contamination. Water loss causes produce to shrivel or wilt, a phenomenon that is aesthetically displeasing, decreases the total weight of marketable produce, and reduces the market value. If fruit or vegetables that generate ethylene (C_2H_4) are placed near C_2H_4-sensitive produce, the C_2H_4 may cause the sensitive produce to prematurely ripen or develop a physiological disorder. Bruises, cuts, abrasions and other injuries can result in losses during distribution and marketing as these usually speed up the development of postharvest decay.

Reducing losses in postharvest fruit and vegetable operations is a worldwide goal. Quality loss can be minimized through the use of appropriate harvest procedures such as harvesting at correct commercial maturity using appropriate harvesting methods, rapid cooling, refrigerated storage and proper handling techniques during transportation and distribution to markets (Kader 2002). To minimize spoilage, produce must be held under optimum storage temperature, relative humidity (RH) and atmospheric conditions from harvest to consumption (Kader 2002). However, it has recently been demonstrated that certain physical stresses, such as short exposures to higher temperature, pressure, a given level of some atmospheric gases, radiation or irradiation, could help maintain or even improve the quality of horticultural produce (Vigneault 2007).

Since the optimum storage and handling conditions vary significantly depending on the type of fruit or vegetables, it is almost impossible to hold all fresh produce under their optimum environmental conditions from harvest to consumption. For example, when different types of produce are stored or transported together, it is expected that a portion of the fruit and vegetables will not be held at their optimum temperature and RH. Furthermore, malfunctioning of the refrigeration equipment, used throughout the cold chain, results in inappropriate environmental conditions at any step between farm and fork. The effect on produce quality of these non-optimum environmental conditions is generally noticed further down the cold chain. Developing a system to follow and/or predict the quality of produce at each step of the cold chain would limit the impact of inadequate environmental conditions by identifying problematic situations before losses occur, offering better management tools for decision makers, and helping quantify the real impact of each inappropriate condition in cases of multiple problems.

In the following sections, various approaches are presented for predicting changes in the quality of fresh produce based on the environmental conditions encountered in the postharvest handling and distribution system. A review of existing data that could be used to model produce quality changes as a function of time, temperature, RH and gas composition has also been included. If such models are developed, they could be incorporated into produce traceability systems with the goal of decreasing the negative impact of inadequate environmental conditions.

MODELLING APPROACHES FOR PREDICTING POSTHARVEST QUALITY

Considering the large variety of fruit and vegetables handled, distributed and marketed worldwide, building a single model to predict the quality of horticultural produce from harvest to retail display would seem to be an almost impossible feat. Although time, temperature, RH, the gas composition of the surrounding atmosphere, and the presence of plant pathogens are the main factors impacting the postharvest quality of fresh produce, other variables such as vibration, radiation, pressure and various sources of physical stress also influence fruit and vegetable quality. The objectives of this section are to demonstrate the possibility of finding common mathematical relationships to simulate postharvest quality evolution for all fruit and vegetables, and to propose a modelling approach for application-oriented postharvest systems.

Dynamic mathematical modelling defines a system as a "limited part of reality that contains inter-related elements", a model as a "simplified representation of a system", and simulation as "the art of building mathematical models and the study of their properties in reference to those of the systems" (de Wit 1982). Model types range from simple regression to complex comprehensive mathematical approaches. Their potential as scientific, educational and predictive tools is quite variable. In general, comprehensive models are more science-oriented, and regression models are more application-oriented. It is thus important to clearly define the objectives of the required model in order to select the proper mathematical approach.

As presented by Rabbinge and de Wit (1989), the formulation of objectives should be the first step in model building and has been divided into three phases: a) the conceptual phase; b) the comprehensive modelling phase; and c) the management tool development phase. To clarify and standardize the method for developing representative and versatile models, these three phases have been further divided into 10 steps, as follows:

Conceptual phase
1. Formulation of objectives
2. Definition of the limits of the system
3. Conceptualization of the system (i.e. states, rates, auxiliary variables, etc.)

Comprehensive modelling phase
4. Quantification through literature, process experiment or estimation of the relations between rate and forcing variables, state or auxiliary variables
5. Model construction (definition of computer algorithms)
6. Verification of the model, i.e. testing the intended behaviour of the model

Management tool development phase
7. Validation, i.e. testing the model in parts or as a whole, using independent experiments on system level
8. Sensitivity analysis, numerical or structural
9. Simplification, development of a summary model
10. Formulation of decision rules or forecasting models to be used in management

Many of these steps require data observed over different periods of time. For stored fruit and vegetables, these data can be obtained from destructive or non-destructive measurements. Of course, destructive measurements require more samples and eliminate the possibility of following the evolution of a given set of fruit or vegetables over time, which generally results in an increase in the number of sampling units per observation to account for produce variability.

Postharvest quality of fruit and vegetables can be characterized in terms of many aspects: visual appearance, firmness, internal constituents, presence of damage caused by disease or physiological disorders, etc. Holt *et al.* (1983) categorized the causes of postharvest deterioration as physiological, pathological, physical or a combination of all three. More recently, food safety became a major concern and therefore also needs to be considered (LeBlanc and Vigneault 2008). All these quality attributes could be affected by the many environmental factors that fruit and vegetables experience before, during and/or after harvest.

Tijskens and Polderdijk (1996) proposed a generic static model to calculate the "keeping quality" of perishable produce based on the kinetics of the decrease in individual quality attributes and expressed as a function of temperature, initial quality and quality acceptance limits. They presented their model in terms of "single limiting quality attributes at constant temperatures" and "multiple limiting quality attributes at constant temperatures"; in the latter, processes could be non-interfering or interfering. Mathematical approaches are presented for all cases except the interfering processes, where the situation becomes very complex and logical assumptions for a common or generic model can no longer be made. Their generic model accounted for the quality behaviour of more than 60 species of fruit and vegetables, including chilling-sensitive produce, over a wide range of temperature.

Many models on postharvest quality evolution have been developed, but the number of applications of these models is quite limited. One potential application for postharvest quality evolution models involves the evaluation of commercial produce cold chains characterized by non-constant temperature (Lukasse and Polderdijk 2003). Such an application imposes specific requirements on the models. The model should be:

1. predictive of the future quality evolution as a function of the current state variables;
2. causal (current quality evolution should be independent of the future conditions);
3. stable in forward time;
4. irreversible in terms of quality evolution during the postharvest stages of the produce; and
5. valid for non-constant temperature.

Lukasse and Polderdijk (2003) presented a modelling methodology in which the class of permitted models is limited by the above requirements; their resulting model fitted well to experimental data collected for mushrooms.

Attempting to develop mathematical models that integrate all the quality attributes and the impacts of all variables, for a large number of fruit and vegetables, would be a very tedious task, especially if specific relations and interactions between them are not well understood or not known. Since such relations are incomplete or not available, application-oriented modelling of the evolution of multiple postharvest produce quality attributes should concentrate on the following components:

1. establishment of empirical mathematical responses of individual quality attributes to environmental conditions (e.g. temperature, RH) under specific atmospheric conditions; and
2. use of these empirical mathematical responses in dynamic simulation models for each postharvest quality attribute in order to follow their evolution along the storage and distribution chains.

This approach, coupled with precise monitoring of the environmental conditions in produce distribution chains, will allow users to simultaneously monitor critical quality attributes and help establish rules for the decision-making process.

The following sections review existing data on various quality attributes measured for fruit and vegetables, the response of these attributes to various environmental conditions, and the techniques that are available for measuring various quality attributes.

PREDICTING THE EFFECT OF ENVIRONMENTAL CONDITIONS ON PHYSIOLOGICAL QUALITY

Consumers generally select produce based on external appearance attributes such as colour, shape, texture, smell and flavour. However, these attributes are largely influenced by the postharvest management and ambient conditions that the produce is submitted to prior to marketing. Among all environmental conditions, temperature is the one that has the most impact on the appearance, texture, molecular composition and eating quality of fruit and vegetables. Good temperature management is the simplest and most important method for delaying produce senescence and deterioration. In addition, the RH and gas composition surrounding the produce also influence its quality.

Effect of temperature

Optimum quality preservation of horticultural produce begins with a precooling treatment, which involves rapid cooling of the produce nearly to its optimum storage temperature immediately after harvest (Vigneault *et al.* 2009). The main advantages of precooling are the rapid reduction of the produce respiration rate and thus its deterioration rate; reduction of condensation on previously-cooled produce caused by warm produce mixed with cold produce in storage room; acceleration of handling processes; adjustment of cooling rate with harvesting rate; decrease of storage room cooling load; and ease of cooling process parameter adjustment for each individual batch of produce (Vigneault *et al.* 2008). In fact, several recent studies confirmed that precooling significantly reduces postharvest quality loss (Vigneault *et al.* 2008). For example, forced-air cooling of asparagus extended its shelf life for at least 7 days compared to room-cooling (Laurin *et al.* 2003). Precooling broccoli immediately after harvest extended its shelf life by 9 days compared to the shelf life obtained when the cooling process was delayed by 24 hours (Xu *et al.* 2006). Decreasing the delay before precooling blueberries from 16 to 2 h significantly reduced mass and firmness losses (Tetteh *et al.* 2004). Precooling strawberries within the first 3 h after harvest significantly improved their shelf life (Nunes *et al.* 2005). In addition, the extension of shelf life is similar regardless of the type of precooling process used. Hydrocooling, vacuum cooling and liquid icing are thus expected to produce the same shelf life extension, as long as the treatment is performed under similar conditions and the horticultural produce is compatible with the adopted precooling method used (Vigneault *et al.* 2008).

Within acceptable limits for each type of commodity, the respiration rate of fresh produce increases with the ambient temperature, and respiration activity requires biochemical energy supplied by the produce; thus, lowering the temperature of the produce results in an extension of its shelf life or in more energy remaining within the produce for the consumer. Thus, the lowest temperature a horticultural commodity can be stored at, without generating physical or physiological damage, is assumed to be its optimum storage temperature. Storing fruit and vegetables at their optimum temperature retards ageing, softening, and textural, colour and flavour changes, and also slows undesirable metabolic changes, moisture loss, and losses due to pathogen invasion (Nunes 2008). Many recent studies have confirmed that holding fruit and vegetables at their optimum temperature from field to retail display is crucial for maintaining their quality. However, fruit and vegetables are often handled, transported and displayed under inadequate conditions, leading to large amounts of produce being discarded at retail or at the consumer's home.

Fruit and vegetables are often rejected when their visual appearance is unappealing as a result of improper temperature management. In fact, appearance (i.e. colour, shrivelling, wilting, chilling injury symptoms, decay, etc.) is one of the most important factors that determine the market value of horticultural produce and is greatly influenced by the ambient temperature the commodity is submitted to after harvest (Nunes 2008). For example, the yellow colour of broccoli florets associated with lower chlorophyll content results in poor marketability. Although the onset of yellowing may vary depending on the cultivar, this process is greatly affected by temperature and may occur within a few days after harvest if broccoli is held under ambient temperature (Nunes 2008). Broccoli stored at 4°C retained its green colour and fresh appearance for 7 days, whereas broccoli stored at 20°C showed traces of yellowing after 3 days, and the heads were completely yellow after 7 days (Rangkadilok *et al*. 2002). The colour of bell peppers also changes depending on the storage temperature. According to González *et al*. (2005), the colour of peppers stored at 7°C did not change during the first 20 days of storage, whereas the colour changed from green to green-orange after 10 to 15 days when the peppers were stored at 22°C. These examples show the potential of using colour as a measurable quality index and as a single parameter capable of predicting changes in the quality of some produce as a function of time and temperature.

Quality losses are also associated with the development of physiological disorders such as chilling injury. The exposure of subtropical or tropical horticultural produce to temperature below 10°C may generate chilling injury. The symptoms and severity of this physiological disorder vary with the commodity (and even with the cultivar), degree of maturity, temperature, length of exposure to low temperature, and ambient temperature and time after the low-temperature exposure ends. Chilling injury symptoms include discoloration, uneven coloration, darkening, browning, pitting, greyish scald, scalding, pulp softening, heterogeneous ripening, internal breakdown, flesh textural change, detectable flaccidity, poor eating quality, reduction of volatile production and flavour, reduction of juiciness, mealiness, and hardening of texture. Some of these symptoms may appear progressively as a function of the external conditions, while others appear suddenly with highly unpredictable progression. Furthermore, these defects are ideal entry points for pathogens, making the quality loss very dependent on the presence of plant pathogens. In such cases, prediction of quality loss would require information on pathogen contamination, which would include not only the environmental conditions during postharvest handling and storage, but also data on the cultural methods, growing conditions, history of pathogens present in the field, weather conditions during the growing season and pesticide applications, as well as many other factors affecting the presence and development of pathogens on the produce. These information requirements significantly complicate the prediction of the quality changes.

Based on published information, it seems relatively easy to predict produce quality loss due to small increases in temperature above the optimum storage temperature during postharvest handling and distribution. However, it seems much more complicated to predict quality loss when temperature drops below the freezing or chilling injury threshold of various fruit and vegetables. Furthermore, the prediction of quality loss has been complicated by research results showing no effect on chill-sensitive produce of an exposure to low temperature, as long as the centre of the produce does not reach the published prejudicial temperature (DeEll *et al*. 2000). Also, Lu *et al*. (2007) showed the possibility of using physical treatments (mainly heat) to neutralize the effect of low temperature exposure on chill-sensitive horticultural produce. As a result, the prediction of chilling injury damage will be impossible unless all information pertaining to any physical treatment sustained by the produce is entered into the model.

Water loss also affects the appearance and eating quality of stored fruit and vegetables. According to Kader (2002), water loss as low as 5% of the produce weight is sufficient to significantly affect the quality appearance of strawberries. The rate of water loss depends on the type of produce, as well as the physiological and morphological characteristics of each individual fruit or vegetable. The water loss rate is also closely related to any increase in temperature or decrease in RH, both of which also generate quality loss in different forms. In leafy vegetables, water loss leads to wilting and shrivelling and causes leaves to become flaccid and lose their attractiveness. In fruit and vegetables with fleshy tissue, water loss leads to softening, one of the most important changes occurring during storage that has a major impact on consumer acceptability.

Other changes in the textural quality of fruit and vegetables include decreased crispness and juiciness, or increased toughness. For example, the firmness of raspberries stored at 0°C was considered unacceptable after approximately 6 days, while at 5°C this fruit lasts only 3 days (Nunes 2008). As well, asparagus tends to become less turgid and tougher as storage time and temperature increase (Villanueva *et al*. 2005). However, it must be remembered that consumers expect crispness in fresh apples, peaches and green onions, but tenderness in asparagus and green beans.

The rate of weight loss may be easily predictable for some types of produce, which are well documented in the literature, but not all. Tomatoes stored under three different storage temperature (5, 12 and 26°C) lost 0.15, 0.49 and 0.68% of their initial weight per day, respectively (Javanmardi and Kubota 2006). Batches of broccoli stored for 7 days at 6 ± 2°C and 17 ± 5°C lost 0.2 and 1.3% of their initial weight per day, respectively (Song and Thornalley 2007). Weight loss is very produce-dependent; for example, under the same ambient conditions (i.e. 20°C and 90 ± 5% RH) and over the same period of time, mushrooms lost 22 times more water than tomatoes.

The temperature also affects the composition and nutritional value of fresh horticultural produce. Increasing the temperature leads to decreases in acidity, soluble solids content (SSC), total sugars and ascorbic acid content, as well as a decrease in some pigments such as anthocyanin and lycopene. For example, cantaloupes stored for seven days at 2°C showed decreases in acidity, SSC, and fructose and glucose contents (Senesi *et al*. 2005). Melons stored at 5°C did not show any change in sugar content, whereas storage at 10°C resulted in a significant decline in sugar content (Lester and Hodges 2008). The SSC, acidity and volatile contents of apples decreased during storage at 0°C (Saftner *et al*. 2005). The total sugar content of snap beans stored at 8°C initially increased but subsequently decreased.

Any segment of a cold chain or commercial postharvest handling/distribution system that is poorly controlled may have a significant impact on the quality of fresh produce (de Castro *et al*. 2005). It has been suggested that quality loss in fresh horticultural produce is proportional to the sum of the duration of any exposure to inadequate temperature multiplied by the temperature difference between the optimum storage temperature and the inadequate temperature. This concept is still at the hypothesis stage for most produce, but research has been initiated to confirm or disprove this hypothesis. However, it is clear that quality lost at any cold chain step cannot be retrieved even if the produce is subsequently stored at the ideal temperature. Fruit submitted to treatments involving a break in the cold chain exhibited signs of abnormal ripening, increased weight loss and fungus development (de Castro *et al*. 2005).

Effect of RH

Softening, discoloration, increased flabbiness, loss of turgidity, wilting, shrivelling and dryness are visual symptoms generally associated with loss of moisture. However, very few studies have measured the effect of the ambient RH on the quality of horticultural produce. Relative humidity is known to be an important factor that must be controlled to maintain fruit and vegetable turgidity, which is directly related to water loss and firmness, also an important quality parameter affecting the consumer's produce-purchasing decisions. In fact, the ambient RH is the critical factor driving any water loss process (Pacco *et al*. 2007). Decreasing the RH, below the optimum level required by any type of produce, results in immediate water loss proportional to the water vapour partial pressure differential between the air and the surface of the produce. For example, the weight loss of grapefruit stored at 30% RH is about 0.4 to 0.5% per day, whereas the weight loss is reduced to 0.3% per day in fruit stored at 90% RH (Alférez and Burns 2004).

The rate of moisture loss from horticultural produce can be reduced by increasing the RH. However, excess RH may lead to fungal decay when the produce is exposed to higher temperature and RH. For example, the percentage of decayed strawberries was significantly higher when the storage temperature and RH increased (Shin *et al.* 2007). These authors demonstrated that, after 4 days, strawberries stored at 10°C and 75, 85 or 95% RH demonstrated a 3.9, 9.3 and 11.7% fruit loss, respectively, whereas fruit loss percentages increased to 59.2 and 90% when strawberries were stored at 20°C and 75 or 90% RH, respectively.

When produce is film-packed, the RH around the produce is considered to be near the saturation point, which limits the amount of water lost. However, atmosphere modification occurs because of respiration activity, increasing carbon dioxide (CO_2) and decreasing oxygen (O_2). To limit the negative effect or even increase the positive effect of this atmosphere modification, the permeability of the film should be chosen according to the produce respiration rate and the effect of the new atmosphere on the produce (Raghavan *et al.* 2005). In such cases, it would be difficult to separate the effect of RH from the effect of gas composition on the quality of the produce inside the package, increasing the difficulty of modelling fresh produce quality loss.

Effect of gas composition

The concept of reducing produce respiration to prolong storage life has been known since 1865 (Hoehn *et al.* 2009). However, it is important to distinguish between an atmospheric composition that reduces respiration and the "real" reason for which a particular storage atmosphere is favoured. For example, a high CO_2 concentration has been found to be beneficial for berries since it inhibits fungal growth and therefore limits fungal spoilage, one of the primary causes of quality deterioration of fresh berries such as blueberries (Day *et al.* 1990) and strawberries (Lépine 1989). Although strawberries had a high respiration rate (20–40 mg CO_2 h^{-1} kg^{-1}) during storage experiments under different atmospheric conditions (2.3 and 17.5% O_2, and 5 and 15% CO_2), El-Kazzaz *et al.* (1983) demonstrated that the best storage performance of strawberries was obtained when the air composition was 17.5% O_2 and 15% CO_2. Studies on the proliferation of *Botrytis cinerea* at 20°C showed that better storability was obtained when a high level of CO_2 and an intermediate concentration of O_2 were used (Lépine 1989). The high CO_2 concentration probably inhibited the pathogen. As a result, the development of models describing the effect of gas concentration on fruit and vegetable quality progression is more complicated, since the optimization procedure must take into account not only the reduction of the respiration rate but also the inhibition of pathogens of various degrees of virulence.

Furthermore, some authors attributed the beneficial effect of low-O_2 and high-CO_2 atmospheres on produce storage life to the influence of such atmospheres on C_2H_4, which is involved in ripening and consequently leads to softening and eventual deterioration (Skrzynski *et al.* 1985). Oxygen is involved in the synthesis and activity of C_2H_4 and inhibits its production at levels of approximately 8% and lower (Kader 1985, 1986), and CO_2 is a competitive inhibitor of C_2H_4.

The above examples show the importance of considering and measuring not only the produce temperature but also the moisture content, velocity and gas composition of the air surrounding the produce, to generate adequate models that predict the quality remaining in fresh produce.

PREDICTING THE EFFECT OF ENVIRONMENTAL CONDITIONS ON MICROBIAL QUALITY

Microbial contamination can occur in the field prior to harvest or during any of several handling steps from harvest to retail display. Adequately predicting microbial proliferation or disease development requires a good understanding of the principal means of potential contamination during every step of the commodity production and distribution chain. Research is needed to identify the strengths and weaknesses of produce distribution systems, from the perspective of both microbial safety and disease development. Such knowledge will help determine what data needs to be measured throughout the produce distribution system to predict microbial contamination and proliferation as well as disease development.

Postharvest diseases are generally caused by microorganisms of fungal origin, although a few bacterial species are also reported to cause decay during storage. Modelling disease development could potentially reduce losses in fruit and vegetables during storage, as long as the inoculation and infection processes are considered. Therefore, an understanding of the whole cycle of the microorganisms involved in postharvest decay is essential for model development.

Epidemiology, the science that studies the factors influencing disease development or epidemics in a population, is the basis of model development (Madden *et al.* 2007). The factors that trigger disease epidemics include the host, which depends on its growth, development and resistance to pathogens; the survival of the pathogen, which depends on its growth, dissemination and reproduction; and the components of the environment in which the epidemic develops, which depends on the characteristics of the disease such as the infection, incubation and latency periods (Campbell 1998). If those factors are understood and quantified, descriptive models can be proposed to illustrate and predict the occurrence and severity of epidemics. Descriptive models are based on the use of mathematical functions, regression, differential equations or simple decision models. In contrast, a more explanatory approach can be taken, leading to the development of conceptual models that distinguish cause from effect and quantify the effects of specific events on epidemic development. This class of models will usually lead to the development of complex simulation models (van Maanen and Xu 2003). Most existing disease models are based on the relationships of temperature and moisture to disease development and pathogen reproduction (Sholberg 2008). Generally, the emphasis during model development is on the pathogenesis stage of the disease cycle, and little energy is spent describing the initial stages of dormancy, reproduction and dispersal. The pathogenesis stage can be subdivided into infection, incubation, latency and senescence periods (Sholberg 2008).

Mathematical models developed to describe or predict plant diseases are numerous, but so far most are restricted to epidemics occurring during crop production, and very few describe postharvest disease development occurring in the cold chain. Although models that describe epidemics occurring in the field may be a good start for assessing the potential of disease development during storage, these models do not take into account the storage conditions that have a large influence on postharvest disease development.

The latency period of the pathogenesis stage is a very important factor to consider when predicting disease development during postharvest handling, storage and distribution. Hand-harvested fruit and vegetables are generally selected to be free of any visible symptoms. However, some fruit or vegetables can be infected by pathogens even if no visible symptoms are present, since the pathogens are in their latency period. In such situations, models that predict disease development in the field could help identify the potential risk of the presence of a latent infection during the postharvest period. Based on this knowledge, treatments could be applied before or at harvest to try to reduce the infection. Such treatments are not always effective, however, and sometimes no treatment is available for a specific commodity. In these cases, the availability of models that predict symptom development in storage, following a latent infection, could be very useful for decisions regarding stock management.

The ability to identify potential contamination would be extremely useful for the management of postharvest diseases. In conjunction with the use of preharvest disease models, the availability of reliable techniques to identify the presence of pathogens on produce will help with the development of effective postharvest disease models as well as with decisions related to the postharvest management of fresh produce stock. Traditionally, produce contamination was determined with immunology and genetic approaches. However, new avenues have been explored by scientists with instrumentation capable of measuring levels of adenosine triphosphate (ATP), an indicator of contamination in food (Fung 2007). With this technology, it is possible to differentiate the ATP of microbial origin from that of plant material. Another technique involves the use of gas chromatography/mass spectrometry (GC/MS) to detect the presence of specific volatiles in the head space of stored produce as a means of detecting the presence of specific pathogens. Moalemiyan *et al.* (2007) showed that it was possible to differentiate between anthracnose and stem-end rot disease of mango based on their volatile production profiles.

Once diseases are detected and identified, it is important to understand how they develop during storage and distribution. Postharvest models capable of predicting disease development as a function of temperature and RH would be very useful since, contrary to the situation in the field, it is possible to control environmental conditions during storage and distribution. The use of such models would help storage and packinghouse managers determine the environmental conditions required to prevent or reduce disease development without inducing physiological damage to the produce. The models could be used to predict the effect of delays in precooling or the rate of precooling on the development of disease. For example, it is well known that *Sclerotinia sclerotiorum*, the causal agent of white mould on several commodities, is strongly influenced by the precooling process. If the produce is cooled rapidly, new infection will not occur. However, if precooling is delayed or if the rate of cooling is too slow, the disease will develop even if the produce is stored at its optimum temperature for the remaining time in storage. This example supports the need for postharvest models capable of estimating the potential that infection occurred in the field as well as taking into account the conditions encountered during all postharvest handling steps, including cooling, packing, storage and distribution.

Global models can describe the potential for disease development following specific conditions during storage. Most postharvest diseases are caused by fungi, microorganisms that are influenced by the presence of moisture for spore germination and/or mycelium development. The presence of moisture on the surface of fruit or vegetables is generally the result of a temperature variation. At a high RH, which is the most prevalent condition for horticultural produce storage conditions, subjecting cold produce to a slightly higher temperature (by 1 to 5°C) will cause water vapour to condensate and form a film of water on the produce surface, favouring fungal spore germination. Subsequent disease progression will depend on the storage facility conditions as well as on the type of pathogen.

Another aspect that can be modelled in postharvest disease epidemiology is the dispersal of the pathogen in the storage facility. Dispersal will depend on the type of pathogen. Some pathogens produce only mycelium and heavy structures, such as sclerotia, which are not usually dispersed by ventilation. Other pathogens produce a tremendous amount of spores than can be easily dispersed by air movement. In the latter case, new infection sites will rapidly occur, increasing losses during storage.

Finally, the survival of the pathogen in the storage facility, packinghouse and produce-handling equipment should be considered in a conceptual model. Some fungal structures, such as sclerotia, can survive a very long time in adverse conditions; therefore, inspection and sanitation of facilities are important to eliminate this potential source of contamination. In contrast, some fungal spores, such as the conidia produced by *Penicillium* sp., will survive a shorter time under high RH than under dry conditions (Smilanick and Mansour 2007). A model that could establish spore survival may help determine the frequency of sanitation required to keep the packinghouse at a low level of contamination risk without excessive cleaning and sanitizing processes.

A literature review has shown that existing models generally address only a few steps of the overall food chain (Sholberg 2008). Some models have been developed for different aspects of the food chain for diseases such as grey mould caused by *Botrytis cinerea*. In fact, this pathogen has been extensively studied, since it attacks a wide variety of economically important commodities grown in diverse climates and regions around the world. The most advanced progress in the modelling of postharvest diseases has likely been made with cereal grains (Magan *et al.* 2003). The particular handling process required by grains and the presence in grains of pathogens that produce mycotoxins harmful to humans and animals explain the extensive efforts invested in developing postharvest models for this specific type of produce. Like the grain industry, the fruit and vegetable industry would benefit from models capable of predicting disease development during postharvest handling and storage. However, given the many steps between harvest and consumption, as well as the different aspects of disease cycles, only conceptual models that take into account the multiple facets of the problem would result in significantly improved produce quality. As always, the real challenge lies in modelling a wide diversity of diseases found on a wide variety of commodities, each with specific storage needs.

Another important aspect of horticultural produce quality is the possible presence of human pathogens and the environmental conditions that enhance their development. In fact, outbreaks of foodborne illness related to fresh fruit or vegetables are regularly reported in the media. Although plant disease development is relatively easy to detect and causes a large portion of postharvest losses because of obvious produce deterioration, the presence and development of human pathogens on horticultural produce is much more insidious, because the quality losses are invisible to the human eye and generally require specific analysis to be detected. Current pre-market sanitation treatments generally rely on the application during washing of a chemical sanitizer, primarily chlorine, to reduce postharvest plant disease development, which could also decrease the activity of or even kill human pathogens. However, such treatments are applied at temperature below 10°C to prevent the onset of heat-induced physiological defects in the produce and are unfortunately only marginally effective in eliminating any human pathogens contaminating the produce. It is also important to note that even if some treatments are effective at decontaminating the surface of fruit and vegetables, no effective treatment has yet been found to eliminate internal contamination (Delaquis and Austin 2007). Thus, factors leading to the internalization of human pathogens in fresh fruit and vegetables need to be better understood in order to prevent, or at least reduce, their occurrence. The development of models capable of predicting and preventing the internalization and development of such pathogens is of great importance. The ability to model the microbial proliferation of human pathogens in fresh produce in response to the environmental conditions (temperature, RH, gas composition, physical stress, etc.) possibly encountered over time would be a powerful tool for predicting the potential problem and would provide the possibility of eliminating any contaminated produce before it reaches the consumer.

MEASURING THE QUALITY OF FRESH PRODUCE

Food quality is a major concern for every stakeholder in the industry. Quality is a relatively complex set of parameters that might have an impact on the purchase decision. Horticultural produce quality parameters include sensory properties, the most obvious attributes perceived by the consumer; nutritive value and functional properties, two characteristics that are being advertised more and more by the food industry and are of increasing interest to the consumer; chemical constituents; mechanical properties; and the presence or absence of defects (Eccher Zerbini 2006; ElMasry *et al*. 2008). Chemical constituents and mechanical properties have a particular significance for the processing industry. Abbott (1999) clearly identified the complexity of quality assessment, which is often subjective since the definition of quality changes along the production and distribution chain based on the destination of the produce (e.g. fresh market, long-distance transportation, short- or long-term storage, processing).

A fresh fruit or vegetable is a living organism removed from its natural environment. As such, from the time a produce is harvested to the moment it is consumed or processed, intrinsic characteristics such as appearance and taste are likely to change as a natural response to ripening (Zion *et al*. 1995) and senescence. The extent of such changes is related to the initial condition of the produce as well as to the environmental conditions in which the produce is handled and stored. While it is important to know the initial characteristics of a type of produce in order to provide growers with valuable information related to harvesting, it is also critical to assess the quality of the produce at various times during handling, storage and processing in order to ensure quality control. Several consumer-driven quality criteria have been identified by the industry, and it is customary to assess some of them at various points along the distribution chain. Unlike colour, firmness, sweetness or acidity, the presence of defects or contaminants have a negative effect on consumer decision making. It is thus imperative to use reliable methods that are based on objective techniques and are capable of providing timely information about a fruit or vegetable to ensure high and consistent quality and to support the consumer's decision.

To determine most quality parameters, tedious techniques based on chemical or physical methods that involve sample destruction have traditionally been used. Time and financial constraints often limit such determinations to small subsamples that can lead to inaccurate evaluations (Tollner and Muhammed 2001). In some cases, such as during visual inspection, fatigue and subjectivity can adversely affect the process. The adequacy of chemical analysis and visual inspection is being questioned more than ever before, with a growing call for non-destructive, fast, accurate, inexpensive and objective quality evaluation methods that could be used in the field or on sorting lines (ElMasry *et al*. 2008). Field instruments could be used to help growers better manage the harvest while informing them about the initial quality of their crop. This information could also be useful for selecting the best handling or processing technique. Premium-quality produce could be identified using in-line instruments. Not only could this approach bring in extra income, it could also be useful in providing fruit and vegetables of constant quality and devoid of any undesirable defects such as bruising, decay or the presence of pathogens.

Over the last decade, there has been increased interest in non-destructive techniques applied to fruit and vegetables as well as to a large array of food products (Hernández Gómez *et al*. 2004; Butz *et al*. 2005; Karoui *et al*. 2006; Nicolaï *et al*. 2007; Huang *et al*. 2008; Moreda *et al*. 2009). Major improvements in computer technology (Studman 2001), sensors and excitation sources (Wang and Paliwal 2007), signal treatments, and statistical analysis (Gabrielsson and Trygg 2006; Small 2006; Haff and Pearson 2007; Wang and Paliwal 2007; Lavine and Workman 2008; Winning *et al*. 2008) have fuelled research all over the world in the field of non-destructive quality determination. Thousands of scientific papers have been published on various non-destructive techniques, as have numerous reviews on the subject (Abbott 1999; Hernández Gómez *et al*. 2004; Zhang *et al*. 2005; Nicolaï *et al*. 2006; Xie *et al*. 2007).

It is likely that the most widely used non-destructive approach to assessing fruit and vegetable quality takes advantage of the interactions (absorption, fluorescence, reflection, scatter and transmission) between electromagnetic radiation and the object under investigation. Numerous studies based mainly on visible (Vis), near-infrared (NIR) and, to a lesser extent, ultraviolet (UV) and mid-infrared (MIR) methods have been published (Brosnan and Sun 2004; Nicolaï *et al*. 2007; Hertog *et al*. 2008; Huang *et al*. 2008; Moreda *et al*. 2009). Most of these methods compensate for known limitations of traditional human inspection such as fatigue, variation in sensory perception, lack of proper training, and bias.

Optical methods can be divided into two main categories: spectroscopy and imaging/computer or machine vision. In spectroscopy, the sample under study is generally considered to be a uniform object, and the signal that it produces is averaged over the entire field of view of the instrument. This approach reduces processing time but involves a reduced field of view (Abdullah *et al*. 2004; Nicolaï *et al*. 2006) and can be problematic when evaluating non-uniform samples. Imaging/computer or machine vision, on the other hand, treats the sample as an assemblage of subsamples. These methods can be considered an extension of spectral analysis, as they take advantage of some of its characteristics such as the correlation between quality parameters and spectral features. Computer vision methods are more suited for larger and heterogeneous samples than conventional spectral techniques such as Vis-NIR spectroscopy. Computer vision methods have been mainly used for dimensional measurements, texture, colour, defects and disease evaluation (Panigrahi and Gunasekaran 2001). The image generated can be decomposed into as many elements as the camera permits, thus allowing for a more detailed analysis of the sample. This gain in spatial accuracy comes with a price, and spectral resolution usually has to be sacrificed in order to keep the data files generated by the acquisition system to a size compatible with in-line application. Hyperspectral imaging can be considered a hybrid of spectroscopy and imaging (Gowen *et al*. 2007). It takes advantage of spectral and spatial resolution, and new equipment is being proposed as advances in technology (Wang and Paliwal 2007) and signal treatment (Lefcourt *et al*. 2006) are being made.

As accurate, fast and affordable tools for sorting and determining the quality of fruit and vegetables, Vis-NIR techniques are very promising, and some commercial equipment is already available (Nicolaï *et al*. 2006). There are cases, however, where external colour does not reflect internal ripeness, and in those cases other techniques should be used. To a lesser extent, the use of Fourier transform infrared (FTIR) analysis to predict quality has also been explored (Gunasekaran and Irudayaraj 2001). Techniques based on fluorescence and delayed light emission are closely related and involve the emission of light at a longer wavelength from an object subjected to electromagnetic radiation, usually in the UV or Vis part of the spectrum. While fluorescence ceases immediately after the excitation source is removed, delayed light emission can persist for several seconds under similar conditions. The intensity of the resulting signal is usually small, the sensors must be protected from daylight, and the samples often have to be dark-adapted prior to measurement. Both techniques are highly dependent on the chlorophyll content of the sample and are affected by temperature (Gunasekaran and Panigrahi 2001). To date, fluorescence has been used mainly to analyze or classify food products (Christensen *et al*. 2006; Kulmyrzaev *et al*. 2007; Møller Andersen and Mortensen 2008) other than fruit and vegetables (Hagen *et al*. 2006; Le

Moigne *et al.* 2008).

Techniques using X-rays, such as X-ray computed tomography, have also been explored over the last 40 years (Yantarasri *et al.* 1998; Ogawa *et al.* 2003) mainly to study internal disorders and quality of fruit and vegetables (Abbott 1999), including water core and bruising in apples and disease in onions (Tollner and Muhammad 2001). It has been shown that Vis-NIR spectrometry is less expensive, safer and faster than X-ray-based techniques for rapid and non-destructive detection of section drying in citrus fruit (Peiris *et al.* 1998). Satisfactory correlations between computed tomography numbers and moisture, titratable acidity, pH, density and SSC were obtained with mango (Barcelon *et al.* 1999a) and peaches (Barcelon *et al.* 1999b). While those results are interesting, the measurements were performed on a small number of fruit and were limited to one variety from one site. Ogawa *et al.* (2003) recommended using X-ray imaging in conjunction with other techniques that explore the UV, Vis or IR regions. Haff *et al.* (2006) clearly stated the limitations of X-ray-based instruments, mainly the slow acquisition time (X-ray photograph and charge-coupled device (CCD)) and the high price of equipment (line scan X-ray machine). Research in this field is still exploratory, and the main commercial application of this technology is the detection of contaminants such as pits, insects (Valesco and Medina 2004), stones, and glass or metal fragments. While X-ray-related techniques are used commercially by the processed food industry, they have not yet been adopted for the inspection of fresh produce (Tollner and Muhammad 2001).

The much less used technology of magnetic resonance imaging (MRI) is based on the observation of the magnetic properties of atom nuclei in the sample when an external magnetic field is applied, and is the basic principle behind nuclear magnetic resonance (NMR). Clark *et al.* (1997) reviewed the application of MRI to pre- and postharvest studies of fruit and vegetables. Recently, Musse *et al.* (2009) used MRI to study the internal structure of tomatoes. Apple mealiness was also studied by NMR imaging and relaxometry (Barreiro *et al.* 2002). The effect of heat stress on tomato was studied by NMR micro-imaging (Iwahashi *et al.* 1999). In their study of mandarins, Clark *et al.* (1999) concluded that there was no trend between the NMR data and important quality parameters such as total SSC, pH and titratable acidity. Despite some encouraging results, NMR should be considered a research tool rather than a processing/sorting facility instrument to predict fruit and vegetable quality. This position is in contrast with the comment by Clark *et al.* (1997) that NMR imaging is bound to become an integral component of pre- and postharvest investigations of physiological changes in fruit and vegetables. While technological advances can be expected in the future, the price of the technology, the size of the equipment, and the complexity of the signal are still limiting factors.

While most of the light reaching a fruit or vegetable will only penetrate its outermost layers, sound waves can easily travel through such material. The acoustic impulse-response technique most likely takes it roots from the popular practice of thumping fruit, particularly melons, to judge ripeness. While this common practice is highly empirical, solid physical principles underlay acoustic impulse-response. Following an impact from a known object, under controlled conditions, sound and mechanical waves travel inside the fruit or vegetable under analysis. Those signals can be recorded using an appropriate non-contact listening device. Proper mathematical treatment allows the decomposition of complex signals into simpler components. Even if some potential applications exist for such a non-destructive method, it will likely be limited to larger fruit and vegetables, such as apples and melons. This method also showed only limited correlation with quality parameters such as texture and internal defects. Finally, the technique was judged difficult to implement and too slow for in-line application (ElMasry *et al.* 2008).

While non-destructive techniques are being perfected, the development of fast, accurate, inexpensive and objective destructive quality evaluation methods could be useful to replace subjective visual inspection techniques or expensive chemical or physical analyses. Recent developments in biosensors (Tinga *et al.* 2009) have lead to devices capable of measuring specific analytes that are indicators of quality in fresh fruit and vegetables (Terry *et al.* 2005). A biosensor combines a biological receptor component with a physicochemical detector component to provide quantitative or semi quantitative information about a specific analyte (Viswanathan *et al.* 2009). For example, a biosensor that quantifies the sugar/acid ratio in juice extracted from fresh fruit could be used to judge the quality of the produce based on taste. Biosensors have also been designed to detect contaminating microorganisms on food and a variety of analytes in fresh produce (Terry *et al.* 2005). By selecting the appropriate analyte or combination of analytes, biosensors could be designed as a sensitive, rapid, and inexpensive tool for use by non specialized persons to monitor the quality of fresh produce at any step in the cold chain, from harvest to retail display.

Visual inspection, chemical/physical analyses and non-destructive methods all require the magnitude of any given quality parameter to vary enough during the ripening process to allow the different stages of maturity to be easily distinguished. The discriminatory potential of all these techniques also depends on the magnitude of the parameter measured relative to a known reference. The potential of biosensors and non-destructive techniques to assess food quality has grown considerably since the turn of this century. Some techniques have progressed to the point of being commercialized, while others still remain experimental with more work required before they satisfy the industry's stringent criteria, including accuracy, ease of use, speed and cost.

Techniques that offer advantages over traditional visual or manual inspection are more likely to be adopted by the industry. Gains in speed, accuracy and consistency combined with limited or no sample preparation would represent major improvements over manual inspection. The capacity to simultaneously assess multiple quality parameters, particularly those that cannot be determined by visual inspection such as sweetness, acidity, bitterness and the presence of internal defects, increases the chances of any technique being adopted by industry. However, more work is needed in the field of instrument performance and signal treatment to provide the industry with robust methods. It is also likely that methods will have to be combined in order to get a comprehensive evaluation of quality (Butz *et al.* 2005).

With rapid and economical techniques available to evaluate the quality of fresh produce at specific steps in the cold chain, and with models capable of predicting the quality of fresh produce based on the environmental conditions that fresh fruit and vegetables are exposed to from harvest to marketing, produce growers, brokers and wholesalers will be able to make informed decisions on how to ensure that consistently high-quality fruit and vegetables are delivered to retail. This would have the added benefit of minimizing produce losses.

MEASURING ENVIRONMENTAL CONDITIONS IN THE SUPPLY CHAIN

Numerous monitoring systems are commercially available to trace the temperature and certain other environmental conditions surrounding perishable foods in the supply chain (Doyon and Lagimonière 2006). These parameters can be recorded with different systems in each segment of the supply chain. To obtain a complete history of the conditions surrounding a particular lot of fresh produce from field to retail display, it would be necessary to obtain the histories recorded while the lot was in each segment of the supply chain (LeBlanc and Vigneault 2006). Although this type of pedigree will indicate whether or not a lot of fresh produce has been exposed to adverse conditions, it does not necessarily represent the temperature, the atmosphere composition or other conditions of the produce itself. Systems that monitor the produce environment from field to retail can be integrated into the inventory management systems used by produce shippers, wholesalers and retailers (Doyon and Lagimonière 2006). Portable data loggers are becoming smaller and more economical every year. When placed inside a unit of fresh produce (container, pallet, box, bag, etc.), loggers could record produce environmental conditions from packing right up to when the contents of the unit are stacked in the retail display. Remote monitoring systems allow shippers to verify the condition of a lot of produce in transit, which is extremely useful for long-duration shipments. To effectively use these environmental condition histories, models need to be developed to predict the shelf-life remaining when a particular type of produce is exposed to specific conditions. Several researchers have tested various systems to determine their accuracy in predicting remaining shelf-life (LeBlanc and Vigneault 2008). For example, radio frequency identification (RFID) labels that record temperature are the ultimate traceability tool, as they will be able to reconstruct the history of a lot of produce from packing to retail display (Doyon and Lagimonière 2006). The RFID labels need to have data on the time-temperature tolerance of each type of produce that they must follow in order to be able to accurately indicate the changes in microbial or sensory qualities of fresh produce that have occurred. Regardless of the type of traceability tool used (portable data logger, time-temperature integrator, RFID label, etc.), external condition tolerance data is required for all types of fruit and vegetables to optimize inventory management.

CONCLUSION

To increase fresh fruit and vegetable availability and create more sustainable production systems, we need to focus on producing larger quantities of more nutritious and better-quality fruit and vegetables while reducing postharvest losses and using the same or fewer agricultural resources (soil, fertilizer, energy, chemicals and human resources).

Physiological quality deterioration varies significantly for each type of fruit and vegetables in response to the temperature and RH conditions encountered over time. Unfortunately, there is insufficient data to model these quality changes for most of the fruit and vegetables that are presently marketed. Research has focused mainly on determining the optimum environmental conditions for maintaining the quality of each specific horticultural product. The real impact of any abusive or even slightly deviated condition is rarely evaluated. Much research is needed to assess the impact of non-optimum environmental conditions on produce quality. Physiologists have much to do to understand the mechanisms involved in such situations before the impact of abusive conditions can be modelled.

Microbial contamination can occur in the field, prior to harvest or during any of several handling steps from harvest to retail display. To adequately predict microbial proliferation or disease development, a good understanding of the principal means of potential contamination during every step of the produce production and distribution chain is required. Research is needed to identify the strengths and weaknesses of produce distribution systems from the perspective of microbial safety and disease development. This knowledge will help determine what data needs to be measured throughout the produce distribution system to predict microbial contamination and proliferation as well as disease development. The ability to predict microbial proliferation or disease development in fresh produce, in response to the temperature and RH conditions encountered over time, would be a useful asset in this era in which consumers are concerned about food safety and food wastage.

Models that use temperature and RH data measured throughout the cold chain and quality data measured at intermittent steps in the chain, need to be developed to predict the produce quality that can be expected at each subsequent step in the chain. The development of such models requires data on the changes in the quality of a wide variety of fresh fruit and vegetables as a function of time, temperature and RH. One of the challenges in developing such models is defining the parameter or parameters that best describe the overall quality of fresh produce, given that the ideal parameters probably vary considerably depending on the type of fruit or vegetables. Associated with this is the challenge of finding the best tool to measure the quality (e.g. physiological quality, food safety and decay development) of fruit and vegetables at any point along the farm-to-fork continuum, thus allowing producers, shippers, wholesalers and retailers to identify the optimum market for a particular load of fresh produce. Once developed, such models will need to be integrated into produce traceability systems. Much work is still required to better track produce and its environmental conditions, but this work has been progressing rapidly over the past five years. Models need to be developed to predict product quality based on the data that is being or should be monitored in the produce production and distribution systems. We must not wait until the data are being recorded with traceability systems before we start developing models that predict produce quality.

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