Final report

Ethylene and microbial hotspots in the fresh produce supply chain

A report exploring the concentrations of ethylene and fungal spores through the fresh produce handling chain, with a view to identifying hotspots for the application of control technologies.
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Legacy research commissioned by the previous government

Front cover photography: Fresh produce in short-term storage at Mack Multiples.

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Executive Summary

WRAP is working with industry to identify ways of reducing wastage of fresh fruit and vegetables through the whole supply chain. From the packhouse, through distribution depots and retail outlets, to domestic households, every step of the chain offers opportunities to realise the benefits of avoiding waste.

This project focuses on the impact of present levels of ethylene gas and fungal spores on fresh fruit and vegetables, as they make their way through the supply chain. It measures these levels, assesses their impact on produce deterioration, and signals where the potential for improvement may lie through the introduction of technology, or where further investigation may be beneficial.

Both ethylene and microbial contamination, in the form of fungal spores, can increase the rate of product deterioration. In the case of ethylene exposure, for vegetables and ripe fruit, relatively long-term exposure is necessary to cause deterioration, in the form of senescence or over-ripening, whereas for fungal spores a short-term exposure is sufficient to cause infection that will lead to product deterioration. The concentrations at which ethylene can affect produce are very low. As it controls so many processes for maintaining quality of fruit and vegetables, it is a very important chemical for the fresh produce handling industry.

Methodology

Ethylene and fungal spore levels were measured at five stages through the grocery supply chain supplying multiple retailers: in storage facilities, packhouses, depots, back of shop stores, and in the retail area. Particular produce was selected for analysis, based on an existing list of ‘most wasted’ fresh commodities. This list comprised 21 items: nine types of vegetable and twelve types of fruit.

Ethylene measurements were taken using sampling bags and a laboratory gas chromatograph (GC) with flame ionisation detector (FID). Fungal spore counts were undertaken using an Oxoid air sampler, directing sampled air onto the surface of an agar plate, with Dichloran Rose Bengal Chloramphenicol agar, which is specific for fungi.

Results and conclusions

The results showed that, with only two exceptions, the highest ethylene concentrations were found within storage facilities, where produce is kept at the highest density and for the longest time within the whole supply chain. The two facilities with the lowest ethylene concentrations were newly designed, using technology designed to remove ethylene. Low concentrations of ethylene were detected in retail areas and back of shop store rooms, suggesting that ventilation in stores was suitably efficient.

Control of ethylene concentrations in the store rooms of storage facilities is likely to have the most significant impact on produce shelf-life, particularly for produce that is stored for longer periods.

Some information already exists on the sensitivity of specific produce to ethylene. The sensitive vegetables are broccoli, cauliflower, lettuce, cabbage and carrot; while the sensitive fruits are kiwifruit, tomato and strawberry. However, for many of these the lowest concentrations of ethylene to which they are sensitive is unknown. The sensitivity of other produce is currently unknown, but should now be measurable given advances in technology.

Fungal spore counts were variable, with hotspots detected in many locations. The highest values were clearly found in packhouses. This is one point in the supply chain where produce is moved from its packaging, so that fungal lesions will be disturbed and spores likely to scatter.

One storage facility had such a low microbial count that the tests were repeated to check their validity. This facility was found to have cleaned its air circulation system recently, highlighting the effectiveness of ‘good housekeeping’.

Recommendations

- The fresh produce industry should consider installing ethylene removal/scrubbing equipment within storage facilities, particularly for the most susceptible produce;
- Ethylene concentrations within packaging, and the effects of ethylene controls in packaging, should be measured, with an initial focus on broccoli and melon;
- Studies should be conducted on the most susceptible produce to define the effect of continuous exposure to low concentrations of ethylene; and
- The fresh produce industry should consider introducing fungal spore control technologies within packhouses, potentially including the use of covered bins to reduce atmospheric spore counts.
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Glossary and acronyms

1-methylcyclopropene (1-MCP): a chemical that inhibits ethylene action in plant tissues, widely used in the UK to treat apples after harvest to extend storage life.

6-methoxymellein: a fungal isocoumarin with a bitter flavour.

Abscisic acid (ABA): a plant hormone with a function in many plant developmental processes.

Abscission: the process by which a plant drops one or more of its parts, such as a leaf, fruit, flower or seed.

1 amino-cyclopropane-1-carboxylic acid (ACC): a chemical in the synthetic pathway of ethylene.

ACC oxidase: an enzyme that catalyses the last step in the biosynthesis of the plant hormone ethylene.

ACC synthase: an enzyme that catalyses a key step in the biosynthesis of the plant hormone ethylene.

Acetaldehyde: an organic chemical compound occurring naturally in coffee, bread, and ripe fruit, produced by plants as part of their normal metabolism.

Alkenes: a class of chemical compounds that includes ethylene.

Alpha- and Beta-Amylases: enzymes that break starch down into sugar.

Aminoethoxyvinylglycine (AVG): a compound that inhibits ethylene synthesis.

Aminooyxacetic acid (AOA): a plant growth inhibitor.

Anthesis: a period during which a flower is fully open and functional.

Anthocyanins: water-soluble vacuolar pigments that may appear red, purple, or blue according to pH. They belong to a parent class of molecules called flavonoids. Odourless and nearly flavourless, contributing to taste as a moderately astringent sensation. Anthocyanins occur in all tissues of higher plants, including leaves, stems, roots, flowers and fruits.

Avoidable food waste: food and drink thrown away that was edible at some point before disposal (e.g. slice of bread, apples, meat).

Carotenoid: organic pigments naturally occurring in the chloroplasts and chromoplasts of plants and some other photosynthetic organisms like algae, some types of fungus, and some bacteria.

Chlorophenyl Isopropyl Carbamate (CIPC): a potato sprout suppressant.

Chlorophyll: a critically important green pigment found in almost all plants and algae, giving leaves their green colour and absorbing light that is used in photosynthesis.

Chlorophyllase: a key enzyme in chlorophyll metabolism.

Climacteric fruit: fruit which have a pattern of ripening that is stimulated by ethylene, involves synthesis of more ethylene and cannot be stopped once started. Large changes occur in colour, texture and taste during ripening and there is a burst in respiration rate to provide the energy for this. Examples include apples and bananas.

Degreening: An artificial process to remove the green colour from otherwise mature fruit, typically involving the use of ethylene.
Dichloran Rose Bengal Chloramphenicol: A selective medium for the isolation and enumeration of yeasts and fungal moulds that are of significance in food spoilage.

Ethylene (C₂H₄): a gas produced by most plant tissues which acts as a plant hormone, stimulating a range of plant responses, including fruit ripening and tissue senescence.

Ethylene scrubbing: ethylene removal.

Flame Ionisation Detector (FID): detects chemicals on the basis of their ionisation in a flame.

Free Radicals: atoms, molecules or ions with unpaired electrons; highly chemically reactive and believed to regulate many processes.

Fungistatic: fungal growth inhibitor.

Invertase: an enzyme that catalyses the breakdown of sucrose.

Isocoumarin: a type of phenolic compound with a bitter taste often produced by plant tissues as part of their defence against rotting pathogens.

Jasmonic acid: a plant hormone that regulates plant growth and development.

Lamella: A component of the cell wall.

Lipoxygenases: enzymes involved in the breakdown of lipids (chemical components of fats).

Mesocarp: a botanical term for the succulent and fleshy middle layer of fruit.

Metabolism: the set of chemical reactions that happen in living organisms to maintain life.

Microbial contamination: contamination with fungi and/or bacteria.

Microfibrils: a very fine fibre-like strand within plant cell walls.

Mucor: a genus of approximately 3,000 species of mould.

Mycotoxin: a chemical produced by fungi that is toxic to humans.

Necrosis: premature death of living cells and tissue.

Non-climacteric plant tissues: those that are sensitive to ethylene but do not respond by synthesising more ethylene. Typical responses include loss of green colour in non-climacteric fruit, such as oranges, and senescence, such as in broccoli.

Packhouse: a facility where fresh produce is graded for quality and packed.

Part per billion (ppb): a measure of concentration equivalent to 0.0000001%.

Part per million (ppm): a measure of concentration equivalent to 0.0001%.

Peroxidase: a large family of enzymes that catalyse the oxidation of a range of chemicals.

Petiole: the stalk of a leaf, attaching the blade to the stem.

Phenolic compounds: chemical compounds with a hydroxyl group bonded directly to an aromatic hydrocarbon group; similar, but not identical, to alcohols; associated with higher acidity and thus distasteful to eat. Often involved in plant defences against rotting pathogens.

Programmed Cell Death (PCD): death by means of a regulated process in accordance with an organism’s lifecycle.
Proteolytic Enzyme: an enzyme that breaks the long chainlike molecules of proteins into shorter fragments (peptides) and eventually into their components, amino acids.

\( Q_{10} \) value: the ratio of respiration rates at one temperature to the rate at 10°C less.

Respiration: the oxidation of sugars, lipids and organic acids to \( \text{CO}_2 \) and water, with the release of energy, including heat.

Rhizobitoxine: an inhibitor of ethylene biosynthesis in plants.

Rhizopus: a genus of common fungi found on plants, particularly associated with mature fruits and vegetables.

Salicylic acid (SA): a hormone found in plants with roles in plant growth and development.

Senescence: death of plant tissues in a controlled process. Examples include shrivelling and drop of flower petals, browning and drop of leaves in autumn.

SmartFresh™: the commercial form of 1-methylcyclopropene.

Watersoaking: a physiological disorder in fruit, such as melon, characterised by a glassy texture of the flesh resulting from cell membrane damage.

1-MCP: 1-methylcyclopropene
ABA: Abscisic Acid
ACC: 1 amino-cyclopropane-1-carboxylic acid
AOA: Aminooxyacetic acid
AVG: Aminoethoxyvinylglycine
CA: Controlled Atmosphere
CIPC: Chlorophenyl Isopropyl Carbamate
DAA: Days after Anthesis
FID: Flame Ionisation Detector
GC: Gas Chromatograph
PCD: Programmed Cell Death
ppb: parts per billion
ppm: parts per million
SA: Salicylic Acid

Acknowledgements

We would like to acknowledge the technical input of the project partners (Mack Multiples, Sainsbury’s, Onnic International, MAPCAP Technology ICA and Landseer Ltd) which was essential for guiding the project. We are extremely grateful to the staff at the supermarkets, depots, packhouses and storage facilities where the mapping studies were carried out, for their time and advice.
1.0 Introduction and background to the project

1.1 Overview of supply chain food waste

The overall level of food waste from the food and drink industry is estimated to be at least 11 million tonnes (Table 1), and much of this goes to landfill. The majority of food and drink waste occurs at household level (8.3 million tonnes). WRAP is carrying out a number of activities to reduce household food waste as part of the "Love Food Hate Waste" programme and Courtauld Commitment, a responsibility deal aimed at improving resource efficiency and reducing the carbon and wider environmental impact of the grocery retail sector. A key principle is that waste in the household depends not only on how fresh produce is treated in the household itself, but also on its treatment throughout the supply chain.

Table 1: Estimated total food and drink waste arisings from the supply of food and drink to households in the UK

<table>
<thead>
<tr>
<th>Supply chain stage</th>
<th>Total waste arisings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Million tonnes</td>
</tr>
<tr>
<td>Manufacture</td>
<td>3.2</td>
</tr>
<tr>
<td>Distribution and retail</td>
<td>0.37</td>
</tr>
<tr>
<td>Household</td>
<td>8.3</td>
</tr>
<tr>
<td>Total</td>
<td>11.87</td>
</tr>
</tbody>
</table>

Source: "Waste arisings in the supply of food and drink to households in the UK" WRAP, 2009

As well as decreasing the amount of material being sent to landfill, the reduction of food waste is key to reducing greenhouse gas emissions. Food 2030 reports that “the greenhouse gas footprint of the UK food chain was 160 million tonnes CO$_2$ equivalent (CO$_2$e) in 2006, an estimated 22% of emissions associated with all UK economic activity”. A WWF report, states that a further 101 million tonnes CO$_2$e from land use change in other countries is attributable to UK food. This results in the food chain contribution to UK CO$_2$e emissions rising to 30%.

Figure 1 indicates that of all household food and drink waste (8.3 million tonnes) 36% is fresh vegetables, salads and fruit (equating to 3 million tonnes).

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1 Waste arisings in the supply of food and drink to households in the UK, WRAP, 2009
2 http://www.wrap.org.uk/retail/courtauld_commitment/index.html
4 How low can we go? WWF, January 2010: http://assets.wwf.org.uk/downloads/how_low_can_we_go.pdf
Ethylene and microbial hotspots in the fresh produce supply chain

1. Food and drink waste can be categorised by how avoidable it is:
   - unavoidably (such as inedible components - bones, egg shells)
   - possibly avoidable (components often not eaten such as potato skins), and
   - avoidable.

Avoidable waste occurs when too much food is prepared for a meal, or when food is not used before it deteriorates. Of the 3 million tonnes of fresh vegetables, salads and fruits wasted in the UK, 1.4 million tonnes is considered to be avoidable. Two thirds of this is wasted because the food is not used in time.

Reducing this waste not only has a direct effect by reducing landfill and greenhouse gas emissions, but will also reduce the level of resources that were used unnecessarily to create and dispose of the food and drink that is produced, but not consumed. These resources include land and water for agriculture, inorganic fertilisers, transport fuel, packaging materials, and electricity for storage at low temperature.

1.2 Objectives

WRAP has been working to identify approaches to reducing wastage of fresh fruit and vegetables through the whole supply chain, from packhouse, through distribution depots and retail outlets to domestic households. This project concentrates on the impact of ethylene and microbial contamination, with the following objective:

To assess the impact of present levels of ethylene and microbial contamination across the supply chain, from packhouse to retail display, on quality/shelf-life of fresh produce and, hence, the potential for improvements in shelf life through the introduction of existing technology.

Both ethylene and microbial contamination can increase the rate of product deterioration, but very little information has previously been obtained on the concentrations of ethylene and microbial spores in the environment at different stages of the supply chain. In the case of ethylene exposure, for vegetables and ripe fruit, relatively long-term exposure is necessary to cause deterioration, whereas for fungal spores a short-term exposure is sufficient to initiate an infection that will lead to deterioration of the product. If useful technical interventions are to be implemented, it is vital to obtain information on concentrations of ethylene and microbial spores and to relate the results to existing knowledge on the levels of sensitivity of fresh produce.
1.3 Technical background

1.3.1 The role of ethylene in deterioration of fruit and vegetables

Ethylene gas (C₂H₄) is produced naturally by most plant tissues, especially ripening fruit. It is a plant hormone that controls many biological processes. Among plant hormones, ethylene is unusual because it is a gas. Consequently if one plant or plant organ starts to produce ethylene, nearby plant tissues are affected. For plants, many processes are actively controlled as part of the natural life cycle, such as those involving tissue death, e.g. leaf drop in deciduous trees, petal drop in flowers, and over-ripening of fruit. Many of these are controlled and/or stimulated by ethylene, which can therefore speed up deterioration in fruits and many vegetables, particularly leafy greens.

As it controls so many processes for maintaining quality of fruit and vegetables, ethylene is an extremely important chemical for the fresh produce handling industry. For example, bananas transported green to the UK are stimulated to ripen by being fumigated with ethylene within warm ripening rooms. However, as ethylene also stimulates deterioration and senescence (an active process of cell death that leads to tissue deterioration), it is important to control concentrations to maintain quality. Thus, there is a growing recognition of the importance of controlling ethylene in fresh produce stores.

The concentrations at which ethylene can affect produce are very low. There is evidence that many products are sensitive to concentrations well below 100 parts per billion (ppb). Ethylene is known to build up in packhouses to concentrations near 1000 ppb (1 part per million (ppm)), which is above the threshold of sensitivity of most produce. As an example, a study conducted on a range of produce showed a 60% extension of post-harvest life when stored in <5 ppb compared with 100 ppb ethylene (Wills et al., 1999).

The biochemistry of how ethylene controls plant processes is very complex and beyond the scope of this report. However, in order to relate the observation of ethylene concentrations to their likely effects on fresh produce, it is useful to understand some of the background principles. Processes controlled by ethylene can be classified into two types in terms of the way in which ethylene control occurs:

- **System 1.** Ethylene ‘stimulates’ the biological process; if ethylene concentrations are increased the process goes faster, and if ethylene concentrations are reduced or ethylene is removed completely then the process slows/stops. This system applies to ethylene stimulation of the deterioration/senescence of vegetables, the over-ripening/senescence of fruit, and the discolouration of cucumber and browning of broccoli.

- **System 2.** Ethylene acts as a switch that cannot be stopped. Thus ethylene ‘triggers’ the biological process. If ethylene levels are reduced or ethylene is removed completely then the process continues, albeit at a slower pace. This is the case for the initiation of ripening of certain fruits, which are called climacteric fruit. These include bananas, apples, tomatoes, kiwifruit, pears and avocados, but not grapes, oranges and lemons.

On the whole, during the stages of the supply chain considered in this project, ripening would already have been initiated in all climacteric fruits and would therefore be out of our control (Figure 2). This project is concerned with System 1 processes and the exposure to continuous ethylene. Figure 3 demonstrates some of the effects of such an extended exposure to ethylene.
Figure 2: Ethylene treatment triggers the ripening of bananas, which are climacteric fruit, through system 2, and therefore bananas need only temporary exposure to ethylene.

![Ethylene treatment triggers the ripening of bananas](image)

Figure 3: Exposure to ethylene can induce brown streaks in leafy vegetables through system 1 (in this case, Chinese leaves).

![Exposure to ethylene can induce brown streaks](image)

1.3.2 Microbial spore count: rotting pathogens and their effects on shelf-life of fruit and vegetables.

Fungi, bacteria and viruses can all attack plant tissues. Generally viral diseases are evident prior to harvest and are therefore not considered a problem for produce quality after harvest. Fungi grow better in acidic environments while bacteria prefer less acidity. As fruit tend to be acidic and vegetables less so, fungal pathogens are more prevalent in fruit, with bacterial pathogens more prevalent in leafy vegetables. During the post-harvest supply chain, losses due to fungal rots of fruit (see Figure 4) are more significant than losses due to bacterial rots of vegetables. Many fungal fruit rots are due to latent infections. In this case the infection occurs before harvest, but is only able to develop as the fruits ripen. Generally, fungal infections that occur during the handling chain can only invade the tissues where the product is damaged.

In this project we are concerned with new fungal infections occurring as a result of fungal spores in the air. Whereas for ethylene relatively long-term exposure is necessary to cause deterioration, for fungal spores a short-term exposure is sufficient to initiate an infection that will lead to deterioration of the product.
1.4 Project team

This work was managed by Neil Hipps of East Malling Research and included combined input from the stakeholders below:

<table>
<thead>
<tr>
<th>Organization</th>
<th>Name</th>
<th>Role</th>
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</thead>
<tbody>
<tr>
<td>East Malling Research</td>
<td>Neil Hipps</td>
<td>Project Manager</td>
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<tr>
<td></td>
<td>Karen Thurston</td>
<td>Postharvest technologist</td>
</tr>
<tr>
<td></td>
<td>David Johnson</td>
<td>Postharvest technologist</td>
</tr>
<tr>
<td>Natural Resources Institute</td>
<td>Debbie Rees</td>
<td>Postharvest technologist</td>
</tr>
<tr>
<td></td>
<td>Richard Colgan</td>
<td>Postharvest technologist</td>
</tr>
<tr>
<td>Mack Multiples</td>
<td>Cristian Metzger</td>
<td>Innovation technologist</td>
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<td></td>
<td>Bruce McGlashan</td>
<td>Fresh produce technologist</td>
</tr>
<tr>
<td>Sainsburys</td>
<td>Theresa Huxley</td>
<td>Fresh produce technologist</td>
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<tr>
<td>Onnic International</td>
<td>Peter Holmes</td>
<td>Ozone technology</td>
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<td>MAPCAP Technology</td>
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<td>ICA</td>
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<tr>
<td>Landseer Ltd</td>
<td>Stephen Lawrence</td>
<td>Ethylene scrubbing technology</td>
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<tr>
<td></td>
<td>Mark Tully</td>
<td>Smartfresh Technology</td>
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</table>
2.0 Methodology

Measurements of ethylene and microbial count levels along the fresh produce supply chain were carried out. The information obtained helped identify where technological interventions could be implemented to reduce ethylene and/or microbial levels.

2.1 Definition of the handling chain and choice of survey locations

It has been estimated that 66% of the UK grocery retail is through the multiples\(^6\); for this reason the surveys of the handling chain reported in this project focused on supply to the retail multiples. The blue dashed line in Figure 5 indicates the parts of the supply chain considered.

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**Figure 5:** components of the UK fresh produce supply chain considered

A list of the locations surveyed during the study, and dates on which they were surveyed, is in Appendix 1.

\(^6\) “Waste arisings in the supply of food and drink to households in the UK” WRAP 2010
2.2 Choice of target produce

When choosing target produce, the objective was to include the products that contribute most significantly to waste; WRAP’s Household Food and Drink Waste in the UK (2009) details the “most wasted” fresh commodities within the household as presented in Figures 6 and 7 below.

**Figure 6:** The amount of vegetable waste within UK households, split by avoidability

![Figure 6: The amount of vegetable waste within UK households, split by avoidability](image)

**Figure 7:** The amount of fruit waste within UK households, split by avoidability

![Figure 7: The amount of fruit waste within UK households, split by avoidability](image)

Source: “Household Food and Drink Waste in the UK”, WRAP 2009
Exodus Diary Research 2007 was also referenced in selecting the produce on which to focus. The produce selected for study in this work were: broccoli, cauliflower, cucumber, lettuce, cabbage, carrot, onion, potato, mushroom, tomato, kiwifruit, apple, pear, avocado, banana, grape, orange, lemon, strawberry, raspberry and melon. The main commodities that contribute significantly to waste not considered are sweetcorn, green beans and stone fruit.

2.3 Review of available information on the effects of ethylene and microbial contamination on fresh produce

The scientific literature was reviewed to provide a basis for assessing the implications of the ethylene and microbial measurements. A review on the effects of ethylene is included in Appendix 2. The information it contains is referred to within the discussion of results. Unlike ethylene, no reports were found in the scientific literature specifying a spore count above which the shelf life of any particular product is affected.

Studies to relate spore count to rates of deterioration would be extremely complex and were considered outside the scope of this project. The most straightforward strategy to determine the impact of exposure would be to carry out tests in which strategies to control fungal spores were implemented, and then the effects on product shelf-life tested. This project concentrated on determining the places in the supply chain where produce was exposed to the highest levels of microbial spores, and therefore where intervention could be most effective.

2.4 Measurement of ethylene

Accurate measurement of ethylene was essential if we were to draw valid conclusions. As more detailed scientific investigations have been carried out on ethylene, its role as a plant hormone, and in particular its effects on post-harvest behaviour of plant products, it has become apparent that plant tissues are sensitive at lower concentrations (<100 ppb) than previously realised. One reason that this was not previously fully appreciated is the technical difficulty of measuring ethylene at concentrations lower than 100 ppb. Although there is a range of ethylene sensors available, these differ in their sensitivity. They also differ in their specificity (i.e. the extent to which other gases may be mistakenly detected as ethylene, thereby presenting false positive reactions).

So that we could be sure that our ethylene measurements were reliable, at the start of the project three methods for measuring ethylene were compared. The most reliable method identified was a laboratory gas chromatograph (GC) with flame ionisation detector (FID).

The laboratory GC used was not portable, and therefore it was necessary to take air samples and transport them to the laboratory. This was done using gas sampling bags. Initially bags were filled using a syringe, but subsequently a pump was purchased to speed up the process. Figure 8 shows the arrangement used to do this. The pump is attached to a sealable chamber (vacuuchamber), into which the bag is placed attached to a tube the other end of which is positioned at the sampling point. The pump is used to pump air out of the chamber. The pressure reduction sucks a sample into the bag. This arrangement ensures that there can be no contamination of the sample from the pump itself. This is important in situations where the concentration of the gas to be measured is low.

Note: throughout this report ethylene concentrations are given in parts per billion (ppb). In the literature ethylene concentrations are often given in parts per million (ppm). 1 ppm = 1000 ppb.

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7 Exodus Diary Research 2007: Kitchen Diary Top Line Results based on 284 Diaries and analysis by WRAP based on Defra’s Expenditure and Food Survey 2004/5.
Tests were carried out that showed the bags could be stored for up to 48 hours without any change in sample composition. Whenever bags were found partially or fully deflated after sampling, indicating a possible leak, they were discarded.

2.5 Assessment of microbial load/fungal spore count

The microbial load of the atmosphere was measured in terms of fungal spore count using an Oxoid air sampler (Figure 9).

Figure 9: Oxoid air sampler

The unit samples air at a fixed rate of 100 litres per minute. Air is drawn through small holes in the sample head and directed onto the surface of an agar plate. The agar plate is then removed and incubated in order to assess the load. For this survey each location was tested using one plate exposed to 5 litres of air and a second plate exposed to 200 litres of air. Dichloran Rose Bengal Chloramphenicol agar was used, which is specific for fungi. Bacterial growth is inhibited by the antibiotic Chloramphenicol.

2.6 Data Analysis

Data on ethylene concentrations and fungal spore count have been presented as means for each location. Ethylene concentrations were consistent within each location so that an average value (with standard error of the mean, SEM) is considered a valid measure of the environment. This is presumably due to the relative rapid rate of diffusion of ethylene, which has the same density as air, and the rates of air movement. Unlike ethylene concentrations, fungal spore counts were variable with hotspots in many locations. Means by location are presented, together with the range.
3.0 Results

3.1 Distribution of ethylene and microbial load within each location and at different stages in the supply chain

The ethylene concentrations and microbial levels measured at different stages in the fresh produce supply chain are given in Table 2. The small variations in ethylene within each location are reflected in the low values of standard errors of the mean (SEM).

The extent to which there may be gradients in the concentration of ethylene depends (a) on rates of ethylene production by produce, and (b) on rates of air circulation to equalise concentrations. We found that within each location mapped the range in ethylene concentration was small. For example, within store rooms air samples were taken from the aisles and also between boxes within pallets (but without breaking packaging). No difference between aisles and no accumulation of ethylene within boxes was observed. In the supermarket retail areas ethylene was usually not detected, except at low concentrations (approximately 20 ppb) near apples and pears both of which are high ethylene producers. Our conclusion was that variation in ethylene within any location is small. Ethylene has a molecular weight of 28, which is the same as that of nitrogen, the main constituent of air. Thus, unlike CO₂, which is heavier than air, we would not expect gradients of ethylene with height. The lack of variation further suggests that in these situations the diffusion of the gas is sufficient to counteract ethylene production by high ethylene producers.

Fungal spore counts, on the other hand, were not homogeneous within locations. For example, in supermarket retail areas significantly higher counts were often observed near the onions and potatoes (probably a result of soil within some consignments). Due to the lack of homogeneity of spore counts, the range of counts, rather than SEM, are given in Table 2.
### Table 2: Average ethylene concentrations and fungal spore counts by location through the supply chain

<table>
<thead>
<tr>
<th>Location</th>
<th>Ethylene concentration (ppb) Mean</th>
<th>SEM</th>
<th>Fungal spore count [m$^{-3}$] Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Retail area</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supermarket A, large</td>
<td>3</td>
<td>4</td>
<td>745</td>
<td>300 - 2600</td>
</tr>
<tr>
<td>Supermarket B, large</td>
<td>2</td>
<td>1</td>
<td>3654</td>
<td>120 - 24200</td>
</tr>
<tr>
<td>Supermarket C, medium</td>
<td>2</td>
<td>1</td>
<td>1838</td>
<td>150 - 18000</td>
</tr>
<tr>
<td>Supermarket D, medium</td>
<td>35</td>
<td>5</td>
<td>131</td>
<td>75 - 190</td>
</tr>
<tr>
<td>Supermarket E, small</td>
<td>31</td>
<td>4</td>
<td>165</td>
<td>110 - 195</td>
</tr>
<tr>
<td><strong>Back of shop store</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supermarket A, large</td>
<td>48</td>
<td>4</td>
<td>50</td>
<td>30 - 220</td>
</tr>
<tr>
<td>Supermarket B, large</td>
<td>37</td>
<td>2</td>
<td>38</td>
<td>25 - 300</td>
</tr>
<tr>
<td>Supermarket C, medium</td>
<td>0</td>
<td>0</td>
<td>715</td>
<td>430 - 935</td>
</tr>
<tr>
<td>Supermarket D, medium</td>
<td>35</td>
<td>2</td>
<td>131</td>
<td>405 - 720</td>
</tr>
<tr>
<td>Supermarket E, small</td>
<td>18</td>
<td>4</td>
<td>175</td>
<td>175</td>
</tr>
<tr>
<td><strong>Depots</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depot A</td>
<td>8</td>
<td>1</td>
<td>1428</td>
<td>170 - 6536</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>4</td>
<td>949</td>
<td>170 - 3000</td>
</tr>
<tr>
<td>Depot B</td>
<td>41</td>
<td>2</td>
<td>772</td>
<td>655 - 970</td>
</tr>
<tr>
<td>Depot C</td>
<td>91</td>
<td>5</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>Packhouses</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Packhouse A, mixed commodities</td>
<td>53</td>
<td>5</td>
<td>15867</td>
<td>6000 - 23800</td>
</tr>
<tr>
<td>Packhouse B, mixed commodities</td>
<td>-</td>
<td></td>
<td>9318</td>
<td>1130 - 30800</td>
</tr>
<tr>
<td>Packhouse C, limited commodity range</td>
<td>174</td>
<td>13</td>
<td>8200</td>
<td>4000 - 12400</td>
</tr>
<tr>
<td>Packhouse D, limited commodity range</td>
<td>28</td>
<td>28</td>
<td>2864</td>
<td>4200 - 4400</td>
</tr>
<tr>
<td><strong>Stores</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage facility A store 1</td>
<td>72</td>
<td>5</td>
<td>2400</td>
<td>2400</td>
</tr>
<tr>
<td>Storage facility A store 2</td>
<td>76</td>
<td>2</td>
<td>1000</td>
<td>800 - 1200</td>
</tr>
<tr>
<td>Storage facility B store 3</td>
<td>222</td>
<td>13</td>
<td>283</td>
<td>245 - 300</td>
</tr>
<tr>
<td>Storage facility B store 4</td>
<td>261</td>
<td>5</td>
<td>190</td>
<td>190</td>
</tr>
<tr>
<td>Storage facility B store 5</td>
<td>327</td>
<td>6</td>
<td>50</td>
<td>45 - 55</td>
</tr>
<tr>
<td>Storage facility B store 6</td>
<td>442</td>
<td>11</td>
<td>810</td>
<td>695 - 925</td>
</tr>
<tr>
<td>Storage facility B store 7</td>
<td>333</td>
<td>8</td>
<td>805</td>
<td>675 - 935</td>
</tr>
<tr>
<td>Storage facility B store 8</td>
<td>336</td>
<td>6</td>
<td>925</td>
<td>665 - 1155</td>
</tr>
<tr>
<td>Storage facility B store 9</td>
<td>183</td>
<td>16</td>
<td>1000</td>
<td>440 - 1465</td>
</tr>
<tr>
<td>Storage facility C store 1</td>
<td>468</td>
<td>10</td>
<td>115</td>
<td>115</td>
</tr>
<tr>
<td>Storage facility C store 2</td>
<td>251</td>
<td>8</td>
<td>208</td>
<td>208</td>
</tr>
<tr>
<td>Storage facility C store 3</td>
<td>220</td>
<td>7</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Storage facility C store 4</td>
<td>291</td>
<td>6</td>
<td>103</td>
<td>103</td>
</tr>
<tr>
<td>Storage facility D store 1 (apples)</td>
<td>3612</td>
<td>68</td>
<td>10</td>
<td>5 – 15</td>
</tr>
<tr>
<td>Storage facility D store 2</td>
<td>548</td>
<td>12</td>
<td>8</td>
<td>5 - 10</td>
</tr>
<tr>
<td>Storage facility D store 3</td>
<td>442</td>
<td>55</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
3.1.1 Ethylene

Ethylene concentrations are consistent within each location so that an average value is a valid measure of the environment. With only two exceptions, the highest ethylene concentrations were found within store rooms, where produce is kept at the highest density and for the longest time within the whole supply chain. The two store rooms with low ethylene concentrations (storage facility A) had a limited range of produce (tomatoes, cucumber and peppers), were newly designed facilities and were using a technology designed to remove ethylene.

Low concentrations of ethylene were detected within retail areas and back of shop store rooms (less than 50 ppb) suggesting that ventilation in stores was suitably efficient. With concentrations of ethylene well below 50 ppb, a detailed investigation of the effects of store design on ethylene concentration was not considered necessary.

For one packhouse the concentration of ethylene was moderately high at nearly 200 ppb (Packhouse C). This was a packhouse that deals with broccoli, cauliflower and cabbage, commodities which are particularly sensitive to ethylene.

One store room had an extremely high concentration of ethylene (Storage facility D, store 1). This was a store for apples, which are very high ethylene producers.

Table 3 summarises the sensitivity of target produce to ethylene, in order to show the implications of the ethylene concentrations that were measured at each stage of the supply chain, and the potential for reducing produce deterioration and waste through improving ethylene control. For vegetables, broccoli, cauliflower, lettuce, cabbage and carrot are likely to be affected by the ethylene concentrations measured in store rooms, while the sensitive fruits are kiwifruit, tomato and strawberry.

<table>
<thead>
<tr>
<th>Product</th>
<th>Critical concentration of ethylene above which the product is sensitive</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vegetables</strong></td>
<td></td>
</tr>
<tr>
<td>Broccoli</td>
<td>&lt;100 ppb</td>
</tr>
<tr>
<td>Cauliflower</td>
<td>&lt;100 ppb</td>
</tr>
<tr>
<td>Cucumber</td>
<td>Sensitive at 1000 ppb, effects of lower concentrations unknown</td>
</tr>
<tr>
<td>Lettuce</td>
<td>&lt;100 ppb</td>
</tr>
<tr>
<td>Cabbage</td>
<td>&lt;100 ppb</td>
</tr>
<tr>
<td>Carrot</td>
<td>&lt;100 ppb</td>
</tr>
<tr>
<td>Onion</td>
<td>Exposure to ethylene probably beneficial as it inhibits sprouting</td>
</tr>
<tr>
<td>Potato</td>
<td>Exposure to ethylene probably beneficial as it inhibits sprouting</td>
</tr>
<tr>
<td><strong>Fruit</strong></td>
<td></td>
</tr>
<tr>
<td>Kiwifruit</td>
<td>&lt;10 ppb</td>
</tr>
<tr>
<td>Tomato</td>
<td>&lt;100 ppb</td>
</tr>
<tr>
<td>Apple</td>
<td>Unknown for ripe fruit, probably about 1000 ppb</td>
</tr>
<tr>
<td>Pear</td>
<td>Unknown for ripe fruit, probably about 1000 ppb</td>
</tr>
<tr>
<td>Avocado</td>
<td>Unknown for ripe fruit, probably high</td>
</tr>
<tr>
<td>Banana</td>
<td>Unknown for ripe fruit, probably high</td>
</tr>
<tr>
<td>Grape</td>
<td>&gt;10 000 ppb</td>
</tr>
<tr>
<td>Orange</td>
<td>Unknown, probably &gt;1000 ppb</td>
</tr>
<tr>
<td>Strawberry</td>
<td>&lt;100 ppb</td>
</tr>
<tr>
<td>Melon</td>
<td>Unknown</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td></td>
</tr>
<tr>
<td>Mushroom</td>
<td>Not sensitive</td>
</tr>
</tbody>
</table>
3.1.2 Microbial levels

Fungal spore counts were variable with hotspots detected in many locations, so that in Table 2 the range in measured values is given as well as the average. Average values by location indicate clearly that the highest values are found in packhouses.

Storage facility D had such a low microbial count that the measurements were repeated to check their validity. These stores and the air circulation systems had been cleaned two weeks before our measurements. This indicates the effectiveness of such cleaning.

To understand the implications of the fungal spore counts on shelf life of product, ideally we should relate fungal spore count to the effect it has on rates of rotting of each product. In practice this was extremely difficult, owing to differences between batches of produce in susceptibility to rotting, and differences in latent infections. An alternative approach, once we have identified packhouses as the critical point in the system for fungal infection, would be to apply a method to control fungal spore and assess its effects on wastage (see Section 5, Recommendations).
4.0 Conclusions

4.1 The impact of ethylene control through the fresh produce supply chain

We have demonstrated that at most stages of the fresh produce supply chain, ethylene concentrations are below 100 ppb (usually below 50 ppb), but that within store rooms they are typically above 200 ppb. A review of the existing information on the sensitivity of produce to ethylene indicates that many products are affected by ethylene concentrations of 100 ppb and below. Consequently, compared to other stages in the handling chain, control of ethylene concentrations in store rooms is likely to have the most significant impact on shelf-life of produce. Given that the magnitude of the ethylene effect is related to the time of exposure, the effects will be particularly significant for products that are stored for longer periods.

The target ethylene concentrations for store rooms depend on the specific ethylene sensitivity of the stored products. For a number of products this specific information is lacking, probably due to difficulties in accurate measurement of low ethylene concentrations. Experimentally, now that it is possible to measure ethylene accurately at low concentration (below 50 ppb), it would be relatively easy to obtain this information.

For many products the concentrations of ethylene within packaging are likely to be high (above 1000 ppb). Preliminary measurements of ethylene concentrations within packaging confirmed that concentrations can be much higher than the surrounding environment, and can reach concentrations where produce shelf-life would be affected. For example, concentrations could be greater than 10 000 ppb for melons, and greater than 1000 ppb for broccoli.

See Appendix 3 for produce-specific information on the ethylene susceptibility of a range of fresh fruit and vegetables.

4.2 The impact of fungal spore control through the fresh produce supply chain

A clear pattern of fungal spore counts emerged, showing that, compared to other parts of the supply chain, spore counts were highest in the packhouses. This is the point in the supply chain where produce is moved from its packaging so that fungal lesions will be disturbed and spores likely to scatter. The magnitude of the effect of fungal spores will not necessarily be related to time of exposure – a short exposure to high spore counts can infect damaged produce. Even though produce may not be in a packhouse for long, therefore, the presence of a high spore count could have a significant effect.

It is not possible, with present knowledge, to specify a spore count above which the shelf life of any particular product will be affected. The most obvious approach to determining the impact of this exposure would be to carry out tests in which strategies to control fungal spores are implemented, and then the effects on product shelf-life tested. This study is intended, however, to help the fresh produce industry by indicating where such strategies could most effectively be implemented.

5.0 Recommendations

- The use of ethylene removal/scrubbing within store rooms should be implemented by the fresh produce industry. Key produce for which this would be most valuable are: broccoli, cauliflower, cucumber, lettuce, cabbage, carrot, kiwifruit, tomato and strawberry.
- Concentrations of ethylene within packaging should be defined and the effects of ethylene control strategies within packaging should be tested. Focus products should include broccoli and melon.
- Studies should be conducted on specific products to define the effect of continuous exposure to low concentrations of ethylene in the range 10 – 200 ppb. These should focus on broccoli, cauliflower, cucumber, lettuce, cabbage and carrot. Additionally, studies should be extended to consider climacteric fruit after ripening (apple, pear and melon).
- The use of fungal spore control technologies within packhouses should be implemented by the fresh produce industry. Appropriate technologies to test include the use of covered bins which could significantly reduce atmospheric spore counts.
Appendix 1: Dates & content of locations surveyed

<table>
<thead>
<tr>
<th>Stage of the fresh produce handling chain</th>
<th>Survey location</th>
<th>Comments</th>
<th>Date(s) surveyed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage (pre and post packhouse)</td>
<td>Storage facility A</td>
<td>2 store rooms, mixed commodities</td>
<td>April 2010</td>
</tr>
<tr>
<td></td>
<td>Storage facility B</td>
<td>7 store rooms, mixed commodities</td>
<td>Sept 2009 / Feb 2010</td>
</tr>
<tr>
<td></td>
<td>Storage facility C</td>
<td>3 store rooms, limited range of commodities</td>
<td>June 2010</td>
</tr>
<tr>
<td></td>
<td>Storage facility D</td>
<td>3 store rooms, mixed commodities</td>
<td>May 2010 / June 2010</td>
</tr>
<tr>
<td>Packhouse mixed produce</td>
<td>Packhouse A</td>
<td>Mixed commodities</td>
<td>April 2010</td>
</tr>
<tr>
<td></td>
<td>Packhouse B</td>
<td>Mixed commodities</td>
<td>April 2009 / Sept 2009</td>
</tr>
<tr>
<td></td>
<td>Packhouse C</td>
<td>Limited range of commodities</td>
<td>June 2010</td>
</tr>
<tr>
<td></td>
<td>Packhouse D</td>
<td>Limited range of commodities</td>
<td>June 2009</td>
</tr>
<tr>
<td>Supermarket depot</td>
<td>Depot A</td>
<td>Large range of commodities</td>
<td>March 2010 / July 2010</td>
</tr>
<tr>
<td></td>
<td>Depot B</td>
<td>Large range of commodities</td>
<td>July 2010</td>
</tr>
<tr>
<td></td>
<td>Depot C</td>
<td>Large range of commodities</td>
<td>March 2010</td>
</tr>
<tr>
<td>Supermarket retail outlets</td>
<td>Supermarket A</td>
<td>Large</td>
<td>April 2009 / Nov 2009</td>
</tr>
<tr>
<td></td>
<td>Supermarket B</td>
<td>Large</td>
<td>Jan 2010</td>
</tr>
<tr>
<td></td>
<td>Supermarket C</td>
<td>Medium</td>
<td>Nov 2009</td>
</tr>
<tr>
<td></td>
<td>Supermarket D</td>
<td>Medium</td>
<td>May 2010</td>
</tr>
<tr>
<td></td>
<td>Supermarket E</td>
<td>Small</td>
<td>May 2010</td>
</tr>
</tbody>
</table>
Appendix 2: Literature review on the effects of ethylene on fresh produce

Introduction

Fruits and vegetables come from a morphologically diverse range of plant tissue, encompass numerous organs in vegetative and or reproductive stages, and belong to a large number of botanical families. Fruits tend to derive from reproductive organs arising from the swelling of floral tissues (e.g. receptacle ovary, septum, pericarp and endocarp), while vegetables cover a diverse range of edible plant tissues. Vegetables can be divided into three main groups: seeds and pods; flowers, buds, stem and leaves; and bulbs, roots and tubers. Some fruits harvested mature (tomato, aubergine), or immature (courgette and cucumber), are considered as vegetables (Wills et al 1998). It is therefore difficult to make general recommendations for the storage and shelf-life of fruits and vegetables, as the merits of particular techniques need to be assessed for individual products.

Post-harvest physiology

Fruits and vegetables undergo three distinct phases during their development: growth, maturation and senescence. Fruit development comprises growth and development, while ripening of fruit starts at the latter stages of maturation and the beginning of senescence, where degradative processes lead to ageing and death of tissue (Seymour 1993).

Most post-harvest technologies are concerned with reducing the rate of produce metabolism, without inducing physiological disorders or abnormalities. This is achieved by storing produce at their optimum temperature, and this may be specific to particular varieties of the same product e.g. apple. The rate of metabolism, including respiration, declines with decreasing temperatures, but this is most noticeable at the lower end of a produce tolerance temperature range, where metabolism will be at its lowest. For example apples are generally stored within a temperature range of 1-4ºC. The lower limit of storage temperature is determined by the sensitivity of produce to low temperature injury (chilling injury).

Respiration involves the oxidation of sugars, lipids and organic acids to carbon dioxide (CO$_2$) and water, with the release of energy (including heat). This process is most efficient when oxygen is in excess (aerobic respiration). Rapid removal of heat will extend the shelf-life of produce. The water generated during respiration is often retained within the cells of the tissue, but if produce is stored under unsuitable conditions then it can undergo excessive water loss, leading to a loss of turgor, and shrivel. In cases when the oxygen concentrations become limiting, respiration will shift from aerobic respiration to anaerobic respiration, when incomplete oxidation of sugars, organic acids or lipids leads to the accumulation of ethanol, acetaldehyde and CO$_2$, and produce can become unpalatable (Robertson 2006). Very little energy or heat is formed during anaerobic respiration. The concentration of oxygen at which respiration switches from aerobic to anaerobic varies among tissues and is termed the ‘extinction point’.

The rate of gas exchange of CO$_2$ and oxygen through tissue is affected by the porosity of the tissue, and the presence and thickness of the cuticle. Fruits and vegetables that present the greatest barrier to diffusion may have lowered respiration rates (Wills 1998), and in extreme cases where external oxygen concentration becomes limiting, localised anaerobic respiration may occur. Produce packaged in plastic modified atmosphere packaging (MAP) films, or those placed in plastic bags, will experience depleted oxygen and altered respiration rates (Robertson 2006).

The rate of respiration varies with the stage of tissue/organ development; as fruits increase in size the amount of CO$_2$ produced increases. Vegetables generally show no sudden increase in metabolic activity similar to that seen in climacteric fruit (see section on ethylene), unless sprouting or re-growth is initiated or in cases where they are harvested in an immature state (sweetcorn, and young legumes). The rate of respiration varies considerably between different fruits and vegetables (Table 1). In general, fruits and vegetables with high rates of respiration have a short-shelf-life, whilst those with lower rates have a longer term shelf-life (Kader 2002).
chlorophyll degradation, carotenoid synthesis and conversion of starch to sugars (Gray and North 1968). In apple, the respiratory climacteric occurs at the same time as an increase in ethylene production. In contrast, Biale and Young (1981) reported that in ripening melons, the rapid increase in ethylene production during ripening, which occurs together with a rise in the rate of respiration. Respiration is responsible for the oxidative breakdown of starch, sugars and organic acids into carbon dioxide and water to release energy. This phenomenon was first termed the ‘climacteric’ by Kidd and West in 1924.

The climacteric rise is represented by an increase in the production of carbon dioxide or a decrease in the internal oxygen concentration. The increase in respiration during the climacteric can be dramatic; in apple a 50-100% increase in carbon dioxide production and oxygen uptake occurs, without affecting the respiratory quotient (Fidler & North 1968). In apple, the respiratory climacteric occurs at the same time as an increase in ethylene production. In contrast, Biale and Young (1981) reported that in ripening melons, the rapid increase in ethylene precedes the rise in the rate of respiration. Ethylene was later found to co-ordinate the expression of genes in climacteric fruit responsible for increasing the rate of respiration, the autocatalytic production of ethylene, chlorophyll degradation, carotenoid synthesis and conversion of starch to sugars (Gray et al. 1992).

Table 1: A comparison of respiration rates and ethylene production capacity (selected from UC-Davis Post-harvest products website: http://postharvest.ucdavis.edu )

<table>
<thead>
<tr>
<th>Fruit</th>
<th>Respiration Rates mgCO₂ kg⁻¹ h⁻¹</th>
<th>Ethylene production rate µL kg⁻¹ h⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°C</td>
<td>5°C</td>
</tr>
<tr>
<td>Apples</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Avocado</td>
<td>nd</td>
<td>35</td>
</tr>
<tr>
<td>Banana</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Broccoli</td>
<td>21</td>
<td>34</td>
</tr>
<tr>
<td>Cabbage</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>Carrot</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Cucumber</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Honey Dew Melon</td>
<td>nd</td>
<td>8</td>
</tr>
<tr>
<td>Table Grape</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Kiwi</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Lemon</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Mushroom</td>
<td>35</td>
<td>70</td>
</tr>
<tr>
<td>Lettuce Head</td>
<td>12</td>
<td>17</td>
</tr>
<tr>
<td>Onion</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Orange</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Pear (European)</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Peach</td>
<td>5</td>
<td>nd</td>
</tr>
<tr>
<td>Pepper</td>
<td>nd</td>
<td>7</td>
</tr>
<tr>
<td>Pineapple</td>
<td>nd</td>
<td>2</td>
</tr>
<tr>
<td>Potato</td>
<td>nd</td>
<td>12</td>
</tr>
<tr>
<td>Strawberry</td>
<td>16</td>
<td>nd</td>
</tr>
<tr>
<td>Tomato</td>
<td>nd</td>
<td>nd</td>
</tr>
</tbody>
</table>

**Temperature**

Temperature is the most important factor in the post-harvest life of horticultural products, because of its dramatic effect on the rates of reactions of biological processes. In vegetables, for typical Q10 values (the ratio of respiration rates at one temperature to the rate at 10°C less), it is calculated that the relative rate of respiration would increase from 1 at 0°C to 3 at 10°C, 7.5 at 20°C and 15 at 30°C (Robertson 2006) Therefore immediate cooling of fresh fruits and vegetables after harvest is essential.

Tropical produce is affected by chilling injury, a disorder induced by storing produce at low but non-freezing temperatures (1 to 12°C). Chilling injury effects are influenced by the storage temperature and the duration of storage. Often the damage caused by storing fruits at too low temperatures is only apparent once produce has been returned to room temperature. Most often symptoms of chilling injury are associated with necrosis of cells, leading to the formation of depressed regions, pitting and external and/or internal browning.

**Ethylene**

The plant hormone ethylene plays a key role in orchestrating events controlling ripening of certain fruits (Knee 1985) and the onset of senescence in plant tissues. Ethylene is physiologically active at concentrations as little a 100 ppb. Fruits’ capacity to produce ethylene varies considerably. Fruits are divided into two categories determined by their respiratory behaviour during ripening: climacteric and non-climacteric.

**Climacteric fruits**

Fruits such as apple, pear, avocado, kiwifruit, plum, peach, nectarine and banana undergo a sharp rise in the rate of ethylene production during ripening, which occurs together with a rise in the rate of respiration. Respiration is responsible for the oxidative breakdown of starch, sugars and organic acids into carbon dioxide and water to release energy. This phenomenon was first termed the ‘climacteric’ by Kidd and West in 1924.

The climacteric rise is represented by an increase in the production of carbon dioxide or a decrease in the internal oxygen concentration. The increase in respiration during the climacteric can be dramatic; in apple a 50-100% increase in carbon dioxide production and oxygen uptake occurs, without affecting the respiratory quotient (Fidler & North 1968). In apple, the respiratory climacteric occurs at the same time as an increase in ethylene production. In contrast, Biale and Young (1981) reported that in ripening melons, the rapid increase in ethylene precedes the rise in the rate of respiration. Ethylene was later found to co-ordinate the expression of genes in climacteric fruit responsible for increasing the rate of respiration, the autocatalytic production of ethylene, chlorophyll degradation, carotenoid synthesis and conversion of starch to sugars (Gray et al. 1992).
In climacteric fruits, the respiratory climacteric coincides with the maximum attainment of fruit size. Climacteric fruits, with the exception of avocado, ripen either on or off the parent plant. Avocado will only ripen once harvested. Commercially, climacteric fruits are normally harvested before they reach their climacteric in order to maintain their storage potential.

Non-climacteric fruits

Non-climacteric fruits, such as strawberries, sweet cherries, pineapple, peppers, citrus and grapes, will exhibit most of the above ripening changes, although these usually occur over a longer period. In contrast to climacteric fruits, non-climacteric fruits are harvested ripe, as no further ripening will occur once the fruit is detached from the plant. Vegetables derived from leafy parts of plants and inflorescences are also sensitive to ethylene, but in these cases ethylene often stimulates the premature onset of senescence.

Ethylene treatment can stimulate respiration in both climacteric and non-climacteric fruits. In the climacteric types, the effect may not be immediate but the normal rise in respiration occurs earlier; endogenous ethylene production by the fruit is also stimulated so that removing the source of exogenous ethylene does not result in a reversion to pre-climacteric respiration rates. Non-climacteric fruits, such as oranges, will also respond to exogenous ethylene, resulting in a rapid increase in respiration, which is in proportion to the log of ethylene concentration up to 1000 ppm (Biale & Young 1981). It will decline to control levels if ethylene is withdrawn. Endogenous ethylene production is not accelerated.

Senescence

In general, plant senescence is a natural part of plant development. It is a highly regulated and complex process, and is under genetic and hormonal control. Genetic and molecular analyses suggest that the cell death associated with senescence is a form of programmed cell death (PCD). A number of hormones and associated compounds are known to have a role in senescence and PCD. Gene expression analysis of signalling pathways involving salicylic acid (SA), jasmonic acid (JA) and ethylene, has shown that these three pathways are all required for expression of many genes during developmental senescence. Ethylene regulates organ senescence through modulation of proteolytic enzyme production (Buchanan-Wollaston et al. 2002). The most visible symptoms are a yellowing of green tissues caused by loss of chlorophyll, loss of protein, and susceptibility to desiccation and decay. Ethylene can promote the yellowing of leafy vegetables, fresh herbs (parsley) and broccoli. Ethylene can also stimulate senescence of certain flowers at very low concentrations.

Other metabolic events

During storage and shelf-life, numerous processes occur that lead to changes in the overall quality of produce. Mobilisation of starch to sugars such as glucose, fructose and sucrose increases sweetness. These are also utilised in respiration, with organic acids leading to a reduction in astringency, and, along with the synthesis of new flavour and aroma volatiles, improve the overall perception of taste.

Changes in colour also affect customer acceptance of produce. Often the loss of chlorophyll unmasks hidden pigments like beta-carotenes, resulting in development of a yellow background colour that can reduce product appeal e.g. broccoli. In some produce, the additional biosynthesis of anthocyanins and carotenoids leads to the formation of orange/red pigment e.g. tomato. Ethylene affects a number of these processes, and in the case of starch mobilisation, it stimulates the synthesis of invertase, alpha and beta-amylases and sucrose-6-phosphate to break down starch into sugars. Ethylene accelerates the synthesis of chlorophyll degradation through the action of chlorophyllases and lipoxygenases. Ethylene also raises the rate of respiration in fruits and vegetables.

Softening

Changes in textural properties of produce have an important bearing on consumer acceptability; while often a certain degree of softening in apple, pears, avocado, banana, melon and peaches is desirable, excessive softening can lead to a rapid loss of quality, and a mealy or pulpy taste sensation.

In general, texture is determined by cell wall composition and structure (Glenn & Pooviah 1990). The cell wall is laid down as a series of layers initially to form the middle lamella, followed by the primary wall, which comprises approximately 90% polysaccharide and 10% protein (McNeil et al. 1984). The primary cell wall and middle lamella contain these polymers, but the middle lamella is also rich in pectic substances.

The primary cell wall consists of three interacting phases: a microfibrillar phase consisting of cellulose microfibrils, which impart cell wall strength. These are embedded in a matrix phase of non-cellulose derived polysaccharides, and the third phase is comprised of structural proteins (Carpita & Gibeaut 1993). An increase in softening can be attributed to a loss of cell-to-cell cohesion, caused in part by the action of pectin-degrading enzymes (endo an exo polygalacturanase, pectin methyl esterase and pectin lyase), which are stimulated by ethylene.
In addition, divalent calcium ions, that aid formation of important pectin cross-bridges between cells, can also be affected indirectly by bi-products (oxalic acid) of ethylene biosynthesis. A reduction in cell wall strength may also lead to a loss of structural integrity. Degradation of cellulose microfibrils, and the disassembly of the complex polysaccharide matrix by ethylene inducible enzymes, such as Beta-galactosidase, xylanase and endo-transglycosylase, will lead to softening of tissue.

Loss of cell turgor associated with post-harvest dehydration can result in shrivel and flaccidness in fresh produce, and as little as 5-10% weight loss can lead to produce being rejected. Fruits in particular, contain a high proportion of their fresh weight as water, and have a relatively high metabolic rate when compared with other fresh produce. This makes them highly perishable with an inherent short shelf-life. Water loss can be reduced by maintaining the optimum atmosphere and relative humidity around the product. This will extend shelf-life, and reduce the rate of deterioration and minimise water loss.

**Non-Climacteric fruits**

**Cucumber**

Greenhouse cucumbers respond to exogenously applied ethylene in a developmentally-dependent manner. Treating immature (4-8 d after anthesis (DAA)) cucumbers with exogenously applied ethylene (10 ppm) leads to mesocarp watersoaking, epidermal sloughing and slight degreening (Hurr, et al. 2009). By contrast, mature cucumbers (10-14 DAA) were more resistant to watersoaking, but more prone to degreening. As maturity progressed at breaker stage (16-20 DAA) and yellow stage (30-40 DAA), cucumbers exhibit rapid degreening due to chlorophyll degradation, the accumulation of beta-carotene resulting in the formation of orange pigmentation, and production of ‘fruit’ aromatic notes. Therefore post-harvest response to ethylene is very dependent on development stage, with older fruit exhibiting climacteric-like responses leading to premature yellowing, and younger fruit exhibiting tissue watersoaking and general fruit deterioration. Sensitivity of harvested cucumbers are quoted as 1-5 ppm (UC Davis 2010)

**Citrus (Orange, Lemon and Lime)**

Citrus are non-climacteric fruits, but will undergo de-greening of the skin if fruits are exposed to ethylene at 1-10 ppm for 1-3 days; lemons are stored during degreening between 20-25°C, while oranges require temperatures between 20-30°C. Ethylene treatments do not affect the internal quality of fruits, but may accelerate the deterioration of external appearance and decay incidence. Wills et al. (1999) found that reducing the ethylene concentration from 0.1 ppm to <0.005 ppm increased the storage life of oranges by 50 days stored at 2.5°C, by reducing the onset of chilling injury-induced dark spots appearing on the skin surface.

**Pineapple**

Although not considered a climacteric fruit, ethylene is used in pineapple production to synchronise flowering and regulate fruit size. It was this that led to the discovery of ethylene as the endogenous ripening agent in fruits; Regeimbal & Harvey (1927) reported that the activity of invertase and proteolytic enzymes in pineapples increased, when treated with either ethylene or propylene. Exposure to ethylene may result in a slightly faster rate of de-greening during storage. The use of an ethylene action inhibitor SmartFresh™ (1-MCP) can mitigate the effects of ethylene on fresh cut sliced pineapple, through a reduction in the rate of respiration, flesh softening, flesh browning and loss of ascorbate. An increase in the edible shelf-life of fresh cut pineapple by 3-4 days is also achieved, suggesting ethylene does influence the shelf-life of these products (Budu & Joyce 2003).

**Strawberry**

Strawberries are harvested fully ripe and do not respond to ethylene to stimulate ripening. Removal of ethylene can help to reduce decay loss from rhizopus and mucor. Wills and Kim 1995 found that reducing the ethylene concentration from 0.1 ppm to <0.005 ppm increased the storage life of strawberries stored at 0°C by 5.5 days by delaying the onset of decay and senescence.

**Grape**

Grapes do not ripen due to elevated ethylene, but are more prone to berry shatter in the presence of exogenous ethylene, where grapes fall off the raceme.

**Pepper**

Peppers respond very little to ethylene and, in order to accelerate ripening or colour changes, are held at warm temperatures of 20-25°C with high humidity.
Climacteric fruits

Kiwifruit

Kiwifruit have a low ethylene production rate when unripe (<0.1 µL.kg/hr at 0°C), with little increase when stored at 20°C (0.1-0.5 µL.kg). However, during ripening ethylene production rates rise rapidly, and can produce between 50-100µL kg. hr of ethylene at 20°C. Kiwis are extremely sensitive to ethylene, and as little as 5-10 nL L-1 (ppb) can stimulate respiration and ethylene production, and premature softening during storage. Reducing the concentration of ethylene from 0.1 µL L-1 to <0.005 µL L-1 increased the length of time kiwifruit took to ripen by 6 days (Wills et al. 2001).

It is therefore not surprising that 1-MCP is often used to reduce the effects of ethylene on kiwifruit during storage and shelf-life. However, the benefit of the ethylene action inhibitor 1-MCP diminishes during long-term storage. In the short-medium term storage, SmartFreshTM (1-MCP) brings several benefits to both green and yellow fleshed cultivars of kiwifruit including: fruits remain firmer throughout storage and shelf-life, with no negative effect on physiological disorders or rots, and reduced fruit losses owing to soft fruit. Two physiological conditions, white core inclusions and hard core, are also related to elevated levels of ethylene accumulating in controlled atmosphere or modified atmosphere stored produce. This results in the core region not ripening normally and remaining hard.

Honeydew melon

The responsiveness of honeydew melons to ethylene is dependent on the stage of fruit maturity. Quantifying maturity in this type of melon is difficult, because no clear abscission from the vine occurs. Therefore maturity is decided by assessing background colour. Mature-unripe melon, defined as where the ground colour is white with a hint of green, produces low rates of ethylene 0.5-1.0 µL kg-1 h-1, and does not respond to exogenously applied ethylene. Mature-ripening melon where a background green colour has started to develop, produces ethylene at 1.0-7.0 µL kg-1 h-1.

Those considered ripe with a yellow background colour produce approximately 7.5-10 µL kg-1 h-1 of ethylene, and the rate of ripening can be accelerated by exposure to 100-150 ppm (100 µL L-1) of ethylene for 18-24 hrs. Exposure of ripened fruit to ethylene may accelerate the onset of senescence, as it is known to increase the rate of lipooxygenase activity in melon and other fruits. This can lead to the formation of free-radicals that destroy cell membranes, with leakage of cellular contents into the interstitial air spaces, resulting in a water-soaked ‘glassy’ appearance (Lester et al. 2000).

Banana

Bananas are harvested in an unripe state and are only ripened on arrival at their destination market to avoid spoilage during transit. They are ripened in specialist ripening rooms, where they are exposed to 100-150 ppm of ethylene for between 24-28 hours at 15-20°C, with relative humidity of 90-95% RH, and forced air systems to aid uniform ripening and prevent the build-up of CO2 that can reduce the effectiveness of ethylene. Technologies such as fast cooling and temperature control at approximately 13°C give a postharvest shelf-life of 3–4 weeks (Scott & Soertini, 1974). Exogenous ethylene accelerates peel colour changes and softening in ripened bananas, so shortening shelf-life (Jiang et al. 1999). Keeping bananas in polythene bags in order to generate a modified atmosphere (MA) can delay fruit ripening and extend banana shelf-life for up to 28 days. This can be increased to 58 days when storage in polythene bags is combined with 1-MCP (1 ppm).

Tomato

Tomatoes can be harvested at the minimum harvest maturity stage 2. However, at this stage off-vine ripening is problematic, and therefore harvesting fruit at the more advanced pink-stage (30-60% of the surface is pink-red colour) leads to more uniform ripening at 18-21°C, 90-95% R.H. Tomatoes ripened at 20°C produce fruit with optimum colour development and retention of vitamin C, and fruit are more responsive to ethylene-induced ripening (100 ppm ethylene for 24-72 hours). Once tomatoes reach the firm ripe stage they have a shelf-life of 8-10 days when stored at 7-10°C. After ripening, tomatoes are still sensitive to ethylene, which can shorten the shelf-life.

For the induction of natural ripening, there is no critical value that internal ethylene levels must reach, although an up-turn in the production rate of ethylene needs to occur for ripening to be initiated. It is complemented by a change in tissue sensitivity, through changes in the expression of ethylene receptors (Hobbs and Grierson 1993). Reducing the concentration of ethylene from 0.1 ppm to <0.005 ppm increased the length of time tomato took to ripen by 2 days (Wills et al. 2001).
Other hormones, such as abscisic acid (ABA), also interact with ethylene to synchronise ripening events in tomato, although it is most likely that the effects of ABA are associated with the early stages of maturation and seed development (Sheng et al. 2008).

Apple

In the UK, early maturing apple varieties (Discovery) are harvested in mid-August, with the main harvest window for other varieties starting in early to mid September (Bramley and Cox, followed by Gala) and continuing through to early-mid October for later maturing varieties (Braeburn and Jonagold). The harvest window not only varies for each variety of apple, but is also dependent on the growing region and seasonal factors. Storage and subsequent shelf-life of apple is dependent on fruit being picked within the optimum harvest window, and stored under optimum conditions.

The typical rate of ethylene production for apples is less than 0.1 µL kg⁻¹ h⁻¹ during the pre-climacteric state prior to harvest, but can rise to approximately 100 µL kg⁻¹ h⁻¹ during the climacteric (Knee, 1985a). Apples are sensitive to sources of exogenous ethylene that can hasten the loss of firmness and the onset of senescence. Moreover, in scald sensitive varieties (Bramley and Granny Smith), ethylene can increase the incidence of superficial scald (a surface staining associated with oxidation of peel constituents) leading to a reduction in visual acceptance.

Pear

European pear (Pyrus communis) requires a period of cold storage (-1.0- 0°C) to ensure uniform ripening during shelf-life. Comice and Conference pears can be stored for 4-6 months and still maintain their capacity to ripen, and attain good eating quality. The length of time pears are stored in cold storage has a significant bearing on the ripening capacity of fruit during shelf-life. This minimum period of chilling requirement is dependent on variety; Bosc pears require only 7-10 days chilling, compared to 14-21 days for Bartlett pears, and 25-31 days for Comice. However, the period of chilling to attain best eating quality is somewhat longer, with Bosc pears 8-10 weeks cold-storage and Comice 8-20 weeks.

Chilling of pears leads to the synthesis of key enzymes in the ethylene biosynthesis pathway: ACC synthase and ACC oxidase. Specific isoforms of these enzymes are under the control of a family of genes, and members of the ACS gene family are differentially expressed during periods of chilling. The length and duration of chilling will have a direct effect on the shelf-life of pears, and likewise their response to ethylene after storage will be modulated by the period of cold induction. In certain situations pears can be prematurely ripened by the use of ethylene 100 ppm for 1-2 days, a practice that is termed ethylene conditioning, which stimulates fruits own ethylene synthesis (Villabos-Acuna and Mitcham 2008). The amount of ethylene and duration of treatment required for conditioning will depend on the length of cold storage. Presence of exogenous ethylene may hasten ripening and senescence and stimulate superficial scald development.

Flower and leafy vegetables

Leafy vegetables include lettuce, cabbage, spinach and kale, while flower vegetables are represented by broccoli, cauliflower and artichoke. Flower and leafy vegetables are very perishable with high rates of respiration and loss of water. Rates of respiration vary considerably, but generally this group of produce has a short storage life, with the exception of cabbage. Rapid changes in chlorophyll lead to yellowing and indicates loss of nutritional value (ascorbic acid, pro-vitamin A). Often flower and leafy vegetables are stored near to 0°C with high relative humidity.

Flower crops (broccoli and cauliflower)

Broccoli florets have high rates of respiration and transpiration, and high ethylene production. The respiration rate of detached florets is higher than the stem, and both have elevated rates when compared to intact heads (Kader 2002). Exposure to ethylene can accelerate chlorophyll degradation (Lozada-Ramierz et al. 2002); yellowing of broccoli heads, due to a loss of chlorophyll, is a major cause of produce rejection. Once detached from the plant, florets rapidly synthesise ethylene, which accelerates the rate of chlorophyll loss through the action of chlorophyllase and peroxidases/hydrogen peroxide system. The rate of degreening can be slowed by cool chain management; plunging heads into iced water to remove field heat. However, chlorophyll loss occurs rapidly when stored above optimum temperature, and the presence of exogenous ethylene generated from produce such as apples, pears, avocados, bananas, cantaloupe melon and tomato, will cause further decline in the shelf-life of broccoli.

The use of modified atmosphere packaging (MAP), with equilibrium concentrations of CO₂ (12.5%) and O₂ (2.8%), and storage at 4°C, extended the shelf-life of broccoli florets. However, the addition of ethylene absorbent material (KMnO₄) sachets had no effect on shelf-life (Lozada-Ramierz et al, 2002). In contrast, Wills et
al (1999) found reducing the concentration of ethylene from 0.1 ppm to <0.005 ppm by potassium permanganate increased the storage life of broccoli by 21 days.

Cauliflower produces an edible head of condensed, malformed flowers with short fleshy stalks. Cauliflowers are very low producers of ethylene, <1 ppm. They are particularly sensitive to exogenous ethylene, which leads to discoloration of the curd, yellowing and abscission of basal leaves. Extension of shelf-life has been achieved by storing cauliflowers under controlled atmosphere conditions (5% CO₂ and 3% O₂) at 0-1°C (Mertens), which leads to reduced ethylene production in the leaves caused by delaying senescence of basal leaves, but little effect was seen on the head.

**Leafy crops (lettuce and cabbage)**

Leaves in general are susceptible to ethylene-induced senescence, although different parts of the leaf will show a differential response to ethylene. Petioles are generally unaffected by ethylene, except at their base where it can accelerate the formation of a defined abscission zone that can result in premature leaf drop. With lettuce, the petiole is also susceptible to ethylene-induced russet spot, which appears as dark brown spots on the mid-rib caused by the accumulation of phenolic compounds (Heredia and Cisneros-Zevallos, 2009).

Leaves can suffer from an increase in yellowing caused by accelerated loss of chlorophyll, through the enhanced action of chlorophyllase and peroxidase activity in the presence of ethylene. Lettuce (Iceberg) can benefit from storage in low oxygen atmosphere (1-3%) at 0-5°C where reduction in respiration rates and a reduction in the effects of ethylene can be seen. Wills et al. (1999) found the concentration of ethylene in commercially marketed lettuce to be in the range of 0.11 to 0.8 ppm. Reducing the ethylene concentration, by the inclusion of potassium permanganate, and storage in plastic bags, can minimise water loss and extend the shelf-life of lettuce stored at 20°C and 0°C. Reducing the concentration of ethylene from 0.1 ppm to <0.005 ppm around Iceberg lettuce stored at 0°C increased storage life from 12.1 to 35.1 days (Wills et al. 1999).

Cut lettuce products are commonly stored in low (<1%) and high CO₂ (10%) because this can reduce browning on cut surfaces (Kader, 2002). Lettuces that receive vacuum cooling immediately after harvest had a longer shelf-life than those subject to room-cooling (Lin & Hall, 2002). Any mechanical damage, crushing, or bruising of lettuce during harvesting and handling will generate wound-induced ethylene leading to a rapid decline in shelf-life.

It is important to avoid exposure of leafy crops to ethylene during the storage and handling chain, as it decreases the shelf-life of all leafy vegetables. Factors that may affect the response to ethylene are variety susceptibility, length of exposure and storage temperature. Iceberg lettuces vary considerably in their susceptibility to ethylene and their propensity to develop russet spotting. It is important therefore to consider all possible sources of ethylene that might be emitted from sources, such as propane-fuelled fork-lifts or ethylene producing fruits, and to provide adequate ventilation during storage to maintain low levels of ethylene.

**Roots, tubers and bulbs crops**

The edible portion of this group of vegetables develops mostly underground, and is derived from several botanical structures. Examples include:

- roots: carrots, radish and parsnip;
- tubers: potato and Jerusalem artichoke; and
- bulbs: onion, shallot and garlic.

Underground vegetables are all storage organs, consist mainly of carbohydrate, and have generally low rates of respiration, although this is dependent on the stage of development. They will re-grow roots and sprouts after harvest, and in general are less perishable and can be stored for relatively long periods.

**Carrots**

Harvested carrots have a high rate of respiration, and those stored with leaves intact have the highest rate, followed by baby carrots (immature), with mature carrots being the most durable. During storage carrots can lose a considerable amount of water, resulting in shrivelling and a loss of crispness. Moreover, where carrots are packed too tightly or in bags without adequate ventilation, elevated concentrations of carbon dioxide and depleted oxygen can give rise to anaerobic respiration, and accumulation of ethanol in the roots which presents unacceptable off-flavours. At harvest, ethylene production rates increase at the beginning of the storage period, but then decline (Halloran et al. 2005).

Low concentrations of ethylene (>0.1 ppm) can accelerate respiration rates further and accentuate water loss and off-flavours, and in particular stimulate synthesis of 6-methoxymellein (isocoumarin) and terpene
compounds, and the conversion of sucrose to glucose and fructose in air-stored carrots. This leads to an increase in bitterness and earthy flavours and reduces sweetness (Seljasen et al. 2001). Freshly harvested carrots, cut carrots and baby carrots develop high concentrations of isocoumarin. However, peeled carrots do not produce isocoumarin because this is formed mainly in the skin (Kader, 2002).

As with other fresh cut vegetables, minimally processed carrots have higher respiration rates than intact carrots and are more perishable. The act of wounding tissue increases ethylene production, which in turn stimulates respiration. Higher respiration increases the loss of sugars and acids, flavour and aroma volatiles and other nutrients. Cut carrots are also more sensitive to ethylene.

Onions

Onions treated with a saturating dose of ethylene, in both the dormant and sprouting states, show reduced leaf blade elongation, and experience alterations in sucrose synthesis. Ethylene can also double respiration rates, which can reduce sweetness of onions. Intermittent exposure to ethylene can lead to breaking of dormancy and accelerate the rate of sprouting once ethylene has been removed.

Potato

Continuous application of ethylene (4 ppm) to potatoes in store (4-10°C) reduces the length of sprouts once they have initiated. Ethylene has been used as an alternative to traditional sprout inhibitors (CIPC) in the UK for the pre-packed potato market. However, ethylene also shortens the natural period of dormancy and breaks apical dominance (Prange et al. 2005). Therefore, once removed from the source of ethylene, the rate to sprout growth and the number of sprout initiation sites of ethylene treated potatoes can be greater than non-treated potatoes (Prange 1998). Likewise, intermittent exposure of potatoes to ethylene in the handling chain can stimulate dormancy break and encourage sprouting. During sprouting, mobilisation of starch to sugars and elevated rates of respiration lead to increases in water loss and shrivel, therefore reducing tuber quality. Moreover, ethylene can also increase the amount of starch hydrolysis in the tuber, leading to elevated concentrations of glucose and fructose, resulting in undesirable levels of sweetening in cooked potato and a darker fry colour in chips and crisps.

Mushrooms

Mushrooms have a short shelf-life of 3-4 days caused by their high metabolic activity, high water content and a lack of a cuticle resulting in a rapid loss of water, shrivel, enzymic browning and microbial spoilage (Aguirre et al. 2009). Normally, mushrooms are transported to the retailer at temperatures of (0-3°C) then placed in display cabinets between 8-11°C with a rapid turnover of produce. Maintaining a high relative humidity (90%) around the product helps to reduce water-loss and prevent shrivel. Mushrooms are not sensitive to exogenously applied ethylene and there is little evidence to suggest they are adversely affected by a build-up of ethylene in the atmosphere. (Kader 2002)

**Ethylene control strategies**

Ethylene antagonists

A number of techniques for controlling ethylene synthesis, perception and action have been developed. Key targets in limiting ethylene biosynthesis are the two terminal enzymes in the pathway: ACC synthase and ACC oxidase. The former is considered the rate-limiting enzyme in the pathway, and has been the focus of much interest in controlling ethylene production. Vinylglycine compounds AVG, rhizobitoxine and AOA are competitive inhibitors of ACC synthase and reduce ethylene production. A commercial preparation of AVG has been marketed as ReTain™ and is available in the US, South America and New Zealand as a pre-harvest spray. SmartFresh™, a competitive inhibitor of ethylene receptors, blocks ethylene action. The current formulation is a cyclodextrin encapsulated 1-MCP product that releases 1-MCP gas on addition of water. SmartFresh™ is available for use on apples in the UK, but is permitted on a wider range of crops world wide (including tomato, kiwi, melon, avocado, tulip bulbs and cut flowers). Recent advances in formulation have lead to a sprayable form of 1-MCP marketed as Harvista™.

Ethylene removal

Scrubbing ethylene from the storage atmosphere has long been demonstrated as an effective way of extending the storage life of controlled atmosphere (CA) stored Bramley apples (Knee et al. 1985c), delaying the effects of ethylene mediated softening and development of superficial scald. Ethylene scrubbing requires catalytic oxidation of volatiles in the storage atmosphere, through passage over a platinum catalyst heated to 220°C, the high energy costs associated with running the catalytic converter limited earlier commercialisation of this technology. More recently commercial scrubbing devices based on oxidation of ethylene by potassium permanganate at ambient temperatures have been tested.

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**Ethylene and microbial hotspots in the fresh produce supply chain**
The use of ozone in oxidising ethylene has also been reported in the literature (Peters and Wingard 1970). Ethylene belongs to a class of compounds known as alkenes. These show the greatest reaction to ozone, due to the susceptibility of the carbon-to-carbon double bond to oxidative attack. Ozone has been reported to extend the shelf-life of fruits and vegetables (Skog and Chu 2000).

**Practical problems associated with storing mixed consignments of produce.**

Storing consignments of fruits of different maturities together can lead to elevated concentrations of ethylene in the storage environment, leading to an accelerated rate of ripening and respiration, loss of turgor and shrivel in produce. Likewise, produce subject to physical damage, bruising, chilling injury, senescent breakdown or pathological decay can also emit elevated rates of ethylene, leading to a premature loss of quality.

Similarly, storing mixed consignments of ethylene-producing products in close proximity to produce that is sensitive to ethylene will lead to premature senescence, leaf abscission and/or the accumulation of bitter tasting compounds, and loss of vitamins or health promoting chemicals. Therefore great care should be taken to mitigate the adverse effects of ethylene throughout the produce supply chain and segregate produce according to their sensitivity to ethylene.

Most produce will respond to ethylene. However, the level of response is dependent on the developmental stage of the produce, and in more general terms the type of tissue from which the produce has formed.

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Ethylene and microbial hotspots in the fresh produce supply chain


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UC-Davis, Postharvest, product facts: http://postharvest.ucdavis.edu


### Appendix 3: Ethylene Commodity Table

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<th>Normal storage time during handling in the UK</th>
<th>Potential for extending shelf-life through ethylene control</th>
<th>What further information would be useful</th>
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| Broccoli    | Increases rate of chlorophyll breakdown leading to yellowing of heads, which is a major cause of produce rejection. | <100 ppb Wills et al. (1999) found an increase in shelf life of 21 days by reducing ethylene from 100 ppb to <5 ppb. | 0 - 3 weeks | High Ethylene control during storage should extend shelf life. Ethylene concentrations of 200 – 500 ppb were measured in broccoli stores during this study, which is within the range of sensitivity. | ■ More information on the effect of continuous exposure to a range of low ethylene concentrations (below 100 ppb) in order to determine what levels of control would be effective.  
■ Once detached from the plant, florets rapidly synthesis ethylene, thereby stimulating the rate of chlorophyll loss. Ethylene control within packaging should be investigated |
<p>| Cauliflower  | Discolouration of the curd, yellowing and abscission of basal leaves.                        | (&lt;100 ppb) Cauliflower is known to be very sensitive to ethylene, but precise information on sensitivity to ethylene is not available. | 0 – 3 weeks | High Ethylene control during storage should extend shelf life. Ethylene concentrations of 200 – 500 ppb were measured in stores used for cauliflower during this study. | ■ The effects on shelf life of continuous exposure to a low range of ethylene concentrations (&lt;100 ppb) for up to 3 weeks. |
| Cucumber    | Degreening due to chlorophyll breakdown, development of orange pigmentation and fruit aromas. Cucumber is an unripe fruit. The changes due to exposure to ethylene are accelerated fruit ripening effects. | Unknown Known to be sensitive to 1000 -5000 ppb but there is a need to test the effects of lower concentrations. | 0 - 4 days | Medium The concentrations of ethylene observed during the handling chain were less than 1000 ppb, so usefulness of ethylene control depends on information on ethylene sensitivity. If cucumber is sensitive below 100 ppb, control during storage should extend shelf life. | ■ The effects on shelf life of continuous exposure to a range of low ethylene concentrations (&lt;100 ppb) for up to 4 days. |</p>
<table>
<thead>
<tr>
<th>Commodity</th>
<th>Ethylene effects on quality</th>
<th>Sensitivity to ethylene</th>
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<th>Potential for extending shelf-life through ethylene control</th>
<th>What further information would be useful</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lettuce</td>
<td>Leaves yellow due to accelerated loss of chlorophyll. Russet spotting in the petiole, which appears as dark brown spots in the mid rib.</td>
<td>&lt;100 ppb</td>
<td>7 - 14 days</td>
<td>Medium Ethylene control during storage should extend shelf life. Ethylene concentrations of 200 – 400 ppb were measured in mixed commodity stores used for lettuce, which is within range of sensitivity</td>
<td>▪ More information on the effect of continuous exposure to a range of low ethylene concentrations (below 100 ppb) in order to determine what levels of control would be effective.</td>
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<tr>
<td>Cabbage</td>
<td>Leaves yellow due to accelerated loss of chlorophyll. Russet spotting in the petiole, which appears as dark brown spots in the mid rib.</td>
<td>&lt;100 ppb</td>
<td>7 - 14 days</td>
<td>Medium Ethylene control during storage should extend shelf life. Ethylene concentrations of 200 – 400 ppb were measured in mixed commodity stores used for cabbage, which is within range of sensitivity</td>
<td>▪ More information on the effect of continuous exposure to a range of low ethylene concentrations (below 100 ppb) in order to determine what levels of control would be effective.</td>
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<tr>
<td>Carrot</td>
<td>Accelerates respiration rates, increases water loss and off-flavours and in particular stimulates synthesis of 6-methoxymellein (isocoumarin) and terpene compounds and the conversion of sucrose to glucose and fructose in air stored carrots. This leads to an increase in bitterness and earthy flavours and reduces sweetness.</td>
<td>100 ppb Lower concentrations have not been tested</td>
<td>7 - 14 days</td>
<td>Medium Ethylene control during storage should extend shelf life. Ethylene concentrations of 200 – 400 ppb were measured in mixed commodity stores used for carrot during this study, which is within range of sensitivity</td>
<td>▪ More information on the effect of continuous exposure to a range of low ethylene concentrations (below 100 ppb) in order to determine what levels of control would be effective.</td>
</tr>
<tr>
<td>Onion</td>
<td>Continuous exposure to ethylene (5000 – 10,000 ppb) can be used to control sprouting during long-term storage of onion, but otherwise does not affect quality.</td>
<td>NA</td>
<td>NA</td>
<td>Low Within the marketing chain.</td>
<td>▪ None required</td>
</tr>
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<tr>
<td>Potato</td>
<td>Continuous exposure to ethylene (5000-10,000 ppb) can be used to control sprouting during long-term storage of potatoes. Ethylene can induce sugar formation which is a problem for processors, but is not considered a quality issue for fresh marketed potatoes.</td>
<td>Low</td>
<td>Potatoes may be stored for many months prior to marketing</td>
<td>Low within the marketing chain.</td>
<td>None required</td>
</tr>
<tr>
<td>Fruit</td>
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<tr>
<td>Kiwifruit</td>
<td>Stimulates respiration and premature softening</td>
<td>5 - 10 ppb</td>
<td>7 - 14 days</td>
<td>Medium The extreme ethylene sensitivity of kiwifruit is well known within the fresh produce handling industry, so that levels are carefully controlled during long-term storage and shipping. During handling in the UK, ethylene control should extend shelf life.</td>
<td>None required</td>
</tr>
<tr>
<td>Tomato</td>
<td>Tomatoes are climacteric fruit. They are passed the climacteric phase during handling, but will still respond to ethylene by ripening/senescing more rapidly.</td>
<td>&lt;100 ppb Reducing the concentration of ethylene from 100 ppb to &lt;5 ppb increased the length of time tomato took to ripen by 2 days (Wills et al 2001).</td>
<td>&lt; 7 days</td>
<td>Medium Concentrations of ethylene observed in tomato stores were between 50 and 100 ppb. Small increases in shelf life would be gained by reducing ethylene concentrations further. Where tomatoes are exposed to higher concentrations of ethylene in mixed stores, ethylene control would be useful.</td>
<td>None required</td>
</tr>
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<tr>
<td>Apple</td>
<td>Ethylene triggers ripening of apples. Most varieties are picked after the ripening event (the climacteric), but a few such as Bramley are picked before, in which case ethylene control during storage can extend storage life by several months. Exposure to ethylene after ripening hastens loss of firmness and onset of senescence. In some varieties ethylene can increase the incidence of superficial scald leading to a reduction in visual acceptance.</td>
<td>Unknown. The sensitivity to ethylene after the climacteric has not been determined for many varieties. It is generally believed to be about 1000 ppb</td>
<td>UK grown apples may be stored up to 10 months depending on the variety. Imported fruit is generally stored for less than 3 weeks.</td>
<td>High During long-term storage ethylene control is very important for varieties, such as Bramley, that are harvested before the climacteric. Potential for extending storage through ethylene control for other varieties is unknown. Effects of ethylene control during short-term storage would be small relative to long-term storage and is therefore lower priority.</td>
<td>• The effect of long-term exposure to ethylene after the ripening event is unknown for many varieties, and should be clarified.</td>
</tr>
<tr>
<td>Pear</td>
<td>Ethylene triggers ripening of pears. Comice and Conference pears may be picked unripe, can be stored for 4-6 months and still maintain their capacity to ripen and attain good eating quality. In fact a period of cold storage is necessary for the fruit to be able to ripen naturally without artificial addition of ethylene. After ripening ethylene may speed up senescence and surface damage (scald).</td>
<td>Unknown The sensitivity to ethylene after ripening has not been determined.</td>
<td>UK grown pears may be stored up to 6 months depending on the variety. Imported fruit is generally stored for less than 3 weeks.</td>
<td>Low During long-term storage pears are stored at very low temperatures (-1.0 - 0°C) and ethylene control is not necessary. Effects of ethylene control during short-term storage after ripening is unknown.</td>
<td>• The effect of long-term exposure to ethylene after the ripening event should be clarified.</td>
</tr>
<tr>
<td>Avocado</td>
<td>High ethylene producer Avocado is a climacteric fruit. During long-term storage ethylene removal can delay ripening. Exposure to ethylene is used to stimulate ripening.</td>
<td>Low. After ripening the fruit is not considered to be very sensitive to ethylene.</td>
<td>0 – 2 weeks</td>
<td>Low Ethylene control is important before ripening. After ripening ethylene concentrations found in the UK handling chain would not be expected to have much effect.</td>
<td>• None required</td>
</tr>
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<td>Banana</td>
<td>Bananas are climacteric fruit. They are harvested in an unripe state and are only ripened on arrival in the UK to avoid spoilage during transit. Ripening occurs in specialist ripening rooms where fruits are exposed to 100,000 - 150,000 ppb of ethylene for between 24-28 hours at 15-20°C. After ripening fruits are still sensitive to ethylene, which accelerates peel colour changes and softening in ripened bananas so shortening shelf life.</td>
<td>Unknown. The concentration of ethylene to which bananas are sensitive after ripening has not been defined.</td>
<td>0 – 1 weeks</td>
<td>Medium Ethylene control is vital before ripening. After ripening the practice of keeping bananas in polythene bags reduces the effects of ethylene due to the modification of the atmosphere within the bag (increase in carbon dioxide and decrease in oxygen) due to fruit respiration. It is not clear whether further ethylene control would have much of an effect.</td>
<td>■ Sensitivity of fruit to ethylene after ripening</td>
</tr>
<tr>
<td>Grape</td>
<td>Exposure to ethylene leads to abscission of fruits from the bunch</td>
<td>&gt;10,000 ppb</td>
<td>0 – 3 weeks</td>
<td>Low. Ethylene concentrations found in the UK handling chain would not be expected to have much effect on grapes.</td>
<td>■ None required</td>
</tr>
<tr>
<td>Orange and Lemon</td>
<td>Exposure to ethylene (1000 - 10,000 ppb) is used to stimulate degreening, and development of orange/yellow colour. Ethylene treatments do not affect the internal quality of fruits but may accelerate the deterioration of external appearance and decay incidence.</td>
<td>Unknown. Has not been defined except for degreening, but probably &gt;1000 ppb</td>
<td>0 – 3 weeks</td>
<td>Low. Ethylene concentrations found in the UK handling chain would not be expected to have much effect on citrus fruits</td>
<td>■ None required</td>
</tr>
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<tr>
<td>Strawberry</td>
<td>Ethylene can increase rates of rotting and senescence</td>
<td>&lt;100 ppb. It has been shown that reducing the ethylene concentration from 100 ppb to 5 ppb can increase shelf life significantly over a wide temperature range.</td>
<td>&lt; 5 days</td>
<td>Medium Concentrations of ethylene observed in a strawberry packhouse were below 50 ppb. Strawberries are moved through the handling chain very rapidly. However, where strawberries are exposed to higher concentrations of ethylene in mixed stores, ethylene control would be useful.</td>
<td>None required</td>
</tr>
<tr>
<td>Melon</td>
<td>Melons are high ethylene producers. Ripening of melon can be stimulated by ethylene. Exposure of ripened fruit to ethylene may accelerate the onset of senescence.</td>
<td>Unknown The concentration of ethylene to which ripe fruit are sensitive has not been clearly defined.</td>
<td>0 – 2 weeks</td>
<td>Medium It is not clear whether melons would be sensitive to the concentrations of ethylene observed in stores (200 – 500 ppb). However, the concentrations of ethylene within packaging is very high (&gt;20,000 ppb). Control of ethylene within packaging is likely to extend melon shelf life.</td>
<td>It would be useful to define the concentration of ethylene to which ripe melons are sensitive.</td>
</tr>
<tr>
<td>Mushrooms</td>
<td>Mushrooms are not sensitive to exogenously applied ethylene and there is little evidence to suggest they are adversely affected by a build up of ethylene in the atmosphere.</td>
<td>Low</td>
<td>&lt; 4 days</td>
<td>Low</td>
<td>None required</td>
</tr>
</tbody>
</table>