Control of ethylene biosynthesis and softening in ‘Cox’s Orange Pippin’ apples during low-ethylene, low-oxygen storage

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Abstract

The response of apples (Malus domestica Borkh.) cv. Cox’s Orange Pippin (‘Cox’) to low ethylene, controlled atmosphere (CA) storage was examined in two seasons. The content of 1-aminocyclopropane-1-carboxylic acid (ACC) and the activity of ACC oxidase (measured as the capacity for formation of ethylene from exogenous ACC) in cortical tissue of apple fruits from low ethylene containers, remained constant for about the first 20 weeks of storage, before increasing. Removal of ethylene from the storage atmosphere was more effective at reducing softening in <1% CO₂ + 1.25% O₂ after a pretreatment with 5% CO₂ + 16% O₂ for 15 days, than storage in <1% CO₂ + 0.75% O₂ without a pretreatment. Low ethylene storage maintained fruit firmness by inhibiting initiation, rather than reducing the rate of softening. Fruit was no softer after more than 28 weeks of storage when ethylene removal was discontinued after 12 weeks (1989–90) or 16 weeks (1990–91) than when the removal had been continuous throughout the storage period. It was concluded that, to obtain a benefit from ethylene removal, internal ethylene concentrations must be maintained below about 4 μmol m⁻³ (0.1ppm). This could not be achieved with ‘Cox’ apples in 1.25% O₂ by removal of ethylene without a 5% CO₂ pretreatment. The onset of autocatalytic ethylene production was not delayed appreciably by the removal of ethylene and was initiated after 2–5 weeks of storage, although the production rate of ethylene increased more slowly in a low ethylene atmosphere. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Apple; Storage; Softening; Ethylene; ACC; ACC oxidase

1. Introduction

Flesh firmness is a major quality attribute of apple and is particularly important for the principal UK cultivar, ‘Cox’s Orange Pippin’ (‘Cox’). Reducing O₂ concentrations below 2% during storage at 3.5°C has been shown to lower the rate of loss of firmness of ‘Cox’ apples, although there was little additional benefit below 1% and ethanol was formed and tainting occurred at 0.5% O₂ (Stow, 1989). For a number of cultivars, retention
of firmness in stores where concentrations of ethylene were maintained below 44 μmol m\(^{-3}\) was better than in those where ethylene was allowed to accumulate (Lidster et al., 1983; Lange and Fica, 1984; Knee and Tsantili, 1988; Dover, 1989; Stow and Genge, 1990; Van Schaik, 1996). It was not clear whether maintaining a low ethylene atmosphere delayed the onset, or reduced the rate of softening. If the mode of action is through a delay in the onset of softening, it should be possible to reduce running costs of low ethylene storage by switching off the ethylene removal system after softening has been initiated.

The effectiveness of ethylene removal in controlling softening depends on the maintenance of a sufficiently low ethylene concentration inside the fruit. The lower the ethylene concentration required and the higher the production rate, the larger the ethylene removal system must be and the higher the capital and running costs (Dover, 1989). However, it is not possible to determine from the above reports the maximum acceptable level of ethylene.

To determine this for ‘Cox’ apples, fruits were stored in low and high ethylene conditions and samples were removed at frequent intervals to measure internal ethylene concentration (IEC) and firmness. Earlier experiments had shown that treatment with 5% CO\(_2\) for 15 days before storage in 1.25% O\(_2\) was necessary for ethylene removal to reduce softening (Stow, 1988, 1990). As production rate of ethylene was lowered by storage in 0.75% O\(_2\) (Stow, 1989) a comparison was made of storage in 1.25% O\(_2\) with a CO\(_2\) pretreatment and storage in 0.75% O\(_2\) with no pretreatment.

2. Materials and methods

2.1. Storage

‘Cox’ apples were picked on 11 September 1989 (the start of the commercial harvesting period) from an orchard at HRRI-East Malling. After drenching in a mixture of benomyl (500g m\(^{-3}\) a.i.) and CaCl\(_2\) (9000 g m\(^{-3}\), commercial flake) 232 random samples of 12 apples and 8 random samples of 80 apples were selected. The remainder of the fruit was allocated randomly to 64 15 kg samples. Sixteen storage chambers in a store at 10°C were each loaded with four boxes of ballast and either seventeen 12-fruit samples (12 chambers, time-course experiment) or twelve 12-fruit samples (four chambers, transfer experiment). After allowing fruit to cool overnight, chambers were sealed and CO\(_2\) and N\(_2\) were admitted into four time-course experiment chambers and the four transfer experiment chambers, to generate an atmosphere of 5% CO\(_2\) + 16% O\(_2\) + balance N\(_2\) (the ‘5% CO\(_2\)’ storage method). This atmosphere was maintained for 15 days. The chambers were then connected to containers of dry Ca(OH)\(_2\) to remove CO\(_2\), and N\(_2\) was admitted to reduce the O\(_2\) to 1.25%. The remaining eight chambers in the time-course experiment were connected to Ca(OH)\(_2\) containers immediately on loading and, after cooling overnight, were sealed and the O\(_2\) concentration was reduced progressively over 9 days to 1.25% ('1.25% O\(_2\)' storage method, four chambers) or over 14 days to 0.75% O\(_2\) ('0.75% O\(_2\)' storage method, four chambers). These two time periods represent the time required to reduce O\(_2\) concentrations in good commercial stores. Two of the chambers from each storage method and two transfer experiment chambers were connected to catalytic scrubbers of ethylene (Dover and Stow, 1993) on loading (‘low ethylene’ treatment). The atmosphere from the cabinets was pumped through the system for removing ethylene at a flow rate of 5 l h\(^{-1}\) per kg of fruit throughout storage, while ethylene was allowed to accumulate in the other two chambers (‘high ethylene’ treatment). Efficiency of conversion of ethylene always exceeded 95%. Fruit temperatures were reduced progressively to 3.5°C over 3 days from loading in all chambers to represent cooling in good commercial stores.

After the final conditions were established, all containers were maintained at 3.5–4°C in less than 1% CO\(_2\) and at the O\(_2\) concentration required (±0.2%). Oxygen concentrations were maintained by a computer-based system that admitted air into chambers when the O\(_2\) concentration fell below that required.

The experimental procedures were repeated in the following season, with the following excep-
tions: fruit was picked on 30 August, 1990 and drenched in metalaxyl (100 g m\(^{-3}\)) + carbendazim (500 g m\(^{-3}\)) + 20 kg m\(^{-3}\) CaCl\(_2\); only the ‘5% CO\(_2\)’ storage method was used as this had resulted in the greatest firmness retention in the first year; the numbers of replicate containers were doubled to increase the precision of the experiment. In addition, a catalytic converter with a conversion rate of 1% of that fitted to the ‘low ethylene’ chambers was placed in the return side of the automated sampling system to reduce contamination of ‘low ethylene’ chambers with ethylene from ‘high ethylene’ chambers. Although this additional catalytic converter slightly reduced the accumulation of ethylene in the ‘high ethylene’ chambers, it allowed calculation of ethylene production rate in these chambers.

2.2. Assessment of fruit

At intervals, one 12-fruit sample was removed from each chamber of the time-course experiment through an ‘airlock’ in the lid. Nitrogen was admitted to the chambers while sampling was in progress and all chambers were returned to their required O\(_2\) condition within 4 h of fruit removal. The IEC in ten of the 12 fruits from each sample was measured immediately on removal from the chamber, followed by determination of ethylene-forming capacity (1990 experiment only), background colour (using a Hunter Colormeter in the L,a,b mode (1989 experiment only)) and flesh firmness, using a motorised penetrometer (Topping, 1981) fitted with an 8 mm diameter probe.

Internal quality was monitored by visual inspection of fruit cut equatorially and samples for the determination of acidity were taken by removing a 10 mm-thick equatorial slice and removing two tissue plugs from just below the peel with a 7 mm diameter cork borer. The yield from each 12-fruit sample was about 50 g of tissue, which was frozen at −20°C until required.

In the transfer experiment, samples of fruit were moved at intervals from a ‘low ethylene’ to a ‘high ethylene’ chamber (the same chamber each time), to simulate switching off the ethylene scrubber. No assessments were carried out on this fruit until after 29 (1989 experiment) or 33 (1990 experiment) weeks of storage.

2.3. Ethylene determinations

Ethylene was measured using a gas chromatograph (Pye Unicam PU4500 with a Trivector computing integrator) fitted with a flame ionization detector and a 300 mm long, 6 mm o.d. glass column filled with alumina maintained at 100°C while flushed with N\(_2\) as a carrier gas. To measure IEC, a 0.7 ml gas sample was removed from the core cavity of an apple, using a needle with the tip bent over to avoid blockage. The needle was replaced with one with a straight tip and 0.5 ml of the sample was injected directly into the gas chromatograph.

2.4. Estimation of ethylene-forming capacity

A 2 mm-thick slice was cut 4 mm in from the skin of each apple of a 10-apple sample. A 20 mm-diameter disc was cut from each slice and placed in a 30 ml vial with 0.5 ml of 12 mM ACC, 600 mM glycerol in 10 mM phosphate buffer, pH 7.0 (Cheverry et al., 1988). Preliminary experiments had indicated saturation in this system at 4–8 mM ACC. After allowing 1 h for the production of wound ethylene to cease and for ethylene in the intercellular spaces to dissipate, the vials were sealed. After a further hour, the concentration of ethylene within the vials was determined. This estimation of ethylene-forming capacity was considered to be a measure of ACC oxidase activity.

2.5. Ethanol and ethyl acetate determination

Samples of chamber atmosphere were injected into a gas chromatograph (Pye Unicam PU4500) fitted with a flame ionization detector and a 2 m long, 6 mm o.d. column of 5% OV3 on Gas Chrom G maintained at 50°C. The carrier gas was N\(_2\) saturated with water vapour.

2.6. Acidity determination

Frozen tissue was allowed to thaw before approximately 40 g was weighed and homogenized in 50 ml of distilled water. The final volume was noted and 5 ml of homogenate were diluted to
100 ml with distilled water before titration to pH 8.1 with 0.1 M NaOH (Smith, 1985).

2.7. Soluble pectin and ACC analysis

Soluble pectin and 1-aminocyclopropane-1-carboxylic acid (ACC) were extracted as described by Bartley et al., (1982) except that the extraction medium was 0.1 M HCl. Soluble pectin was precipitated from 80% acetone and estimated as anhydro-galacturonic acid using 3-phenyl-phenol (Blumenkrantz and Asboe-Hansen, 1973). ACC was estimated directly from the extract by the method of Lizada and Yang (1979).

2.8. Rates of respiration and production of ethylene

At the end of the time-course experiment, approximately 1.5 kg of ballast apples from each storage chamber were placed in a sealed jar at 3.5°C flushed with 5 l h⁻¹ of 1.25% O₂ or 0.75% O₂, as appropriate, and the content of ethylene and CO₂ of the effluent was monitored.

3. Results

3.1. Concentrations of ethylene in storage chambers

In 1989–90, for the first 8 weeks of storage in chambers without converters of ethylene, the concentrations of ethylene increased at similar rates. Thereafter concentrations in ‘0.75% O₂’ remained constant at about 6600 µmol m⁻³. In chambers of the other two storage methods (‘5% CO₂’ and ‘1.25% O₂’), accumulation continued, reaching a maximum of 26000 µmol m⁻³ after 24 weeks, and then declined over the next 8 weeks to 17600 µmol m⁻³. In 1990–91, in ‘high ethylene’ chambers, concentrations rose to about 40 µmol m⁻³ within 7 days of loading, increasing to about 2200 µmol m⁻³ at 18 weeks and 2600–3100 µmol m⁻³ after 32 weeks. The slower rise and generally lower concentration of ethylene in 1990–91 was a consequence of the removal of ethylene by the automatic sampling system (see Section 2.1).

In both years, the concentrations were lower in ‘low ethylene’ chambers than in ‘high ethylene’ chambers, reaching a maximum of less than 35 µmol m⁻³ in ‘low ethylene’ chambers by the end of the storage period (Fig. 1A). In both years, the concentration of ethylene started to increase after

Fig. 1. Ethylene concentration in the storage atmosphere (A) and internal ethylene concentration (B), of ‘Cox’ apples stored in ‘low ethylene’ chambers using different methods. 1989–90: ‘1.25% O₂’ method: <1% CO₂ + 1.25% O₂ throughout (○); ‘5% CO₂’ method: 5% CO₂ + 16% O₂ for 15 days followed by <1% CO₂ + 1.25% O₂ (□); ‘0.75% O₂’ method: <1% CO₂ + 0.75% O₂ throughout (△). 1990–91: ‘5% CO₂’ method: 5% CO₂ + 16% O₂ for 15 days followed by <1% CO₂ + 1.25% O₂ (■). Upper vertical bar: SED ((a) 81 df, (b) 48 df), 1989–90. Lower vertical bar: SED ((a) 78 df, (b) 66 df), 1990–91.
about 5 weeks where the 5% CO₂ treatment had been applied and after about 2–3 weeks where it had not. In 1989–90 the rate of accumulation was similar in ‘1.25% O₂’ and ‘0.75% O₂’ and slowest in ‘5% CO₂’, for about the first 10 weeks of storage, after which the concentration in ‘0.75% O₂’ chambers increased very little and at the end of storage was less than half the concentration in the ‘5% CO₂’ chambers.

3.2. Internal ethylene

In ‘high ethylene’ chambers in 1989–90 and 1990–91, the IEC of fruit increased from week 1 with a pattern similar to that of the accumulation in the chamber atmosphere. The IEC was slightly higher than concentration in the chamber atmosphere in both years (data not shown).

In 1989–90 the IEC of apples from ‘low ethylene’ chambers increased after 3–5 weeks but, in 1990–91, this rise was delayed for about 14 weeks (Fig. 1B). By the end of storage, the average IEC was 260–1100 μmol m⁻³. There was also a seasonal variation in the change in the distribution of internal ethylene. In 1989–90 95% of fruits stored using the ‘5% ‘low ethylene’ method had an IEC of less than 4 μmol m⁻³ after 5 weeks. After a further 13 weeks all fruits had an IEC in excess of 22 μmol m⁻³ (Fig. 2). Although, in 1990–91, fruit IEC remained predominantly below 4 μmol m⁻³ for longer, this transition from low IEC to high IEC took only 6 weeks.

3.3. Production of ethylene

Ethylene production in ‘low ethylene’ ‘5% CO₂’ fruit increased from 0.4 to 40 pmol kg⁻¹ s⁻¹ over the storage period in 1989–90 and from 0.3 to 19.5 pmol kg⁻¹ s⁻¹ in 1990–91 (Fig. 3). In 1990–91 ethylene production in ‘high ethylene’
‘5% CO₂’ samples increased from 0.85 to 61 pmol kg⁻¹ s⁻¹. Although in the ‘high ethylene’ ‘5% CO₂’ and ‘low ethylene’ ‘5% CO₂’ samples a maximum rate was observed after about 25 weeks of storage, the rate was lower in ‘low ethylene’ fruit.

3.4. Ethylene-forming capacity and ACC content

The capacity for forming ethylene from exogenous ACC (a measure of ACC oxidase activity) in ‘low ethylene’ ‘5% CO₂’ apples remained constant for the first 22 weeks of storage, then increased...
Fig. 5. Firmness of ‘Cox’ apples, 1989–90, during storage using different methods. ‘High ethylene’: (●) (average of the 3 methods). ‘Low ethylene’: ‘1.25% O2’ method: <1% CO2 + 1.25% O2 throughout (○); ‘5% CO2’ method: 5% CO2 + 16% O2 for 15 days followed by <1% CO2 + 1.25% O2 (□); ‘0.75% O2’ method: <1% CO2 + 0.75% O2 throughout (△). Vertical bar is SED (96 df).

3.5. Firmness

3.5.1. Time-course experiment

In 1989–90 there was little effect of the storage method on softening of ‘high ethylene’ samples and for clarity, only average firmness values for the three storage treatments are presented in Fig. 5. In samples from all chambers, there was an initial decline in firmness over the first 4 weeks of storage. In ‘high ethylene’ chambers this continued for about another 16 weeks, when softening ceased. For the ‘low ethylene’ ‘5% CO2’ fruit, firmness remained constant for 16 weeks following the initial decline, then decreased until the experiment ended at 32 weeks. The ‘1.25% O2’ and ‘0.75% O2’ ‘low ethylene’ fruit were intermediate in softening between the ‘high ethylene’ and ‘low ethylene’ ‘5% CO2’ samples.

In 1990–91 a similar result was obtained (Fig. 6), with an initial decline in firmness in all samples, followed by a further decrease in ‘high ethylene’ samples and a cessation of softening in ‘low ethylene’ samples for a further 18 weeks before softening restarted.

3.5.2. Transfer experiment

In the 1989–90 experiment, fruit held in ‘low ethylene’ storage for less than 12 weeks before transfer to ‘high ethylene’ storage were softer at the end of storage (32 weeks) than those held in ‘low ethylene’ storage for 12 weeks or longer before transfer (Fig. 7). A similar result was obtained in 1990–91, when no further benefit of continued ‘low ethylene’ storage was obtained after fruits had been held in a low ethylene atmosphere for more than 16 weeks.
3.6. Soluble pectin

In ‘high ethylene’ chambers in 1990–91, soluble pectins of fruit increased above harvest levels after about 4 weeks from harvest and continued to do so for the next 12 weeks (Fig. 8). Soluble pectin in ‘low ethylene’ samples did not start to increase until after 22 weeks of storage. Where the firmness was less than 40 N, the concentration of soluble pectin was correlated negatively with firmness, with correlation coefficients (18 df) of –0.63 for ‘low ethylene’ samples and –0.87 for ‘high ethylene’ samples. However, when treatments were combined, there was no overall correlation between soluble pectin and firmness.

3.7. Acidity

Fruit titratable acidity in 1989–90 was 10 g malic acid equivalent kg\(^{-1}\) fresh weight at harvest; it declined linearly to 6 g after 32 weeks storage. Storage method or ethylene removal did not affect acid loss (data not presented).

3.8. Ethanol and ethyl acetate

After 10 weeks of storage, the concentrations of ethanol and ethyl acetate in the atmosphere of ‘0.75% O\(_2\)’ ‘high ethylene’ chambers was equivalent to 400 and 8 mg kg\(^{-1}\) fresh weight in the fruit flesh, respectively. The concentrations of these compounds declined to 150 and 0.5 mg kg\(^{-1}\) fresh weight equivalent after 32 weeks. Neither compound was detected in ‘low ethylene’ chambers or chambers maintained at 1.25% O\(_2\). However, the catalytic converters of ethylene oxidised ethanol and ethyl acetate in the vapour phase.

3.9. Respiration activity

There was no effect of storage method or ethylene removal during storage on rate of production of CO\(_2\) after storage for 32 weeks (Table 1). Overall, ‘low ethylene’ samples had a lower production rate of ethylene \((P < 0.05)\) and the lowest production rate was in samples from ‘0.75% O\(_2\)’. 

![Fig. 7. Firmness of 'Cox' apples at the end of storage, 29 (1989–90) or 32 (1990–91) weeks, following transfer from 'low ethylene' to 'high ethylene' at different times during storage. Fruit was stored in 5% CO\(_2\) + 16% O\(_2\) for 15 days followed by <1% CO\(_2\) + 1.25% O\(_2\), 1989–90 (○); 1990–91 (●). Upper vertical bar is SED (27 df), 1990–91. Lower vertical bar is SED (6 df), 1989–90.]

![Fig. 8. Soluble pectin in the flesh of 'Cox' apples stored in 1990–91 in high and low ethylene. Fruit was stored in 5% CO\(_2\) + 16% O\(_2\) for 15 days followed by <1% CO\(_2\) + 1.25% O\(_2\). 'High ethylene' (■); 'low ethylene' (□). Vertical bar is SED (46 df).]
Table 1

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3.10. Disorders and ground colour

Disorders were not found in 1989–90 but core flush, brownheart and flesh breakdown were observed in 1990–91 after storage for 32 weeks. In ‘low ethylene’ samples, 20% of apples had developed core flush and 5% were affected by flesh breakdown. In ‘high ethylene’ samples, 5% had brownheart and 10% flesh breakdown. These disorders were all in the ‘slight’ category and were not commercially significant. There were no effects of storage method or ethylene removal on ground colour in 1989–90. Measurements were not made in 1990–91.

4. Discussion

It had been considered that transferring fruit from a ‘low ethylene’ to a ‘high ethylene’ chamber was equivalent to switching off the system for removing ethylene. It was calculated from measured production rates of ethylene by apples in ‘low ethylene’ ‘5% CO₂’ chambers that, if the converter of ethylene was switched off, concentration of ethylene would have reached 44 μmol m⁻³ within three days early in storage and within one day at the time of later fruit transfer. This rate of increase suggests that fruit would respond similarly to the effects of transfer and to the switching off of the ethylene converter.

Transferring fruit from a ‘low ethylene’ chamber to a ‘high ethylene’ chamber did not affect firmness of fruit at the end of the storage period when the transfer was carried out later than 12 weeks (1989–90) or 16 weeks (1990–91), when concentration of ethylene in the ‘low ethylene’ chambers was about 2 μmol m⁻³. It was concluded that switching off the converter after such a concentration was reached was a means of reducing running costs while still retaining the benefits of ‘low ethylene’ storage.

The time course study of softening indicates that the effect of ethylene removal was predominantly to delay the onset of softening, rather than to reduce the rate of softening. The longer delay in the onset of softening in 1990–91 than in 1989–90 is consistent with the more effective control of ethylene production by fruit stored in an atmosphere low in ethylene in 1990–91. The earlier start but longer duration of the transition in distribution of IEC in 1989–90, suggests that the less effective control was a result of a greater initial range in the rate of ethylene production for individual fruit rather than an overall increase in responsiveness to ethylene. Factors responsible for the onset of softening are uncertain. It is possible that softening was initiated when the IEC reached a particular value. The linearity of response to time in an atmosphere low in ethylene (transfer experiment) and the apparent abrupt cessation of further benefit suggest that softening is initiated when a threshold is reached and that low ethylene slows, but does not inhibit, this process. From the transfer experiment, the time in ‘low ethylene’ storage after which no further benefit of ethylene removal was obtained was 8–12 weeks in 1989–90 and 14–16 weeks in
At this time, the average IEC in ‘5% CO₂’ ‘low ethylene’ apples were 4.4–13.2 and 2.6–8.8 μmol m⁻³ respectively, for 1989–90 and 1990–91 and the distribution of IEC was changing from predominantly low (< 4.4 μmol m⁻³) to predominantly high (> 22 μmol m⁻³). Knee et al. (1983) found a range of IEC of 0.4–4.4 μmol m⁻³ in apples on the tree just prior to a sustained rise in the IEC. Thus it is possible that for ‘Cox’ apples in 1.25% O₂, biochemical events that lead to softening are initiated when IEC reaches about 4.4 μmol m⁻³ and the first decline in the penetrometer firmness value occurs about 8 weeks later.

The effectiveness of maintaining firmness of ‘Cox’ apples in a CA store by removing ethylene thus seems to depend on the successful maintenance of an IEC below about 4.4 μmol m⁻³. A positive feedback system is thought to function in apples and other climacteric fruits, whereby ethylene concentration in the fruit affects ACC synthase (Bufler, 1984) and oxidase (Bufler, 1986) activity. This corresponds to the system 2 described by McMurchie et al. (1972). It has also been suggested that there is a two-phase receptor system in apples (Knee 1985), an hypothesis supported by studies on Arabidopsis mutants (Chang, 1996). Maintaining a low ethylene CA environment should prevent the internal ethylene rising sufficiently to trigger autocatalytic production. This has been achieved with ‘Gloster 69’ apples (Knee and Tsantili, 1988). However, it appears that in ‘Cox’, the positive feedback system is operational shortly after harvest as, even in ‘low ethylene’ samples, ethylene production increased from 5 weeks after the start of storage, although ACC did not increase until 15 weeks and ethylene-forming capacity did not increase until after 22 weeks. In 1990–91, storage in an atmosphere low in ethylene reduced the gain of the positive feedback system (slope of log ethylene production rate) until approximately 15 weeks, when the gain increased to a level similar to that exhibited by ‘high ethylene’ fruit early in storage. It was expected that the ‘low ethylene’ treatment should subsequently appear to have no further effect on softening (transfer experiment, 1990–91). The rate of the accumulation of internal ethylene in ‘Cox’ apples can be reduced by increasing the rate of removal of ethylene from storage containers, but this was only found to reduce softening where ethylene production was reduced (Dover and Stow 1993). Any further improvements must await the development of methods for further reducing the rate of production of ethylene.

Concentrations of soluble pectin in apple fruit increase during softening (Knee and Bartley, 1981) and it has been suggested that this is a result of the degradation of cell wall pectin (Bartley, 1978). Softening in this study did not correlate well with soluble pectin even though the onset of softening, at 22 weeks, in ‘low ethylene’ fruit coincided with an increase in soluble pectin. For the first 5–6 weeks of storage in the 1990–91 experiment, fruit from the ‘high ethylene’ and ‘low ethylene’ containers softened, though little change in soluble pectin was evident. Further, when softening started in fruit from ‘low ethylene’ containers, the absolute concentration of soluble pectin was higher than for ‘high ethylene’ fruit at a similar firmness. Knee and Sharples (1981) similarly found a poor correlation between softening and soluble pectin accumulation in ‘Cox’, and Knee (1989) reported softening of Bramley apples without an increase in soluble pectin.

The lack of effect of storage in low ethylene on the ground colour of apples has been reported previously (Knee, 1986; Stow, 1990; Stow and Genge, 1990) and Streif and Bangerth (1976) concluded that breakdown of chlorophyll in tomato fruit is affected more by O₂ than ethylene.

From the data presented here it can be concluded that removal of ethylene from the storage atmosphere of ‘Cox’ apples delays the onset of softening for about 20 weeks. This delay was only achieved when the ethylene production rate was reduced by treatment with 5% CO₂ for 15 days at the beginning of storage. Further, to obtain a firmness benefit from storage in a low ethylene atmosphere, it was necessary to maintain an IEC of less than 4 μmol m⁻³, which corresponded to an ethylene concentration in the storage atmosphere of less than 2 μmol m⁻³. It is possible that the failure of some other varieties to respond to low-ethylene storage resulted from a lack of a
similar reduction in ethylene production rate and a consequent loss of control of IEC.

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References