Storage Quality of Apples following Natural and Artificial Tufted Apple Bud Moth Feeding Injury

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Abstract. ‘Golden Delicious’, ‘Delicious’, and ‘York Imperial’ apples (*Malus ×domestica* Borkh.) with various amounts of tufted apple bud moth (TABM) [*Platynota idaeusalis* (Walker)] feeding injury were evaluated for quality at harvest and following storage in air and controlled atmosphere. In addition, apples were artificially injured during two seasons to mimic TABM feeding injury. There was little or no effect of natural TABM injury on the quality of apples in many experiments. At harvest, firmness was not influenced by natural TABM injury, soluble solids concentration (SSC) was increased in three of 11 experiments, and starch levels decreased in two of 11 experiments. These results indicate a slight advancement of maturity of injured fruit. More severely injured fruit tended to have more decay after storage than fruit with less injury. Some injury, especially first brood injury, up to ≈7 to 10 mm² surface damage, can be tolerated without compromising storage quality of processing apples. However, severe injury (>79 mm²) can increase decay. Second brood injury, whether caused by natural feeding of TABM or through artificial means, usually caused a higher incidence of decay than first brood injury. Artificial injury imposed close to harvest led to more decay in storage than did similar injury imposed earlier.

Tufted apple bud moth (TABM) is the most serious direct pest of apples in the mid-Atlantic region of the United States (U.S. Dept. of Agriculture, 1995). Fruit injury from TABM in Pennsylvania was 6.1% in 1986 (Knight and Hull, 1988), up from 0.3% in 1973 (Colburn, 1974). Hull (unpublished data) has more recently estimated injury to be 8% to 13%.

Larvae of TABM overwinter in the ground cover under fruit trees (Knight and Hull, 1988). Following pupation in the ground cover, beginning in late April to early May, the emergence of first-brood adults peaks in early June. Larvae from this generation are active during July and early August and feed on both leaves and fruit during this period. Second-brood adult emergence peaks in late August with subsequent larvae feeding on fruit from mid-August to October. Since many growers stop spraying late in the season because of increasing workloads, days-to-harvest limitations for

insecticides, and the difficulty of getting good spray coverage because of fruit load, late-season control of TABM can be difficult. Therefore, a large percentage of fruit injury at harvest is usually a result of the feeding of second brood larvae (Hull and Meagher, 1987).

Injury to the fruit by TABM appears as tiny holes (early larval instar feeding), as irregular scarring or galling of the apple surface, or as an area of decay, generally found around the stem (Meagher and Hull, 1990). Fruit injured in late July and August by larvae of the first brood usually exhibit callus formation, a depression around the injured area due to growth of the uninjured portion of the apple, and/or decay, depending upon environmental conditions and the fungicide program used. Even though the number of fruit injured by first brood TABM is usually lower than that injured by the second brood, the amount of injury at this time of the season is usually more extensive because TABM larvae can feed on the fruit until pupation. Less injury to individual fruit occurs in the fall because the larva can only develop to a third or fourth instar before the fruit are either harvested or the larvae go into overwintering diapause (Hull and Rajotte, 1988). Larvae occasionally enter the apple calyx and feed unnoticed within the seed cavity.

Fresh-market apples are downgraded for any skin breaks, such as those caused by TABM feeding. However, ≈72% of the apples grown in Pennsylvania are sold to processors (Pennsylvania Dept. of Agriculture, 1996). Processing grades (i.e., U.S. #1, #2, cider, or cull) are determined by the amount of trim

waste resulting from “the usual commercial preparation for use” (U.S. Dept. of Agriculture, 1979). Loss resulting from normal peeling and coring operations is not counted in the trim waste for grade determination. An apple is not downgraded from U.S. #1 to U.S. #2 until 5% trim waste is required to remove all defects. Hull and Rajotte (1988) found that in storage, TABM-injured ‘Yorking’ fruit lost more mass and decayed more than did uninjured fruit in the same processing grade.

Tufted apple bud moth has become resistant to the organophosphate insecticides that have low toxicity to the major mite predator, *Stethorus punctum* (LeConte), in Pennsylvania (Biddinger and Hull, 1995). More recently, Hull et al. (1997) reported that TABM had become resistant to the carbamate methomyl, an insecticide used in conjunction with the organophosphates to control TABM for >20 years. However, use of the remaining registered insecticides that are toxic to TABM would severely threaten successful biological control programs for the European red mite (Knight and Hull, 1988). If apples with insect injury can be stored without a loss of quality, insecticide use can be reduced, allowing expanded use of parasitoids as biological control agents for TABM. For example, Biddinger et al. (1994) reported a total parasitoid complex of 41 species that attack TABM, and parasitism was much higher in orchards using pheromone mating disruption than in conventionally treated orchards. Therefore, more information is needed to assess the impact of TABM injury on the apple industry in the mid-Atlantic region. The objective of this study was to evaluate the effects of TABM injury on quality deterioration of several fresh-market and processing cultivars, and to further examine the relationship between TABM injury and changes that occur in fruit quality during storage under various environmental conditions. Categories of TABM injury used in this study were narrowly defined to determine more accurately the effects of small amounts of injury on the storage potential of apples.

Materials and Methods

Natural TABM Injury

General. Fruit were harvested at maturity from orchards at the Penn State Fruit Research and Extension Center, brought into the lab, and sorted according to categories of TABM injury based on the aggregate amount of feeding injury. Apples showing no visible signs of TABM injury from the same trees were used as controls. In 1992 experiments, a replication refers to an individual orchard. In 1993–95 experiments, subsamples were taken within each orchard. Fruit within each damage category were randomized into samples, which were weighed and analyzed for starch index (Cornell scale 1–8, Blanpied and Silsby, 1992), firmness, soluble solids concentration (SSC), titratable acidity (TA), and disorders. Firmness was determined using an Electronic Pressure Tester (EPT) (Lake City Technical Products, Kelowna, B.C., Canada). Juice samples

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collected during firmness testing were used to determine SSC with a refractometer (Atago; Markson Lab Sales, Hillsboro, Ore.) and the remaining juice saved for TA determination. TA was determined by adding 100 mL water to 1 mL apple juice and titrating to 8.1 with 0.01 N NaOH (Schott Geräte autotitrator; Visco/Alpha, Middletown, N.Y.). Samples for storage were placed in mesh bags, weighed, immediately cooled, and then put in chambers under the atmosphere(s) specified in each experiment (Table 1). Fruit were stored in the controlled-atmosphere facility at the Penn State Fruit Research and Extension Center (FREC). Atmospheres in the individual chambers (208-L barrels) were controlled by an Oxystat 2® Model 930 (David Bishop, Sussex, England). Following storage, all fruit were evaluated for firmness, SSC, loss of mass, decay incidence, and internal disorders after 24 h at 20 °C.

1992-93

Expt. 92-1. 'Golden Delicious' were harvested in late September and stored under either controlled atmosphere (CA) (2.4% O₂ + 0% CO₂) or air at 0 °C. There were three or four replications, each with 11 to 47 fruit per sample (injury category × storage atmosphere × storage length combination) within a replication depending on the number of injured fruit within each category (categories in Table 2). Apples were removed after 3, 6, and 9 months of storage.

Expt. 92-2. 'Delicious' apples were harvested during the first week of October. There were three replications per injury category × storage atmosphere × storage length combination (Table 1), each with 18 to 20 fruit, depending on the number of injured fruit in each category (categories in Table 2). In two of the storage atmospheres, the CO₂ was held at 4% for 21 d followed by 7 d at 8% or 12% and this cycle repeated for the duration of storage (Table 1). Following cooling, the samples were stored for 3 and 6 months under six CA atmospheres.

Expt. 92-3. 'York Imperial' apples were harvested in mid-October. Following cooling, the samples were placed under three CA atmospheres and stored for 3, 6, and 9 months. There were three replications per treatment, each with 20 fruit (total of 2700 apples) (categories in Table 2).

1993-94

Expt. 93-1. 'Golden Delicious' from two blocks were separated by first and second brood injury and then sorted into categories based on the aggregate area of TABM injury. Injury categories were as follows: 1 = 0, 2 = <7, 3 = 7-20, 4 = 21-39, 5 = 40-79 and 6 = 80-314 mm². Apples in each category were further divided into individual samples for analysis and storage. The number of subsamples (three to four) and number of fruit in each treatment varied (four to 16) depending on the number of injured fruit in each category. The remaining samples were held in CA storage (2.4% O₂ + 0% CO₂) at 0 °C for 6 months. Half of the samples (when sufficient fruit were

Table 1. Apple cultivars used, storage conditions, and times of evaluation of response to natural and artificial TABM^a injury.

Expt.	Cultivar	Storage conditions			Time of evaluation Storage for (mo.)
		Temp (°C)	Gas mixture		
			% O ₂	% CO ₂	
<i>Natural injury</i>					
92-1	G. Delicious	0	2.4	0	3, 6, 9
92-2	Delicious	0	2.4	0	3, 6
		0	2.4	4.0	
		0	2.4	8.0	
		0	1.0	0	
		0	2.4	4.0 (21 d) ^y	
				8.0 (7 d, repeat)	
		0	2.4	4.0 (21 d)	
				12.0 (7 d, repeat)	
92-3	York Imperial	0	2.4	0	3, 6, 9
		0	2.4	4.0	
		0	1.0	0	
93-1	G. Delicious	0	Same as 92-1	6	
93-2	Delicious	0	Same as 92-1	6	
93-3	York Imperial	0	Same as 92-1	6	
94-1	G. Delicious	0	2.0	< 1	5
94-2	Delicious	0	Same as 94-1	5	
94-3	York Imperial	0	Same as 94-1	4, 8	
95-1	York Imperial	0/1	Air		4, 7
		0/1		3.0	< 2
95-2	York Imperial	1	3.0	< 2	6
<i>Artificial Injury</i>					
93-4	Delicious	0	2.4	0	6
93-5	G. Delicious	0	2.4	0	6
93-6	G. Delicious	0	2.4	0	6
94-4	Delicious	0	2.0	<1	5, 7
94-5	G. Delicious	0	2.0	<1	5, 7

^aTufted apple bud moth.

^bSamples were stored for 21 d at 4% CO₂ followed by 7 d at 8% or 12% CO₂. This cycle repeated for the duration of storage.

Table 2. Effects of TABM^a injury on percent decay in 'Golden Delicious', 'Delicious', and 'York Imperial' apples after 3, 6, and 9 months of storage. Expts. 92-1, 92-2, and 92-3.

			Damage category							
			1	2	3	4	5			
Storage			0	<7	7–20	21–79	80–314			
(wk.)			Area (mm ²)					R ²	P value	n
<i>G. Delicious</i>										
3			0.4	1.3	4.5	0.0	12.2	0.436	0.0006	59–240
6			0.0	3.7	0.0	6.7	10.0	0.410	0.0137	30–97
9			0.5	0.5	0.0	0.0	7.8	0.586	0.0073	65–146
<i>Delicious</i>										
3			0.2	0.2	0.4	1.9	1.6	0.113	0.005	18–73
6			2.5	1.5	3.6	3.8	6.2	0.119	0.001	56–73
			Damage category							
			1	2	3	4	5			
Storage			0	<20	21–79	80–177	>177			
(wk.)			Area (mm ²)					R ²	P value	n
<i>York Imperial</i>										
3	0.6	0.6	2.2	0.6		---		0.003	0.772	540
6	0.9	1.7	4.4	5.1		---		0.132	0.560	540
9	3.9	12.9	7.2	21.5		42.2		0.560	0.0001	540

^aTufted apple bud moth.

available to include the inoculation treatment) were removed from storage in December and oversprayed with blue mold (*Penicillium expansum* Link) spores (50,000 spores/mL), to insure the presence of decay inoculum, and returned to storage for the remainder of the storage period. Inoculated samples were stored on pulp trays rather than in mesh bags.

Expts. 93-2 and 93-3 utilized 'Delicious' (harvested from four orchards with three to

four subsamples per orchard) and 'York Imperial' (harvested from three orchards with two to four subsamples per orchard), respectively. Fruit were handled as in Expt. 93-1.

1994-95

Expt. 94-1. 'Golden Delicious' were harvested and sorted into natural injury categories (See Expt. 93-1). The apples were har-

vested between 20 and 22 Sept. 1994 from one orchard with four subsamples. The at-harvest evaluations were the same as previously described (1993–94). Half of the samples were oversprayed with blue mold (See Expt. 93-1) prior to storage. The samples were stored for 5 months in CA ($2\% \text{O}_2 + <1\% \text{CO}_2$) at 0°C .

Expt. 94-2. 'Delicious' apples were harvested between 26 Sept. and 3 Oct. from two orchards for brood two injury and one orchard for brood one injury (three to four subsamples in each orchard). The rest of the experimental details were the same as previously described.

Expt. 94-3. 'York Imperial' apples were harvested between 4 and 14 Oct. 1994 from three orchards (four subsamples each). Only brood two samples were stored for 4 and 8 months. The rest of the experimental details were the same as for Expt. 94-1.

1995–96

'York Imperial' apples with natural TABM injury were utilized in both experiments in the 1995 season. In these experiments apples were stored at 1°C to determine if storage at this slightly elevated temperature would exacerbate any effects of TABM injury on fruit storability.

Expt. 95-1. 'York Imperial' apples were harvested the 2nd week in October and separated into categories based on the amount of TABM injury (same categories as Expt. 93-1). There were three subsamples (20 apples each) of each injury category stored in each of four regimes: 1) CA ($3\% \text{O}_2 + <2\% \text{CO}_2$) at 0°C ; 2) CA ($3\% \text{O}_2 + <2\% \text{CO}_2$) at 1°C ; 3) Air at 0°C ; 4) Air at 1°C . Fruit were removed from each regime after 4 or 7 months of storage and evaluated for quality as in previous experiments.

Expt. 95-2. 'York Imperial' apples were harvested 16 Oct. 1995 and sorted into TABM injury categories (as in Expt. 93-4). There were three subsamples in each injury category for each storage regime. Half of the apples were inoculated with blue mold (atomized with 75,000 spores/mL). Apples from each treatment were stored in CA ($3\% \text{O}_2 + <2\% \text{CO}_2$) at 1°C for 6 months.

Artificial TABM injury

Experiments were initiated to artificially mimic the natural TABM injury on apples. Their purpose was to develop a method to more uniformly manipulate the timing and amount of injury to the fruit, thus providing equal numbers of injured fruit across all injury categories. In 1993, the artificial injury was accomplished while fruit were on the tree by using cork borers (20-mm² area), fitted with metal washers 1.5 mm from the tip, to control depth of penetration into the flesh. Injury was located about midway between the stem and calyx ends of the apple. The skin of the apple was cut with the borer and the disk removed with tweezers. This technique caused only shallow injury (i.e., similar to natural TABM feeding), but with a controlled diameter. The artificial injury inflicted with a cork borer

caused excessive preharvest drop of 'Delicious' apples. For example, artificial injury designed to mimic first brood TABM injury caused 18%, 57%, 77%, and 97% drop in fruit with one, three, seven and 15 punches (20, 60, 140, and 300 mm²), respectively. In addition, injury on fruit that remained on the trees became deeper than the natural TABM injury that was to be mimicked. Therefore, in 1994–95 the protocol for artificial TABM injury was modified. The injury was inflicted using a 2-mm-diameter nail (area of injury $\approx 3 \text{ mm}^2$) that was inserted through a cork so only 1 mm of the tip protruded to injure the apples. The number of times that fruit were injured was also adjusted. The at-harvest and storage quality evaluations were the same as in natural damage experiments.

Expt. 93-4. 'Delicious' were injured once a week (the same set of fruit each week) for 4 weeks during the time first brood TABM larvae were damaging fruit (21 and 28 July, 5 and 13 Aug.) with five categories ranging from a total of zero to 15 punches (Table 3). The amount of injury inflicted varied by week and by category (Table 3). For example, apples assigned to category five received one, two, four, and eight punches at weeks 1 to 4, respectively, for a total of 15 punches (300 mm²). This would mimic a TABM larva feeding on an apple during the 4-week period and eating an increasing amount of the fruit each week while the larva matures in size. A second set of apples was injured once a week for 4 weeks during the time of second brood injury (23 and 31 Aug., 7 and 14 Sept.) with a total of zero to six punches (Table 3). There were four subsamples per treatment per brood. Seventy apples were injured in each category per replication and brood. The apples were harvested 27 Sept. and held in CA storage ($2.4\% \text{O}_2 + 0\% \text{CO}_2$) for 6 months. The number of apples in each subsample varied from eight to 34 depending on number of harvested fruit, because fruit that fell from the tree before harvest were excluded from the sample. Percent drop was determined by accounting for all tagged apples whether on the tree or dropped under the tree.

Expt. 93-5. 'Golden Delicious' fruit were injured once a week for 4 weeks during the period of second brood larval injury (23 and 31 Aug., 7 and 14 Sept.) for a total of zero to six punches (same as brood two for 'Delicious' in Table 3). There were four subsamples per treatment. Seventy apples were injured per category in each subsample per brood. The apples were harvested 24 Sept. 1993 and stored in CA storage ($2.4\% \text{O}_2 + 0\% \text{CO}_2$) for 6

months. The number of fruit per treatment within each subsample varied from eight to 35.

Expt. 93-6. This experiment evaluated the effect of timing of TABM injury. 'Golden Delicious' were artificially injured at 1-week intervals for 5 weeks. A new set of apples was injured each week giving five sets of apples with 20-mm² injury per fruit (injured between 23 Aug. and 20 Sept.). There were four subsamples. Sixty fruit were injured on each date. The apples were harvested 27–28 Sept. 1993 and stored in CA storage ($2.4\% \text{O}_2 + 0\% \text{CO}_2$) for 6 months. The number of fruit per subsample varied from 12 to 38.

Expt. 94-4. 'Delicious' were injured once a week (5, 12, 19, and 26 July) to mimic first brood injury and a second set of apples was injured once a week to mimic second brood injury (24 and 31 Aug., 8 and 14 Sept.). A total of 70 fruit were injured per injury category per subsample in each brood. Apples in both sets were injured a total of zero to four times (with 0, 3, 6, 9, or 12 mm² of injury). The apples were harvested 19 Sept. and the subsamples divided into groups of 20. With the exception of one or two fruit in random subsamples, all damaged fruit remained on the tree until harvest. One sample in each replication was analyzed at harvest and the remainder were placed in CA storage for 5 or 7 months.

Expt. 94-5. This experiment was identical to Expt. 94-4 except that 'Golden Delicious' fruits were used. All damaged fruit remained on the tree until harvest.

Statistical analyses

SuperANOVA (ABACUS, Berkeley, Calif.) was utilized to analyze all data. Analysis of variance and regressions were used using replicate or subsample means. Each factorial experiment was designed as a randomized complete block.

Results

Natural TABM injury

Effects of CA. In experiments where apples were stored in different atmospheres, quality parameters responded in an expected manner. For example, fruit stored in CA were firmer, lost less mass, and retained higher acidity than fruit stored in air storage, regardless of the amount of TABM injury. Low-oxygen storage maintained better quality than conventional CA conditions. Since these storage responses have been documented in many other

Table 3. Categories of artificial tufted apple bud moth (TABM) injury to apples. Expts. 93-4 and 93-5.

Category	Weeks damaged	Brood 1		Brood 2	
		No. punches ^a	Area (mm ²)	No. punches ^a	Area (mm ²)
1	---	0	0	0	0
2	1	1	20	1	20
3	1–2	3	60	2	40
4	1–3	7	140	4	80
5	1–4	15	300	6	120

^aWeek 1 damage = 1 punch, week 2 = 2 punches, week 3 = 4 punches, week 4 = 8 punches.

^bWeek 1 damage = 1 punch, week 2 = 1 punch, week 3 = 2 punches, week 4 = 2 punches (1 punch = removal of skin within area broken by cork borer).

studies, the data are not presented in this paper. In addition, there were no significant interactions between atmosphere and TABM injury in any experiments.

1992-93

Expt. 92-1. At harvest, firmness and SSC of 'Golden Delicious' apples were not affected by TABM injury; however, apples with >7.1-mm² injury had lower starch levels (higher starch indices) than uninjured fruit (data not shown). There were significant differences between orchards for SSC and starch index. Firmness, SSC, and mass loss were not affected by TABM injury, but decay incidence increased linearly with increasing TABM injury after 3, 6, or 9 months of storage (Table 2). There were no significant interactions between storage atmosphere and effects of TABM injury.

Expt. 92-2. Injury by TABM did not influence ripening of 'Delicious' apples at harvest (firmness, SSC, starch index), and there were no significant interactions between injury and storage atmosphere. After 3 months of storage, there were no statistically significant differences in firmness, SSC or mass loss due to TABM injury (data not shown). Firmness and SSC differed significantly between orchards. Decay incidence tended to increase in fruit with increasing injury when stored for 3 or 6 months (Table 2). Mass loss and SSC were not affected by TABM injury after 6 months in storage, but injured fruit were slightly firmer than control fruit (data not shown). There were no significant interactions between effects of storage atmosphere and TABM injury.

Expt. 92-3. At harvest 'York Imperial' fruit with >177 mm² TABM injury had slightly higher SSC (13.7%) than did fruit with <177 mm² (12.9%); however, firmness and starch indices were not influenced by the injury (data not shown). After 3 and 6 months of storage, quality of fruit was not affected by TABM injury (firmness, SSC, mass loss). Decay incidence was unaffected by injury level at 3 months, but it increased in fruit with injury after 6 months and even more so after 9 months of storage (Table 2). After 9 months of storage, the variation in TABM injury accounted for >50% of the variation in decay incidence, as was also true in the 'Golden Delicious' data (Table 2).

1993-94

Expt. 93-1. This experiment provided data on the effects of first and second brood natural TABM injury on the quality of 'Golden Delicious' apples. 'Golden Delicious' apples injured by brood two natural TABM were slightly softer than fruit with brood one injury (79 and 81 N, respectively, $P = 0.0007$); however, the more severe injury did not significantly decrease firmness at harvest. Starch index, SSC, and TA at harvest were not influenced by TABM injury. After 6 months of storage, firmness, SSC, mass loss, decay incidence, and TA were not affected by TABM injury. Fruit with second brood injury were still slightly

softer than those with first brood injury (61 and 65 N, respectively, $P = 0.0065$). Inoculation with *P. expansum* had no significant effect on blue mold incidence (data not shown).

Expt. 93-2. At harvest, firmness of 'Delicious' apples was not affected by natural TABM injury, and fruit with first vs. second brood injury did not differ in quality. In two out of three orchards, SSC increased with increased TABM injury and in one out of three orchards starch decreased with TABM injury. After 6 months of storage there were no effects of TABM injury on firmness, SSC, decay incidence, loss of mass, or TA. Decay of inoculated fruit did not differ from that of noninoculated fruit (data not shown).

Expt. 93-3. As with 'Golden Delicious' and 'Delicious', natural TABM injury had little or no effect on at-harvest quality parameters (firmness, SSC, starch, TA) of 'York Imperial' apples. After 7 and 9 months of storage in CA, there was little or no difference in quality due to TABM injury (where regressions were significant, the R^2 values were <0.2). Decay incidence did increase in one of three orchards because of brood two TABM injury. In one out of three orchards firmness decreased with increased brood one TABM injury after 9 months of storage ($R^2 = 0.42$, $P = 0.0065$). Inoculation with *P. expansum* did not increase decay incidence. After 9 months of storage, incidence of decay was significantly greater in fruit with brood two injury than in those with brood one injury (19% and 11%, respectively, $P = 0.0008$).

1994-95

Expt. 94-1. At-harvest quality (firmness, SSC, starch score, and TA) of 'Golden Delicious' fruit was not influenced by natural TABM injury, and there were no differences between fruit with first and second brood injury. At harvest, fruit quality parameters at harvest across all injury categories averaged 79 N (firmness), 11.7% (SSC), and 6.6 (starch index). Only apples with brood two injury were placed in storage. Firmness, SSC, and TA values after 5 months of storage were not affected by TABM injury level. However, decay incidence in 'Golden Delicious' increased with severity of TABM injury (Table 4). Blue mold incidence was not increased by inoculation.

Expt. 94-2. At-harvest quality measurements were not affected by natural TABM injury to 'Delicious' apples. Fruit with brood one injury had slightly lower starch levels and higher TA than those with brood two injury. After 5 months of CA storage, firmness decreased with increased TABM injury in one of two orchards, but SSC was not affected by injury (data not shown). Apples with brood two injury decayed more frequently than those with brood one injury (3.3% and 0.3%, respectively, $P = 0.0657$), and in fruit with brood two injury, decay incidence increased with severity of injury ($R^2 = 0.231$, $P = 0.0002$). Inoculation did not increase decay incidence. Loss of mass increased slightly with increased brood two injury ($R^2 = 0.070$, $P = 0.0489$), and

titratable acidity decreased slightly with TABM injury (brood one and two) (brood 1: $R^2 = 0.239$, $P = 0.0132$; brood 2: $R^2 = 0.143$, $P = 0.0104$).

Expt. 94-3. At-harvest SSC of 'York Imperial' apples increased with first brood natural TABM injury in one out of two orchards ($R^2 = 0.747$, $P = 0.0001$), but firmness, starch levels, and TA were unaffected. In fruit with brood two injury, decay incidence increased with increased TABM injury after 4 and 8 months of CA storage (4 months: $R^2 = 0.575$, $P = 0.0001$; 8 months: $R^2 = 0.748$, $P = 0.0001$). During 4 months of storage the inoculated fruit decayed more frequently than noninoculated fruit (27% vs. 16%, $P = 0.0001$); however, after 8 months there were no differences. Other quality parameters were unaffected by TABM injury.

1995-96

Expt. 95-1. At harvest there were no differences in quality of 'York Imperial' fruit in the six injury categories (mean quality across categories: firmness, 100 N; SSC, 11.5; starch index, 2.4). After 4 and 7 months of storage, firmness decreased and decay incidence increased as TABM injury increased (4 months, firmness $R^2 = 0.5$, $P = 0.0001$, and decay $R^2 = 0.2$, $P = 0.0001$; 7 months, firmness $R^2 = 0.6$, $P = 0.0001$, and decay $R^2 = 0.46$, $P = 0.0001$). Quality was not affected by storage treatments.

Expt. 95-2. Injury by TABM did not affect harvest maturity of 'York Imperial' apples. During 6 months of storage at 1 °C, incidence of fruit decay increased with TABM injury (Table 4). Inoculation with *P. expansum* increased decay significantly (13% and 21% for noninoculated and inoculated, respectively, $P \leq 0.021$). Loss of mass during storage was not affected by TABM injury.

Artificial TABM injury

1993-94

Expt. 93-4. At harvest, firmness and starch levels fell and SSC rose with increasing artificial first brood injury (Table 5). During storage, loss of firmness and mass, and decay incidence all increased with increasing artificial first brood injury levels (Table 5). Artificial second brood injury caused the same ef-

Table 4. Effects of TABM^a damage on decay in 'Golden Delicious' and 'York Imperial' apples after 5 months of storage at 0 °C or 6 months at 1 °C, respectively. Expts. 94-1 and 95-2.

TABM damage (mm ²)	% Decay	
	Golden Delicious 5 mo. at 0 °C	York Imperial 6 mo. at 1 °C
0	1.0	3.3
<7	6.3	9.2
7-20	13.8	5.8
21-39	15.4	21.7
40-79	25.0	18.5
80-314	---	42.6
R^2	0.445	0.575
P value	0.0001	0.0001

^aTufted apple bud moth.

Table 5. Quality measurements of 'Delicious' apples artificially injured to mimic Brood 1 and Brood 2 TABM² injury. Expt. 93-4.

Artificial TABM injury (mm ²)	At harvest			After 6 mo. of storage			
	Firmness (N)	SSC (%)	Starch index ^y	Firmness (N)	SSC (%)	% Mass loss	% Decay
<i>Brood 1</i>							
0	76	11.2	2.0	63	13.4	1.3	3.1
20	74	11.8	2.0	58	13.8	1.6	3.6
60	74	12.5	2.3	54	14.9	3.2	23.1
140	71	13.9	3.3	---	---	---	---
<i>R</i> ^{2x}	0.304	0.766	0.492	0.528	0.349	0.909	0.614
<i>P</i> value	0.0268	0.0001	0.0024	0.0265	NS	0.0001	0.0125
<i>Brood 2</i>							
0	74	11.0	2.0	61	13.4	1.4	1.7
20	73	12.2	2.3	52	13.8	1.6	0.0
40	72	12.5	2.8	49	14.0	1.5	5.4
80	71	12.9	3.0	49	14.1	2.2	17.0
120	71	13.0	2.8	48	13.8	3.0	47.1
<i>R</i> ^{2x}	0.447	0.589	0.236	0.505	0.191	0.518	0.738
<i>P</i> value	0.0013	0.0001	0.0298	0.0010	NS	0.0008	0.0001

^xTufted apple bud moth.^yCornell generic starch chart scale 1-8.^zAll regressions are linear. Quadratic did not improve *R*² values.^{ns}Nonsignificant at *P* ≤ 0.05.

fects as first brood injury, but its effect on decay incidence was even more pronounced (Table 5).

Expt. 93-5. Only artificial second brood injury was inflicted on 'Golden Delicious' apples. At harvest, firmness and starch levels decreased and SSC increased with severity of artificial TABM injury (cork borer) (Table 6), while TA was not affected. After 6 months of CA storage, quality differences between injured and control fruit were nonsignificant (data not shown). Decay incidence appeared to increase as injury increased from 0 to 40 mm² (1%, 8%, 19% decay for 0, 20, and 40 mm², respectively), but this trend was nonsignificant. No decay occurred with 80 mm² of injury, but these data may be misleading, as only one replicate was used.

Expt. 93-6. At harvest and after 6 months of storage, firmness, SSC, starch indices, and TA of 'Golden Delicious' were not affected by the date of artificial injury (data not shown). However, fruit developed more decay as injury was delayed (Fig. 1).

Table 6. Firmness, soluble solids concentration (SSC), and starch indices at harvest for 'Golden Delicious' apples artificially injured with cork borer prior to harvest to mimic TABM² injury. Expt. 93-5.

Artificial TABM injury (mm ²)	Firmness (N)	SSC (%)	Starch index ^y
0	76	12.5	4.5
20	73	13.5	6.8
40	68	13.8	8.0
80	65	14.6	7.8
120	66	14.5	7.8
<i>R</i> ²	0.455	0.631	0.434
<i>P</i> value	0.0011	0.0001	0.0016

^xTufted apple bud moth.^yCornell generic starch chart scale 1-8.

was still significant but its magnitude was less. The data for decay incidence in this experiment are similar to those for artificially injured fruit with similar amounts of TABM injury in Expt. 94-2 (Table 5).

Discussion

In many of the experiments, natural TABM injury had little or no effect on quality measurements. At harvest, firmness was not influenced by natural TABM injury, SSC were increased in three, and starch hydrolysis was increased in two of 11 experiments. Minor injury (≈1 to 79 mm²) is of little consequence if the fruit is to be processed immediately, as the injury will be removed in the peeling process. Obviously, even minor injury can reduce the grade of fresh-market fruit much before it is severe enough to cause a loss of quality other than the surface blemish.

Natural injury by TABM influenced decay more often than it did other characteristics (firmness, SSC, TA, mass loss, starch index). Loss of mass may be more of a problem in storages with relative humidities lower than those we used (>95%). More severely injured fruit often exhibited more decay after storage than fruit with less injury. Hull and Rajotte (1988) reported significant increases in mass loss and decay incidence following natural TABM injury, but the injury categories used in their study were much broader [U.S. #2 fruit have >5% trim waste (U.S. Dept. of Agriculture, 1979)]. Since the injury categories in our study were much more narrowly defined, we can further determine how much injury can occur without affecting quality. For example, the results suggest that some injury, especially first brood injury up to ≈7 to 10 mm², can be tolerated without compromising storage quality. In the experiments reported here, 83% to 94% of the naturally injured 'Golden Delicious', 81% to 92% of the injured 'Delicious',

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Expt. 94-4. At harvest, firmness, SSC, starch, and TA of 'Delicious' fruits were not influenced by artificial first or second brood TABM injury categories; after 5 and 7 months of CA storage the effects were still nonsignificant (firmness, SSC, mass loss, or decay). Fruit with brood two injury were softer, had less starch, and higher SSC and TA than those with brood one injury, both at harvest and after 5 and 7 months of storage.

Expt. 94-5. Like the 'Delicious' in Expt. 94-4, the at-harvest quality of 'Golden Delicious' was not affected by the artificial brood one or brood two TABM injury. This was also true after 5 months of CA storage, but decay incidence increased with amount of brood two injury (Table 7). After 7 months of storage the difference in decay due to second brood injury

Fig. 1. Percent decay in 'Golden Delicious' apples artificially injured at different times prior to harvest on 24 Sept. 1993 and stored for 6 months. Expt. 93-5. (0.8% of undamaged control fruit decayed).

Table 7. Decay after 5 and 7 months of storage for 'Golden Delicious' apples artificially injured with a nail to mimic brood 2 TABM^a injury prior to harvest. Expt. 94-5.

TABM category area (mm ²)	% Decay	
	5 mo.	7 mo.
0	0.0	1.3
3	5.0	1.3
6	10.0	7.5
9	18.8	10.0
12	21.3	12.5
R ²	0.656	0.236
P value	0.0001	0.0299

^aTufted apple bud moth.

and 76% to 85% of the injured 'York Imperial' apples harvested had <79 mm² TABM injury. The data also suggest that while severe injury (>79 mm²) can lead to some increase in decay incidence, minor TABM injury has little effect on storage quality of apples, especially in CA. Hull and Rajotte (1988) also found less effect of TABM injury in fruit stored under CA conditions than in those in regular air storage.

In these studies there were often significant differences between orchards. This is indicative of the numerous preharvest factors that can influence the quality of fruit and the effects of blemishes such as TABM feeding injury.

The majority of the fruit used in these studies originated from orchards that were treated with varying amounts of different insecticides. To establish viable economic injury levels for fruit destined to be stored, further relating the aggregate amount of TABM feeding injury on apples to the cost of various insecticide programs will be important. For example, some insecticides appear to mitigate the amount of feeding injury on individual fruit (Hull, unpublished data). This

type of activity could lessen insecticide usage.

Second brood injury, whether natural or artificial, usually caused more decay than did first brood injury. Typically, the second brood larvae, which feed on the fruit from the latter part of August through October, cause most TABM injury (Knight and Hull, 1988; Meagher and Hull, 1987). Therefore, TABM control is more important during the second than during the first brood hatch, especially for fruit that is to be stored for any length of time. Egg hatch occurs during August and early September. However, growers usually have a more difficult time controlling the second brood of TABM because of restrictions on timing of pesticide application, fruit load on the tree, and increasing work schedules. If fruit is to be used immediately after harvest, chemical management practices for TABM could be minimized during the second brood.

Effects of TABM injury appear to be the same regardless of the CA atmosphere; thus, optimum storage conditions are similar for both injured and noninjured fruit.

In most experiments where fruit were oversprayed with *P. expansum*, the inoculation did not increase decay incidence. This may indicate some healing or callusing of the tissue prior to the inoculations.

The artificial injury that was attempted in the first season (1993) was too severe and caused excessive preharvest drop, especially in 'Delicious', probably because the injury occurred at one time, as opposed to the natural TABM injury that occurs over a course of weeks, perhaps allowing some healing of the tissue. However, the second season protocol for artificial injury was successful, and the injury more closely mimicked natural TABM injury. In the future, this method could be used for further studies on the effects of injury on storage quality of apples to allow the harvest of fruit from a given block with a known amount of injury, thus aiding in experimental design.

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