The Potential Impact of Ice-Minus Bacteria as a Frost Protectant in New York Tree Fruit Production

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Ice-nucleating bacteria, which are known to occur naturally on many crops and have been associated with frost damage, may be subject to control with genetically engineered bacteria, dubbed "ice-minus" bacteria. Ice-minus technology is designed to depress the critical temperature at which frost damage begins by displacing the natural population of ice-nucleating organisms. A trial product has been tested in the field with strawberries. Although tests with bacteriacidal compounds have suggested other mechanisms for controlling the critical temperature in deciduous fruit crops, ice-minus may prove to be effective. This analysis examines the possibility of ice-minus being adopted by New York tree-fruit growers and the likelihood of it causing a major economic impact on the state's fruit industry. Based on the climatology, phenology of fruit trees, and the record of actual frost damage in New York, the need for ice-minus is apparently not great enough to conclude that its adoption would cause a significant impact on New York fruit production.[1]

Bacterial ice-nucleating agents (INAs) are known to occur naturally on many crops and have been associated with frost damage (Gross et al., Lindow, 1981a, 1981b, and 1983, Lindow and Connell, and Yankofsky). Genetically engineered bacteria, dubbed "ice-minus" bacteria, have the potential of protecting plants against frost damage by interfering with the natural population of INAs. The possibility of controlling ice nucleation in plants with ice-minus bacteria has drawn wide public attention as an example of future agricultural biotechnologies. Initially, attention was focused on the environmental regulatory process and its control over the deliberate release of genetically altered organisms. An early test of that regulatory process was completed in the spring of 1987 when the first field trial of ice-minus bacteria was approved and conducted. Field trials have not conclusively shown that ice-minus prevents frost damage, and other research has questioned the role of bacterial INAs in frost damage on certain tree-fruit crops (Proebsting and Gross). Nevertheless preliminary results indicate at least the potential of this product as a future agricultural technology (Marx).

Ice-minus technology is designed to depress the critical temperature at which frost damage begins (Lindow, 1983). Bacterial INAs naturally produce a substance that can cause ice to form at higher temperatures. If the engineered bacteria can displace the natural population, then the critical temperature for ice formation may be lowered and the chance of frost damage reduced. While the details are not yet known, apparently ice-minus must be applied well before the time of expected frost damage to allow the organism to become established and compete with the naturally-occurring bacteria. As frosts cannot be predicted well in advance, ice minus is expected to be applied annually to provide protection should frost occur. If the organism is short-lived or the exposure period to frost damage is long, then repeated applications may be required to insure efficacy.

A season with frost damage may occur sporadically, but the effects may last over several subsequent seasons. When the air temperature drops to below the critical temperature for fruit buds, the death of tissues that normally develop into that season's crop means higher average costs and lower total revenues. A season with severe frost damage, in which 90% or more of the buds are killed, can cause biennial bearing in subsequent years. Since

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[1] "Ice-minus" is a patented technology—No. 4766077.

total fruit number per tree is correlated negatively with individual fruit size, as are total fruit number per tree and vegetative growth, pruning and other cultural costs to control fruit load may be increased in several seasons following a severe frost.

Critical temperature depression has been accomplished traditionally by breeding for increased tolerance to low temperatures and by crop/site selection to avoid planting susceptible species in frost-prone areas. Frost avoidance strategies may include planting on terrain with good air drainage or in locations with a history of few frost problems, such as the leeward side of large bodies of water. The other major class of frost prevention technology relies on orchard heating. This is accomplished by burning fuel in the orchard, by large fans or helicopters mixing the warmer air in a temperature inversion with the colder ground-level air, or by releasing the energy of freezing water (energy released when water applied from overhead sprinklers changes to ice).

Fruit growers may use several approaches concurrently to avoid frost damage, which typically occurs in the late spring on calm, clear nights. In frost-prone areas, wind machines and fuel-burning heaters may be used. The costs of these mechanical means of frost protection are notable in that the equipment need be operated, and variable costs incurred, only when a frost threat is imminent. Ice minus and site selection approaches effectively do not have a discretionary variable cost component.

The purpose of this report is to evaluate the potential impact of ice-minus and similar bacteria on the structure and location of the New York tree fruit industry. The objectives include a brief description of New York tree fruit production, an assessment of the losses of New York fruit due to frost damage, and the likelihood of ice-minus being adopted in the general strategies available to fruit growers. These objectives address the potential for direct impacts of ice-minus. The potential for indirect impacts from adoption of ice-minus in other fruit growing regions is also examined.

The evidence of a potential frost problem in New York is analyzed using published climatological and fruit tree phenological data. Actual instances of frost-related crop loss in fruit are established from reports of the New York Department of Agriculture and Markets. The estimated cost of production and use of existing technologies in New York apple production are reviewed. Finally, the potential for ice-minus use in New York fruit production and its possible impacts are discussed in light of the available evidence.

Our conclusions about the potential impact of ice-minus bacteria in the New York fruit industry are negative, generally. Based on the apparent lack of a significant frost problem in the established growing areas, there is little apparent need for ice-minus. However, the conclusions are important to policymakers concerned with the possible future of New York agriculture as affected by new technologies. Biotechnology has received considerable attention as a potential source of change in agriculture, and ice-minus is one of its early "successes." Therefore, the following *ex ante* analysis may be helpful in making future agricultural policy.

The Fruit Industry in New York

Location

The first step in describing the potential problem of frost damage in fruit production is to review the geographic locations of orchards and the relative importance of individual crops. The major tree fruits in New York are apples, pears, peaches, sweet cherries, tart cherries, and plums and prunes (Table 1). In terms of share of U.S. value of production, apple and tart cherry are the most important tree fruit crops in New York—apples, by far, the most important. Apples are produced on 38% of New York's fruit farms, are 57% of the fruit acreage, and 68% of the value of fruit production. By contrast, tart cherries are produced on 13% of the farms, are 5.3% of the acreage, and account for only 5.5% of the value of fruit production. Grapes are an important fruit in New York, but are not considered a tree fruit and are considered relatively free from frost problems (Stiles). Therefore, New York grape production industry is excluded from the remaining analysis.

New York tree fruit production is split between east and west (Figure 1). The western counties produce about 50% more fruit than the east, and except for peaches, a portion of all fruit production has shifted to western counties during the last 40 years (Table 2). For apples, the share of western production has increased apparently at the expense of production in counties other than eastern. That is, New York has tended to become more of a two-region state in fruit production.

Climatology and Phenology

Westerly winds blowing over Lake Ontario in the spring lose energy to the lake, and this cooling effect lowers air temperatures in the leeward orchards of western New York. Fruit buds develop at a rate that is strongly influenced by the available

Table 1. New York Fruit Production: Number of Farms, Acres, Production, and Value and Share of U.S. Value of Fruit Production, by Crop, 1985

Fruit Crop	Number of Farms	Acres	Production Quantity	Production Value	Share of U.S. Value
			Million Pounds	Million Dollars	Percent
Apple	1,043	68,520	1,090	75.1	8.2
Pear	447	2,868	32.0	3.9	1.9
Peach 1/	377	2,260	14.0	3.3	1.6
Sweet Cherry	257	1,073	3.0	1.0	1.0
Tart Cherry	347	6,339	22.5	5.8	9.2
Plums and Prunes	274	827	5.4	—	—
Total 2/	2,754	120,113	1,454	110.3	4.0

1/ U.S. value excludes California clingstone peaches. 2/ Includes grapes.
SOURCES: New York Department of Agriculture and Markets, 1985 (farms and acres), United States Department of Agriculture (production and value).

supply of energy. The lower temperatures delay fruit bud development, causing buds to remain hardy longer than buds in the eastern region. Full bloom dates in western New York average about 5 to 9 days later than in eastern areas, allowing western growers a greater chance of escaping late-spring frost damage (Table 3). Some fruit trees begin development earlier than others and exhibit variable degrees of susceptibility to low temperatures, even in roughly comparable stages of development. For

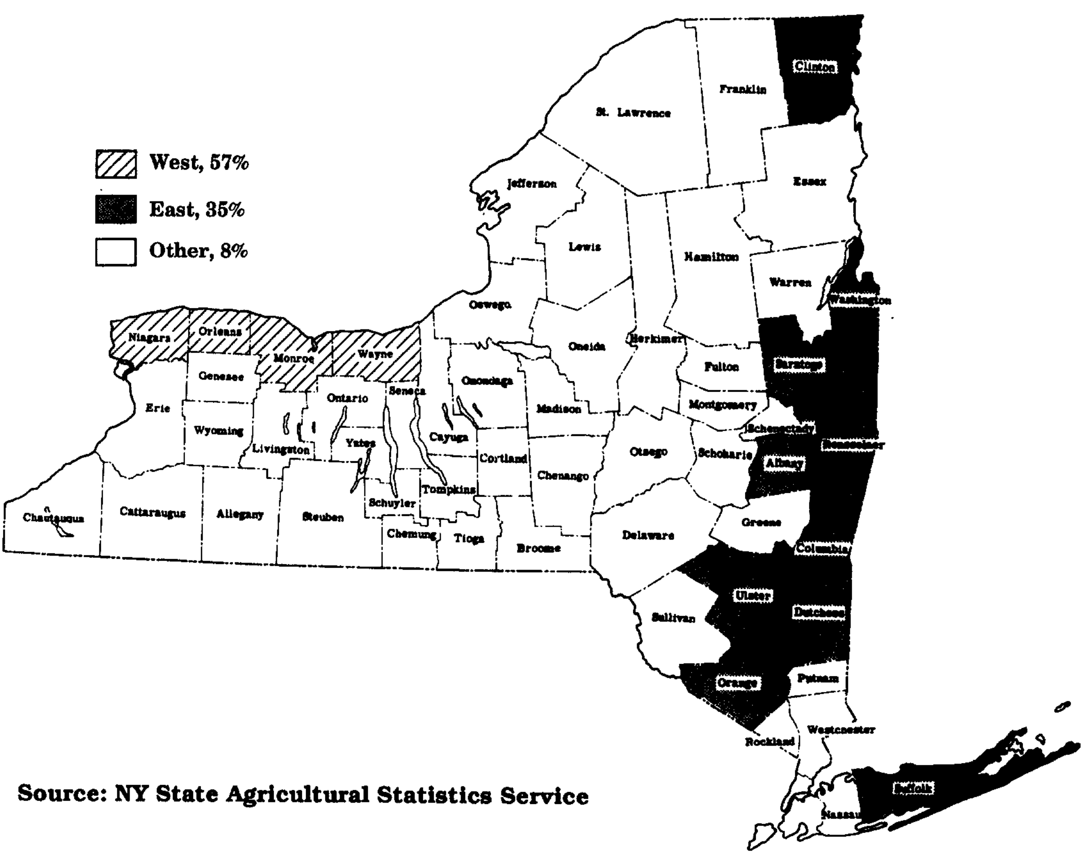

Figure 1. New York: Regional Distribution of Tree Fruit Acreage, 1985.

Table 2. New York Fruit Production: Regional Distribution by Crop and Year

Fruit Crop	Year	Region 1/ Eastern	Western	Other
			Percent	
Apple	1949	30	52	18
	1982	30	60	10
Pear	1949	27	49	24
	1982	35	58	7
Peach	1949	17	71	12
	1982	32	55	13
Sweet Cherry	1949	23	58	19
	1980	3	91	3
Tart Cherry	1949	6	75	19
	1980	1	97	2

1/ Eastern counties are Clinton, Columbia, Dutchess, Orange, Suffolk and Ulster; western counties are Monroe, Niagara, Orleans, and Wayne Counties.
SOURCES: Census of Agriculture (1949, 1982), New York Department of Agriculture and Markets (1980).

Table 3. Date of Full Bloom in New York, by Fruit Crop and Region, 1925–87 Average

Fruit Crop	Region 1/ Lake Ontario	Hudson Valley	State Average
		May Date	
Apple	18	9	15
Pear	13	6	11
Peach	11	4	8
Cherry, Sweet	7	2	6
Cherry, Tart	13	6	12

1/ Regional data include 1950–70 only. Lake Ontario corresponds to the western region, Hudson Valley corresponds to the eastern region. The state averages use New York State Department of Agriculture and Markets 1950–52 weights.

the major New York tree fruits, maximum susceptibility to frost damage occurs at 21 to 25 degrees F during full bloom (Table 4).

A ninety percent flower bud loss on fruit trees is generally referred to as "severe" frost damage (Ballard and Proebsting), although that level may vary with different fruit crops. A severe frost would normally occur when air temperatures fall to 24–28 degrees F. Based on the average distribution of temperatures in New York, a severe frost is not likely to occur after May 1 in most of the principal production areas (Figure 2). Fruit production far-

Table 4. Critical temperatures required to kill 90 percent of flower buds at various stages of fruit tree development

Stages of Development	Fruit Crop Cherry	Peach	Prune	Pear	Apple
			Degrees Fahrenheit		
Initial					
First swelling	1	0	1	—	—
Scales separating	—	—	—	0	—
Silver tip	—	—	—	—	0
Intermediate					
First white	23	—	18	15	—
First pink	—	15	—	—	21
Final					
Full bloom	25	23	21	23	24

SOURCE: Ballard and Proebsting.

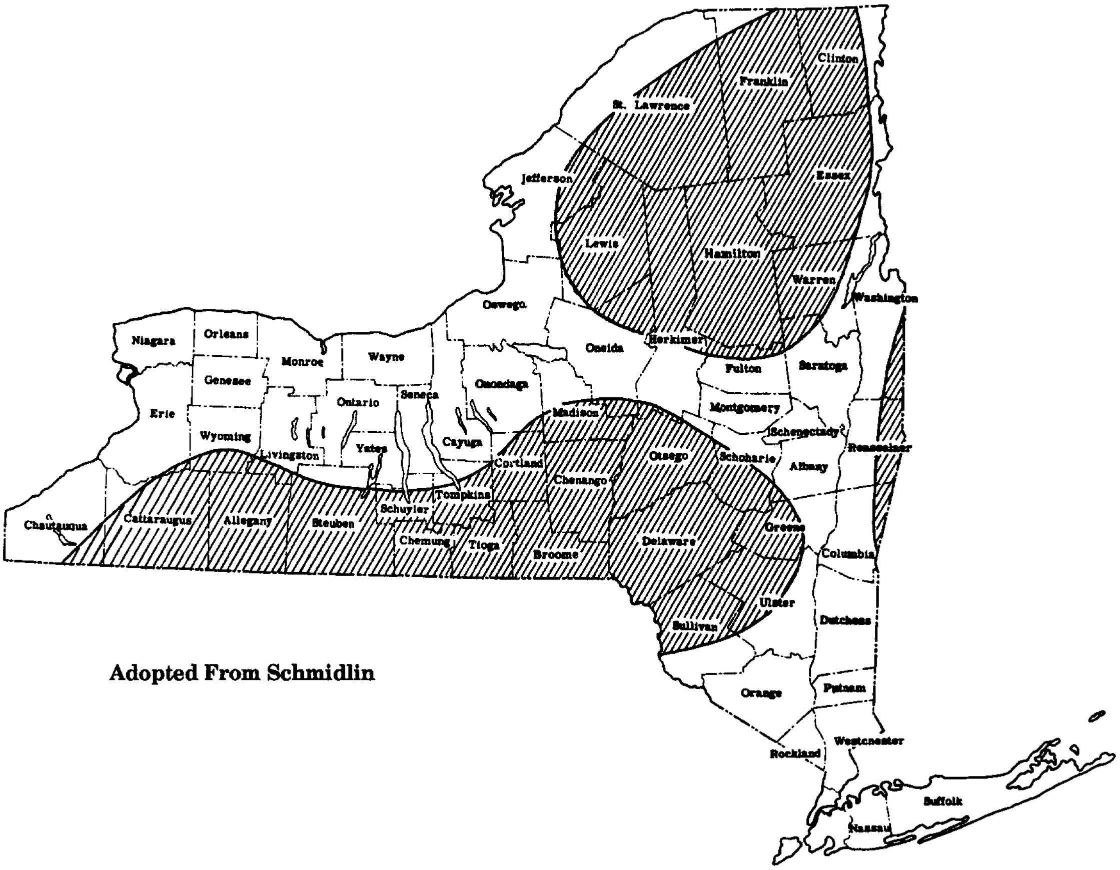

Figure 2. New York Average Date of Last 28°F Spring Freeze

ther inland from the Lake Ontario and Hudson Valley areas is more likely to experience a severe frost during bloom, but tree fruit production farther inland is less extensive. Thus, the combination of climatology and phenology of fruit trees in New York are such that widespread crop losses from frosts are expected to be uncommon in the principal fruit producing areas. Losses of economic significance may nonetheless be more prevalent.

Impact of Frost Damage

Incidence of Frost Damage in New York

A threshold level of 20% or more of trend production is set as the criterion for a significant economic loss in the New York tree fruit industry. Although chosen somewhat arbitrarily, a 20% loss on average New York apple farms results in a yield reduction of about 80 bushels per acre. Twenty percent is also about one standard deviation from the 1940–85 trend mean of New York apple production. In economic terms, the 1979–86 average farm price of New York apples is about $4.20 per bushel (New York State Department of Agriculture and Markets), suggesting that a 20% yield loss would be valued at $336 per acre. This is roughly equal to the 1986 average difference between fruit receipts and cash expenses per acre (variable profit) on western New York fruit farms (DeMarree). On eastern New York fruit farms, the variable profit is roughly double that (Castaldi and Forshey).

Examination of the 1940–85 trend in New York fruit production indicates a total of 28 years when at least one fruit crop had production more than 20% below trend. The range among fruit types was 15 years for sweet cherry to 7 years (15% of the seasons) for the hardier apple. The estimates, of course, incorporate all causes of reduced production and probably overstate the importance of frost alone.

To isolate frost as a damage source from other causes, the annual June 1 conditions as reported in the New York State Department of Agriculture and Markets *Fruit Crop Report* were used. According to those reports, severe spring frosts were associated with between 0.5 and 18% of the seasons during 1940 and 1985, depending on the crop (Table 5). Frost damage on apple occurred in about 9% of the seasons. However, the concurrence of frost, poor pollinating weather, and other causes of reduced fruit set confounds the problem of isolating the damage due to frosts alone.

To illustrate the problem of concurrent causes of reduced fruit production, the New York fruit industry's experience with spring frosts is often told by relating the infamous 1945 episode. The New York Agricultural Statistics Service reported in its May 1, 1945 'Special Fruit Crop Report':

> The fruit situation in New York is very uncertain at this time. All fruits have suffered more or less from the freezes after they came into bloom and from the poor pollinating weather. During March the buds developed very rapidly and on April 1 were far in advance of what they usually are at that date. About April 6 there were several mornings when the temperature dropped to below freezing. Several of the fruits were practically in full bloom in some areas at this time. In these areas a large number of the fruit buds were severely damaged. Also, during this period and again beginning about April 15, there were many cold cloudy or rainy days during which the bees failed to fly and hence failed to give the fruit blossoms good pollination. Freezing temperatures about April 22 again did varying damage to fruit buds over the State with heaviest injury in the Eastern Counties. The results are that all fruits have suffered to some extent but it will be some time yet before the exact condition can be determined.

The result was markedly less production of apples, pears, and tart cherries (Table 6). Total New York production of apples was 87% less, pear was 73% less, and tart cherry was 63% less than average. The peach and sweet cherry crops were not affected, probably because of their different stages of development.

When analyzing the impact of climate on fruit set during this unusual spring of 1945, a Cornell University pomologist stated ". . . frost injury was responsible for a loss of crop in some of the early [blooming] orchards but there was relative little actual frost damage to the flower parts [of fruit trees] in a large majority of the orchards. The failure of the fruit to set was due to the long period of cool, cloudy, wet weather which set in just prior to the peak of apple bloom" (Hoffman). The concurrence of poor pollination weather, winter kill, early-season disease problems, and frost damage often obscures the effect of any single cause of reduced fruit set. The years in which strong anecdotal evidence (as reported in *Fruit Crop Reports*) points to a role for frost damage in significantly lower production are listed in Table 7, but in many cases, these are years in which other factors are also cited as important.

The available evidence then suggests that frost damage could have been a significant problem in fewer than 10% of the seasons since 1940. Although sweet cherry production was 20% or more below trend in 18% of the seasons, the value of sweet cherries to the New York fruit economy is relatively small. The range of yield loss among all fruit types is about 20 to 50% (excluding 1945). For apple, a one-in-ten-year average rate of incidence of frost damage with a 20 to 25% average loss would indicate an annualized estimate of frost damage between 2% and 2.5% of production. With this estimated range of average annual loss in apple production times 400 bushels per acre yield and

Table 5. Climatic Causes of Below-Normal Production of Fruit in New York, by Crop, 1940–85 1/

Fruit Crop	Low Winter Temperatures	Spring Frosts	Cool, Rainy Weather	Other 2/	All Causes 3/
			Number of Years		
Apple		4	7		7
Pear	1	3	6	1	10
Peach	7	2	1		8
Cherry					
Sweet	3	8	2	5	15
Tart	1	5	6	3	9

1/ Below-normal annual production is less than 80 percent of trend.
2/ Sweet cherry: no indication in 1943, 1965, 1952, 1986, brown rot in 1947; pear, no information in 1968; tart cherry, no information for 1960, 1966, 1977.
3/ The number of years of below-normal production may be less than the sum when multiple causes affect any single year's production.
SOURCE: Compiled from New York Department of Agriculture and Markets, *Fruit Crop Report*.

Table 6. New York Fruit Production: 1935–44 Average, 1945–47

Year	Fruit Type			Cherry	
	Apple	Pear	Peach	Sweet	Tart
	1,000 Bushels			Tons	
1935–44 avg.	16,306	1,025	1,431	2,114	19,571
1945	2,106	272	1,660	2,600	7,300
1946	15,116	693	1,682	1,400	15,500
1947	15,045	960	1,440	2,200	14,800

SOURCE: New York State Department of Agriculture and Markets, *Fruit Crop Report.*

Table 7. Years from 1945 to 1987, When Fruit Production Was More Than 20 Percent Below Normal and Frost Damage Was Reported 1/

Apple	Pear	Peach	Sweet Cherry	Tart Cherry
1945(85)	1945(69)	1967(55)	1946(50)	1945(61)
1948(25)	1957(21)	1976(36)	1947(26)	1947(23)
1956(21)	1976(52)		1956(62)	1956(34)
1981(22)			1967(24)	1976(42)
			1976(34)	1981(67)
			1977(51)	
			1981(43)	

1/ Numbers in parentheses are percent below trend production.

$4.20 per bushel price, frost damage may be as high as $34 to $42 an acre, annually.

Frost Prevention in New York

The most commonly recommended frost-prevention strategy is site selection. The preference for frost-free sites, together with other factors including rising land values in the Hudson Valley, partially explain the shifts in production to the western region over the past four decades (Table 2). For producers operating in the eastern region—particularly in Columbia, Dutchess, Ulster and Clinton Counties—another approach is the use of mechanical devices including fans and heaters (Stiles). The estimated total costs of operating selected frost protection technologies in the Hudson Valley of eastern New York indicate a range of $211 to $939 an acre of apples (Table 8). Castaldi (1987) estimated a per bushel apple price of $13 to $17, depending on variety, to cover the cost of operating a combined wind machine and heater system. This price is above the range of statewide prices during the 1980's, suggesting that these technologies are not economically viable for many operators. However, the variable operating costs of wind machines is $40 an acre (Table 8), which is closer to the projected annual loss from frost. Thus an operator with this equipment in place would be expected to operate it annually in the short run if needed.

Based on these data and estimates, a tentative conclusion can be reached. The annualized cost of frost-related damage to tree fruit production in New York is relatively modest compared to the traditional set of orchard heating technologies. For ice minus to be adopted by "risk neutral" apple growers, it appears that the annualized applied cost would have to be in the range of $34 to $42 an acre. Considering that the 1986 annual labor cost of spraying an acre of apple trees is about $30 an acre (Castaldi and Forshey), and that ice minus would need to be applied at least once annually and maybe more, then the formulation would have to be low in cost, very effective and long lived to be economically viable in New York. In relation to the question of efficacy, experiments with bacteriacides on Washington fruit trees over a six-year period suggested that factors other than bacterial INAs were responsible for frost damage (Proebsting and Gross). However, the need for this product may further decline in the future if the trend of the past four decades continues to concentrate tree fruit production in the Lake Ontario region. This region appears to have more natural frost prevention than other producing areas around the State. Considering all these factors, the direct role for ice minus in the New York tree fruit sector appears limited.

Table 8. Summary of Annual Operating Costs Per Acre for Selected Frost Protection Technologies in Hudson Valley of Eastern New York

Cost	Technology		
	Wind Machine	Wind Machine Plus Heaters	Stack Heaters
		Dollars 1/	
Variable			
fuel and lubrication	184	784	6,000
other	237	394	500
total	421	1,178	6,500
Fixed			
depreciation	785	860	747
interest on investment	785	841	560
labor	25	125	1,395
other	90	108	183
total	1,685	1,934	2,885
Total	2,106	3,112	9,385
per hour	105	156	469
per acre	211	311	939
per bushel	0.32	0.47	1.44

1/ Based on a 10-acre block of apple trees.
SOURCE: Castaldi (1987).

Frost Damage in Competing Regions

Frost damage on fruit crops elsewhere in the United States is a related concern if reducing the losses would significantly affect New York fruit prices. A detailed examination of frost damage across the country is not our objective; however, a measure of the problem is indicated by the purchase of Federal crop insurance. If the purchase of policies suggests the presence of a significant frost threat, then the problem appears limited, as only nine counties in three other states (North Carolina, Oregon, and Washington) carried Federal insurance for apples during 1963 to 1983. Annual indemnities paid to apple producers averaged only one million dollars during 1982 to 1984, compared to an average U.S. crop value of $872 million (U.S. Department of Agriculture). Of that one million dollars average annual indemnity, 77% is paid out for frost, freeze, and other cold damage (which could include poor pollination).

It may be argued that the limited use of crop insurance against frost-related losses in fruit is due to problems of supplying insurance, rather than the lack of significant demand. But, historically New York growers have obtained Federal crop insurance for grape acreage and other states' growers have obtained insurance for tree fruit acreage (for example, cherry acreage in Michigan), suggesting that need and not prohibitive transaction costs are limiting the demand for this insurance.

As in New York, the possibility exists elsewhere that frost damage is averted through the use of available equipment rather than avoided by site selection and other passive approaches. However, the high cost of operating current frost protection equipment means its widespread use is economically viable only if an area has a strong comparative advantage in cost or prices. This might occur in frost-prone areas outside New York State, where producers can capitalize on high early-season prices or above-average quality. But, there is no indication of a broad cost-of-production advantage for tree fruits, especially apples, in frost-prone areas outside New York.

Concluding Comments

The potential need for ice-minus bacteria in the New York tree fruit industry is examined by evaluating the likelihood of frosts occurring when fruit buds are susceptible and tabulating the record of actual frost damage. The available climatological and phenological evidence suggests that severe frost damage would be rare in the major fruit producing regions of the state. Depending on the fruit type, losses of economic significance actually occurred between 0.5 and 18% of the seasons during 1940 to 1985. The annualized average loss of 2% to 2.5% represents $34 to $42 an acre for apples, but even these figures overstate the effect of frost alone. Many years of below-average production are beset by multiple causes including poor pollination.

For ice minus to be competitive in New York fruit production, it must cover its cost in preventing annual frost damage. Thus it would seem to have a major impact only if it is economical, efficacious, and long-lived. Further field experimentation is required for sufficient efficacy and production cost data to be useful in analyzing specifically the cost competitiveness of this product.

As the potential of ice-minus to directly impact the New York fruit industry seems limited, so does the indirect impact from outside the state, at least for apples. This judgement is based on the low utilization of Federal crop insurance by tree fruit producers. Overall, then, ice-minus is a potential technology with limited potential to impact New York's tree fruit industry. Although this is a negative finding, policymakers may find it useful in deciding future funding of agricultural research and development, location of fruit industry inputs and services, and other resource allocation policies directly tied to the fruit industry. Related questions for further research include the actual productivity of the various traditional frost protection technologies in New York. What other biotechnologies are likely to come along in the near-term to affect New York's fruit industry? How rapidly would New York fruit growers adopt new biotechnologies?

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