Economics of reducing insecticide use on celery through low-input pest management strategies

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Abstract

A low pesticide input management system for celery, *Apium graveolens*, was developed and implemented. The overall effectiveness of this system was compared with a conventional pesticide application program and an untreated control, over 4 years in field station trials, and then implemented in a commercial trial. The low-input program relied on biological control agents and rotations of selective, environmentally-safe biorational insecticides (*Bacillus thuringiensis*, spinosad, tebufenozide) applied only when pests exceeded threshold levels. The conventional program included prophylactic applications of broad spectrum synthetic pesticides. Yield losses from key insect pests were documented and economic analyses comparing the monetary returns accruing from the use of the different programs were generated. Insect damage was lower for conventional program in only one of the 4 years. The integrated pest management (IPM) program utilized significantly fewer applications of insecticides, but there were no significant differences in the total number of marketable cartons. These lower insecticide costs resulted in greater net profits for the IPM program. A commercial trial, which included a low input program for managing the fungal pathogen *Septoria apiicola*, was conducted in collaboration with a celery producer in Ventura county, California and provided similar results to the field station trials. The combined IPM program used over 25% fewer pesticides than the grower's program, and pest management costs were over \$250 ha^{-1} lower for the IPM program than for the grower standard program. Although the IPM program used fewer pesticide applications, there were no significant differences in yield or net profits among treatments. © 1999 Elsevier Science B.V. All rights reserved.

1. Introduction

In 1993 the US government set a goal to have 75% of US agriculture managed under integrated pest management (IPM) programs by the year 2000 (News Release 0815093, 21 September 1993, United States Department of Agriculture, United States Environmental Protection Agency, United States Food and Drug Administration). Other countries have mandated reductions in the use of pesticides (Jansma et al., 1993). Although the concepts underlying IPM are well known (Stern et al., 1959), and substantial research has been conducted to develop IPM pro-

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grams, the implementation of IPM continues to lag (Sorensen, 1993; Steffey, 1995; Hutchins, 1995). A continuing impediment to implementation IPM lies in providing growers with a convincing reason to adopt more IPM tactics (i.e., economic incentives).

The vegetable industry in the US has a clear need for improved management strategies. Insecticide resistance is a significant problem in the production of many crops (Georghiou, 1990; Georghiou and Lagunes-Tejeda, 1991; Leibee and Capinera, 1995). The $20 million loss documented by California's celery industry in the mid-1980s, following the development of resistance by the leafminer, *Liriomyza trifolii* (Burgess) (Diptera: Agromyzidae) to all available pesticides illustrates the point (California Celery Research Advisory Board, 1986). Similar problems with insecticide resistance have been identified for the beet armyworm, *Spodoptera exigua* (Hübner) (Lepidoptera: Noctuidae), a major pest of most vegetable and many field crops in California (Brewer and Trumble, 1991).

In addition to increased resistance, registrations for many commonly used pesticides are currently under review, and could well be cancelled as part of the Food Quality Protection Act (US Government, 1996). Furthermore, these de facto and de jure limitations have accelerated rates of resistance development through the increased application of the remaining registered compounds (Trumble and Parrella, 1987; Knight and Norton, 1989; Kazmierczak et al., 1993). Thus, there is a clear need for the vegetable industry to move toward less pesticide intensive pest management practices, and to use available pesticides judiciously.

Environmental and regulatory considerations have led to the development of new classes of insecticides that are less environmentally disruptive and have low mammalian toxicity. A major concern regarding the use of new and existing classes of pesticides is prolonging their utility through resistance management. One resistance management strategy is to rotate among pesticides with different modes of action to delay development of resistance to any one insecticide (Tabashnik, 1989; Georghiou, 1994). However, implementation of IPM strategies that incorporate these new classes of insecticides is unlikely to proceed solely on the basis of environmental benefits. Similarly, coercive legislated regulations are unlikely to enhance wide scale adoption of novel IPM strategies. The demonstration of clear economic benefits of IPM strategies to producers is likely to be a more effective means of accelerating the adoption of IPM programs and creating a demand for development of additional IPM programs for other agroecosystems (Hutchins, 1995).

Celery, *Apium graveolens* L. (Apiaceae) was selected as a model agroecosystem for the development and implementation of a low-input IPM program. Because of exceedingly high aesthetic standards and low damage thresholds, celery is one of the most intensively managed vegetable crops in California. Two of the primary insect pests of celery in California are *S. exigua* and *L. trifolii* (Trumble and Hare, 1997). Increasingly, *L. huidobrensis* (Blanchard) is a significant pest in central and northern celery production regions of California (Koike et al., 1997). The successful development and implementation of low-input programs in such an intensively managed, high value crop system will facilitate the acceptance of similar low-input programs for other vegetable crops nationally.

Previously, Trumble et al. (1997) compared the benefit of current chemical standard pesticide practices with an IPM program based solely on *Bacillus thuringiensis* Berliner to control lepidopteran pests and conservation of parasitoids to control *Liriomyza* pests. In experimental plantings at a field station, the IPM program generated substantially higher net profits in both years of the test ($600–$1400 ha^{-1} greater). This program was validated in 1995 on a commercial celery operation in Ventura county, California. The IPM program generated a net profit more than $410 ha^{-1} higher than that of the grower's conventional program. Because reduced potential for insecticide resistance in the IPM program was not accounted for in the economic analysis, and the validation trials were conducted on a progressive operation using ≈40% fewer pesticides than most celery producers, the results of those economic analyses are conservative.

However the potential for resistance to *B. thuringiensis* (see McGaughey, 1994) has led to the development of a rotational approach using two new, environmentally benign, insecticides. Trumble et al. (1997) have suggested that IPM programs incorporating conventional and new classes of insecticides could be economically viable for many growers. Therefore,

the present goal was to compare the performance of low pesticide input IPM programs with more chemically intensive management programs. To evaluate the performance of these systems, a partial economic budget was used to compare monetary returns (gross costs, net gain/profit) accruing from the use of current conventional pesticide practices with those from the low-input program on a standard commercial variety of celery, based on field station trials.

To demonstrate the economic viability of such low-input IPM programs, a comparison was made of the performance of these approaches with a standard grower program on a commercial scale. In addition to insect pests, celery is extremely susceptible to *Septoria apiicola* Speg., the causal organism of Septoria late blight, and other fungal pathogens (Berger, 1970; Sherf and MacNab, 1986; Lacy et al., 1996). Concerns about pathogen management are as great, if not greater, than concerns about managing insect pests. Therefore, in the commercial trial, a management program for Septoria late blight based on a disease forecasting model was included. This threshold-driven program was compared with the grower standard program for pathogens to provide information on a more comprehensive IPM program.

2. Materials and methods

2.1. Field station trials

Experimental 0.4 ha plantings of celery ('Conquistador') were established at the University of California's South Coast Research and Education Center in Orange county, CA during the autumn seasons of 1994, 1995, 1996 and 1997. Fields were sprinkler irrigated for the first 3 weeks after transplanting and drip irrigated thereafter. All plants were grown using local commercial practices, with the exception of treatments for insect control. No fungicides were applied to the fields.

Three treatments were evaluated in a randomized complete block design. Experimental plots were eight beds wide (two rows per bed on 101 cm centers) by 20 m long with four replicates of each treatment. The three treatments included (1) a standard approach using preventative chemical treatments, (2) a second treatment consisting of a low-insecticide, IPM

approach, and (3) a control treatment in which no insect control measures were taken.

Insecticides used in the standard program were selected based on recent high usage patterns for celery grown in California (Eickhoff et al., 1990; California Department of Pesticide Regulation, 1996). Materials used included a combination of two broad spectrum insecticides, methomyl (Lannate 1.9 L, DuPont, Wilmington, DE, at 1.1 kg [AI] ha^{-1}]) and permethrin (Pounce 3.2 EC, FMC, Philadelphia, PA, at 0.22 kg [AI] ha^{-1}).

Insecticides for use in the IPM treatments were selected to balance control of lepidopteran pests (primarily *S. exigua*) with minimal disruption to the *Liriomyza* spp. parasitoid complex (Trumble, 1985; Trumble et al., 1994). Disruption of this parasitoid complex can results in pest resurgence (Oatman and Kennedy, 1976; Johnson et al., 1980; Trumble, 1985). Insecticides selected for use to control lepidopteran pests in the IPM treatments were *B. thuringiensis* (Xentari, Abbott Labs, Chicago, IL)) and, tebufenozide (N-t-butyl-N-3,5-dimethylbenzoyl-N′-4-elhyl-benzoylhydrazine, Confirm, Rohm Haus, Philadelphia, PA), and spinosad (spinosyn A and D, Success, Dow Elanco, Indianapolis, IN). The insecticide selected for use to control *Liriomyza* spp. in the IPM treatments was abamectin (Agrimek, Novartis, Greensboro, NC).

All insecticides were applied by a tractor-mounted boom sprayer operated at 7.03 kg cm^{-2} with four nozzles per row and carrier (H$_2$O) at 935 l ha^{-1}. Disc-type cone nozzles incorporated D-3 orifice discs, #25 cores and 50 mesh screens. All applications included a spreader sticker (Leaf Act 80A, PureGro, West Sacramento, CA, or Latron CS-7, Rohm Haus, for tebufenozide).

The need for pesticide applications in the IPM treatment was based on insect counts. Insect samples were conducted weekly beginning approximately 1 month after planting. Evaluations of lepidopteran populations were based on weekly counts of 10 plants per replicate. For lepidopteran pests, a mean of greater than one larva per 10 plants was considered the threshold indicating the need for insecticide treatments (J.T.T., unpublished). *Liriomyza* spp. populations were evaluated by weekly counts of leafminer larvae and puparia collected in four, 10.2 cm × 20.4 cm trays per replicate. *Liriomyza*

spp. populations exceeding a mean of 10 per tray were considered above threshold (Trumble, 1985). This threshold was not exceeded and no treatments were necessary to control *Liriomyza* spp. in any year.

In 1994, the celery was transplanted on 30 August, and harvested on 30 November. There were eight applications of methomyl and permethrin in the standard treatment. Applications were made weekly, beginning 5 weeks after transplanting. Three insecticide applications were made in the IPM treatment, two of tebufenozide (Confirm 2F at 0.131 kg [AI] ha^{-1}, on 20 October and 3 November) followed by one application of *B. thuringiensis* (at 1.24 kg [AI] ha^{-1}, on 17 November).

In 1995, the celery was transplanted on 30 August and harvested on 7 December. There were nine applications of methomyl and permethrin in the standard treatment. Applications were made weekly, beginning 5 weeks after transplanting. Three insecticide applications were made in the IPM treatment, two of tebufenozide (Confirm 70 WP at 0.131 kg [AI] ha^{-1}, on 12 October and 9 November) rotated with one application of *B. thuringiensis* (at 2.47 kg [AI] ha^{-1}, on 26 October).

In 1996, the celery was transplanted on 5 September and harvested on 9 December. There were nine applications of methomyl and permethrin in the standard treatment. Applications were made weekly, beginning 5 weeks after transplanting. Four insecticide applications were made in the IPM treatment, two of *B. thuringiensis* (at 2.47 kg [AI] ha^{-1}, on 24 October and 14 November) rotated with two applications of spinosad (Success 23% DE at 0.086 kg [AI] ha^{-1}, on 11, 30 November).

In 1997, the celery was transplanted on 5 September and harvested on 9 December. There were 10 applications of methomyl and permethrin in the standard treatment. Applications were made weekly, beginning 4 weeks after transplanting. Four insecticide applications were made in the IPM treatment, two of tebufenozide (Confirm 2F at 0.131 kg [AI] ha^{-1}, on 16, 23 October) followed by two applications of *B. thuringiensis* (at 2.47 kg [AI] ha^{-1}, on 6, 25 November).

At harvest, the number of damaged plants found in 25 plants/replicate (100 per treatment) from the center two rows of each replicate was recorded. Then, all plants were harvested from a 15.25 m section of row per replicate and were classified by industry sizes ('2' = two dozen plants per carton, '2.5' = two and half dozen plants per carton, '3' = three dozen plants per carton, '4' = four dozen plants per carton). Some insect-damaged plants could be salvaged for sale as hearts if the interior of the plant was not damaged. In the standard and IPM treatments, the conservative value of 90% salvageable was used, but in the control treatments only approximately 20% of the damaged plants could be salvaged.

2.2. Commercial trial experimental design and agronomic practices

The commercial scale trial was conducted in cooperation with Gene Jackson Farms of Ventura county, CA. Celery seedlings ('G20') were transplanted on 27 August 1997. Fields were sprinkler and furrow irrigated. The two insect management treatments in this commercial scale trial were the IPM program and the grower's standard management program. The two treatments for management of Septoria late blight were the grower's standard fungicide application program (primarily prophylactic weekly applications of fungicides), and the IPM treatment where fungicides for *S. apiicola* control were applied in response to disease severity forecasts. The insect management treatments and *S. apiicola* management treatments were cross-classified in a randomized block design with three blocks and four replicates per block. Each replicate was 0.4 ha (1 acre) in size. No untreated control was incorporated into the design because the grower could not be expected to tolerate the probable economic loss. Furthermore, the commercial nature of the project necessitated that the grower have ultimate discretion in applying pesticides to the field.

The need for insecticide applications in the IPM treatment was based on insect counts. Evaluation of lepidopteran populations was based on weekly counts of 20 plants per replicate, starting 2 weeks after transplanting. For lepidopteran pests, treatments were applied when average densities exceeded 1 larva per 10 plants (J.T.T., unpublished). *Liriomyza* spp. populations were evaluated firstly by weekly counts of the number of larvae per 20 plants per replicate. *Liriomyza* spp. populations exceeding 20 live larvae per replicate were considered above threshold. Secondly, later in the growing season, when the plant canopy had closed over, *Liriomyza* sampling was accomplished by count-

ing the number of larvae and puparia collected in four (10.2 cm by 20.4 cm) trays per replicate. *Liriomyza* spp. populations exceeding 10 per tray were considered above threshold (Trumble, 1985).

The need for fungicide applications in the IPM treatment was based on a disease forecasting model (modified from Madden et al., 1978; Lacy, 1994). In this forecasting model, disease severity values (DSV) are calculated on the basis of duration of leaf wetness and mean daily temperature. This model specifically predicts conditions favorable for Septoria late blight. Leaf wetness and temperatures were recorded by a portable leaf wetness and temperature recorder (model 3610T, Spectrum Technologies, Plainfield, IL) within the celery canopy between two plants in the middle of the field. An initial threshold of 30 DSVs was used early in the crop cycle because of the open canopy which provided adequate aeration. As the crop matured and the canopy closed over, a more conservative threshold of 20 DSVs was used to indicate the need for fungicide application. The grower selected the fungicides used in both the IPM and grower standard. Fungicides used included benomyl (Benlate SP, DuPont, Wilmington, DE), chlorothalonil (Bravo 500, ISK Biosciences, Mentor, OH), 2,6-dichloronthoaniline (Botran 75W, Gowan, Yuma, AZ), and propiconazole (Tilt, Novartis, Greensboro, NC).

Under supervision of the authors, the commercial company employed by Gene Jackson Farms made all pesticide applications. The insecticides and the number of respective applications in the grower standard treatment were at the discretion of the grower. Insecticides for use in the IPM treatment to control lepidopteran pests above threshold levels were commercial formulations of *B. thuringiensis* (Xentari, or Crymax, Ecogen, Langhorne, PA, up to 1.86 kg [AI] ha^{-1}), tebufenozide (Confirm, at 0.1254 kg [AI] ha^{-1}), and spinosad (Success, at 0.065 kg [AI] ha^{-1}). These insecticides were selected for their minimal effects on *Liriomyza* spp. parasitoids. The insecticides selected for use to control *Liriomyza* spp. in the IPM treatments were abamectin (Agrimek) and cyromazine (Trigard, Novartis, Greensboro, NC).

The plants were harvested on 26–27 December by commercial harvesters who were unaware of the differences between treatments or the respective locations of the plots. Data were collected on the numbers of cartons of each size class of all plants harvested in each replicate. All values were standardized on a per hectare basis by scaling up yields from the experimental plots.

2.3. Economic analysis

Economic data on costs of applications were collected from several sources, including eight commercial growers (Trumble et al., 1997, Table 1). The values used in analyses were based on these numbers, although averages or intermediate values were not used in every case if some growers included overhead in a particular category and others did not. Insecticide costs were provided by distributors. Prices were based on the purchase of at least enough material to treat 4 ha (10 acres) (quantity discount). The Free on Board (FOB) shipping prices for each harvest date were obtained from Market News Service, Sacramento, CA for the Southern (Central/South Coast) region. Because most growers currently employ scouts (generally for disease monitoring, but monitoring for insects in the chemical treated-fields is also common to catch migrations and outbreaks), and the cost of scouting is minimal compared with the aggregate of other costs (Table 1), the expenses associated with scouting were assumed to be similar among the treatments.

All values were standardized on a per hectare basis by scaling up yields from the research plots. The economic analyses were conducted by determining the potential gross value of the crop (value marketable portion of the crop), the horticultural costs needed to produce and harvest the crop, and the costs associated with the different management programs. The costs associated with pest control were not included in the horticultural expenses. Therefore, direct economic comparisons could be made among management strategies. Net profits were then calculated as the gross value from of each treatment minus the costs of production and the costs of pesticides and their application.

2.4. Data analysis

For field station trials, data on the amount of insect damage, numbers of marketable cartons, and net profit were recorded, and subjected to analysis of variance (ANOVA), after appropriate transformations. Years

Table 1
Production costs (in US$) for celery grown in field station trials (1994–1997)

Costs ha^{-1}		Standard	IPM	Control
		Fixed costs		
Water		370.65	370.65	370.65
Seed		49.42	49.42	49.42
Transplants		2223.90	2223.90	2223.90
Planting labor		494.20	494.20	494.20
Scouting		49.42	49.42	49.42
Other costs		4942.00	4942.00	4942.00
Subtotal fixed costs		8129.59	8129.59	8129.59
		Variable costs		
1994	Harvest costs ($3.70 per carton) and sales costs ($0.40 per carton)[a]	12077.89	11778.45	4968.36
1995	Harvest costs ($3.70 per carton) and sales costs ($0.40 per carton)[a]	12344.03	11953.80	7305.77
1996	Harvest costs ($3.70 per carton) and sales costs ($0.40 per carton)[a]	11855.44	12617.95	4480.00
1997	Harvest costs ($3.70 per carton) and sales costs ($0.40 per carton)[a]	12294.43	12779.80	7298.80
1994	Insecticide costs	806.40	142.08	0
	Insecticide application costs	434.88	163.08	0
	Subtotal insecticide costs	1241.28	305.16	0
1995	Insecticide costs	907.20	180.38	0
	Insecticide application costs	489.24	163.08	0
	Subtotal insecticide costs	1396.44	343.46	0
1996	Insecticide costs	907.20	353.36	0
	Insecticide application costs	489.24	217.44	0
	Subtotal insecticide costs	1396.44	570.80	0
1997	Insecticide costs	1008.00	256.38	0
	Insecticide application costs	543.60	217.44	0
	Subtotal insecticide costs	1551.60	473.82	0
1994	Costs[a]	21478.03	20213.20	13097.95
1995	Costs[a]	20875.41	19496.14	15785.97
1996	Costs[a]	21381.47	21318.34	12609.59
1997	Costs[a]	21975.62	21383.21	15428.39

Horticultural production costs reflect industry norms and were kept constant over years for comparative purposes (after Trumble et al., 1997).
[a] Based on a mean of four replicates per year.

were analyzed separately because of program differences from year to year. For the commercial trial, data on the numbers of marketable cartons and net profit were subjected to ANOVA, after being examined for normality. Total numbers of marketable cartons were logarithmically transformed to stabilize variances. Treatment means were separated by Fisher's protected least significant difference (LSD).

3. Results

3.1. Field station trials

In all 4 years of field station trials, the standard and IPM outperformed the control treatment in terms of marketable yield. However, there was considerable variation in insect pressure from year to year (Table 2). In addition, fluctuations in market prices resulted in considerable variation in the net profits for each program. There were 50–67% fewer insecticide applications in the IPM program than in the standard program. Because of the greater number of insecticide applications made, costs for the standard averaged over $970 ha^{-1} more per year than costs for the IPM treatment.

In 1994, there was a large amount of damage from lepidopteran larvae (Table 2). The IPM plots received two applications of tebufenozide and one application of *B. thuringiensis*. The standard plots received eight applications of methomyl and permethrin. Damage

Table 2
Percentage of insect-damaged celery plants in each of 4 years of field station trials

Treatment	1994	1995	1996	1997
	Damage (%)			
Standard	20.0 ± 5.9 a	5.0 ± 2.5 a	33.0 ± 4.4 a	4.0 ± 1.6 a
IPM	38.0 ± 2.6 b	9.0 ± 3.8 a	39.0 ± 6.6 a	5.0 ± 1.0 a
Control	74.0 ± 2.6 c	50.0 ± 5.3 b	79.0 ± 3.4 b	50.0 ± 2.6 b
	Total marketable cartons			
Standard	2953.0 ± 115.1	3010.7 ± 108.3 a	2891.6 ± 83.9 a	2998.6 ± 78.4 a
IPM	2872.8 ± 107.3 a	2915.6 ± 229.7 a	3077.5 ± 159.3 a	3117.0 ± 93.4 a
Control	1211.8 ± 82.4 b	1781.9 ± 151.9 b	1092.7 ± 111.2 b	1780.2 ± 85.9 b

Twenty-five plants were evaluated at harvest per replicate. There were four replicates per treatment per year.
Means ($\pm$SEM), within years, followed by the same letter are not significantly different ($P > 0.05$, Fisher's protected LSD).

was significantly higher for the IPM treatment than for the standard ($P < 0.05$, Table 2), and, therefore, the standard produced higher marketable yields for most size classes. Yet as a result of the lower costs associated with the IPM program, there was no significant difference in net profit between the two approaches (Fig. 1, $P > 0.05$). Had no insect control program been implemented, a grower would have lost approximately $2600 ha^{-1}.

In 1995, insect pest pressure was considerably lower than during 1994 (Table 2). Three insecticide applications were made in the IPM treatment, two of tebufenozide and one of *B. thuringiensis*. The standard plots received nine applications of methomyl and permethrin. There was no significant difference in marketable cartons between the standard and IPM treatments. Low market prices in December of 1995 meant that a grower would have had a net loss using either the IPM or standard approach (Fig. 1). However, as a result of the lower costs for the IPM treatment, the IPM program would have lost significantly less money than the standard program.

In 1996, insect pest pressure was again high, and the standard and IPM programs did not achieve satisfactory levels of control for lepidopteran larvae (Table 2). The IPM plots received two applications of *B. thuringiensis* and two applications of spinosad. The standard plots received nine applications of methomyl and permethrin. There was no significant difference in the number of marketable cartons between the standard and IPM programs ($P > 0.05$). The high levels of damage combined with relatively low prices for celery resulted in a net loss for both the standard and IPM programs. However, the net loss for the IPM program

was significantly less than the net loss for the standard ($P < 0.05$, Fig. 1).

In 1997, insect pest pressure was lower than in either 1994 or 1996 (Table 2). Two applications each of *B. thuringiensis* and tebufenozide were made in the IPM treatment. Ten applications of methomyl and permethrin were made in the standard treatment. There was no significant difference in the marketable yield between the IPM and standard treatments ($P > 0.05$). There was no significant difference in net profit between these two treatments ($P > 0.05$, Fig. 1). For these 4 years (1994–1997), profits were highest in 1997 because of higher prices for celery.

3.2. Commercial trial

In both the grower standard and IPM insect management plots, there were significant infestations of Lepidoptera, *Liriomyza*, and aphids. Production costs (excluding harvesting and marketing costs) for the grower standard program were approximately $200 ha^{-1} more than the production costs for the IPM program (Table 3). This difference was a result of the greater number of pesticide applications made by the grower, although this grower employed a progressive pest management program.

To control pest lepidopteran larvae, the grower standard program used three applications of *B. thuringiensis* (Xentari and Crymax, 0.62–1.86 kg [AI] ha^{-1}), three applications of thiodicarb (0.18–0.67 kg [AI] ha^{-1}, Larvin 3.2, Rhône-Poulenc, Research Triangle Park, NC), and three applications of spinosad (0.065–0.130 kg [AI] ha^{-1}). The IPM program used five applications of insecticides to control lepidopteran larvae.
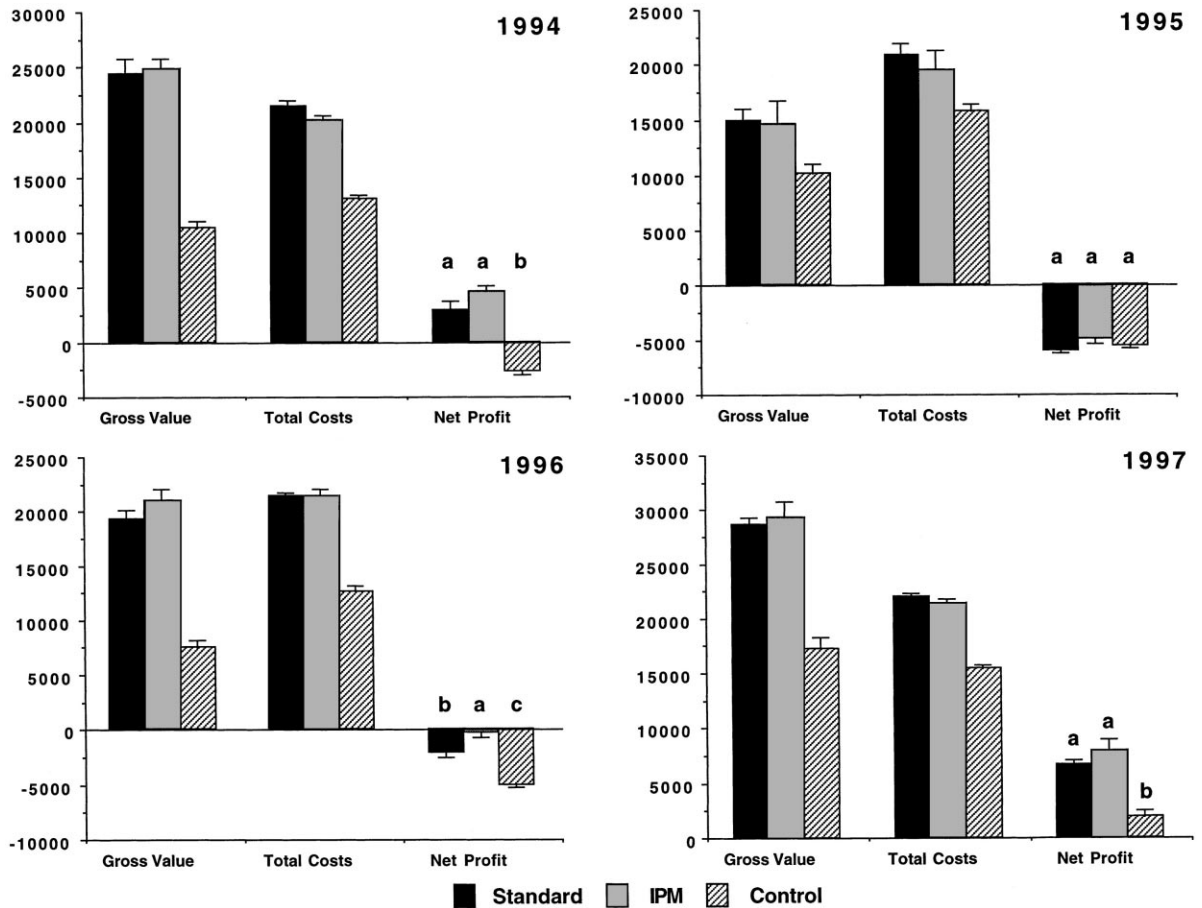
Fig. 1. Mean total production costs, gross value, and net profits for celery grown using standard, IPM, and control treatments, from 1994 to 1997. Net profits for each year denoted with different letters are significantly different ($P < 0.05$, Fisher's protected LSD). Bars represent standard errors of the mean. Note – scale differs among years.

There were two applications of *B. thuringiensis* (Xentari and Crymax, at 1.86 kg [AI] ha^{-1}), two applications of tebufenozide (0.14 kg [AI] ha^{-1}), and one application of spinosad (0.065 kg [AI] ha^{-1}). On 12 November, a corporate decision was made to apply thiodicarb to control lepidopteran larvae. Because of the late date in the growing season, it was necessary to apply the thiodicarb (0.67 kg [AI] ha^{-1}) through the sprinkler system (i.e., chemigation) to all plots. These costs were also charged to the IPM program.

The grower standard used three insecticide applications to control *Liriomyza* (abamectin, 0.004 kg [AI] ha^{-1} and cyromazine, 0.05 kg [AI] ha^{-1}), and one application of spinosad also targeted *Liriomyza*). On one occasion (8 October) *Liriomyza* populations

exceeded threshold densities in the IPM plots. Because of increasing populations of the more destructive *L. huidobrensis*, these high leafminer populations were treated with a single application of cyromazine (0.05 kg [AI] ha^{-1}).

On 28 October, one application of oxamyl (Vydate L, DuPont, Wilmington, DE, 1.07 kg [AI] ha^{-1}) was made via side dressing the beds, to control an infestation of aphids. These costs were charged to both the grower standard and IPM programs.

Threshold values for Septoria late blight were exceeded three times. In contrast the grower applied fungicides specifically for *S. apiicola* control four times. Because the forecasting program is only designed to forecast conditions favoring *S. apiicola*

Table 3
Production costs (in US$) for celery grown in the commercial trial (1997)

	Standard/standard Insect/pathogen	Standard/IPM Insect/pathogen	IPM/standard Insect/pathogen	IPM/IPM Insect/pathogen
Fixed costs	8129.59	8129.59	8129.59	8129.59
	Variable costs			
Harvest costs ($3.70 per carton) and sales costs ($0.40 per carton)[a]	11188.11	11346.83	11198.24	11356.96
Insecticide costs	592.61	592.61	422.82	422.82
Fungicide costs	701.92	656.74	701.92	656.74
Pesticide application costs	460.84	460.84	421.92	421.92
Subtotal pesticide costs	1755.37	1710.19	1546.66	1501.48
Total costs	21073.07	21186.61	20874.49	20988.03

The commercial trial compares the low-input IPM programs for insect pest and Septoria blight management with the grower standard management programs.
Horticultural production costs reflect industry norms (after Trumble et al., 1997).
See Table 1 for explanation of fixed costs.
[a] Based on a mean of three replicates per treatment.

outbreaks, treatments for other fungal pathogens (e.g., *Rhizoctonia solani* Kühn, *Sclerotinia sclerotiorum* [Lib.] de Bary) were necessary. The grower standard pathogen management program used ten separate applications of fungicides, whereas nine applications were made in the IPM pathogen program.

Even though the IPM programs used fewer pesticides compared with the grower standard programs, there were no significant differences in the number of marketable cartons among the treatments ($P > 0.05$, Table 4). As a result of the reduced number of pesticide applications, the fixed production costs were lower for the combined IPM program by approximately $250 \, ha^{-1}$ compared with the combined grower standard program. Costs for the insect component of the IPM program were lower by $208 \, ha^{-1}$, and costs for the pathogen component of the IPM program were lower by $45 \, ha^{-1}$ (Table 3). The lower pest management costs combined with the lack of differences in yields meant that net profits did not differ significantly for the IPM and the grower standard programs ($F = 0.25$, $P > 0.85$, Fig. 2).
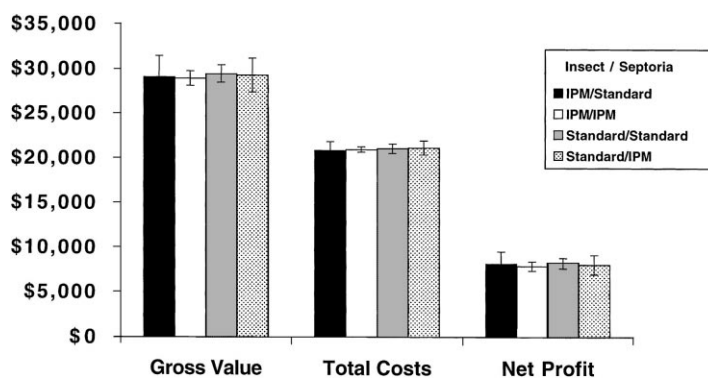

Fig. 2. Mean total production costs, gross value, and net profits for celery grown in the commercial trial during 1997. Net profits were not significantly different among treatments ($P < 0.05$, Fisher's protected LSD). The legend indicates the combination of insect and *S. apiicola* management programs. Bars represent standard errors of the mean.

Table 4
Harvest results for the commercial trial comparing the low-input IPM programs for insect pest and Septoria late blight management with the grower standard management programs

Treatment (insect/pathogen)	Size class	Marketable cartons[a]	$ per carton	Gross value
Standard/standard	2.0	217.67 ± 59.82	9.85	7188
Standard/IPM	2.0	295.33 ± 108.13	9.85	5298
IPM/standard	2.0	238.00 ± 88.84	9.85	5793
IPM/IPM	2.0	251.67 ± 27.76	9.85	6125
Standard/standard	2.5	416.33 ± 79.06	9.85	9565
Standard/IPM	2.5	393.00 ± 28.75	9.85	10133
IPM/standard	2.5	417.00 ± 49.00	9.85	10150
IPM/IPM	2.5	408.00 ± 35.10	9.85	9930
Standard/standard	3.0	178.33 ± 51.07	10.85	4826
Standard/IPM	3.0	180.00 ± 60.74	10.85	4781
IPM/standard	3.0	207.67 ± 33.47	10.85	5568
IPM/IPM	3.0	232.00 ± 31.51	10.85	6220
Standard/standard	4.0	29.00 ± 29.00	10.35	1526
Standard/IPM	4.0	59.67 ± 30.15	10.35	742
IPM/standard	4.0	39.33 ± 4.33	10.35	1006
IPM/IPM	4.0	110.67 ± 24.34	10.35	2830
Standard/standard	Hearts	263.00 ± 53.23	13.00	6168
Standard/IPM	Hearts	192.00 ± 18.90	13.00	8448
IPM/standard	Hearts	203.33 ± 4.98	13.00	6532
IPM/IPM	Hearts	118.67 ± 28.47	13.00	3812
Standard/standard	Total	1104.33 ± 55.15 a	–	29273
Standard/IPM	Total	1120.00 ± 78.04 a	–	29402
IPM/standard	Total	1105.33 ± 96.73 a	–	29048
IPM/IPM	Total	1121.00 ± 30.29 a	–	28918

Total yields marked with the same letter are not significantly different ($P > 0.05$, Fisher's protected LSD).
[a] Mean ± SEM.

4. Discussion

The present project was designed specifically to address grower concerns about the perceived risks in the use of low-input system for managing pests in high value crops. Growers and pest control advisors have repeatedly identified risk and incomplete information as reasons for not employing more IPM tactics (Sorensen, 1993). The results from 4 years of field station tests indicate that potential losses from pests in these systems are significant enough to warrant the use of pesticides. However, these results also demonstrate that pesticide use can be reduced without sacrificing yield or inflating costs. Furthermore, use of threshold driven IPM programs can generate net profits equal to or greater than those generated by prophylactic pest management practices.

Although in the field station trials low market prices at the time of harvest for 2 years would have resulted in net losses for growers using the IPM approach, those losses would have been greater for growers using the standard program. Harvesting these crops the week before two major US holidays, when market prices are typically higher, would have produced higher net profits for the IPM program than the standard (Fig. 3). In the one period where the IPM program produced a net loss, that loss would have been less than the loss for the chemical standard. Therefore, employing such an IPM program could not only increase profits but also mitigate losses when market prices are unfavorable.

Another important component of this IPM approach is its sustainability. A major concern in pest management is the evolution of pesticide resistance. Programs such as the present IPM approach would help to mitigate or delay resistance by moderating the amounts of pesticides applied and using multiple insecticides with different modes of action (Tabashnik, 1989; Georghiou, 1994). Furthermore, the present results demonstrate that these goals can be accom-
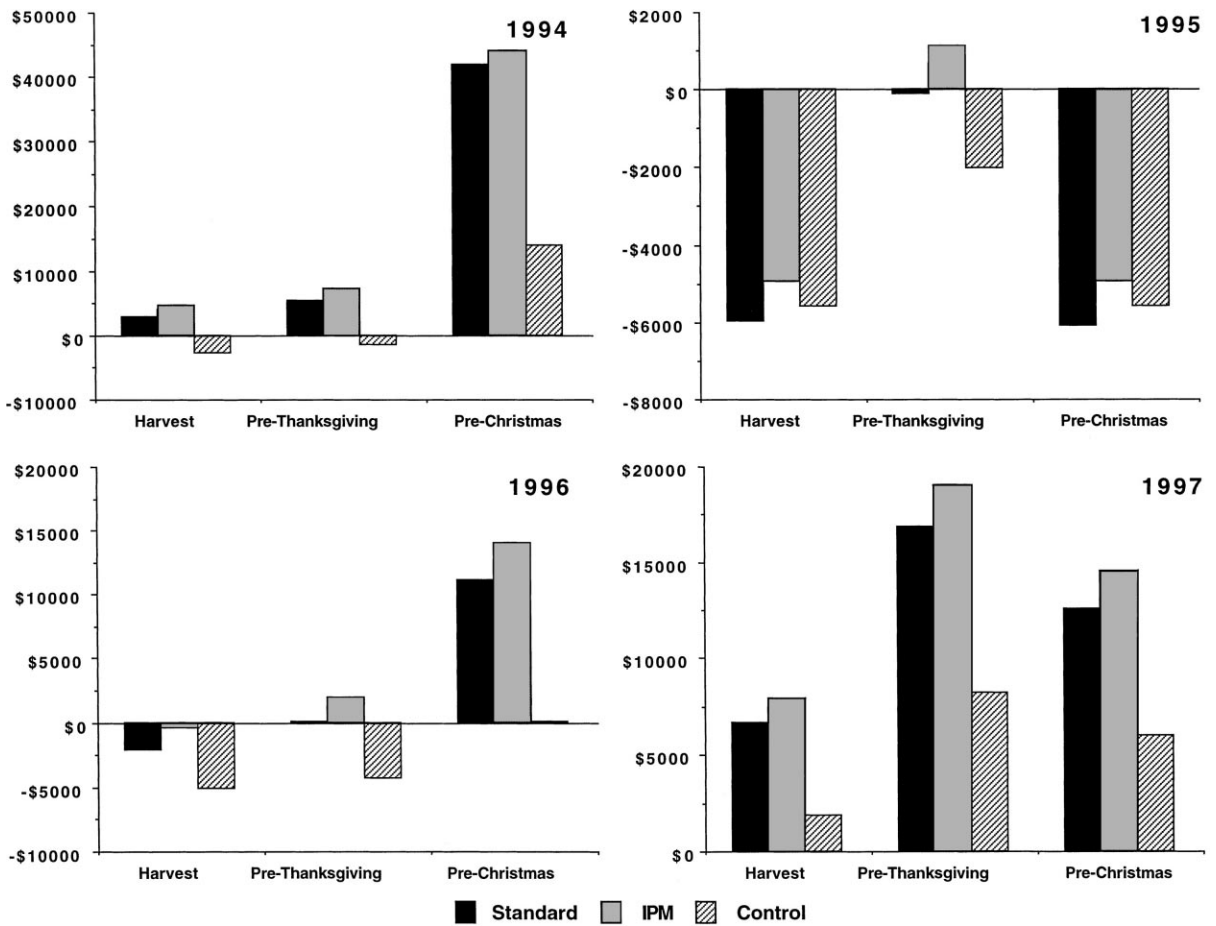
Fig. 3. Estimated net profits for celery grown in field station trials when harvested on different dates. The data reflect F.O.B. prices at the actual harvest date, the week prior to Thanksgiving holiday (fourth Thursday of November), and the week prior to Christmas (25 December), for each year from 1994 to 1997. These data are for comparative purposes to demonstrate the effect of different market prices on the net returns of the standard, IPM, and control programs. Note – scale differs among years.

plished with a move to less environmentally disruptive insecticides.

The commercial validation trial of this project demonstrated that such low-input IPM programs are economically viable. Although numerous IPM programs have been developed, testing such programs on a commercial scale is necessary to gain grower confidence and refine program logistics to meet the constraints inherent in large-scale commercial agriculture. In addition, growers are faced with management decisions regarding all aspects of production. Therefore, evaluation of truly comprehensive programs are necessary. The present results indicate that through adequate sampling to determine the appro-

priate need for insecticide applications, further significant reductions in insecticide use can be made by the vegetable industry. In the comparison of insect management programs, the IPM program used one third fewer insecticides than the grower standard did. Because the grower program in the commercial trial is relatively progressive in terms of insecticide use, other growers could realize even greater net profits from adopting the IPM program.

Additional progress in successfully reducing pesticide use could be made by enhancing similar threshold-driven, low-input programs for the control of fungal pathogens (e.g., Lacy, 1994; Lacy et al., 1996). The development of monitoring programs for

other fungal pathogens, similar to the one for Septoria late blight should be encouraged. Refinement of such low-input programs for insect and fungal pests will produce successful, comprehensive intelligent plant management programs and create a demand for development of additional low-input IPM programs for other agroecosystems.

Not only will these evolving approaches to insect pest management in celery allow producers to achieve equivalent economic returns to current conventional practices, they can provide significant societal and environmental benefits in terms of reducing petrochemical use, soil compaction, pollution generation, and runoff.

Acknowledgements

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