Although several beneficial insect parasites control California red scale, Aonidiella aurantii *(Maskell) in southern California desert citrus-growing areas, parasites are much less effective in the San Joaquin Valley. Chemical control has been the standard practice in Valley citrus, but potential development of resistance in California red scale has led to a search for alternative methods.*

Two articles in the May-June issue of California Agriculture *discussed computer simulation of red scale populations and prediction of infestations by trapping males. The following two articles report on CRS development in relation to degree-days and on the economic value of pheromone monitoring. The research has been funded by the Citrus Research Board, U.S. Department of Agriculture, and University of California Integrated Pest Management Project.*

Pheromone monitoring is cost-effective

Robin T. Ervin □ Daniel S. Moreno □ John L. Baritelle □ Philip D. Gardner

Citrus pests accompanied the establishment and growth of California's citrus industry in the late 1800s, and by 1910, the California red scale (CRS), *Aonidiella aurantii* (Maskell), was a major pest. The control method at that time consisted of placing a tent over each infested tree and releasing cyanide gas within the tent. Various other methods have been used since then, but all have proved costly in time and money.

Before 1971, citrus growers relied on repeated visual inspection of orchards for the presence of California red scale. If the insect was found, chemical pesticides were applied over an entire orchard. This approach was labor-intensive and was not necessarily the most reliable. Also, since red scale is not always equally distributed but tends to predominate in a few locations within an orchard, some of the pesticide may have been applied needlessly.

A new method of detecting California red scale populations in citrus orchards was developed by Richard E. Rice and Daniel S. Moreno in 1969. Detection entails the use of the CRS sex pheromone and sticky trap cards. Field tests have shown that trapping male red scale in this manner is an accurate means of monitoring the insect's presence in a grove, even at low infestation levels.

The monitoring program was first field-tested in the Coachella Valley, where the Riverside County Citrus Pest Control District No. 2 became the first to adopt the program in August 1971. Red scale had first been found in the valley in 1935, and visual inspection had been used for detection until 1971. Since pheromone-trap monitoring, California red scale control has increased in effectiveness, and total suppression is expected in the near future. This district is now monitoring approximately 6,475 hectares (16,000 acres) of citrus by this method.

California red scale was discovered in Yuma County, Arizona, in 1973. The Yuma County Citrus Pest Control District used visual inspection for two years in an eradication program until the pheromone trap was introduced in 1975. By the end of 1979, no infestations had been found in a commercial grove for three years, and the insect was considered eradicated. Monitoring has continued on approximately 11,331 hectares (28,000 acres) to ensure that commercial groves do not become reinfested from residential sources.

In California's San Joaquin Valley, where red scale was first identified in 1939, citrus growers monitor and control their own infestations. Not all growers use the pheromone trapping program; approximately 34,399 hectares (85,000 acres) are monitored by this method.

Use of the trap has resulted in more reliable detection, reduced application of pesticides, and other intangible societal benefits. In this study, we compared the costs of the research and development of this monitoring program with the benefits received from the program in these three citrus-producing areas. We defined the primary economic benefits as the decrease in hours needed to detect red scale and the reduction in the amount of chemicals required for its control. Other possible benefits are discussed but not put into monetary terms.

We used a standard benefit-cost formula to calculate the efficiency of the research project (see table 1 footnote). The study assumed that the costs and benefits would apply to the period from 1966 to 1990. An accounting of all benefits and costs and the proper definition of the discount rate are necessary to ensure that the comparison is accurate.

Costs

Cost categories included research, trapping, visual inspection, and chemicals (table 1). Several additional costs incurred regardless of detection method were assumed to be equal in both methods and therefore cancelled. Between 1971 and 1980, wage rates rose from $2.21 to $4.63 per hour, and the cost of the traps rose from $1.18 to $2.41. We assumed both to remain at 1980 levels throughout the remaining life of the project (1981-90). These values assist in determining trapping and visual inspection costs.

TABLE 1. Research and other costs used to determine resource savings from adopting the pheromone monitoring program (in 1967 constant dollars)

Year	Research costs (C_t)	Visual inspection (C_v)	Monitoring program (C_p)	Savings from decreased working hours (C_v-C_p)	Savings in chemical costs	Total benefits (B_t)
	$ (1,000)					
1966	46.0	—	—	—	—	—
1967	56.1	—	—	—	—	—
1968	45.1	—	—	—	—	—
1969	23.2	—	—	—	—	—
1970	32.6	—	—	—	—	—
1971	43.5	53.4	15.2	38.2	−2.2	36.0
1972	46.9	54.7	15.4	39.3	−1.2	38.1
1973	49.7	63.7	16.6	47.1	23.1	70.2
1974	38.5	61.9	16.3	45.7	17.9	63.6
1975	40.1	324.6	40.9	283.6	416.3	699.9
1976	35.2	308.9	39.8	269.1	437.2	706.3
1977	55.4	301.4	38.3	263.1	447.3	710.4
1978	58.4	337.7	42.5	295.1	577.2	872.3
1979	35.1	341.7	44.5	297.2	724.8	1,022.1
1980	41.4	386.9	51.1	335.8	1,020.8	1,356.6
1981	41.4	386.9	51.1	335.8	1,021.2	1,357.0
1982	41.4	386.9	51.1	335.8	1,021.6	1,357.4
1983	—	386.9	51.1	335.8	1,021.9	1,357.8
1984	—	386.9	51.1	335.8	1,022.4	1,358.2
1985	—	386.9	51.1	335.8	1,022.7	1,358.5
1986	—	386.9	51.1	335.8	1,023.1	1,358.9
1987	—	386.9	51.1	335.8	1,023.5	1,359.3
1988	—	386.9	51.1	335.8	1,023.9	1,359.7
1989	—	386.9	51.1	335.8	1,024.3	1,360.1
1990	—	386.9	51.1	335.8	1,024.7	1,360.5

NOTE: Benefit-cost formula used was:

$$\frac{B}{C} = \frac{\sum_{t=1}^{T} B_t/(1-i)^t}{\sum_{t=1}^{T} C_t/(1-i)^t}$$

where B= present discounted value of the benefits; B_t = total benefit in year t; C = present discounted value of the costs; C_t = total costs in year t; i = discount rate; and T = time period.

Chemical costs per hectare were estimated to be $136 ($55 per acre) in 1971, increasing to $292 ($118 per acre) in 1980. The costs were assumed constant at the 1980 level throughout the rest of the project.

We adjusted all costs to remove the effect of inflation by using the 1967 consumer price index. Therefore, all are in 1967 dollars.

This California red scale research project began in 1966 and ended with the 1982-83 fiscal year. The project received principal support from the U.S. Department of Agriculture (USDA), with funding also from the State of California and the California Citrus Research Board. We determined the amount of USDA support by reconstructing project budgets, which were then verified by the project's participants.

Trapping costs included the traps, labor required for placing and removing traps from the field, and labor for recording the male catches. Records from each area provided information on purchase price for the synthetic pheromone and the hourly wage rates. The hourly wage rate was assumed to be the same for both visual inspectors and personnel handling the traps.

Each area differed in the number of traps per hectare used for general detection. The Riverside district used approximately one trap to each 1.1 hectare; the San Joaquin Valley averaged one per 2.4 hectares; and the Yuma district used one per 4.1 hectares.

The cost of visual inspection depends on the speed of the inspector, the total number of hectares inspected, the hourly wage rate, and the frequency of inspection. In eradication districts, visual inspection occurs only once a year, unless a localized infestation is found and requires more frequent inspection. In areas where the scale is established and under an integrated pest management (IPM) program, the IPM practitioner does not spend prolonged periods per visit in a given orchard, but vigilance requires frequent visits. However, had the pheromone trap not been developed, it is assumed intensive visual inspection would have continued in the eradication districts. We estimated that in eradication districts two people walking along both sides of a row can visually inspect an average of 4 hectares per eight-hour day. This equals four hours per hectare.

The average annual cost of chemical control of red scale, including materials and application, was developed from chemical cost data reported by the California Department of Food and Agriculture. We assumed data to be representative of Arizona costs also.

Benefits

The monitoring program benefits the grower through savings from reduced hours to detect red scale and lower amounts of pesticides used for control. Consumers may also benefit by being able to purchase what they perceive to be higher quality fruit. For purposes of this study, we calculated only the benefits received by the grower.

Benefits to parties other than the grower and the consumer are considered societal. Agricultural research has been identified as contributing to a positive balance of trade, improving the quality of the environment, sustaining the general health and safety of the population including agricultural workers, and enhancing the quality of life. California red scale research, as exemplified by the monitoring program has had some part in these societal benefits, but since they cannot be assigned a specific value, we excluded them from our analysis.

Discount rate

The discount rate represents the opportunity cost of capital, or the rate of return if the funds were to remain in the next best alternative use in the private sector for approximately the same period. This is a judgmental issue. For this study, we assumed the discount rate at a low estimate of 5 percent and a high estimate of 10 percent from 1966 to 1990.

The internal rate of return provides an additional criterion for judging the efficiency of the utilization of the research funds. This is the rate that equates the benefits to the costs.

Results

The California red scale research cost was estimated to be about $730,000 in 1967 dollars. The USDA contribution has been about 85 percent of the total. Most of these funds were spent on professional salaries, equipment, transportation, lease of laboratory space, and administrative needs.

In 1971, when commercial pheromone monitoring began in the Riverside Pest Control District, the benefits began to accrue for the area monitored by this technique. The total benefit in a particular year is determined by subtracting pheromone monitoring costs from visual inspection costs and adding the difference to the savings in chemical costs. This represents the savings or benefits to growers. Somewhat surprisingly, chemical costs increased in the first years that the monitoring program was used, as indicated by the negative initial values of "Savings in chemical costs" (table 1). We believe this occurred because of the identification of small infestations that were previously missed by visual inspection.

At the 5 and 10 percent discount rates, the benefits-cost ratios are 16.6 and 10.7, respectively. In other words, for each dollar spent on the research, a savings in resources of $10.70 to $16.60 is estimated under the model's assumptions. The internal rate of return was determined to be 41.3 percent. In either case, the decision criterion for economic efficiency seems to be more than adequately met.

The total benefits are probably undervalued because they do not include those related to the environment. More astute and careful monitoring of red scale may lead to more judicious use of chemical controls, which, in turn, could extend the useful life of those chemicals. In addition, worker safety and general environmental conditions may be improved.

Based on this analysis, the funds expended for research on California red scale and the development and subsequent implementation of an effective monitoring program appear to have been well utilized. While the quantifiable benefits will primarily accrue to growers, society may also enjoy several intangible benefits.

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Tracking CRS development by degree-days

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Mature virgin California red scale females possess a sex attractant useful in monitoring CRS populations. After researchers showed that adult red scale males responded positively to sticky card traps baited with caged, live, virgin female scales, the sex pheromone was synthesized. Since then, synthetic sex pheromone traps have become widely used in the detection and management of red scale in citrus integrated pest management programs.

We conducted a study to define California red scale phenology by degree-days (°D) and to determine if male flight patterns accurately reflected the development of CRS generations in the San Joaquin Valley.

Field tests

The study took place in an untreated 2-hectare (5-acre) orchard of mature navel orange trees at the University of California Lindcove Field Station in Tulare County. We selected a block of four adjacent trees with equivalent red scale populations, and followed CRS life stages and their seasonal changes by sampling 300 live scales each from leaves and twigs. Samples were taken every 10 days from January through April, weekly from May through October, and every two weeks in November and December. We ignored the motile first-stage crawlers.

Male CRS flights were monitored from April through September by means of a synthetic sex pheromone trap in each sample tree. The pheromone source was replaced every four weeks. Sticky cards were changed daily when possible but never less frequently than twice weekly.

A hygrothermograph next to the sample trees recorded within-orchard temperatures and relative humidities.

Starting on January 1, we used daily maximum and minimum temperatures to calculate degree-days above the developmental threshold (t). The threshold, below which no measurable development occurs, was estimated from constant temperature developmental data as 11.6°C (52.9°F).

The thermal constant, K, is the total degree-days required for an organism to complete its development. We estimated K to be 673°D for CRS on grapefruit, and 616.4°D on lemon fruit (using $K = T - t(D)$, where T is temperature, D is total developmental time in days, and $t = 11.6°C$, the developmental threshold).

CRS phenology

Relative densities (percent) of life stages of the overwintering population (fig. 1) remained unchanged between 0 and 129°D (January to mid-March). All scale stages were present during this period except newly settled crawlers (whitecaps) and pupal and pre-emergent adult male stages. The absence of whitecaps indicates a lack of reproduction by the overwintering gravid females.

After about 129°D, the percentages of first-stadium and molt and second-stadium and molt scales declined (fig. 1a, b), and the percentage of virgin adult females increased (fig. 1c), peaking at 344°D in early May. The first peak of male flight (fig. 1d) coincided with this peak of virgin females. At this time (344°D), adult virgin females and overwintering gravid females (fig. 1c,e) represented more than 97 percent of the live female red scale population.

A sharp increase in first-stadium scales beginning at 344°D (fig. 1a), indicated the onset of the spring generation arising from overwintering gravid females. This first cohort peaked at 520°D. A second but lesser peak of first-stadium scales occurred at 817°D, and represented offspring of overwintering immature CRS. This second cohort occurred 297°D, or about ½ K, after the first cohort and originated from the small peak of adult females at 722°D (fig. 1e).

Maturation of the spring generation is indicated by serial increases in relative abundances of all stages and a peak in adult male capture. Coincidence between the virgin adult females and the adult male peaks (950°D) (fig. 1c,d) was again observed.

The start of the summer generation is indicated by an increase in whitecaps (first-stadium scales) (fig. 1a) at about 908°D. This increase occurred about 564°D after the start of the spring generation and coincided with an increase in gravid and reproductive (parturient) females (fig 1e). No sequential peaks were observed in the second-stadium and molt and adult virgin females in this scale generation (fig. 1b,c); immature males were

TABLE 1. Duration of developmental stages and total developmental time (°D) in female California red scale at Lindcove Field Station, Tulare County, California during 1980*

	Stage						
	1st†		2nd†		Adult‡		
	°D	Percent§	°D	Percent§	°D	Percent	Total °D
Spring generation	142.2	0.23	186.7	0.31	276.7	0.46	605.6
Autumn generation	132.8	0.23	197.2	0.34	242.8	0.42	572.8

* Degree-days above 11.7°C (53°F) used for ease of calculation.
† Includes stadium and molt stages.
‡ Virgin adult to reproductive adult.
§ Proportion of total developmental time.