Potential of the Asian Predator, *Harmonia axyridis* Pallas (Coleoptera: Coccinellidae), to Control *Matsucoccus resinosae* Bean and Godwin (Homoptera: Margarodidae) in the United States

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ABSTRACT Studies were conducted in Connecticut from 1983 to 1986 to determine the ease with which the Asian coccinellid, *Harmonia axyridis* Pallas, can be reared in the laboratory, its ability to control *Matsucoccus resinosae* Bean and Godwin on *Pinus resinosa* Aiton, and its ability to overwinter outdoors. The beetle was reared on a diet of pea aphids, *Acyrthosiphon pisum* (Harris), grown on *Vicia faba* L. at 27°C and a photoperiod of 16:8 (L:D). Mean development time from oviposition to adult eclosion was 18.6 ± 1.3 d and the average female produced 718.7 ± 93.6 offspring during her adulthood of 83.6 ± 18.7 d. Percentage of predation was high (>80%) if scale-infested pine branches were caged with different densities of *H. axyridis* larvae when the conspicuous eggs, cysts, and adults of *M. resinosae* were present. Percentage of predation was significantly lower when scales were predominantly first instars concealed beneath pine bark. Cannibalism was common (>50%) among *H. axyridis* larvae at all experimental densities. Most of 905 paint-marked adult beetles released uncaged onto infested pines dispersed within the first few days after release. However, before departure, some adults laid eggs on the pines and established a resident population of *H. axyridis*. Less than 10% of the adult beetles (n = 762) placed in overwintering cages in the field survived from November through March, a period during which weather conditions were normal for Connecticut.

KEY WORDS *Acyrthosiphon pisum*, biological control, establishment, overwintering success, predation

THE LADYBIRD BEETLE, *Harmonia axyridis* Pallas (Coleoptera: Coccinellidae), distributed throughout Asia (Yasumatsu & Watanabe 1964), is an important predator of the scale, *Matsucoccus matsumurae* (Kuwana) (Homoptera: Margarodidae), in Japan (McClure 1986). It is also a common predator of *M. matsumurae* in Korea and in eastern mainland China (Cheng & Ming 1979, Li et al. 1980, McClure et al. 1983), but its ability to control scale populations in these countries has not been documented.

In the northeastern United States, the red pine scale, *Matsucoccus resinosae* Bean and Godwin, probably the same as *M. matsumurae* (McClure 1983, Young et al. 1984), is a destructive introduced pest of *Pinus resinosa* Ait. Studies conducted in Connecticut revealed that scale populations quickly attain injurious levels and that none of the natural enemies that inhabit pine forests have a significant impact on scale density (McClure 1977, 1983).

The effectiveness of *H. axyridis* in controlling outbreak populations of *M. matsumurae* in Japan (McClure 1986) sparked my interest in this beetle as a biological control agent for *M. resinosae* in the United States. Here I report results of studies conducted in Connecticut to establish *H. axyridis*, to determine the ease with which this beetle can be reared in the laboratory, and to evaluate its ability to control scale populations and overwinter in plantations of *P. resinosa*.

Materials and Methods

Rearing *H. axyridis*

Four colonies of *H. axyridis* originally acquired from sources in Asia and eastern Europe (Table 1) were obtained from the U.S. Department of Agriculture Beneficial Insect Research Laboratory in Newark, Del., during 1983 and 1984 and reared at 27°C and a photoperiod of 16:8 (L:D) on a diet of pea aphids, *Acyrthosiphon pisum* (Harris), grown on fava beans, *Vicia faba* L. First and second instars were reared in 30-ml plastic cups with clear plastic lids; older larvae and adults were reared in 4.5-liter Nalgene jars. Eggs laid onto cheesecloth strips were removed from the jars daily and transferred to cups. Records were kept for each colony for several generations on fecundity, sex ratio, duration of developmental stages, and

Table 1. Colonies of *H. axyridis* introduced into the United States for studies on the biological control of *M. resinosae*

Origin	Date collected	Collection site	Latitude (°N)	Collection
China	July 1983	Menjiagang	45°15′	P. W. Schaefer
Japan	June 1984	Kyoto	34°55′	M. S. McClure
Korea	May 1983	Pocheon	37°40′	R. Carlson, Han, V. Morrone
U.S.S.R.	Oct. 1981	Primorskiy	43°10′	V. N. Cusnecov

longevity. Adult beetles were occasionally stored for later use in an incubator at 15°C and 12:12 (L:D) photoperiod on a diet of honey/water solution. The relationship between adult age and egg production was analyzed by linear regression.

Ability of *H. axyridis* to Control *M. resinosae*

Field-plot Experiment, 1983. An experiment was conducted during 1983 in a field plot at the Connecticut Agricultural Experiment Station, New Haven, to determine the ability of *H. axyridis* to control *M. resinosae* on seedlings of *P. resinosa*. On 27 April, 100 4-yr-old pines were obtained from a common stock (Western Maine Nursery, Fryeburg, Me.) and were planted the next day in 8-liter containers in a peat/lite mixture. Trees were set out in the field plot 50 cm apart in four rows of 25 trees each. Trees were watered weekly (in addition to rainfall) from the time of planting through September. At the time of planting all seedlings were ca. 50 cm tall and appeared to be healthy.

On 25 May, during peak abundance of *M. resinosae* crawlers (mobile first instars), branches were collected from a heavily infested stand of *P. resinosa* located in Old Saybrook, Conn. One infested branch ca. 50 cm long was placed in contact with the base of each seedling and left for 2 wk, which allowed sufficient time for crawlers to transfer. On 9 August, nylon-mesh sleeve cages (30 by 30 cm; 32 strands per 1 cm mesh) were placed over the top portion of 50 randomly selected seedlings and cages were tied off at the base with string to prevent arthropods from entering or leaving. On two dates (9 and 26 August) first instars of Korean *H. axyridis* reared in the laboratory were released into cages. On each occasion cages were set up with 40, 20, 10, 5, or 0 larvae per plant, with five replicates of each density. Plants were randomly assigned to each density. These beetle densities encompass those that occur naturally in scale-infested pine stands in Japan (McClure 1986). Three weeks after each release date the five caged trees of each beetle density were harvested and examined in the laboratory to determine survivorship of *H. axyridis* and number of dead and living *M. resinosae* beneath 50 bark flakes of 3-yr-old growth. The 3-wk period that commenced on 9 August encompassed the time during which scales were cysts, adults, and eggs, stages that are exposed and readily accessible to predators. The period beginning on 26 August corresponded to the time during which scales were first instars, a stage when scales conceal themselves beneath the bark. This enabled me to assess the ability of *H. axyridis* to exploit *M. resinosae* at times of the year when prey were more or less available.

Plantation Experiment, 1985. An experiment was conducted during 1985 at Lockwood Farm of the Connecticut Agricultural Experiment Station, Mount Carmel, Conn., to appraise the ability of *H. axyridis* to control *M. resinosae* in a mature plantation of *P. resinosa*. The 52 pines that composed this stand are all that remain of 100 trees that were planted in 1964. Nearly half of the original trees have been killed by *M. resinosae* since the stand was artificially infested 7 yr ago. At the time of this experiment all surviving trees were heavily infested and injured, as indicated by discoloration and distortion of branches.

On 17 May six terminal branches on each of 20 randomly selected trees were examined and any spiders or other predators were removed. These branches were then enclosed within cages, described previously, which were tied off at the base with string to prevent arthropods from entering or leaving. On each of four dates during the spring and summer (20 May, 17 June, 19 August, and 16 September), first instars of Japanese *H. axyridis* reared in the laboratory were released into the cages on five trees as follows: two cages per tree contained 20 larvae; two contained 10 larvae; and two contained no larvae. On each of the first two dates 40 additional first instars were scattered uncaged onto each of the same trees containing caged beetles so that the relative performance of caged and free-living *H. axyridis* could be appraised.

Three weeks after each release date the six caged branches and two additional uncaged branches that larvae were released on were harvested from each of the five trees and examined in the laboratory. The four 3-wk intervals corresponded to the periods during which most individuals of the overwintering and summer generations of *M. resinosae* were either exposed stages (cysts, adults, eggs) or concealed stages (first instars), which again enabled me to appraise the ability of *H. axyridis* to exploit hosts that were more or less accessible. The number of living and dead beetles in each cage and their stage of development were recorded, and caged and uncaged branches were examined microscopically to determine the number of living and dead scales beneath 50 bark flakes of 3-yr-old growth.

Differences in the survivorship of *H. axyridis* and *M. resinosae* in cages containing various densities of beetles and during periods when prey were concealed and exposed were analyzed for statistical significance using analysis of variance

(ANOVA) and Duncan's multiple range test (Duncan 1955) for both the 1983 and 1985 experiments.

Ability of *H. axyridis* to Overwinter

Field-plot Experiment, 1983–84. An experiment was conducted from November 1983 through March 1984 in the field plot described previously to determine the ability of adults of *H. axyridis* to survive winter conditions outdoors. On 1 November two screen cages (eight strands per 1 cm mesh) measuring 60 cm on each side were placed on the ground among the red pine seedlings in the plot. Cored bricks (20 by 9 by 7 cm) with five 2-cm holes were stacked in tiers on a rectangular base (40 by 54 cm) to a height of 56 cm in the center of each cage. The holes in the 72 bricks composing the structure were aligned to create vertical tunnels that enabled adult beetles to occupy the various tiers. A mixture of deciduous leaves and pine needles collected from the forest floor was placed in each cage around the base of each of the brick structures to a height of 28 cm. On 1 November a total of 111 adults of Korean *H. axyridis* was released onto the top of each structure and then cages were tied to prevent beetles from escaping.

On the last day of each of the succeeding 4 mo, 18 bricks composing a different corner of the stack were disassembled and the beetles, living and dead, that were encountered while so doing were removed and counted. Disturbed bricks were repositioned and cages were resealed. The percentage of beetles that survived during each interval was calculated.

Plantation Experiment, 1985–86. A second experiment was conducted from October 1985 through March 1986 in the pine plantation at Lockwood Farm, described previously, to determine the survivorship of *H. axyridis* in a more realistic overwintering environment. On 30 October three cubic screen cages described above were placed on the ground beneath the red pines near the center of the plantation. Three more cages were placed ca. 40 m away in an adjacent woodlot comprised of deciduous tree species. Cored bricks described above were stacked in tiers on a rectangular base (40 by 36 cm) to a height of 28 cm in the center of each cage. The 23 bricks that composed each structure were aligned so that vertical holes enabled adult beetles to occupy any tier. Ninety adults of Japanese *H. axyridis* were released onto the top of each stack on 30 October. The three cages in the plantation were then filled to the top (60 cm) with fallen pine needles; the cages in the woodlot were filled with leaf litter. On 31 March each stack was disassembled and living and dead beetles were recovered and counted.

Throughout both overwintering experiments detailed weather data were collected at the official weather station in Mount Carmel, located ca. 300 m from the plantation and 8.4 km from the field plot. The ability of *H. axyridis* to survive normal overwintering conditions in Connecticut was assessed on the basis of this weather data.

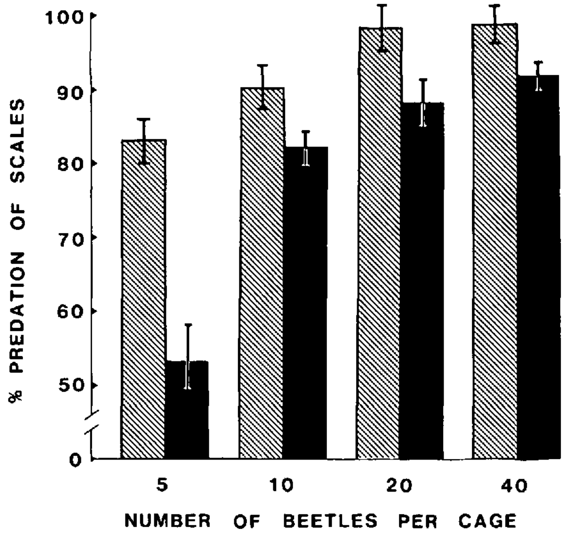

Fig. 1. Mean (±SEM) percentage of mortality of *M. resinosae* in cages containing different densities of *H. axyridis* for the periods during which scales were predominantly small, inconspicuous first instars (solid bars) or larger, more conspicuous ovisacs, cysts, and adults (cross-hatched bars).

Establishment of *H. axyridis*

The persistence of *H. axyridis* on infested red pines was examined in 1985 in a mark/release study conducted in the plantation at Lockwood Farm. In May, when most scales were conspicuous later stages, 500 adult beetles were marked on the right elytron with a small drop of Testors 1108 blue paint, and then released in equal numbers onto five infested pines. In July, when most scales were inconspicuous first instars, another 405 adults were marked with Testors 1114 yellow paint and released onto five different pines. Other adult beetles that were marked with blue or yellow paint were kept in the laboratory to monitor any ill effects of marking on survival and behavior. Trees were examined for 10 min each from the ground every 3 or 4 d for a period of 4 wk following each release date. Marked and unmarked individuals (offspring of released beetles) of *H. axyridis* were counted but were not removed from the trees.

Results

Rearing *H. axyridis*

There were no significant differences in the rearing and development of the four colonies of *H. axyridis*, and all readily hybridized. Mean

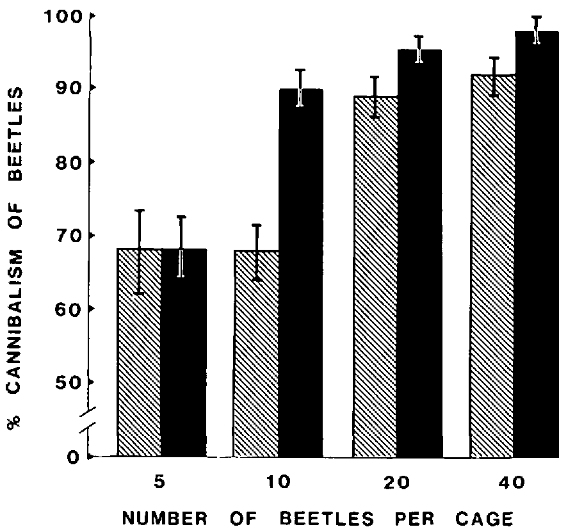

Fig. 2. Mean (±SEM) percentage of cannibalism of *H. axyridis* in cages containing different densities of beetles for the periods during which scales were either inconspicuous or conspicuous stages (see Fig. 1).

(±SD) development time from oviposition to adult eclosion was 18.6 ± 1.3 d (n = 1,617) and the mean duration (days) of life stages was as follows: egg, 2.5 ± 0.3; larva (I), 2.4 ± 0.3; larva (II), 2.0 ± 0.3; larva (III), 2.8 ± 0.6; larva (IV), 3.5 ± 0.9; pupa, 5.4 ± 1.0; adult female, 83.6 ± 18.7 (n = 1,158); male, 69.7 ± 20.3 (n = 957). The sex ratio was 1.21 females: 1 male. Adult females began oviposition 7.3 ± 1.4 d after eclosion at the rate of 15.9 ± 4.3 eggs per d for a period of 45.2 ± 13.3 d. In its lifetime the average female produced 718.7 ± 93.6 eggs. Daily egg production could not be shown to be related to adult age ($r = 0.17$; df = 23; $P > 0.05$; linear regression analysis).

Cannibalism was the only significant mortality factor during all developmental stages of *H. axyridis*. In cages containing mixed developmental stages of *H. axyridis*, the stages most heavily cannibalized were the eggs (by adults and first instars) and the second and third instars and pupae (by fourth instars). The intensity of cannibalism was not related to the abundance of aphid prey; cannibalism was as prevalent in cages containing many aphids as in cages containing few aphids. Rearing *H. axyridis* in groups of individuals of the same life stage greatly reduced mortality from cannibalism.

Adult beetles could be stored in the incubator at 15°C for several months with no apparent effects on their survivorship and fecundity. The same adult beetles could be transferred between the incubator and the growth room several times with no apparent ill effects. As many as 15 continuous generations of *H. axyridis* were produced annually in the growth room.

Ability of *H. axyridis* to Control *M. resinosae*

Field-plot Experiment, 1983. The potential of *H. axyridis* to control scale populations in the red pine field plot is illustrated in Fig. 1. During the period of time when the scale population was predominantly ovisacs, cysts, and adults, the more conspicuous life stages, nearly all scales were killed in cages containing the higher beetle densities (20 and 40 larvae per cage). Even in the lower-density cages containing 5 or 10 beetles, 84–90% of these conspicuous scales were killed. Percentage of predation of *M. resinosae* was significantly less for all beetle densities ($F_{1,38} = 5.2$; $P < 0.05$; ANOVA) during the 3-wk period when scales were predominantly first instars concealed beneath the pine bark (Fig. 1). Mortality of all scales in cages containing no beetles was low (<10%), indicating that the cages themselves did not affect scale survivorship.

Cannibalism was common among *H. axyridis* larvae at all experimental densities (Fig. 2). The highest percentage of cannibalism occurred in cages that contained the most beetles and during the period when scales were inconspicuous first instars. In cages containing only 10 beetles, cannibalism was significantly less when most scales were conspicuous than when they were concealed ($F_{1,38} = 13.4$; $P < 0.001$; ANOVA). The maximum number of larvae that survived to the end of the

Table 2. Mean (±SD) percentage of predation of *M. resinosae* and mean (±SD) percentage of cannibalism of Japanese *H. axyridis* on plantation red pines in cages containing 10 or 20 beetles during the periods when scales were inconspicuous first instars or conspicuous eggs, cysts, and adults

Scale generation	Scale stages	% predation[a]			% cannibalism[a]		
		10 beetles/cage	20 beetles/cage	P	10 beetles/cage	20 beetles/cage	P
Overwintering	Concealed	13.0 ± 3.9	25.0 ± 6.9	<0.01	75.0 ± 5.5	90.7 ± 4.5	<0.0005
	Exposed	81.4 ± 4.3	92.8 ± 3.6	<0.005	64.3 ± 5.4	84.4 ± 3.2	<0.0005
	P	<0.0005	<0.0005		<0.005	<0.01	
Summer	Concealed	23.4 ± 4.0	32.4 ± 5.6	<0.02	88.0 ± 4.5	94.4 ± 1.8	<0.005
	Exposed	80.0 ± 4.3	88.6 ± 5.2	<0.02	71.5 ± 7.5	79.5 ± 3.7	<0.025
	P	<0.0005	<0.0005		<0.005	<0.0005	

[a] Percentages were transformed to arcsine $\sqrt{\%}$ for analysis.

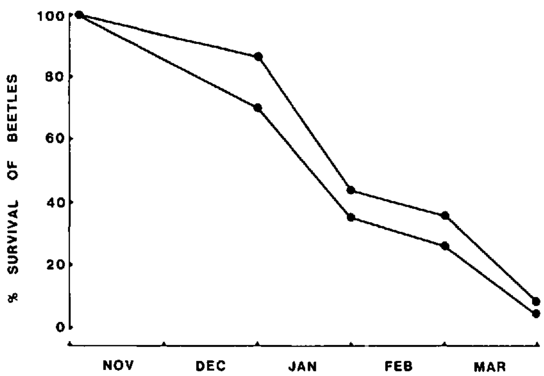

Fig. 3. Percentage of cumulative survivorship of adults of Korean *H. axyridis* in two cages in a field plot during the 1983–84 overwintering period.

experiment in any cage was two during the period when scales were concealed and four when scales were exposed, regardless of the number of beetles initially present.

Plantation Experiment, 1985. The impact of *H. axyridis* on the survivorship of *M. resinosae* in cages in a red pine plantation is given in Table 2. Percentage of predation was high (>80%) in all cages during the periods of both the overwintering and summer generations, when *M. resinosae* was predominantly exposed ovisacs, cysts, and adults. At both beetle densities, percentage of predation was significantly less (<33%) when scales were the more concealed first instars. Cannibalism again was prevalent among larvae in all cages, but was significantly greater at the higher beetle density and when scales were concealed than at the lower density and when scales were exposed (Table 2).

Free-living (uncaged) *H. axyridis* also had a significant impact on the abundance of *M. resinosae* in the plantation. Scales incurred 74.4 ± 4.8% predation and 16.0 ± 5.2% predation as exposed and concealed life stages, respectively, on pines on which 40 larvae were released. On pines with no beetles, *M. resinosae* incurred only 4.6 ± 3.1% predation and 3.2 ± 3.0% predation (exposed and concealed life stages, respectively). Scale mortality on trees on which *H. axyridis* had not been released was probably due to native predators.

Ability of *H. axyridis* to Overwinter

Field-plot Experiment, 1983–84. The survivorship of Korean *H. axyridis* in the field plot during the 1983–84 overwintering period is illustrated in Fig. 3. Nearly 80% of the original 222 adult beetles survived through December, a period during which minimum monthly temperatures and heating degree days were relatively normal as judged by the 1931–60 average (Table 3). Survivorship declined sharply during a somewhat colder-than-normal January, a month in which the lowest temperature for the overwintering period was recorded (−23.9°C). By the end of February, which was milder than normal, 25% of the beetle population remained. Approximately 10% of the beetles survived to the end of the experiment on 31 March.

Table 3. Temperature data recorded at the Mount Carmel weather station during the 30-yr period from 1931 to 1960 (averages), and during 1983–84 and 1985–86 when overwintering studies on *H. axyridis* were conducted

Period	Month	Monthly mean minimum temp (°C)	Minimum temp (°C) recorded	Monthly heating degree days[b]
1931–60[a]	Nov.	−0.8	−17.2	393
	Dec.	−6.0	−27.8	599
	Jan.	−7.6	−27.2	654
	Feb.	−7.0	−31.1	564
	Mar.	−3.1	−23.9	501
				2,711
1983–84	Nov.	2.0	−2.8	334
	Dec.	−4.8	−19.4	612
	Jan.	−7.4	−23.9	667
	Feb.	−1.7	−18.3	446
	Mar.	−3.6	−16.7	540
				2,599
1985–86	Nov.	3.5	−3.3	363
	Dec.	−5.3	−14.4	604
	Jan.	−5.8	−17.8	598
	Feb.	−6.1	−13.3	572
	Mar.	−0.8	−13.9	423
				2,560

[a] Data from Brumbach (1965).

[b] Summation of daily values equal to 18.3°C base temperature less that day's mean temperature.

Plantation Experiment, 1985–86. Mortality of Japanese *H. axyridis* during the 1985–86 overwintering period was nearly complete despite the fact that temperatures were milder than normal, and milder even than in 1983–84 when 10% of the beetles survived (Table 3). None of the 270 adult beetles in cages in the pine plantation, and only 1 of the 270 beetles caged in the adjacent woodlot, survived to the end of the experiment (31 March). In all, a total of 448 living and dead beetles was recovered (83.0%); the remainder were probably either cannibalized or were overlooked when cages were examined at the end of the experiment. All cages remained intact throughout the experiment, making it impossible for beetles to escape.

Establishment of *H. axyridis*

Most of the adult beetles that were marked with paint and then released on scale-infested red pines dispersed from the plantation within the first few days after release, and all had left after 2 wk. Only 10 of the 500 beetles (2.0%) released during May, when *M. resinosae* was predominantly exposed stages, were seen on pines during the 50-min observation period 3 d later. Only two marked adults were observed after 7 d and only one was counted after 12 d. However, prior to their departure, some adults laid eggs on the pines, thereby establishing a resident population of *H. axyridis*. These offspring from marked adults fed upon the scales and matured within a month. All of these new adults dispersed from the plantation within 1 wk after eclosion and no eggs were seen on pines following their departure.

Of the 405 adults that were marked and released in July, a period during which most scales were concealed first instars, only seven beetles (1.7%) were observed on the pines 3 d after release, and only four adults were observed 7 d after release. No marked adults were observed after 7 d and there was no evidence that adult beetles had laid eggs on these pines before their departure.

None of the 905 marked adults were observed in any other areas of Lockwood Farm, and none were trapped on the many yellow sticky traps (which are attractive to coccinellids) that were present from May through October (for other experimental purposes) in the fields, forests, and orchards surrounding the pine plantation. The fate of the released adult beetles after departing the plantation was undetermined. However, marked beetles held in the laboratory showed no apparent ill effects from the marking procedure and survived for several months.

Discussion

Results of the cage experiments in Connecticut are similar to those obtained in Japan (McClure 1986), and revealed that *H. axyridis* can have a significant impact on the abundance of *M. resinosae*, especially when scales are conspicuous eggs, cysts, and adults. However, *H. axyridis* is a much less effective predator during those times of the year when scales are predominantly first instars concealed in cracks and crevices of the bark. The beetle is better able to exploit the small first instars in Japan than in the United States, because the relatively untextured bark of Japanese pines does not afford as much protection for nymphs as does the textured bark of *P. resinosa* (McClure 1985, 1986). The limited ability of *H. axyridis* to locate and exploit concealed scales on *P. resinosa* may reduce its value as a biological control agent for *M. resinosae* and may account for the transience of released adult beetles and the lack of reproduction in the plantation when most scales were concealed first instars.

Cannibalism was prevalent among caged beetle larvae in Connecticut, as it was among the caged and uncaged free-living natural populations of *H. axyridis* in Japan (McClure 1986). Because scale density on each caged branch was similar (range in number of scales per 50 bark flakes was 911–961 for concealed and 113–122 for exposed scales), the number of beetle larvae that were cannibalized was not a function of number of prey available per larva, but rather reflected the amount of branch space that was available per beetle. This supports data from laboratory rearing and from the study in Japan (McClure 1986), and indicates that the frequency of encounter between beetle larvae is a greater determinant of cannibalism than is the availability of prey. The cannibalistic nature of *H. axyridis* not only increases the difficulty of rearing large numbers of this beetle collectively, but also seemingly undermines its effectiveness as a control agent for *M. resinosae*. However, this behavior does ensure the survival and reproduction of at least some beetles when prey are scarce or inaccessible.

Results of the two overwintering experiments suggest that the ability of *H. axyridis* to survive winter conditions in the northeastern United States is also limited. However, the survival of at least some beetles during both overwintering periods is somewhat encouraging, considering that experimental cages provided only minimal protection from weather relative to natural overwintering sites. In Asia, *H. axyridis* successfully overwinters at even more northern latitudes than Connecticut, in areas with cliffs, caves, and rock outcroppings (Cheng & Ming 1979; P. W. Schaefer, personal communication). Because such overwintering habitats are also available in Connecticut and throughout the northeastern United States, free-living *H. axyridis* would probably overwinter much more successfully than did the experimental caged populations. Overwintering success of *H. axyridis* probably also would have been improved had the experiments been conducted using beetle colonies obtained from more northern latitudes such as China (ca. 45°N) or the U.S.S.R. (ca. 43°N) (Table 1).

Despite its cannibalistic nature and its limited ability to exploit inconspicuous stages of *M. resinosae*, *H. axyridis* can have a significant impact on scale numbers and can successfully overwinter when provided with only minimal protection from weather. These are two important attributes of an introduced natural enemy. However, the success of *H. axyridis* as a persistent biological control agent for the red pine scale will ultimately depend upon its ability to locate adequate overwintering sites and to find and exploit alternate prey, such as aphids, to sustain it when *M. resinosae* is inaccessible or unavailable. The importance of *H. axyridis* in the natural regulation of endemic scale populations in Japan (McClure 1986) certainly justifies our continued efforts to establish this beetle in North America.

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