Prospects for a Classical Biological Control Project Against Purple Loosestrife (*Lythrum salicaria* L.)[1]

Stephen D. Hight

John J. Drea, Jr.

Insect Biocontrol Laboratory, PSI
Agricultural Research Service, USDA
10300 Baltimore Avenue
BARC-East, Building 406
Beltsville, Maryland 20705-2350

ABSTRACT: Purple loosestrife, *Lythrum salicaria*, was introduced into North America from Europe at the beginning of the nineteenth century. The plant has progressively spread westward and now occurs throughout the northern half of the United States and southern Canada. It aggressively invades wetlands and displaces native vegetation. The high cost and transitory nature of various chemical and cultural control methods have led to the development of a classical biological control program against purple loosestrife. Research has shown that three phytophagous European insects—a weevil, *Hylobius transversovittatus*, and two leaf beetles, *Galerucella calmariensis* and *G. pusilla*—are very host-specific and highly damaging to the plant. These insects are being considered for release into North America in an attempt to control *L. salicaria*. If these insects are as effective as research indicates, the outlook for successful classical biological control against purple loosestrife is excellent.

CLASSICAL BIOLOGICAL CONTROL

An exotic plant species that invades a new region usually does so without the guild of phytophagous insects, mites, and pathogens that help suppress populations of the plant in its area of origin. In many cases a natural enemy carefully selected from this guild and introduced into the area invaded by the plant will reduce the plant to nonpest status. This concept is referred to as "classical biological control." The term classical differentiates this more traditional use of exotic organisms for pest control from other biological control approaches that utilize, for example, augmentation and mass releases of natural enemies. Still other approaches are based on insect byproducts such as pheromones and kairomones.

A successful classical biological control project reduces the population density of a pest to an environmentally or economically acceptable level through the action of one or more natural enemies. This is accomplished without totally eliminating the target plant. There will be oscillations in the populations of the pest and its control agents over time in response to environmental conditions, activities of people, and the normal interactions of the host plant and its associated organisms. In an ideal situation, peaks of these fluctuations remain below the damaging population level and the plant remains innocuous. Residual populations of the plant act as reservoirs of the natural enemies.

An essential activity of a classical project is the research required to reunite one or more of the most effective natural enemies with their host in the invaded area (Rosenthal et al. 1984). The phytophagous agent must be introduced without its own parasites and diseases, which would decrease or nullify the impact of the natural enemy on the target plant. A successful natural enemy has several basic attributes: the agent must substantially damage the host; the damage must be done during a vulnerable phase of the host's life cycle; attack should interrupt the reproductive ability of the plant population; and a natural enemy should be introduced into a niche that is free of other phytophages, otherwise the introduced agent will be in direct competition with other organisms and will be susceptible to their parasites and diseases (Harris 1984).

Before an organism can be introduced into North America for release against a target plant, the agent must be subjected to a rigorous host specificity screening program. This screening process ensures that the agent is acceptably host-specific and will not itself become a pest when introduced (Drea 1991). Usually the first organisms selected for study are those that are monophagous or restrictively oligophagous. This selection may be based on an examination of the literature, information from museum collections, direct observations, or preliminary laboratory and field studies. An agent will be proposed for introduction only if it develops exclusively on the target weed, or within acceptable limits on a few

[1] Paper presented at a session on exotic species control at the Sixteenth Annual Natural Areas Conference, October 17-20, 1989, Knoxville, Tennessee.

closely related species.

The use of insects and other types of natural enemies to control exotic unwanted plants has been successfully applied throughout the world since 1863 (Rosenthal et al. 1984). As of 1980, 192 organisms had been established on 82 introduced weed species throughout the world (Julien 1982). Only an isolated few of these subsequently have attacked other nontarget plants. For example, Andres (1985) reports that three insects introduced against *Hypericum perforatum* (Klamath weed), an exotic plant of European origin, develop to varying degrees on other species of *Hypericum* in California. But in no instance has an insect introduced against an exotic weed in North America become a pest itself or endangered a native plant species (Harris 1988).

Biological control of weeds was first used successfully in North America in the 1940s against Klamath weed (Huffaker and Kennett 1959). Other plants of economic importance that have been the target of classical biological control in the United States are alligatorweed [*Alternanthera philoxeroides* (Mart.) Griseb.] (Coulson 1977), leafy spurge (*Euphorbia esula* L.) (Pemberton and Johnson 1985), musk thistle (*Carduus thoermeri* Weinm.) (Kok and Pienkowski 1985), and tansy ragwort (*Senecio jacobaea* L.) (Pemberton and Turner 1990). In all of these cases the target of control was an introduced plant that had dramatically increased its population in its new habitat. The plant clogged waterways, poisoned livestock, or was otherwise detrimental to agricultural areas.

There is great potential for the use of classical biological control against *Lythrum salicaria* L. (purple loosestrife) in North America. The plant has many of the attributes of other plants that have been controlled by biotic agents. It is (1) a perennial plant, (2) an introduced species, (3) host to a series of effective biotic agents in its area of origin, (4) restricted to a specific and relatively stable habitat, (5) found in more or less continuous populations, (6) is relatively isolated taxonomically from economically valuable plants, and (7) a plant that offers feeding niches that are unfilled in North America by natural enemies.

THE TARGET PLANT

Lythrum salicaria is an erect, emergent, aquatic to semiaquatic plant occurring in wetlands, coastal areas, ditches, and along stream banks. This perennial herbaceous plant grows to an average height of 1.5–2 m. It is readily identified during the summer months by the reddish-purple flowers that cover the terminal spikelike panicles from late-June to early-September. Dense flowering stands are readily visible from a distance. Three forms of the species are distinguished based on the length of the style (Levin and Kerster 1973, Teale 1982). The flowers are self-incompatible and insect-pollinated (Mulcahy and Caporello 1970). Minute seeds are produced in capsules, and a mature plant (average of 30 stems) may produce as many as 2.5 million seeds annually (Thompson et al. 1987). Stems die in late autumn but may remain standing throughout the winter. New stems emerge from the perennial roots, and the plant can establish dense stands within a few years. Reproduction occurs by sexual means; *L. salicaria* does not produce rhizomes (Thompson et al. 1987).

The plant is native to Eurasia (Hultén 1971). Its European distribution extends from Great Britain to central Russia and from Italy northward to the 65th parallel. The Asian distribution is centered on the main islands of Japan, with populations extending into the lowlands of Manchuria and China to southeast Asia and northern India. The plant has invaded northern and eastern Africa, Australia, Tasmania, and North America (Thompson et al. 1987).

L. salicaria appeared in North America prior to 1830, probably arriving as a contaminant in ship ballast (Stuckey 1980). By the 1830s, the plant was well-established along the New England seaboard. The construction and heavy use of canals and waterways for commerce during the 1880s favored the spread of the plant westward throughout New York and the St. Lawrence Valley (Thompson et al. 1987). Today it occurs in dense stands throughout the northeastern United States and southeastern Canada, and in scattered locations in the Midwest, the Pacific Northwest, California, and south-central Canada (Figure 1) (Thompson et al. 1987). The development of new irrigation systems in many of the western states has favored the establishment and spread of *L. salicaria* in these areas.

Because *L. salicaria* replaces native species in wetland plant communities, it is considered a highly competitive and unwanted species (Stuckey 1980). In some states the plant has been officially declared a "noxious weed," indicating that control is mandated by law where the plant is found. The plant is a serious problem for private, state, and federal range, wildlife, and natural area managers. Purple loosestrife develops rapidly in new areas and quickly expands its range by infesting all suitable terrain; this is accompanied by the loss of native flora (Malecki 1987). Disappearance of native plants leads to the elimination of the essential natural food and cover of many wetland inhabitants, including waterfowl (McKeon 1959, Smith 1964, Friesen 1966, Pfannmueller and Djupstrom 1983). The formation of monotypic stands of *L. salicaria* has jeopardized various already threatened and endangered native wetland plants and wildlife, such as an endemic bulrush (*Scirpus longii* Fern.) in Massachusetts (Coddington and Field 1978), dwarf spike rush [*Eleocharis parvula* (R. & S.) Link] in New York (Rawinski 1982), and the bog turtle (*Clemmys muhlenbergii* Schoepff) in the northeastern United States (Thompson et al. 1987).

The impact of *L. salicaria* on agriculture is seen in the degradation of wetland pastures and wild hay meadows. The weed is much less palatable to livestock than the displaced grasses and sedges (Thompson et al. 1987). Sites with heavy infestations are less productive and are difficult to mow and manage. The plant can be devastating to irrigation systems. Based on a cost-benefit analysis of infestations of *L. salicaria* in 19 states, Thompson et al. (1987) reported an estimated loss of nearly $46 million annually due to the devaluation of freshwater real estate, the reduction for hunters of populations of muskrats and migratory waterfowl, and the destruction of "natural" habitats for recreational enjoyment.

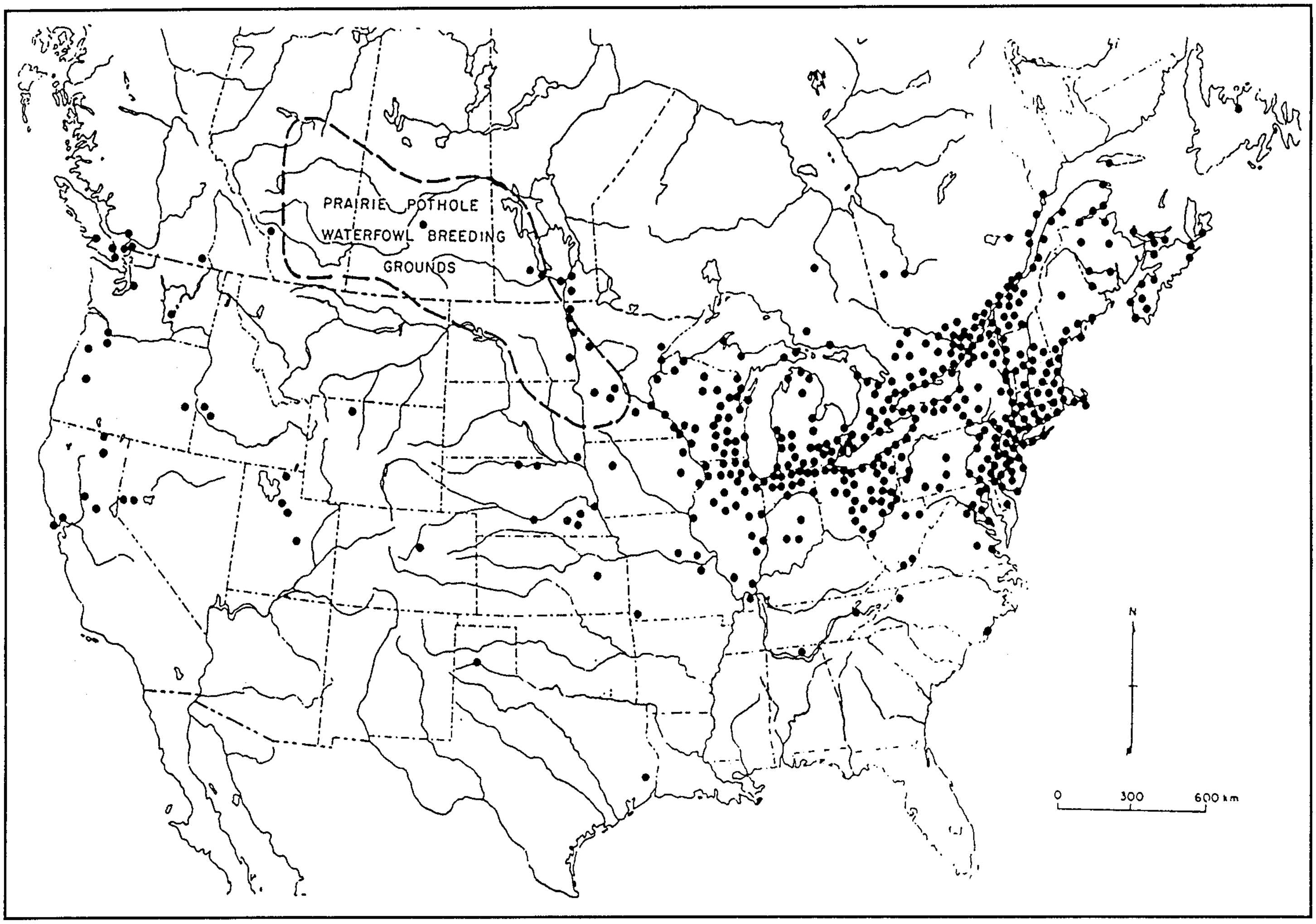

Figure 1. Distribution of *Lythrum salicaria* in North America as of 1985 (after Thompson et al. 1987).

Small localized stands of *L. salicaria* can be controlled by hand uprooting of plants and removal of all vegetative parts (Rude 1988). Other methods include water level manipulation, mowing or cutting, burning, and herbicide application (McKeon 1959, Smith 1964, Malecki and Rawinski 1985). These techniques can eliminate small and young stands, but they are costly, temporary, and require periodic application. A control method was needed that would be permanent, effective, relatively inexpensive, environmentally safe, widespread, and that would require minimal human effort. Because *L. salicaria* is an introduced pest, the possibility of using classical biological control was investigated.

RESEARCH PROGRAM

Before introducing exotic natural enemies, it was important to determine the composition of the existing fauna associated with the plant in North America and in Europe. Did empty niches occur on the plant in the invaded area? What organisms associated with the plant in Europe already occurred in North America?

Surveys

Stands of *L. salicaria* were surveyed in the northeastern United States to determine the fauna associated with the plant in North America (Hight 1990). Fifty-nine species of phytophagous insects were collected. Their identification indicated that they had moved onto *L. salicaria* from other plants in the environment. There were 50 species on the foliage, 3 on the stems, and 6 feeding on the reproductive parts. No species were recovered in or on the roots. None of the insects reduced populations of *L. salicaria* or caused appreciable damage to plants. Most of these species appeared to be incidental feeders on the plant and would not be severely competitive with a biotic agent introduced into the same niche.

We found no reports in the American or European literature of important pathogens being recovered from purple loosestrife (Schroeder and Mendl 1984). The few species of fungi reported as incidental and minor pathogens of *L. salicaria* were from other species of plants including native North American *Lythrum* spp. and *Oenothera* spp. (Farr et al. 1989). Field surveys conducted in Europe did not uncover any pathogens attacking *L. salicaria* (Blossey and Schroeder 1986).

Surveys for natural enemies in Europe uncovered 15 oligophagous insect species closely associated with *L. salicaria* throughout its range in Europe (Schroeder and Mendl 1984, Batra et al. 1986). Of these, three were selected for testing and screening as potential control agents. The most promising insect was a root-infesting weevil, ***Hylobius transversovittatus*** (Goeze). Two species of leaf-feeding beetles, *Galerucella calmariensis* (L.) and *G. pusilla* (Duftschmidt), also were selected because they could defoliate plants and destroy the flowers. Studies of the insects' life history, population dynamics, impact on *L. salicaria*, and host specificity conducted at the CAB-International Institute of Biological Control (CIBC), were completed in February 1991 (Blossey and Schroeder 1988, 1989, 1991). Quarantine screening and testing studies at the Virginia Polytechnic Institute and State University (VPI&SU) to obtain biological data essential to request authorization for the release of these insects into North America were completed in November 1990 (Kok and McAvoy 1989, 1990). The following information was derived from these reports prepared at the two institutes.

Natural Enemies

Hylobius transversovittatus

Adults of this weevil emerged from overwintering sites in mid-April. Oviposition began in April, peaked in July and August, and ended in September. Eggs were deposited singly or in groups in stems at ground level, or on or near the roots just under the soil surface. A female may lay one to three eggs per day during peak period. Many adults hibernated for a second winter and began activities, including oviposition, the following spring.

Eggs hatched in about two weeks. The first instar larvae fed on the root surface. Second instar larvae mined into the root and consumed the vascular tissue. Mature larvae prepared pupal chambers in the upper parts of the root. Pupation itself lasted three to four weeks. The adults that emerged, usually in July and August, were often sexually inactive before hibernating in the autumn. Normally, a female required two years from the egg stage to develop to an actively ovipositing adult. Males apparently required the same amount of time for development. The beetles were well adapted to flooding. All stages survived total immersion in water for several days. Larvae survived and developed normally after seven months of submersion within plants.

Weevil larvae and adults seriously damaged the root system of *L. salicaria*. Plants may be killed by the attack, or stunted and produce fewer stems and consequently fewer seeds. Field studies showed that nearly 100% of the roots may be infested. Smaller roots produced smaller weevils.

Galerucella calmariensis and G. pusilla

The two species of *Galerucella* were found throughout the range of *L. salicaria* in Europe. In the north, *G. calmariensis* was the dominant species; *G. pusilla* was more abundant in the south. Both insects often occurred in the same field. The two species had very similar life histories. Overwintered adults appeared on young *L. salicaria* in early May and their feeding produced holes in the new leaves. Copulation began within a few days and oviposition commenced shortly thereafter. During the period from mid-May to mid-July, a female may produce up to 500 eggs. Most eggs were laid in small clusters, primarily on the lower stem, shoot axils, or lower side of the leaves.

Larvae hatched in about a week and fed on developing buds of stems, leaves, and flowers. The late instar larvae that fed on the leaf surfaces removed the chlorophyll-containing tissues and formed the "window" type of damage so characteristic of many chrysomelid beetles. Because of the extended oviposition period, larvae were present on the plant throughout the summer. Three weeks after hatching, the mature larvae moved into the soil and pupated a few centimeters below the surface. In flooded areas, the larvae formed pupal cells in the thick aerenchyma tissue of the plant stems. Adults emerged in approximately three weeks. Both of the species had only one generation per year. The adults entered hibernation in late September to mid-October.

Feeding by the leaf beetles had an important and substantial impact on the growth and survival of *L. salicaria*. At high densities of attack (200 larvae/plant) plants were entirely stripped of all green tissue, leaving only whitish skeletons and thereby preventing seed production. Larvae readily left defoliated plants and sought unattacked plants. At lower populations of the beetles, adult and early larval feeding prevented normal growth of *L. salicaria* by destroying meristematic regions. The continued larval feeding throughout the period of maximum plant growth delayed, and often prevented, the production of flower spikes. Both species of *Galerucella* had a negative impact on *L. salicaria*. In outbreak densities the beetles killed seedlings, completely defoliated mature plants, and destroyed or prevented the formation of flower spikes.

Host Specificity Studies

In 1987, the Agricultural Research Service (ARS) and the U.S. Fish and Wildlife Service (FWS) agreed to support the research required to determine the host specificity of the insects selected. A list of 50 different plant species was prepared. The plants fell into four categories: (1) species in the family Lythraceae (18 species); (2) species in families closely related to Lythraceae, based on the phylogenetic system of Cronquist (1981) (11 species); (3) wetland species most commonly associated with purple loosestrife habitat, especially those important to wildlife (14 species); and (4) important agricultural crops (7 species). This list was reviewed and approved by Plant Protection and Quarantine (PPQ), a division of the Animal and Plant Health Inspection Service (APHIS), through their Technical Advisory Group for the Introduction of Biological Control Agents for Weeds (TAG).

The majority of the host specificity tests were conducted by CIBC in 1988–1990 (Blossey and Schroeder 1989, 1991). Supplemental screening with plants not available to CIBC were conducted in the VPI&SU quarantine laboratory in 1989 and 1990 (Kok and McAvoy 1990). The screening tests confirmed that *H. transversovittatus*, *G. calmariensis*, and *G. pusilla* are highly host-specific for purple loosestrife. The scientists at the VPI&SU

and CIBC laboratories have recommended that these insects be considered for release into the United States. A report derived from this data has been submitted to TAG for consideration and subsequent recommendation of the release of the insects into North America.

Release Sites

Normally, introduced natural enemies are not haphazardly released in the field without consideration to the environmental conditions of the release sites. This is especially true for organisms that have been subjected to long and expensive research. A list of criteria constituting "acceptability for study sites" was developed; it describes the minimum conditions a site must meet to be selected for the initial release of the exotic insects for the purple loosestrife project.

A release site should

- Be in the climatic regions of the northern United States or southern Canada. This is to avoid the more southern limits of the plant's range in North America, where the introduced insects might not be able to survive.
- Be in a marsh or wetland that does not normally have standing water from May through September. This is to facilitate the development of the insects.
- Have a dense, well-established stand of *L. salicaria* more than 2 ha in extent.
- Have neighboring stands of the plant within a kilometer to reduce isolation and permit the spread of an insect out of the release site after establishment.
- Not be subject to chemical applications or cultural control methods (e.g., burning, mowing, water level manipulation, etc.).
- Be free from major environmental changes (flooding, grazing, commercial development, camping).
- Be relatively isolated from human activities but reasonably accessible.
- Be available to the project for a seven- to ten-year period.

The list was sent to approximately 50 potential cooperators in 1988. From the responses, 30 sites were selected and visited during 1988. Of these, 12 met all the criteria and were chosen for study and use as eventual release sites for any of the approved natural enemies.

During the growing seasons of 1989 and 1990, basic information was gathered at the 12 selected sites. The density of the populations of *L. salicaria* was estimated using three methods: (1) percent cover (of *L. salicaria* and associated vegetation) along randomly established transects, (2) density counts of the number of *L. salicaria* individuals within randomly distributed quadrats, and (3) number of stems per *L. salicaria* plant within each quadrat. Abiotic data collected were soil pH, soil type, topography, and site orientation. The study sites will be monitored periodically before, during, and after the release of any of the approved natural enemies. Examination will be more frequent at more accessible sites.

FUTURE PLANS AND OUTLOOK

As of February 1991, the host specificity tests were essentially completed and the test results appeared to be acceptable. A request for field release of the insects has been submitted to APHIS-PPQ. The first releases are expected to occur during 1991. Field-collected insects of foreign origin will be reared in quarantine to ensure the absence of all parasites and diseases. The natural enemies will be released, probably as adults, at the 12 study sites as soon as a sufficient number of individuals become available.

To determine the impact of the three species on *L. salicaria* infestations, present plans are to release each species alone at some sites, and in combination with one or two of the other species at other sites. Fifty or more beetles per release per site is the minimum number being considered at this time. The availability of insects for release will be the deciding factor. The weevil will be the hardest to obtain in large numbers because it has a longer life cycle and fewer individuals per host plant.

The sites will be monitored annually for (1) the establishment of the insects, (2) changes in the purple loosestrife populations and other vegetation (as discussed earlier), and (3) relative impact of the various combinations of species released on the plant population.

Questions that this biological control project is expected to address include (1) Can successful biological control be achieved through a single release (lottery model) or are multiple releases (cumulative stress model) necessary (Meyers 1985)? (2) What constitutes a "successful" biological control agent (i.e., what type of organism should be considered for establishment in future projects)? (3) How do insects allocate resources on a "new" host? (4) What changes occur in habitat partitioning of insects released into a new environment?

SUMMARY

Biological control of weeds is generally perceived as more environmentally safe than the use of herbicides (Pimentel et al. 1984). Phytophagous insects are not poisonous to humans or other animals; they do not contaminate groundwater supplies or accumulate in the soil; and, unlike most herbicides, insect agents are selected because of their specificity to a single plant. However the inability to recall a natural control agent once it has been successfully introduced raises the concern that the agent itself may become a pest. To reduce this risk, the introduction of plant-feeding biological control agents into the United States is regulated (Klingman and Coulson 1983, Drea 1991).

Regulation guidelines have been followed with respect to the purple loosestrife project. This included the following activities: (1) developing an approved list of plants for use in the host specificity testing, (2) conducting host specificity tests in Europe with the three potential control agents (the research included adult and larval no-choice and multiple preference feeding tests and oviposition tests), and (3) introduction of the three insects into a quarantine facility in the United States for completion of host specificity tests on plants that were not tested in Europe. The host specificity tests suggest that *H. transversovittatus*, *G. calmariensis*, and *G. pusilla* have excellent potential for successfully controlling *L. salicaria* in North America without jeopardizing other organisms in the environment.

ACKNOWLEDGMENTS

We wish to thank W. Lamp, University of Maryland, College Park, for helpful comments on an earlier draft of this manuscript. We thank R. Henderson, Wisconsin Department of Natural Resources; N. Rees, ARS, Bozeman, Montana; J. Schwegman, Illinois Department of Conservation; and C. Turner, Agricultural Research Service, Albany, California, for their critical reviews. Special appreciation is extended to R.A. Malecki, U.S. Fish and Wildlife Service, Ithaca, New York for his substantial participation in this biological control project, and to V. Nuzzo, Native Landscapes, Rockford, Illinois for her editorial comments on this manuscript.

LITERATURE CITED

Andres, L.A. 1985. Interaction of *Chrysolina quadrigemina* and *Hypericum* spp. in California. Pp. 235-239 *in* E.S. Delfosse, ed., Proceedings of the Sixth International Symposium on Biological Control of Weeds, August 19-25, 1984, Vancouver, Canada. Canadian Government Publishing Centre, Ottawa.

Batra, S.W.T., D. Schroeder, P.E. Boldt, and W. Mendl. 1986. Insects associated with purple loosestrife (*Lythrum salicaria* L.) in Europe. Proceedings of the Entomological Society of Washington 88:748-759.

Blossey, B. and D. Schroeder. 1986. Final report: a survey of arthropods and fungi associated with *Lythrum salicaria* in selected areas in northern Europe. European Station, Commonwealth-International Institute of Biological Control, Delemont, Switzerland. 38 p.

Blossey, B. and D. Schroeder. 1988. First annual report: study and screening of potential biological control agents of purple loosestrife (*Lythrum salicaria* L.). European Station, Commonwealth-International Institute of Biological Control, Delemont, Switzerland. 31 p.

Blossey, B. and D. Schroeder. 1989. Second annual report: study and screening of potential biological control agents of purple loosestrife (*Lythrum salicaria* L.). European Station, Commonwealth-International Institute of Biological Control, Delemont, Switzerland. 25 p.

Blossey, B. and D. Schroeder. 1991. Final report: study and screening of potential biological control agents of purple loosestrife (*Lythrum salicaria* L.). European Station, Commonwealth-International Institute of Biological Control, Delemont. 41 p.

Coddington, J. and K.G. Field. 1978. Rare and endangered vascular plant species in Massachusetts. Committee for Rare and Endangered Species of the New England Botanical Club, Cambridge, Mass. 62 p.

Coulson, J.R. 1977. Biological control of alligatorweed, 1959-1972, a review and evaluation. U.S. Department of Agriculture, Washington, D.C. 98 p.

Cronquist, A. 1981. An integrated system of classification of flowering plants. Columbia University Press, New York. 844 p.

Drea, J.J., Jr. 1991. The philosophy, procedures, and cost of developing a biological control of weeds project. Natural Areas Journal 11:143-147.

Farr, D.F., G.F. Bills, G.P. Chamuris, and A.Y. Rossman. 1989. Fungi on plants and plant products in the United States. APS Press, St. Paul, Minn. 1252 p.

Friesen, G. 1966. Aquatic weed control studies in Manitoba. North Central Weed Control Conference 21:42-43.

Harris, P. 1984. Current approaches to biological control of weeds. Pp. 95-103 *in* J.S. Kelleher and M.A. Hulme, eds., Biological control programmes against insects and weeds in Canada 1969-1980. Commonwealth Agricultural Bureau, Farnham Royal, Slough, England. 410 p.

Harris, P. 1988. Environmental impact of weed-control insects. BioScience 38:542-548.

Hight, S.D. 1990. Available feeding niches in populations of *Lythrum salicaria* L. (purple loosestrife) in the northeastern United States. Pp. 269-278 *in* E.S. Delfosse, ed., Proceedings of the Seventh International Symposium on Biological Control of Weeds, March 6-11, 1988, Rome, Italy. CSIRO Publications, E. Melbourne, Australia.

Huffaker, C.B. and C.E. Kennett. 1959. A ten-year study of vegetational changes associated with biological control of Klamath weed. Journal of Range Management 12:69-82.

Hultén, E. 1971. The circumpolar plants. II Dicotyledons. Svenska Vetenskapsakademiens Handlingar 13:1-463.

Julien, M.H. (ed.). 1982. Biological control of weeds. A world catalogue of agents and their target weeds. Commonwealth Agricultural Bureau International, Wallingford, Oxon, U.K. 108 p.

Klingman, D.L. and J.R. Coulson. 1983. Guidelines for introducing foreign organisms into the United States for the biological control of weeds. Bulletin of the Entomological Society of America 29:55-61.

Kok, L.T. and T.J. McAvoy. 1989. Progress report: quarantine screening of phytophagous insects for the biological control of *Lythrum salicaria*. Virginia Polytechnic Institute & State University, Blacksburg, Va. 22 p.

Kok, L.T. and T.J. McAvoy. 1990. Second progress report. Quarantine screening of phytophagous insects for the biological control of *Lythrum salicaria*. Virginia Polytechnic Institute & State University, Blacksburg, Va. 27 p.

Kok, L.T. and R.L. Pienkowski. 1985. Biological control of musk thistle by *Rhinocyllus conicus* (Coleoptera:Curculionidae) in Virginia from 1969 to 1980. Pp. 433-438 *in* E.S. Delfosse, ed., Proceedings of the Sixth International Symposium on Biological Control of Weeds, August 19-25, 1984, Vancouver, Canada. Canadian Government Publishing Centre, Ottawa.

Levin, D.A. and H.W. Kerster. 1973. Assortative pollination for stature in *Lythrum salicaria*. Evolution 27:144-152.

Malecki, R.A. 1987. Purple loosestrife (*Lythrum salicaria*). Pp. 39-45 *in* D.J. Decker, ed., Exotic plants with identified detrimental impacts on wildlife habitats in New York State. Natural Resources Research and Extention Series 29, Ithaca, N.Y. 56 p.

Malecki, R.A. and T.J. Rawinski. 1985. New methods for controlling purple loosestrife. New York Fish and Game Journal 32:9-19.

McKeon, W.H. 1959. A preliminary report on the use of chemical herbicides to control purple loosestrife (*Lythrum salicaria*) on a small marsh. Proceedings of the Northeastern Weed Control Conference 13:329-332.

Mulcahy, D.L. and D. Caporello. 1970. Pollen flow within a tristylous species: *Lythrum salicaria*. American Journal of Botany 57:1027-1030.

Myers, J.H. 1985. How many insect species are necessary for successful biocontrol of weeds? Pp. 77-82 *in* E.S. Delfosse, ed., Proceedings of the Sixth International Symposium on Biological Control of Weeds, August 19-25, 1984, Vancouver, Canada. Canadian Government Publishing Centre, Ottawa.

Pfannmueller, L. and B. Djupstrom. 1983. Purple loosestrife: aggressive invader of meadow and wetland. The Minnesota Volunteer 46:36-39.

Pemberton, R.W. and G. Johnson. 1985. Two new insects (*Dasineura capitigena* and *Aphthona flava*) for leafy spurge control in the United States. Pp. 29-32 *in* Proceeding of the 1985 Leafy Spurge Symposium, July 17-18, 1985, Bozeman, Montana. University of Montana.

Pemberton, R.W. and C.E. Turner. 1990. Biological control of *Senecio jacobaea* L. in northern California, an enduring success. Entomophaga 35:71-77.

Pimentel, D., C. Glenister, S. Fast, and D. Gallahan. 1984. Environmental risks of biological pest controls. Oikos 42:283-290.

Rawinski, T.J. 1982. The ecology and management of purple loosestrife (*Lythrum salicaria* L.) in central New York. M.S. thesis, Cornell University, Ithaca, N.Y. 88 p.

Rosenthal, S.S., D.M. Maddox, and K. Brunetti. 1984. Biological methods of weed control. California Weed Conference, Monograph #1. Thomson Publications, Fresno, Calif. 88 p.

Rude, K. 1988. Beware of the purple plague (it's spreading!). Ducks Unlimited 52:30-32.

Schroeder, D. and W. Mendl. 1984. Report: a survey of phytophagous insects and pathogens associated with purple loosestrife, *Lythrum salicaria*, in Europe. European Station, Commonwealth-International Institute of Biological Control, Delemont, Switzerland. 32 p.

Smith, R.H. 1964. Experimental control of purple loosestrife (*Lythrum salicaria*). New York Fish and Game Journal 11:35-46.

Stuckey, R.L. 1980. Distributional history of *Lythrum salicaria* (purple loosestrife) in North America. Bartonia 47:3-20.

Teale, E.W. 1982. Stems beyond counting, flowers unknown. Audubon 84:38-43.

Thompson, D.Q., R.L. Stuckey, and E.B. Thompson. 1987. Spread, impact, and control of purple loosestrife (*Lythrum salicaria*) in North American Wetlands. Fish and Wildlife Research No. 2. U.S. Department of Interior, Washington, D.C. 55 p.