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Integrated pest management techniques in thistle suppression in pastures of North America

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Summary: Résumé: Zusammenfassung

Thistles in the genera *Carduus, Cirsium, Onopordum*, and *Silybum* of the subtribe Carduinae have been the subjects of considerable research designed for chemical, biological, cultural, and integrated control in the United States. Problems and costs associated with chemical and cultural control techniques stimulated the introduction of biological control agents from many locations in Europe and the Middle East. Although some natural enemies have successfully suppressed thistle infestations, economic losses during the time lags between introduction and effective suppression prompted investigations into integrated control procedures. The rationale, history, and potential direction for thistle suppression has been documented in this manuscript.

Techniques de lutte integree contre le chardon dans les paturages d'Amerique du Nord

Les chardons du genre *Carduus, Cirsium, Onopordum* et *Silybum* de la sous-tribu *Carduinae* ont été l'objet aux Etats-Unis de recherches importantes concernant la lutte chimique, biologique, culturale et intégrée. Les problèmes et les coûts relatifs aux techniques de lutte chimique et culturale ont entraîné l'introduction d'agents de lutte biologique dans de nombreuses localités d'Europe et du Moyen Orient. Malgré le succès obtenu dans la lutte à l'aide d'ennemis naturels du chardon, les pertes économiques dues au décalage entre l'introduction du parasite et son action ont rapidement entraîné l'étude de procédés de lutte intégrée. Les diverses méthodes sont décrites dans ce document tant du point de vue chronologique que du point de vue technique.

Integrierte Verfahren zur Unterdrückung von Disteln auf Weideflächen in Nordamerika

Disteln der Gattungen *Carduus, Cirsium, Onopordum* und *Silybum* des Subtribus Carduinae, waren in den USA hinsichtlich ihrer Bekämpfung mit chemischen, biologischen, Kultur- und integrierten Verfahren, Gegenstand beträchtlicher Forschungsaktivitäten. Die mit der chemischen Bekämpfung und den Kulturmaßnahmen verbundenen Kosten und Schwierigkeiten, stimulierte die Einführung von Organismen aus vielen Teilen Europas und des Mittleren Ostens für die biologische Bekämpfung. Wenngleich durch einige natürliche Feinde die Distelverseuchung erfolgreich unterdrückt wurde, zwangen die wirtschafl tichen Schäden, die in der Zeit zwischen der Einführung und dem Wirksamwerden zu verzeichnen waren, zu Untersuchungen auf dem Gebiet der integrierten Bekämpfung. Die vorliegende Arbeit befasst sich mit den Ursprüngen, der Geschichte und den möglichen Entwicklungen in der Unterdrückung der Disteln.

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Introduction

Development of an integrated pest management (IPM) program for controlling thistles in pastureland requires information on the crop system, the life cycles of the weeds and potential biological control agents, and the various control techniques intended for inclusion in the program. This basic information includes:

I. The crop system
  A. *Justification of thistle suppression*
  B. *The major thistle species*
II. Available control techniques
  A. *Cultural and mechanical methods*
  B. *Chemical pesticides*
  C. *Biological control by natural enemies*
III. Compatibility of control techniques

Fortunately, much of this information is currently available (Table 1). However, broad gaps in knowledge in several crucial areas have hampered the creation of an IPM package for thistle control which includes all available suppression techniques. Additional research necessary to fill these gaps will be suggested in the following sections as applicable.

The crop system

Justification of thistle suppression

Weeds in pastures compete with desirable plants for space, nutrients, moisture and light. Weedy thistles in the genus *Carduus* have been recognized as serious threats to pasture productivity since the late 1940s and early 1950s [70, 71]* when intensive control efforts began in the United States. By the mid-1970s, approximately one out of every 10 counties in the United States reported potentially economic infestations [19]. The midwest and the Appalachian regions suffered the most serious invasion; in excess of 65,000 infested ha have been reported from Virginia and Nebraska alone [19, 48, 70]. In response to the rapid spread of these weeds, several states including Kansas, Nebraska and Virginia enacted noxius-weed-and-seed laws requiring thistle control and restricting transport of seeds [2, 13, 19]. These laws provided state workers with access to private land for the purpose of thistle control, and contained provisions for charging control costs to landowners.

In spite of increased regulation and the development of new suppression techniques, *Carduus* species populations continue to expand, due in part to their prolific seed production. Several authors reported 'average plants' produced 10,000 seeds each, with some individual thistles releasing up to 120,000 achenes [46, 66, 69, 72]. The fine filaments of the pappus permit rapid windborne dispersal of these seeds over long distances. Reinfestation of pastureland frequently occurs from roadsides or waste areas where repeated control efforts are not practical or economically feasible, or from germination of the long-lived seeds deposited in the pasture during previous years.

Once established, thistles reduce pasture productivity in several ways. Through competition for space, nutrients, moisture, and light, a single *Carduus* spp. thistle/1·49 m^2 has been reported to reduce pasture yields an average of 23% [48]. Yield losses from *Cirsium arvense* (L.) Scop. (Canada thistle) at a density of only two shoots per 0·91 m^2 have ranged as high as 15% [42]. Additionally, thistles have the undesirable effect of limiting the use of infested areas by livestock or for recreational purposes because of the physical hazard presented by the prominent spines on the leaves, stalks, and blooms [8, 41].

The major thistle species

Carduus, *Cirsium*, *Silybum*, and *Onopordum* are the primary genera of thistles in the subtribe Carduinae in the family Compositae occurring in the United States. Although there are many representatives of these genera in North America, only *Carduus pycnocephalus* L. [32, 34], *C. nutans* (L.) or *C. thoermeri* Weinmann [59, 91, 101, 105], *C. acanthoides* L. [62, 108], *C. macrocephalus* Desfontaines [43], *Cirsium arvense* (L.] [92, 94] *Cirsium vulgare* (Savi) Tenore [94], and *Silybum marianum* (L.) [35, 119] have been the targets of extensive control programmes.

Currently, the genus *Carduus* contains the most destructive thistle species in the United States. Unfortunately, the species distinctions in this group are not clear. In 1950, three species were recognized: *C. nutans* L., *C. acanthoides* L., and *C. crispus* L. [27]. Confusion developed in 1954 when *C. nutans* was split into three subspecies, and then two of these subspecies, *C. nutans* ssp. *leiophyllus* (Petrovic) Arenes and *C. nutans* ssp. *macrocephalus* (Desfontaines) Fiori, were elevated to species status as *C. thoermeri* and *C. macrocephalus* Desfontaines respectively [51, 82]. Both of these species exhibit the constricted involucral bracts that Linnaeus used to define the

* References throughout this paper are cited by number instead of by the author's name and date. This is necessary because of the large number of citations involved.

Table 1 A categorized bibliography of selected references related to thistle biology and suppression

Category	Manuscript No. in 'References Cited'*
Thistle biology and systematics	8, 11, 18, 19, 27, 28, 42, 51, 66, 69, 70, 72, 73, 74, 75, 80, 81, 82, 104, 119
Cultural control techniques	9, 26, 42, 46, 52, 53, 71, 76, 77, 78, 79
Chemical control techniques	3, 15, 26, 29, 41, 42, 46, 47, 48, 49, 52, 53, 67, 71, 104
Biological control	
Biology of natural enemies	7, 11, 14, 20, 21, 23, 24, 25, 30, 38, 50, 55, 57, 58, 61, 62, 65, 83, 85, 86, 89, 93, 94, 95, 96, 97, 100, 101, 102, 105, 107, 108, 114, 115, 116, 117, 118, 120, 122, 123, 124, 126, 127, 128, 129
Systematics	4, 6, 16, 44, 45, 112
Foreign exploration	1, 5, 10, 12, 30, 32, 33, 96, 121, 125
Release, establishment and evaluation	7, 14, 34, 35, 36, 37, 39, 40, 43, 54, 56, 59, 60, 63, 64, 68, 83, 85, 87, 88, 91. 92, 96, 97, 98, 99, 100, 104, 108, 113
Integrated control procedures	79, 106, 109, 110, 111

* Some references may appear in more than one category if applicable; only references dealing specifically with thistles or weed control were included in this bibliography.

original *C. nutans*, but vary in the shape of the bracts, pubescence of leaves, colour and form [12, 72]. *C. nutans* ssp. *nutans* remained a viable species. Recent research suggests that seven *Carduus* species are present in the United States, and most of the thistles in the United States presently designated as *C. nutans* are actually *C. thoermeri* under the new classification [70].

Classification of *Carduus* species in the United States by flower characteristics

I. Large-flowered group
  A. *Carduus nutans* L.
  B. *Carduus macrocephalus* Desfontaines
  C. *Carduus thoermeri* Weinmann
II. Small-flowered group
  A. *Carduus acanthoides* L.
  B. *Carduus crispus* L.
III. Slender-flowered or Italian group
  A. *Carduus pycnocephalus* L.
  B. *Carduus tenuiflorus* Curt.

Additional complications in the classification of these weeds have arisen from the hybridization of *C. nutans* ssp. *nutans* and *C. acanthoides*. Analysis of chromosome numbers for *C. nutans* ($2n=16$) and *C. acanthoides* ($2n=22$) established that the species are clearly distinct [80]. However, hybrids of these two species produced offspring containing chromosome complements relating to all the intervening values ($2n=17$–21). A common hybrid was reported from Europe as early as 1881 [28], and additional studies on a hybrid designated as *C. orthocephalus* in North America were published in 1964 [81]. An index based on chromosome number was developed to differentiate among the hybrids [80], but lack of use by other authors indicates the index has not been generally accepted. Preparation of keys separating these hybrids and other economically important thistle species should be given a high priority for future research. Since thistle control with chemicals and effectiveness of biological control varies with thistle species, development of a viable IPM programme for thistles is dependent on accurate separation and identification of the species.

The life cycles for most thistle species in the genus *Carduus* are variable. Depending on location, these species develop as biennials [27, 66], annuals [13, 74], or winter annuals [73]. Variation in growth rates and germination attributable to regional environmental conditions is probably responsible for the diverse life histories [72, 75]. Descriptions of life stages for key species have been reported for several geographical locations in North America [27, 66, 72, 73, 74, 97].

The available control techniques

Cultural and mechanical methods

Pasture degeneration frequently results from lack of proper management practices [52, 53]. Techniques such as rotational or deferred grazing, water conservation and erosion control, mowing, fertilizing, and periodic re-seeding produce dense, hardy grass cover [76, 77]. Because thistles are pioneer species, dense ground cover with a closed canopy can prevent establishment and help to reduce infestations. Analysis of growing practices has shown that continuously grazed pastureland is more susceptible to thistle development than rotationally grazed or nongrazed pastureland [9, 26]. Total herbage (yield) increases with declining grazing pressure; as herbage increases, the number of thistle seedlings per ha decreases. Other deleterious effects of overgrazing pastures on weed infestations have been documented for musk thistle (*C. nutans*) [41] and for many other annual and perennial weeds [53, 78].

Mechanical control by means of a hoe, shovel, scythe, or mower can be effective in reducing thistle populations. Although use of a hoe or scythe is limited to small acreages or light infestations, the mowing technique can be applied to substantially larger areas. Experimental data from Nebraska have indicated that mowing musk thistle within 2 days of anthesis of the terminal blooms will prevent seed production without regrowth [71]. However, mowing thistles 4 days after anthesis allowed production of significant amounts of viable seed. Unfortunately, the uneven maturity of thistle stands required more than one treatment per season. The necessity of repeated applications and the impracticality of mowing on steep terrain limit the usefulness of this technique. In spite of these drawbacks, mowing the flower stalks of the thistles, and thereby decreasing the height from which seeds are released, serves to reduce both seed dispersal and the plant's ability to produce a maximum complement of seeds. As with all mechanical controls, the long-term efficacy of these methods is conditional upon the use of sound management practices.

A simplified flow diagram of a decision-making process suitable for implementing cultural and mechanical techniques for thistle control is presented in Fig. 1. This diagram does not cover all available options or possibilities, nor has the key component of 'timing' been included. Nonetheless, the basic rationale is sound and serves to illustrate the complexity and multiplicity of choices which must be considered when attempting suppression of thistles by cultural means. The diagram is utilized by continually making decisions until the thistle populations are reduced to an acceptable level. Terms such as 'small', 'moderate' and 'large areas' are intentionally ambiguous, and interpretation will vary from one situation to the next depending on the quality and quantity of equipment and the availability of labour. Exceptional circumstances, such as dense infestations of thistles or an immediate need for thistle control predicated on economic considerations or state noxious weed laws, may require an early deviation from cultural and mechanical practices into chemical usage. As presented, the flow diagram includes the concept of IPM, but only after key management practices have been attempted. Compatibility and interactions of specific cultural techniques with chemical and biological control strategies will be discussed later in this paper.

Chemical pesticides

Pasture and rangeland weed control was revolutionized by the development of inexpensive growth regulator herbicides capable of selective removal of broadleaved weeds from grasses. The most commonly used chemical in this group is 2,4-dichlorophenoxyacetic acid (2,4-D) [15]. This herbicide is rapidly translocated throughout the plant and interferes with crucial plant functions such as respiration, synthesis and utilization of food, enzyme activity, stomate operation, turgor pressure maintenance, and most obviously, cell division [15, 52, 90]. Since the efficacy of herbicides on individual thistle species can vary [47], more research is needed to delineate the impact of pesticides by species as separated under the current classification scheme. Information on the response of each species to chemical treatment is essential to the development of an effective IPM programme.

Although picloram (4-amino-3,5,6-trichloropicolinic acid), dicamba (2-methoxy-3,6-dichloro-o-anisic acid), silvex (2-2,4,5-trichlorophenoxy propionic acid) and MPCA (2-methyl-4-chlorophenoxyacetic acid) have proven useful and, in some cases, superior as chemical control agents, the herbicide 2,4-D has been the most widely recommended chemical for thistle control [3, 18, 29, 41, 46, 49, 67, 104]. Most authors agree that plant maturity affects herbicide efficacy; larger plants are less susceptible. Timing of application, therefore, becomes critical since best results were obtained when thistles were small but actively growing. Spring and autumn treatments with 2,4-D at rates of 1·1 to 2·2 a.i. kg/ha can reduce *Carduus* population density [46, 71], but several years of herbicide treatment may be required to depress thistle infestations to a level suitable for control by cultural techniques [41]. The high costs in terms of labour, energy, and pesticides, as well as the constant threat of reinfestation from untreatable areas, have prompted researchers to consider alternative and integrated control techniques.

Biological control by natural enemies

Interest in biological suppression of thistle infestations has increased substantially during the last 15–20 years. Following extensive explorations in Europe and Pakistan [5, 10, 12, 33, 121], a wide variety of thistle-feeding insects has been released in North America [20, 31, 32]. The most promising natural enemies are discussed in the following section, beginning with those that have prompted the most research and have the greatest potential in an IPM program.

Rhinocyllus conicus Froelich (Coleoptera: Curculionidae). *Rhinocyllus conicus*, a curculionid seedhead feeder, has stimulated more interest than any other insect species introduced for biological control of the *Carduus* species. Explorations in several European countries and on a variety of *Carduus* species [10, 12, 32, 121, 124] were followed by detailed host specificity tests [122, 128], and ultimately by release in Canada in 1968 [39]. Since 1969, *R. conicus* has been released in the United States in California [35, 36, 40], West Virginia [37], Montana [1, 91, 92], Maryland [8], Virginia [59, 63, 97, 103] and Missouri [88]. Establishment has occurred in each of these states although the thistle species vary between locations. The establishment of adult releases in Tennessee, New Jersey, and at least 12 other states is anticipated [8, 60].

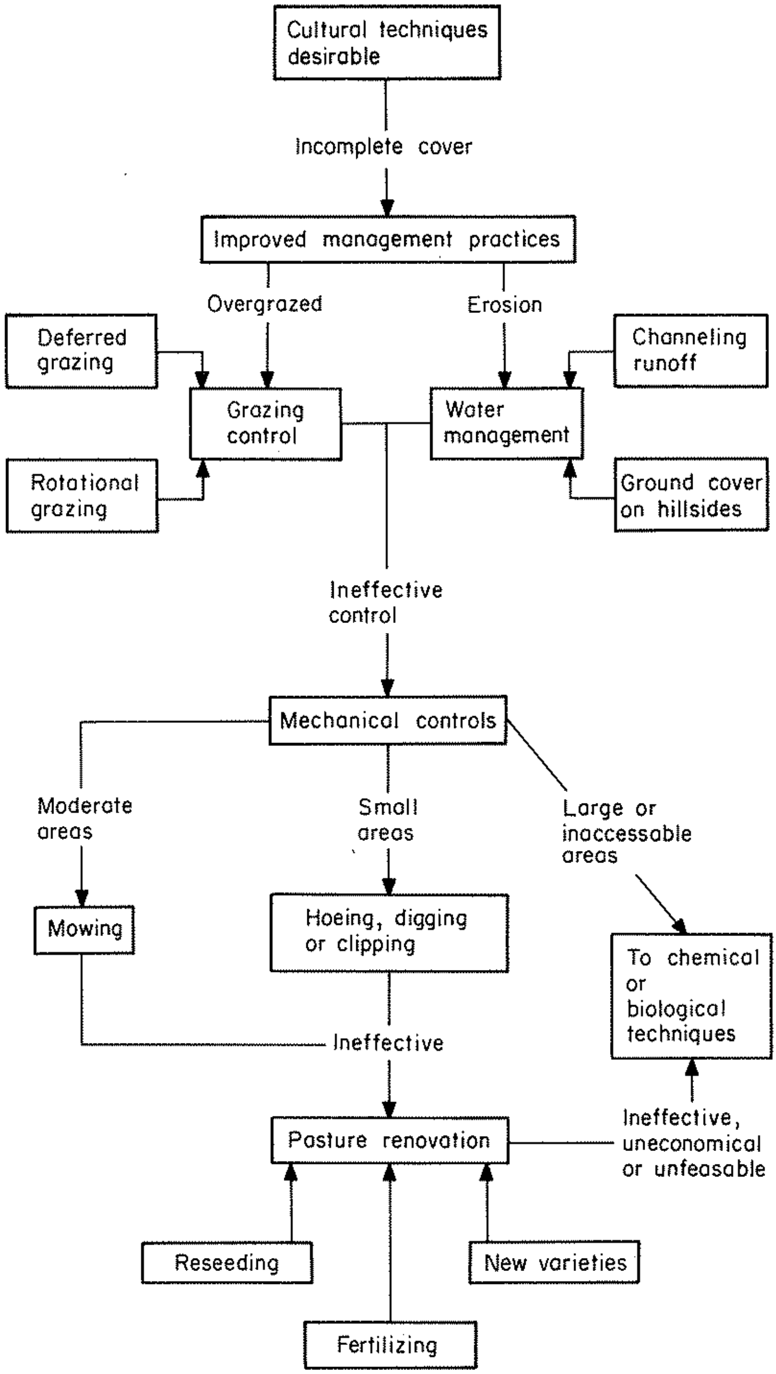

FIG. 1 A simplified flow diagram of the decision-making process for thistle suppression by cultural and mechanical techniques.

The life history of *R. conicus* has been documented from both Europe and the United States [97, 122]. Eggs are oviposited on the bracts and stems of thistle booms, and the resulting larvae feed in the receptacle beneath the developing seeds. The larvae pupate in the blooms and generally emerge as adults by mid-summer. Adults feed upon emergence, and then migrate to overwintering rosettes. The biology and key mortality factors [34, 57, 58, 61, 101, 121], and the response of thistles to *R. conicus* attack have been reported in detail [91, 101, 102]. Statistically adequate sampling plans based on vacuum sampling are available for monitoring *R. conicus* populations on *Carduus* thistles [113].

Successful colonization of weevils introduced from Europe may depend, in part, on the geographic location and the thistle species from which they were collcected. The unsuccessful colonization of milk thistle by *R. conicus* collected from musk thistle from the Rhine Valley of France [124], followed by the successful establishment of adults collected from milk thistle in Italy, suggests the development of races or biotypes [34]. Selection of European biotypes from areas compatible with local environmental conditions may result in populations which can adapt readily and achieve successful suppression of thistle populations faster than the 6-year interval reported from Virginia [63]. The collection of 'acclimated' *R. conicus* adults from locations within the United States selected for environmental compatibility with the proposed release site should also provide colonies capable of rapid expansion.

Synchronization of *R. conicus* oviposition varies with the phenology of thistle species and geographic location. Reports from Virginia indicate that although oviposition was well synchronized with *C. nutans* (*C. thoermeri*), the impact of this weevil was reduced by the extended blooming period of *C. acanthoides* [98, 100, 101]. Attempts to extend the oviposition period through sequential releases of adults were generally unsuccessful [99]. This technique proved effective in field cage tests, but fecundity was reduced by prolonged captivity and subsequent larval survival diminished due to insufficient developmental time. More recent studies have indicated that a *R. conicus* biotype characterized by delayed oviposition and an extended lifespan may be developing on *C. acanthoides* [93]. Establishments of *R. conicus* on either thistle species in Virginia and on *C. nutans* in Canada were enhanced by releases made in the spring (prior to oviposition) rather than in the summer or autumn [53, 56, 68].

Trichosirocalus horridus (Panzer) (Coleoptera: Curculionidae). In spite of the taxonomic chaos surrounding the generic position of *T. horridus* (which was previously designated as *Ceuthorhynchidius horridus*) [16, 112], the life history of this rosette-feeding weevil has been documented from both Europe and North America. Regardless of location, this species produces one generation annually and the life cycles follow a similar pattern [4, 95, 106]. Adults oviposit in the midribs of thistle leaves, and upon eclosion the larvae migrate to the basal-crown of the rosette. Feeding is completed during the third instar and larvae move to the soil to pupate. Teneral adults, which have a reddish to reddish-pink coloration, feed immediately upon emergence and then migrate to rosettes where either hibernal or aestival diapause occurs.

The life cycles of *T. horridus* in central and southern Europe are not synchronized [30, 44, 45]. In southern Europe where the climate is moderated by the Mediterranean Sea, oviposition occurs from mid-December to early March. Adult emergence in April and June is followed by an aestival diapause during the hot summers. In contrast, oviposition in central Europe follows spring thaws from mid-May to the end of June. Adults emerge in September, feed, and then enter a hibernal diapause extending through the winter months. Life cycle studies of laboratory-reared progeny of *T. horridus* adults imported from southern Europe and released in Virginia have shown that in spite of the snow and cold winter temperatures more characteristic of central Europe, the weevils exhibited seasonal life cycles similar to those reported from southern Europe [108]. The hardiness and adaptive ability of this apparent biotype suggests that selection of individuals from central or southern Europe can be used to 'tailor' insect-plant synchronization, and thereby increase the biological pressure on specific thistle species. The occurrence of mating is also temporally differentiated; central European populations mate in the spring, southern European weevils copulate in the autumn. Weevils from both European biotypes have been released in Virginia to determine if they can coexist as reproductively separate populations. Selection of specific biotypes will profoundly affect the timing of cultural and chemical control procedures suitable for an IPM programme.

The biology and host specificity of *T. horridus* have been studied in detail [30, 55, 65, 107, 114, 116]. Although adults have been released in Canada, and colonies established in Virginia, releases on the west coast of the United States have not been attempted because laboratory-reared weevils feed and oviposit on artichoke (*Cynara scolymus* L.) and lettuce (*Lactuca sativae* L.), two economically important crops in California [20, 64, 118]. As a host, lettuce is considered inconsequential since: (1) *T. horridus* has not been recorded as a pest of lettuce, (2) the essentially bland nature of lettuce permits feeding by many stenophagous insects, and (3) few larvae can develop to the last instar on lettuce [118]. Even though these weevils have not been reported as pests in European artichoke producing regions, concern for California's multi-million dollar artichoke industry has caused scientists to proceed with considerable caution, and request additional host specificity and development studies prior to release. In light of the intense pesticide application programmes currently in practice on both artichokes and lettuce, these fears may be unrealistic. However, the introduction of a new pest would not only slow development of practical IPM programmes for these crops, but would reduce grower acceptance of new crop protection programmes which included introductions of biological control agents.

Altica carduorum Guérin-Méneville (Coleoptera: Chrysomelidae). *A. carduorum*, a native of Europe, has been imported to North America as a biological control agent for *C. arvense* (Canada thistle, creeping thistle) [83]. Larvae and adults weaken Canada thistle through defoliation and by feeding on flower buds. Since *C. arvense* reproduces vegetatively as well as through sexual reproduction, repeated defoliations are required to deplete nutrient reserves stored below ground level. Adults feed throughout the summer, overwinter in the soil, and then emerge to oviposit on the abaxial surface of thistle leaves in spring. Pupation occurs in the soil [50, 94]. Prolonged feeding by the adults, even after oviposition terminates, maintains a long-term biological pressure on the thistle and helps prevent acquisition and storage of additional nutrients by the thistle.

Although found in various countries in Europe, *A. carduorum* appears to be restricted to areas where temperatures do not fall below 20°C for several months out of the year [38, 120]. Attempts to establish this species in England, Canada and the United States have indicated that the beetles are quite sensitive to other weather-related parameters [7, 14]. At low temperatures (< 20°C), egg and larval maturation are delayed, and the population suffers from intense predation. The carabid *Lebia viridis* Say has been implicated as a major predator on the immature stages [87]. Excessively high temperatures and low humidities have also affected colonization through egg desiccation, increased developmental time, and initiation of a flight response which leads to overdispersal. Difficulty in establishing *A. carduorum* and evidence that caged beetles will feed and develop on artichokes have caused a shift in research priorities away from this species [10].

Ceuthorhynchus trimaculatus F. (Coleoptera: Curculionidae). *C. trimaculatus*, a rosette-feeding weevil, has a life history similar to that of *T. horridus* found in the Mediterranean regions of Europe [11, 30]. Oviposition occurs on the leaves of growing thistles from November into March. Larvae feed initially on newly developed leaves and then migrate to the crown. As in *T. horridus*, larvae leave the leaf just prior to pupation.

In Europe, *C. trimaculatus* does not seriously interfere with *T. horridus* since the life cycles are not synchronous; *C. trimaculatus* feeds 1 month later [10]. A similar situation in the United States would be highly desirable. If *C. trimaculatus* maintains this temporal spacing in the South, then the majority of these weevils will be developing when *C. acanthoides* is the primary host plant available. An increase in biological pressure against this weed is necessary to prevent the encroachment of *C. acanthoides* into niches vacated by *C. thoermeri* and *C. nutans* under severe pressure from *T. horridus* and *R. conicus*.

Experiments delineating the host range and host preferences of *C. trimaculatus* have been completed, and the results appear promising; larval development through to the adult stage occurred primarily on weeds in the Cynareae [62]. Unfortunately, 0·4% of the larvae innoculated on artichoke survived to the adult stage. Since survival was poor on *S. marianum* [62], one of California's major thistle species [19], releases in the western United States should not be attempted until the weevils are shown to effectively attack *C. pycnocephalus* and *C. tenuiflorus*, two other important thistle species in California, and additional tests prove conclusively that *C. trimaculatus* will not pose a threat to California's artichoke industry. Additional host specificity testing is necessary prior to release on the east coast of the USA in order to protect endangered native *Cirsium* species.

Ceuthorhynchus litura (F.) (Coleoptera: Curculionidae). *C. litura* is native to Europe and host plants suitable for the development of weevils are restricted to the genera *Cirsium, Silybum* and *Carduus* [127]. In Europe, *C. arvense* is the primary host; *C. nutans* and *C. crispus* have been reported as hosts [44], but more recent investigations in Europe have been unable to substantiate this claim [127]. *C. litura* has been successfully established in Canada on *C. arvense* and exhibits a life history similar to that of *T. horridus* collected from central Europe [85, 108]. As temperatures rise in early spring, the adults emerge from a hibernal diapause and feed prior to oviposition which occurs from March to May. Larvae, emerging from eggs in the midribs of the leaves of thistle rosettes, are present from April to June. Like *T. horridus*, the larvae mine the leaf veins and root crown. Pupation occurs in the soil. Adults of *C. litura* can be found from July to early October in Ontario, Canada [85].

Although *C. litura* is host-specific and has considerable potential for reducing the vitality of *C. arvense*, difficulty in collecting and rearing this weevil and an apparently poor dispersal ability may limit the usefulness of the species. Nevertheless, releases of this insect at geographic locations with different environmental conditions may prove more productive. Additional research on its laboratory propagation is necessary and, if successful techniques can be developed, large releases in a broad variety of locations will become feasible. Due to the narrow range of host acceptance and suitability, *C. litura* is well suited for use in areas where artichoke is grown commercially. The association of *C. litura* with the thistle-infesting rust, *Puccinia punctiformis* (Str.) Rohl, is very promising and opens entirely new avenues for research in thistle control [85]. Laboratory and field cage experiments detailing this association, and similar tests on the transmission of *P. punctiformis* and related pathogens by other natural enemies of thistles, are crucial for achieving disruptions of thistle infestations and producing environmentally stable ecosystems which exhibit minimal fluctuations in thistle populations.

Urophora cardui (L.) (Diptera: Tephritidae). *U. cardui* is a univoltine and stenophagous species which has only been found on *C. arvense* in Europe [123]. When tested for host specificity in the laboratory, *C. vulgare* and *C. acanthoides* were the only other plants accepted as oviposition sites, and then only when *C. arvense* was not present [86]. *U. cardui* females oviposit in newly developed vegetative buds. The larvae hatch during the second instar and begin producing fusiform or spherical galls on the stem which contain 1–10 larvae per gall. Overwintering occurs in the galls and, in Europe, pupation and adult emergence occur during late spring and early summer [89, 126]. This insect has been released in Canada, but information on its effectiveness in suppressing thistle populations is not currently available.

The possibility of competition between *Urophora* species (including the flower feeding *U. sibynata* (Rondani) and *U. solstitialis* (L.)) and *R. conicus* has limited interest in these species [10]. However, in light of the host specificity and narrow range of host acceptance, *U. cardui* may be suitable for releases in the eastern United States where *R. conicus* is ineffective in suppressing *C. acanthoides*. Since *C. arvense* is not a noxious weed along the Atlantic coast of the USA and *C. thoermeri* (*C. nutans*) is not accepted by *U. cardui* as an oviposition site, competition between *R. conicus* and *U. cardui* would be limited to interactions on *C. acanthoides*. Such interference would be minimal since *R. conicus* prefers to feed and oviposit on *C. nutans* (*C. thoermeri*), and oviposition by this weevil is poorly synchronized with bud formation by *C. acanthoides* [100]. Thus, *U. cardui* could be used safely to apply additional biological pressure against *C. acanthoides* without damaging or interfering with *R. conicus* populations. In essence, *U. cardui* would simply be filling the niche left nearly vacant on *C. acanthoides*.

Tingis ampliata H.-S. (Heteroptera: Tingidae).
Psylliodes chalcomera (Illiger) (Coleoptera: Chrysomelidae).
Cassida rubiginosa Müller (Coleoptera: Chrysomelidae). *T. ampliata, P. chalcomera* and *C.*

rubiginosa have all been studied extensively and considered for release in various thistle-infested regions in North America [21, 23, 24, 25, 115]. All three have been rejected because of their ability to feed on artichoke [10, 84, 125]. *T. ampliata* and *P. chalcomera* do not occur in North America. *C. rubiginosa* has been present on the east coast of North America since at least the early 1900s [6] and currently can be found from eastern Canada to Virginia, and as far west as Michigan [117]. The westward expansion of this species should be observed closely both in Canada and the United States. The movements of *C. rubiginosa* can provide not only important data on the ability of thistle-feeding insects to increase their geographic range, but also may furnish useful and practical information on the distribution of thistles and potential expansion routes for insects imported for thistle control and released in North America.

Many other potential biological control agents are in the early phases of testing for effectiveness, suitability and host specificity. Several recent publications are available which contain detailed discussions on these insects [10, 96, 129].

Compatibility of the control techniques

Many studies are available on the impact of pesticides on arthropod biocontrol agents [17], but few deal with the effects of herbicides on beneficial insects. The effect of 2,4,5-trichlorophenoxyacetic acid (2,4,5-T) on a carabid predator of springtails is a notable exception [22]. In this study, carabids treated with 2,4,5-T by topical application, placed on treated surfaces, or fed 2,4,5-T treated springtails showed reduced activity and longevity.

Unfortunately, little is known concerning the impact of herbicides or cultural controls on biological control agents of thistles. However, some general deductions are evident from the available information. First, proper timing of chemical or cultural control techniques is crucial to minimizing damage to natural enemy populations. Control treatments resulting in host-death prior to the completion of physiological development of beneficial insects may effectively eliminate small populations or seriously reduce the population density of established natural enemies. Also, timing of applications will be affected by both the species of biological control agents and thistles present. Finally, since life histories of thistles and beneficial insects are dependent on geographic location and hybridization of the thistles and/or biotypes of insects, these factors should be considered when attempting cultural or chemical suppression of thistles.

A flow diagram of the typical decision processes used in biological and chemical control of thistles has been presented in Fig. 2. Frequently the integration of these techniques is not considered until the original method (biological or chemical) has proven inadequate. A simple pesticide screening test during the selection of effective candidates could help choose between two or more suitable species and greatly increase the potential for integrated control if the biological agent alone proves ineffective. Although this type of test may not be practical for individuals or small groups of researchers during foreign explorations, many of the US facilities overseas have both the capability and the expertise for pesticide screening studies. Also, the selection and utilization of herbicides known to exhibit minimal toxicity to insects will aid in the migration and establishment of biological control agents of thistles in all areas where chemicals are used.

As the number of different species or new biotypes of natural enemies increases within a given area, the potential for integrating successfully chemical and biological techniques without loss of biocontrol agents decreases. Therefore, if chemical application is anticipated, natural enemies should be selected not only for compatibility with each other, but also for compatibility with an integrated pest management system which may become necessary.

Of the available natural enemy complex of thistles, only *R. conicus* and *T. horridus* have been assessed for pesticide tolerance. In Montana, field trials demonstrated that the effect of 2,4-D varies with density of *R. conicus*; as the larval population per head increases, survival decreases [91]. In Virginia, laboratory and field tests with *T. horridus* reared from southern European stock and *R. conicus* from central Europe determined that spring application of 2,4-D when *C. thoermeri* is just beginning to bolt is the most advantagous time for herbicide treatment [111]. Thistles in this stage of development are growing rapidly and the herbicide is translocated readily to sensitive tissues, resulting in death of treated plants. Further, the biological control agents are not seriously affected by 2,4-D at this time. In late spring and early summer, *R. conicus* adults are tolerant of

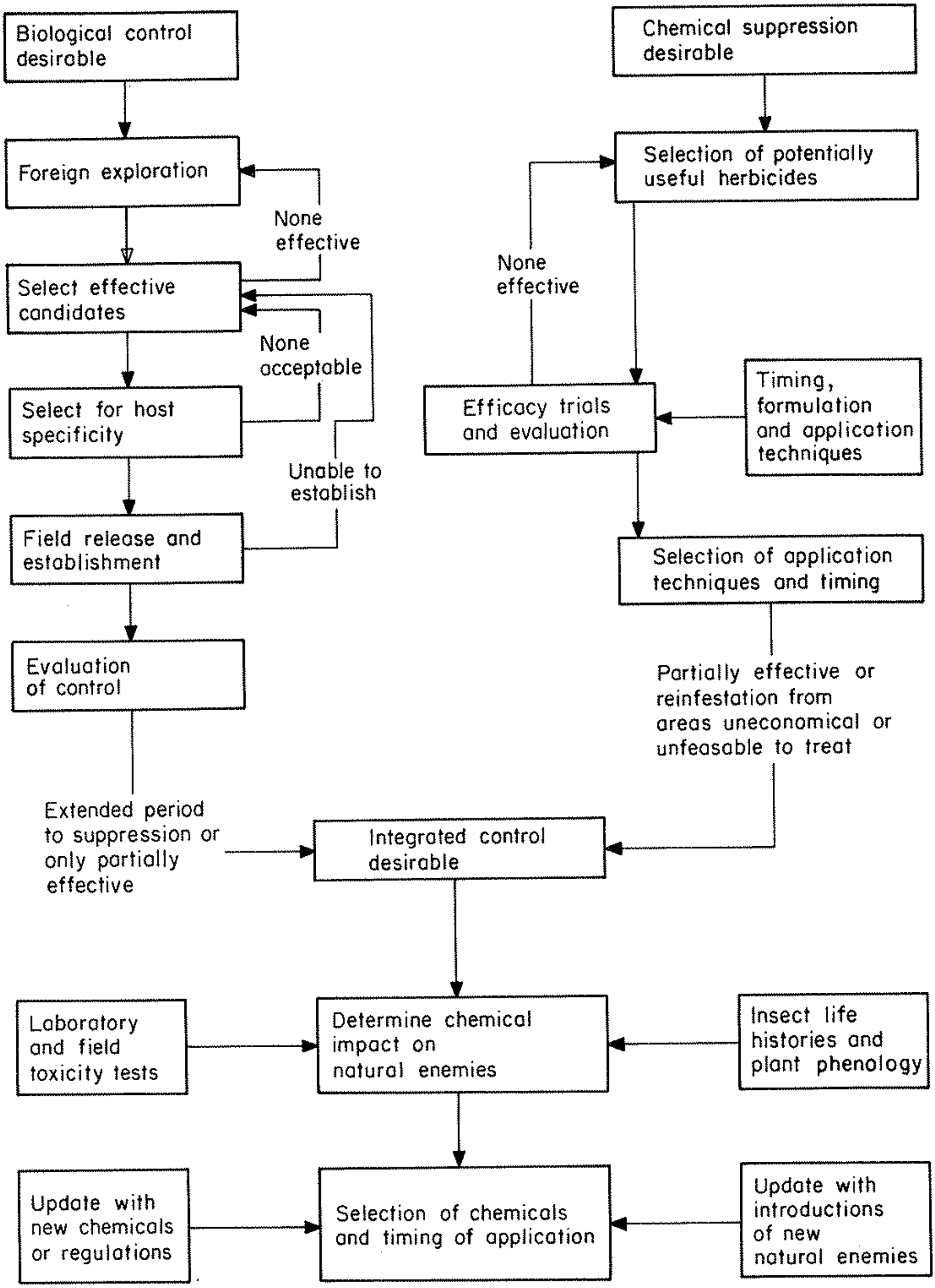

FIG. 2 A flow diagram of biological and chemical control techniques and their integration for developing pest management systems for thistles.

2,4-D and LC_{50} values average 120 kg/ha. Similar results have been reported from field tests in Montana [79]. *T. horridus* occurs in the pupal stage when thistles begin to bolt and field trials have indicated herbicide treatment during this stage of development would not affect adversely weevil survival, reproduction or population increase [110].

2,4-D can also be applied when the terminal bloom of musk thistle is in the late-bud to early-bloom stage [109]. Treatment at this time causes death of the host plants but does not prevent survival of *R. conicus* populations. Although most *T. horridus* have become adults by this stage of plant development, the weevils are tolerant to 2,4-D application at the recommended rates of 1·68–2·24 kg/ha (LC_{50} values average 68 kg/ha) [110]. Field observations also indicate that *R. conicus* and *T. horridus* adults on herbicide-treated thistles will move to unsprayed plants. This migration increases the biological pressure on *Carduus* species in waste areas where herbicide use is unfeasible or uneconomical.

Autumn applications of 2,4-D can also be used compatibly with these biological control agents for thistle control, although timing sprays during the autumn is more difficult than in the spring [111]. Treatments should be late enough in the season for most thistle seeds to have germinated, but early enough that the herbicide can be applied while the plants are still growing. In southwestern Virginia, treatment during early to mid-October generally assures enough warm weather for 2,4-D effectively to reduce thistle populations and for *T. horridus* and *R. conicus* adults to move to untreated plants before the onset of cold weather. Herbicide treatments should be adjusted to achieve similar results at other locations.

Thus, 2,4-D applications can be manipulated to have a minimal impact on the complex of biological control agents present. However, more information is needed on the impact of the other major herbicides on survival and population development of all beneficial insects considered for introduction into North America for thistle control before complete pest management programmes can be established. With this information herbicide treatments can be timed to manage thistle populations without adversely affecting the biological control agents and use of herbicides can be reduced without increasing thistle densities.

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