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Thistle management

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Proceedings of a workshop held at CSIRO Division of Entomology, Canberra on 12–13 June 1996

Organized by S. Corey, D.T. Briese and T.L. Woodburn and sponsored by the Co-operative Research Centre for Weed Management Systems

Editors: T.L. Woodburn, D.T. Briese and S. Corey

CRC Weed management systems

CRC AUSTRALIA

Established and supported under the Australian Government's Co-operative Research Centres Program

Co-operative Research Centre for Weed Management Systems

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MISSION STATEMENT

The CRC is committed to increasing the sustainability of agriculture and protecting the natural environment by developing ecologically sound, cost effective weed management systems.

OBJECTIVES

- To reduce the impact of weeds on farm productivity and profitability by developing sustainable management programs that optimize the integration of chemical, biological and ecological approaches for annual crop and pasture systems in the cropping zone of southern Australia.

- To develop practical integrated weed management systems that reduce weed infestation, protect the environment and enhance sustainability and productivity of Australian temperate perennial pasture ecosystems.

- To develop integrated strategies for the sustainable management of weeds invading natural ecosystems in temperate Australia, in order to maintain biological diversity of native flora and fauna and to prevent further degradation of natural habitats.

- To implement a suite of weed science and weed management education programs which, for the first time in Australia, offers a coordinated approach to educating undergraduates, postgraduates, professional land and natural resource managers, and the community.

- To interact with researchers and land managers to communicate the results of weed research and foster the adoption of resulting weed management strategies.

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The thistle illustration on the cover is reproduced from the 'Tasmanian Weed Handbook' by Brian H. Hyde-Wyatt and Dennis I. Morris, illustrated by Dennis I. Morris and published by the Tasmanian Department of Agriculture 1975.

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Preface

The Co-operative Research Centre for Weed Management Systems was set up to co-ordinate research and enhance collaboration between groups working on weed management. As part of this aim the CRC is sponsoring a number of workshops to gather together researchers and practitioners so that better weed management systems can be established. The thistle management workshop was one of these.

Of the dozen or so species of thistle in Australasia which are weeds of pastures and crops, several belonging to the genera *Carduus, Carthamus, Cirsium, Onopordum* and *Silybum*, are key weeds in particular situations. Considerable effort has gone into their control with little progress to date.

The workshop was a unique opportunity to discuss with researchers, extension workers and end users, the potential to integrate the various weed management practices that are currently being utilised. These include work on the ecology of the weeds, grazing and pasture management, herbicide use and biological control.

The papers presented in these proceedings outline some of the research which has recently been conducted along with some of the problems which are currently being faced. The papers are summarised in the outcomes paper at the end of these proceedings and 24 final recommendations are listed. There was general consensus amongst the workshop delegates that integration of weed management techniques, rather than relying exclusively on one control strategy as has tended to happen in the past, was the key to successful thistle management. Some of the most highly ranked recommendations related to communicating results to end users, an area which the CRC had previously recognised as a high priority.

It is the hope of the organisers that the recommendations made at this workshop will lead to further research to fill in some of the 'gaps' in our current knowledge along with assuring a better communication link with the end users. The final aim being implementation of better weed management systems.

We gratefully acknowledge the support provided by the Co-operative Research Centre for Weed Management Systems, CSIRO Division of Entomology and all who participated in the workshop.

Aspects of thistle population dynamics with reference to *Onopordum*

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Summary

An understanding of the population dynamics of the target weed is considered to be a key element in the evaluation of any biological control project. In the case of *Onopordum* thistles, data collection commenced prior to the release of agents and a set of data is now held on the demography of several infestations over a five-year period. This period covers climatic extremes of drought and high rainfall and provides a measure of the fluctuations in thistle population levels that occur in the absence of natural enemies. Such data will provide a basemark from which to measure the impact of future control strategies, including biological control. The study illustrates the type of data, such as seed bank estimates and survival between life stages, that will be important for the assessment of control strategies. The study also enables comparisons between populations of *O. acanthium* and those having an affinity to *O. illyricum*, the latter showing a greater tendency to perennation. Differences in life history traits will have implications for management of these thistles in particular, and other species of thistle in general.

Introduction

Onopordum acanthium and *O. illyricum* are herbaceous, monocarpic plants with mainly biennial or perennial life-cycles which reproduce only by seeds (achenes). They form rosettes in their first year and develop a thick tap root that supports the development of an erect flowering stem 1–2.5 metres in height later in the life-cycle. In south-eastern Australia the plants have a tendency to form dense stands, smothering desirable vegetation with their rosette leaves, thus reducing pasture stocking rates (Briese 1990). Plants may produce up to 20 000 seeds (unpublished data), a proportion of which become incorporated in a long-lived soil seed bank (Cavers *et al.* 1995). Seed which becomes incorporated into the soil may acquire burial-induced dormancy (Young and Evans 1972, Campbell *et al.* 1991) and remain viable for more than 20 years (Toole and Brown 1946).

The aim of the present study is to establish baseline data against which the effectiveness of current or proposed weed management practices, such as biological control (Briese 1990), may be assessed. While other demographic studies have been carried out on *Onopordum* thistles in Australia, these have only been for one or two years duration and have looked at particular aspects, such as soil seed banks (Cavers *et al.* 1995) or the fate of particular seedling cohorts (Groves *et al.* 1990). The present study is the first comprehensive study of plant and seed population dynamics over a sufficiently long period (five years) to encompass a range of climatic conditions. This paper summarizes the initial findings of the demographic study carried out on two populations of *Onopordum* thistles, one of *O. acanthium* and the other of *O. illyricum*. There is considerable morphological variation among plants currently referred to as *O. illyricum*, and the question of the identity of Australian plants assigned to this taxon remains to be resolved (Michael 1996). For simplicity, the name *O. illyricum* has been maintained for populations of *Onopordum* having a close affinity with that taxon.

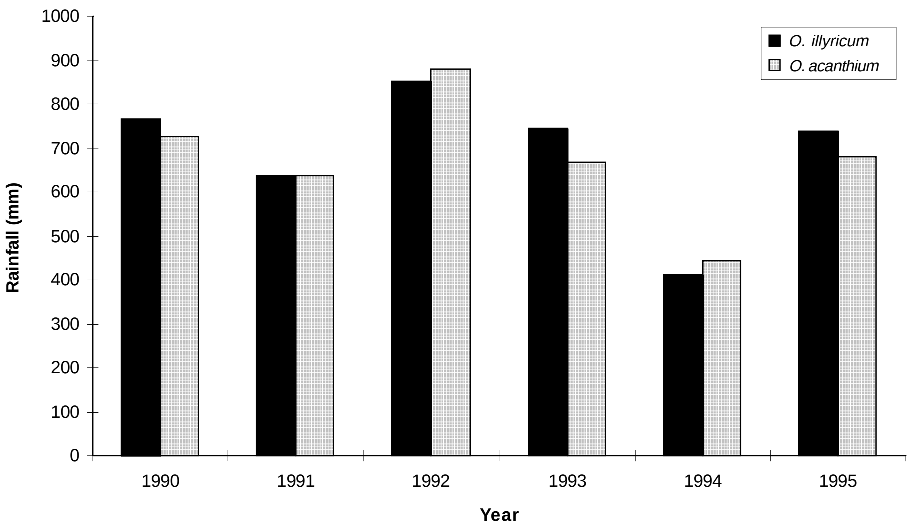

Figure 1. Yearly rainfall totals at 'Lanyon' (*O. acanthium*) and 'Bobbara' (*O. illyricum*) study sites.

Methods

The *O. illyricum* infestation was situated at 'Bobbara', Galong, New South Wales (34° 36'S, 148° 34'E). The pasture was composed of Mediterranean annual grasses and several introduced herbs (Groves *et al.* 1990), and was grazed predominantly by sheep and occasionally by cattle. The paddock had a history of cultivation for oats and wheat prior to 1985. The *O. acanthium* infestation was situated at 'Lanyon', Australian Capital Territory (35° 29'S, 149° 05'E). Perennial grasses, annual grasses and herbs formed the pasture at this site, which was grazed exclusively by cattle. Productivity of the pasture species has been increased through the application of superphosphate fertilizer.

Monthly rainfall records for 'Bobbara' were obtained from the property manager, while those for 'Lanyon' were compiled from the records of the Bureau of Meteorology. Both study sites experienced similar rainfall patterns throughout the study period. Rainfall occurred throughout the year and showed no seasonal pattern, while differences in the yearly rainfall totals between sites were negligible (Figure 1).

The study sites (a 50 × 30 m plot at 'Bobbara' and a 25 × 25 m plot at 'Lanyon') were visited at six to eight week intervals. On the initial visit to each site the position and size of every rosette in ten randomly positioned 1 × 0.5 m quadrats was recorded. On subsequent visits the fate of plants was monitored and the position of newly established plants recorded. During summer months when *Onopordum* plants at each study site were in flower, the diameter of each capitulum on each plant flowering within a quadrat was recorded. Potential seed production for each plant was determined using a regression equation relating the diameter of a mature seedhead to the number of viable seeds it contains. Regression equations were determined separately for each site from data collected by dissecting 100 mature capitula of varying diameters and determining the number of viable seed within each (Briese unpublished). In summers when the number of flowering plants within quadrats was low, an additional area within the study plot containing 40–60 flowering plants was delimited, and every flowering plant within it monitored as mentioned above.

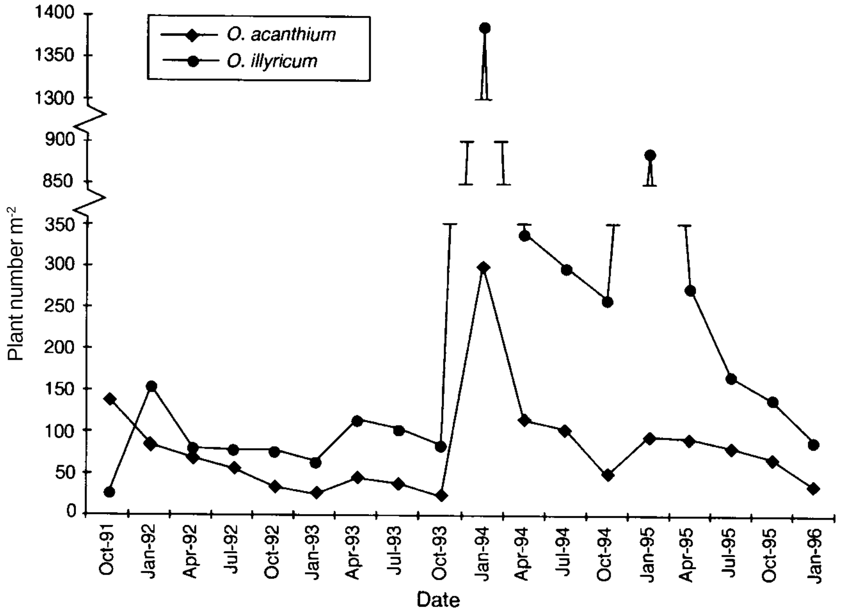

Figure 2. Variation of *Onopordum* spp. plant density at two study sites.

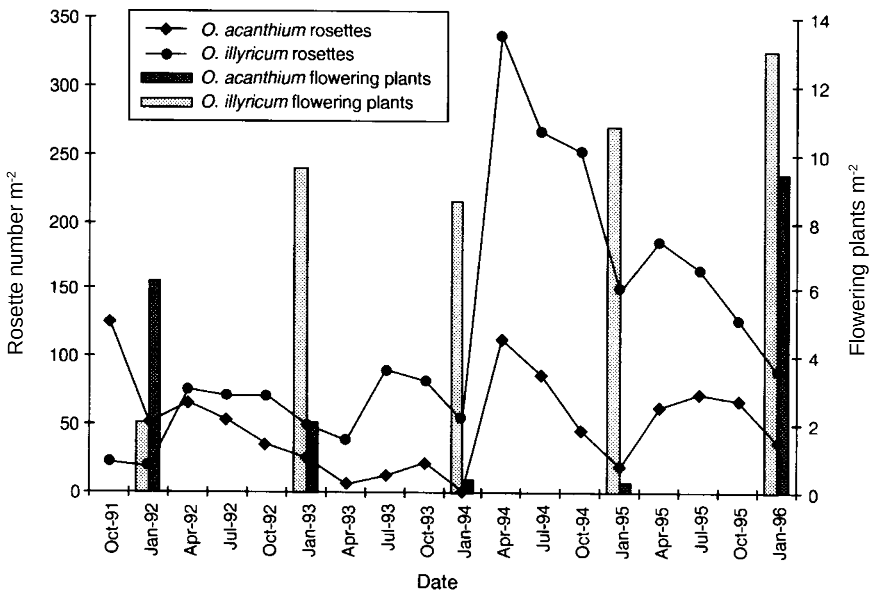

Figure 3. Variation of *Onopordum* spp. rosette density at two study sites (seedlings excluded).

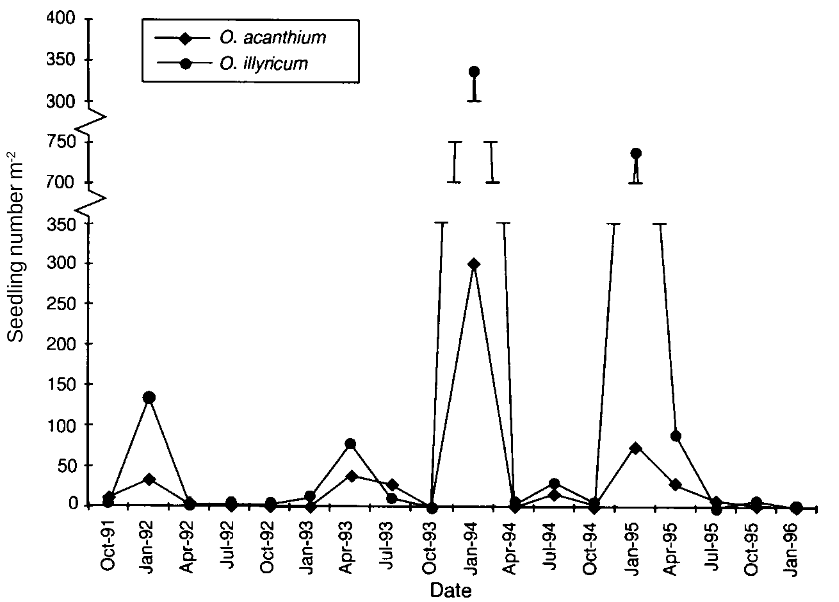

Figure 4. Variation of *Onopordum* spp. seedling density at two study sites.

Each year soil cores were taken before and after seeds had been shed. On each occasion 100 random cores measuring 3.2 cm in diameter and 10 cm in depth were taken within the study sites, but not within the quadrats. In the laboratory *Onopordum* seed was isolated from each soil core by washing. This seed was then placed in small petri-dishes on moist filter paper in a humidity cabinet (20°C / 8 h daylength) in order to determine its viability.

Data collected periodically from the quadrats at each site have been combined and averaged to produce a seasonal summary of seedling recruitment, plant death and seed production for each site over the five year period.

Results

Plant demography

The variation in plant density at both *Onopordum* study sites was seasonal over the term of the study, and the pattern of this variation was similar between the infestations (Figure 2). As *Onopordum* thistles are not capable of vegetative reproduction, increases in plant density were driven by seed germination events, predominantly occurring through summer (December–February) and autumn (March–May) (Figure 4). An increase in the density of rosettes at either site was followed by a gradual decline in density until the next period of high germination occurred (Figure 3). At the *O. acanthium* site, rosette densities declined gradually over the first two years of the study from 126 plants m^{-2} in spring 1991, to a low of 1.8 plants m^{-2} in summer 1993/94. Over the same period, the density of rosettes at the *O. illyricum* site increased from a low of 19.6 plants m^{-2} in summer 1991/92, to 54 plants m^{-2} in summer 1993/94. A period of high germination in summer 1993/94 at both study sites led to a large increase in rosette density (114.2 *O. acanthium* rosettes m^{-2} and 337 *O. illyricum* rosettes m^{-2} in autumn 1994) (Figure 3). Drought conditions from late autumn 1994 and to spring precluded the establishment of large seedling cohorts and increased mortality amongst rosettes (Figure 3). The density of rosettes at both study sites increased in autumn 1995 due to germinations that occurred through summer 1994/95 (Figure 4). Through 1995, the density of rosettes declined at a rate similar to that observed in the years of the study prior to 1994.

The variation in the densities of both rosettes and of flowering plants between summers followed very similar trends at both sites over the course of the study (Figure 3). Due to the different phenologies of the two species caution should be taken in interpreting these data directly however. In the case of *O. illyricum*, the majority of flowering plants in each summer did not originate from seedling

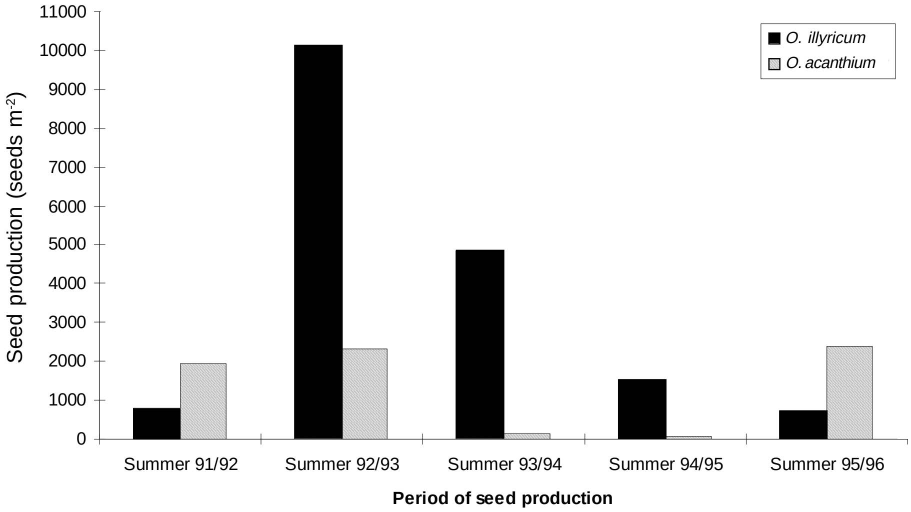

Figure 5. Estimated seed production for *Onopordum* spp. infestations at two study sites.

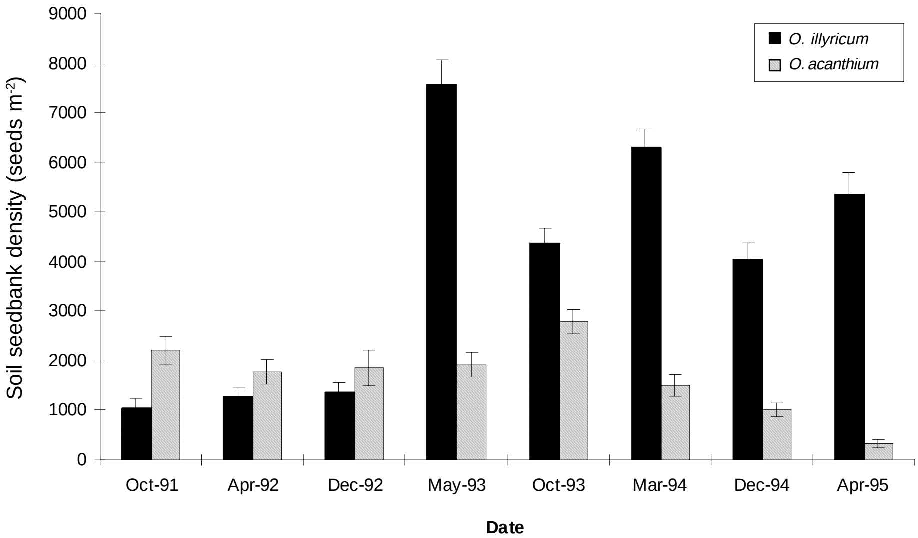

Figure 6. Estimated soil seedbank density for *Onopordum* spp. infestations at two study sites.

cohorts established in the previous summer. In summer 1995/96 for example, the flowering plant density was 13.0 plants m^{-2}, with the majority of these having passed two or more winters as a rosette before bolting. Plants that had established in the summer of 1994/95 contributed only minimally to this total (0.2 plants m^{-2}). *O. acanthium* on the other hand exhibits a more biennial nature, although some degree of perennation has been observed. The majority of plants contributing to the flowering population in summer 1995/96 had germinated in either summer 1994/95 or autumn 1995 (4.6 and 2.2 plants m^{-2} respectively).

Seedling emergence

At both sites maximum germination occurred during summer, with peaks of moderate germination in autumn, and some germination within other seasons (Figure 4). Conditions for germination were exceptionally favourable at the *O. illyricum* site during summer 1993/94 when two periods of seedling emergence were recorded, the first in January (85.2 seedlings m^{-2}), and the second in February (1212 seedlings m^{-2}). Over the same period at the *O. acanthium* site a single instance of germination was recorded in February (299.6 seedlings m^{-2}). Seedling emergence at any one time at the *O. acanthium* site was typically an order of magnitude smaller than that recorded at the *O. illyricum* site.

Seed production

Over the five years of the study, seed production in the *O. acanthium* and *O. illyricum* infestations was highly variable (Figure 5). At the *O. illyricum* site a relatively small seed rain in summer 1991/92 (798 seeds m^{-2}) was followed by a massive seed rain in summer 1992/93 (10 134 seeds m^{-2}). In following years seed production was again smaller (4860 and 1534 seeds m^{-2}), the latter value showing the effect of low rainfall during 1994 on seed production. Despite a large number of flowering plants, a lower number of seeds was produced in summer 1995/96 (732 seeds m^{-2}) due to mechanical slashing of the study plot by the landholder (Figures 3 and 5). This caused early flowering plants to tiller and produce a smaller number of capitula than expected. At the *O. acanthium* site, seed production was similar in summer 1991/92 (1920 seeds m^{-2}) and summer 1992/93 (2325 seeds m^{-2}), but this level was greatly reduced in the following two years (122 and 70 seeds m^{-2} respectively), before it returned to earlier levels of seed production in summer 1995/96 (2384 seeds m^{-2}) (Figure 5).

Soil seedbank

The total number of viable seeds in the seedbank at the *O. acanthium* infestation varied little between sample dates until 1993, but showed a gradual decline over the next two years. This decline corresponded with two consecutive years of low seed input. Soil seed reserves at the *O. illyricum* site were rapidly augmented from 1380 seeds m^{-2} in 1992 to 7584 seeds m^{-2} in 1993, as a result of high seed production in the intervening summer (Figure 6). Subsequently, seed loss due to such processes as predation, germination and exposure significantly reduced the amount of viable seed in the soil seedbank to just over 4376 seeds m^{-2} by spring 1993. Seed production in summer 1993/94 and summer 1994/95 was sufficiently high to prevent the density of viable seed in the soil seedbank from returning to the low levels recorded at the commencement of the study (Figure 6).

Discussion

These data establish a baseline range of demographic parameters for *Onopordum* infestations by which to assess the success of control measures imposed subsequently. The five-year period of the study included periods of drought and high rainfall, as well as variation in pasture cover. Annual fluctuations in the density of mature plants were of the order of 40-fold for *O. acanthium*, and 10-fold for *O. illyricum*. Seed production varied by two orders of magnitude at both sites, though this was dampened by the longevity of seed in the soil seed bank. Soil seed reserves varied by less than one order of magnitude at both sites over the study period. As indicated by events at Galong, the *O. illyricum* soil seed bank can be augmented rapidly following a season of high seed production. Seed production of an *Onopordum* population is not directly related to plant density, as plant growth is strongly affected by rainfall. The positive effect of rainfall on seed production can, however, be modified by competition from other pasture components. This may well explain the fact that, unlike *O. illyricum*, there was not a large increase in seed production of *O. acanthium* at Lanyon in summer 1992/93 following a year of particularly high rainfall (Figure 5).

While germination can occur year round, it is mainly summer and autumn peaks that contribute to subsequent cohorts of *Onopordum* plants (unpublished data, Cavers *et al.* 1995). The intensity of seedling emergence appears to be closely related to both the size of the soil seed reserves, and rainfall and pasture cover (unpublished data). For example, there were two very high peaks of germination at the *O. illyricum* site, one following a large seed input in the previous season, and the other, despite reduced soil seed reserves, after the breaking of a drought period when pasture cover was very low. Seedling mortality was initially high at both sites, leading to cyclical patterns in plant density that peak in late summer or autumn. Intra-specific competition is probably the main cause of the high levels of seedling mortality, though grazing-mediated competition from other pasture components may also play a role (Groves *et al.* 1990).

Fluctuations in the number of mature plants will have been moderated to some extent at the *O. illyricum* site because a large proportion of the plant population behaved as facultative perennials rather than strict biennials. A much lesser degree of perennation was observed at the *O. acanthium* site. Perennation may well be a response to stress (Klinkhammer *et al.* 1996), and the fact that a proportion of the thistle population may persist in the rosette stage for several years before flowering will need to be considered when developing management strategies.

Population levels at the *O. acanthium* site showed similar patterns to that observed for *O. illyricum*, but with a generally lower amplitude (Figure 2). The main exceptions to this were reductions in the density of flowering plants at the *O. acanthium* site in summer 1993/94 and summer 1994/95 (Figure 3). An application of superphosphate to the study site in January 1992 led to an increase in pasture grass cover throughout 1992 and 1993 (Briese unpublished data). The *O. acanthium* plants that had established at the site prior to the application of fertilizer were able to compete with pasture and contribute to seed production in summer 1992/93. However, seedling germinations through 1992 and 1993 were low and establishment was poor due to inter-specific competition (Cavers *et al.* 1995) which resulted in few plants flowering and setting seed in the subsequent season (Figure 3). Long-term differences in thistle densities and seed bank size between the two sites probably reflect differences in pasture management (annual vs. perennial) and grazing practices (sheep vs. cattle), rather than climatic or species-specific variation.

In conclusion, these data show the trends that occur in the demography of *Onopordum* thistle populations under a range of conditions, and indicate the limits of population parameters that need to be exceeded before control measures can be judged effective. Further analyses are required however, to demonstrate fully the dynamic processes involved. To effectively manage a weedy plant, it is essential that the impact of various control measures on these processes is understood. Furthermore, detailed knowledge of demographic events can help to identify stages of the weed that are vulnerable to particular control strategies (Shea 1996). More detailed analyses of the data sets summarized here will permit the development of models of population dynamics of *Onopordum* thistles that should help guide the development of integrated management strategies for these noxious weeds.

Acknowledgments

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The demography of *Carduus nutans* as a native and an alien weed

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Summary

Comparative demographic and phenological studies of nodding thistle, *Carduus nutans*, populations were carried out in both native (European) and Australian localities over at least three years or until the population became extinct. Seed banks under established thistle populations were at least 100 times greater in Australia. Germination was largely restricted to spring and autumn in Europe, but occurred in all seasons in Australia. Most plant mortality occurred soon after germination and was far higher in Australia where seedling densities were also higher (>500 cf <55 m^{-2}). In Australia a higher proportion of the winter and summer recruits survived to flowering than autumn and spring recruits. Most plants in both regions behaved as biennials, flowering after their first winter. Flowering plant density (× 2), capitula per plant (× 3) and actual seed rain (× 100) were greater in Australian thistle populations, where the flowering season was also nearly 50% longer. These differences are discussed in relation to this thistle's greater importance as a weed in Australia, and to provide insight into its potential control strategies.

Introduction

The recent Biology of Australian Weeds chapter on *Carduus nutans* ssp. *nutans* L. (Popay and Medd 1995) provides a comprehensive review of this noxious weed. In summary, *C. nutans* is endemic to Europe, Siberia, Asia Minor and North Africa, and has become a serious weed in North and South America as well as in Australasia. It was first introduced to Australia in the late 1940s as a seed contaminant, which happened repeatedly until it was declared a prohibited contaminant in the 1960s. It is spread over tens of thousands of square kilometres in Tableland New South Wales, and it also occurs sporadically in Queensland, Victoria and Tasmania. It has the potential to spread further, especially in New South Wales (Popay and Medd 1995). As part of a prerequisite for a biological control program, basic ecological studies were mounted in both its native range, and in Australia. These data were to determine which ecological factors were having a controlling influence on the population dynamics of *C. nutans* in the two areas where the plant has a contrasting weed status. The Australian data were also to provide baseline data to assess the impact of any organism released to control the weed.

Materials and methods

Study sites for thistle populations (usually 20 × 30 m) were selected in both France and Australia. The procedures adopted in France for demography / phenology and soil seed bank determination have been detailed in Sheppard *et al.* (1990, 1994). Similar procedures were used in Australia, excepting that 10 permanent quadrats (0.5 × 0.5 m) were used. The plant populations at these sites were monitored every six weeks over several years. On each visit any seedling recruitment was recorded. The growth of individual plants was assessed on each visit. Each plant was given a unique number and had its position in the quadrat determined. Additional visits were undertaken each fortnight in the flowering season. Data collected on these visits included measurement of flowering capitula. The season of recruitment and time to flowering were used to classify plants / cohorts into summer annuals (germinated in spring and flowered in the next summer), winter annuals (germinated in autumn and flowered in the next summer), biennials (completed whole life-cycle in more than one, but less than two calendar years and triennials (completed life-cycle in more than two years). The number and sizes of capitula matured per plant and per square metre were used to measure the potential seed rain (see Woodburn and Cullen 1993), whilst in France the actual seed rain was measured by collecting mature capitula before seed fall and counting the numbers of viable in the laboratory. The proportion of the seed rain destroyed by insects in the capitula was estimated from the difference between actual and potential seed rain. The maximum annual soil seed banks were estimated in France and Australia by washing and sieving 100 random soil cores (10 cm deep and 3.2 cm diameter) from each study area in late autumn following the seed rain.

Results

Details of one French site, and part of one Australian site are presented in Figure 1a and b. For ease of visual display these data have been summed over two recording times, corresponding by and large to a season, and then averaged. Detailed results are to be found for part of another French site in Sheppard *et al.* (1990). Differences in plant and population measurements over all sites are summarized in Table 1.

Recruitment, survival and life history

Germination followed rainfall in both regions. In France germination was therefore limited to spring, summer and autumn (Figure 1a), but recruitment in summer was not observed at all sites (Sheppard *et al.* 1990). In Australia recruitment occurred throughout the year and at much higher densities than in Europe (Figure 1b) due to the higher soil seed bank (see below). Most plant mortality occurred soon after germination. Plant survival was higher in France than in Australia for both seedlings to rosettes, and from rosettes to flowering (Table 1). Competition resulting from high seedling densities recorded in Australia (often >500 m^{-2}) would have contributed to this. In Australia, higher proportions of the winter and summer recruits survived to flowering than autumn and spring recruits. In France, survival to flowering was higher among autumn recruits than spring recruits largely because the hot dry southern French summers induced higher mortality in the smaller spring germinated rosettes (Sheppard *et al.* 1990). In certain years densities of flowering plants fell to similarly low levels corresponding to very dry periods in either region, but in good 'thistle years' the difference in flowering plant density was 6.8 times greater in Australia than in Europe. In both regions, plants mostly took between one and two calendar years to complete development; one cohort flowered in its third year in Australia (triennial). Winter annual cohorts occurred in both regions, but were more common in France. Also, two of nine cohorts followed in France, (same year different sites), behaved as summer annuals. *C. nutans* has a vernalization requirement for floral development (Popay and Medd 1995). Summer annual cohorts were possible because the spring recruitment was vernalized as seedlings. This life history was not observed in Australia.

Flowering period

Individual plants and populations flowered for longer in Australia (Table 1), and the average number of capitula produced plant^{-1} was greater in Australia than in France for similar life history strategies. Biennial plants produced more capitula than either of the two annual flowering strategies (Sheppard *et al.* 1990). Despite these differences large biennial plants of similar reproductive potential did occur in both regions (Table 1).

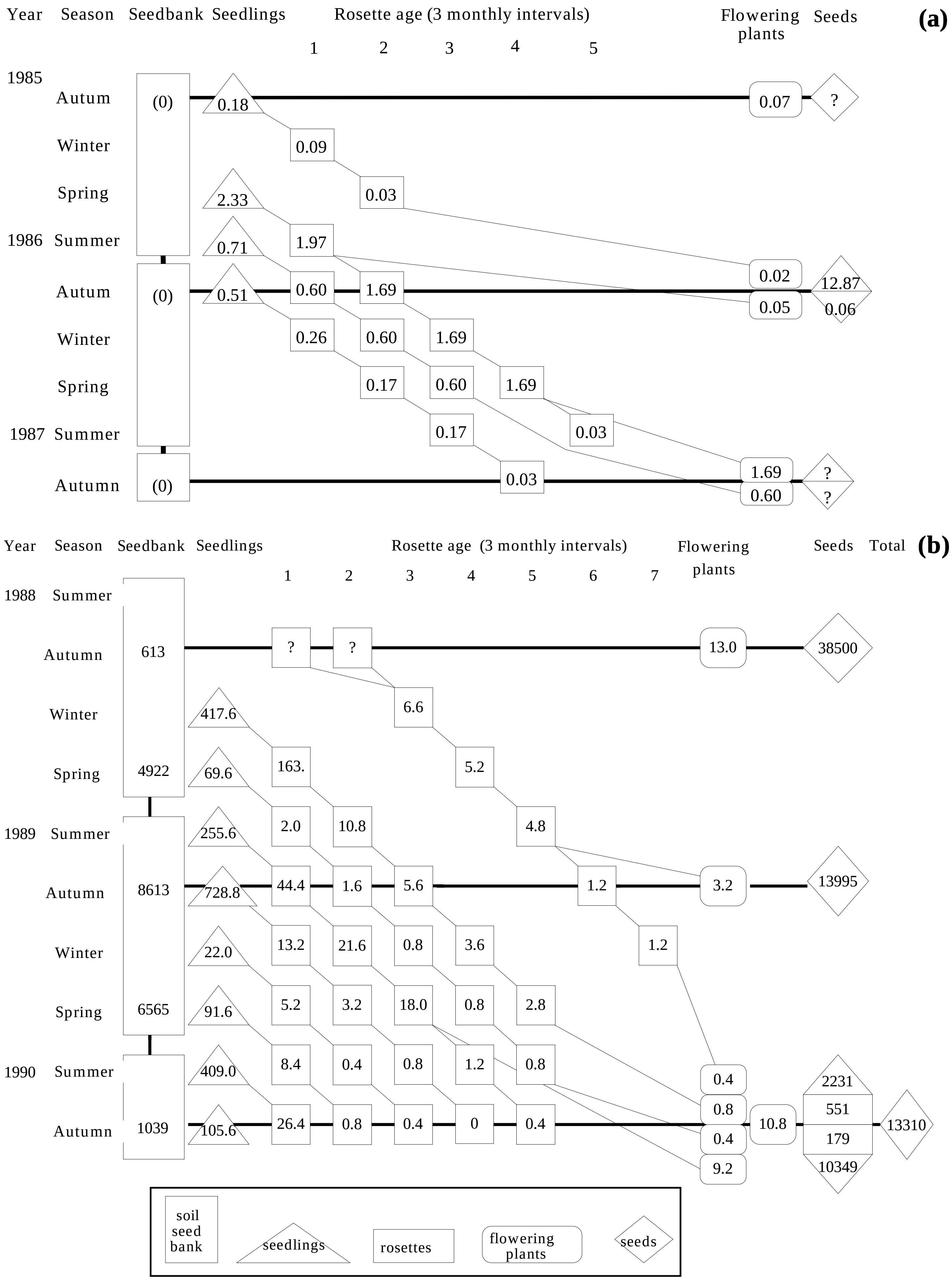

Figure 1. Demography of the different developmental stages of *C. nutans* for cohorts germinating during differing seasons. The numbers are individuals per square metre. Figure 1a show data from France, 1b show data from Australia.

Table 1. Summary of population demography/phenology of *C. nutans* in Europe and Australia (numbers are expressed as per square metre unless indicated otherwise).

Attribute	France	Australia
Seed bank range	undetectable–140	3000–13 000
Prop. seedbank that recruits	0.02–0.67	0.02–0.23
Recruitment	spring, (summer) and autumn	all seasons
Seedling density	0.18–54.3	2.4–728.8
Seedling survival (prop.)	0.69 (0.12–0.93)	0.26 (0.02–0.83)
Rosette survival (prop.)	0.58 (0.22–1.0)	0.16 (0.0–0.61)
Flowering type (prop of cohorts followed)	summer annuals (0.18) winter annuals (0.27) biennials (0.55) triennials (0)	summer annuals (0) winter annuals (0.1) biennials (0.8) triennials (0.1)
Flowering plant density	0.03–4.7	0.02–13.0
Flowering period of population (months)	4 (June–September)	7 (November –May)
Flowering period of individuals (weeks)	8 (2–14)	10.2 (2–19)
Av. no. mature capitula / biennial plant	7 (2–93)	29.3 (2–120)
Potential seed rain	13–4261	171–38 500
Actual seed rain	0.4–240	171–38 500
Actual (potential) seed production / plant	0–1116 (6978)	57–24 334
Proportion seed destroyed	0.82–0.99	0

Seed production and seed banks

Potential annual seed rain was 10 times greater in Australian than in French populations, although the observed seed rain and the existing seed bank under a range of high density populations was two orders of magnitude greater in Australia than in France. The high seed banks in Australia suggest that the weed is rarely seed limited in this region. This is supported by the observation that a lower proportion of the seed bank successfully germinates and recruits in any given year in Australia than in France. The seed bank decay rates could not be estimated as no sites were available where seed rain had been prevented over several seasons. The proportion of the seed rain that enters the bank may also explain why the population dynamics of this weed varies between the two regions as this will indicate the levels of post-dispersal seed predation, for example. However, the seed bank sampling protocol used was not sufficiently detailed to allow accurate assessment of this parameter in France.

Discussion

These data provide some understanding as to why this plant is a more serious weed in Australia than in its native range. In Australia, there is a longer flowering season and a higher seed production per plant resulting from both the greater plant size and the absence of any specific seed predators (Sheppard *et al.* 1994). This has enabled the plant to lay down large soil seed banks which in established thistle infestations always stabilize an order of magnitude greater than in the weed's home environment. Other factors not specifically measured here, such as higher post dispersal seed predation and shorter seed survival in the soil, may also be important (Sheppard 1996). The large seed bank leads to higher densities of seedlings and ultimately of flowering plants, as seed limitation (the successful occupancy of all germination microsites) no longer inhibits recruitment. Australian thistle infestations appear to be above the threshold where seed-limitation is important. They are also not in a situation where populations tend to be limited by the chance that a seed will successfully produce a flowering plant. Evidence for this are the lower proportion of the seedbank that successfully recruits in any given year in Australia and the lower survival to flowering than in France. Modelling the dynamics found in these thistle populations will help determine the level of seed production control necessary to force Australian *C. nutans* populations below the threshold where they become seed limited (Shea 1996).

Successful weed control will have been achieved if the dynamics of this weed in Australia are manipulated such that they are similar to those found in the French populations studied. This requires a reduction in the size of the seed bank either directly, by using such practices as will reduce seed bank persistence (e.g. regular cultivation) or indirectly by using biological control agents (Woodburn and Briese 1996) to reproduce in Australia the levels of seed predation observed in Europe. This will reduce both the rate at which seed banks are replenished, as well the spread of the weed. Additional practices, such as spray-topping and graze-topping, (to reduce seed production), and better pasture management (to reduce the availability of suitable germination microsites and increase the levels of pasture competition), will also contribute to this goal.

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Necessary background for studies in the taxonomy of *Onopordum* in Australia

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Summary

In the absence of a recent and informed world revision of *Onopordum* it is very difficult to ascertain just which taxa occur thoroughly naturalized or as casuals in Australia. Three species, *O. acaulon* L., *O. acanthium* L., and *O. illyricum* L., are commonly listed as widespread and hybrids between the two latter have been suggested. In Flora Europaea, various subspecies of these three species have been included. In the Flora of New South Wales, occurrences of *O. acanthium* are restricted to *O. acanthium* ssp. *acanthium* and of *O. illyricum* to *O. illyricum* ssp. *illyricum*. *O. tauricum* Willd., *O. leptolepis* DC. and what I consider to be *O. arabicum* L. (usually known as *O. nervosum* Boiss.) have been found or may possibly occur as casuals in Victoria. In this paper, attention is given especially to difficulties in the typification of *O. illyricum* L. Doubts are expressed as to the validity of using *O. illyricum* for some of the plants so called in Australia and evidence is given suggesting that other taxa not yet recorded here may be involved. Material is also presented relevant to the origins, cultivation and naturalization of the genus.

Introduction

Of the thistles in the tribe Cynareae naturalized in Australia, the taxonomy of *Onopordum* as it occurs in south-eastern Australia is the most complex, particularly as it relates to plants called *O. illyricum* L. (Illyrian thistle) and to plants showing affinities with *O. illyricum* and *O. acanthium* L. (Scotch thistle). These latter are referred to as 'perhaps hybrids' by Michael (1968) and 'this intermediate taxon' by Groves *et al.* (1990). Parsons and Cuthbertson (1992) refer to the existence of 'a complex' consisting of Scotch and Illyrian thistles and their 'intermediates' in New South Wales. This paper is an attempt to place these thistles in proper taxonomic perspective.

Origins and cultivation

The genus *Onopordum* shows greatest diversity in south-western Asia and the Aegean region, extending west in countries to the north (Europe) and south of the Mediterranean Sea (North Africa) as far as the Canary Islands, further north in European Russia and east as far as Pakistan and Kashmir, Mongolia and north-western China. *O. acanthium,* the type of the genus and the most widespread species in Europe and Asia, originated in south-west Asia and is now a plant of disturbed sites, often rather uncommon, almost throughout the whole area specified.

There appear to be some 50 species, but there has been no recent world revision, the last attempt being made by Rouy (1896) who included 24 species with a number of infra-specific taxa of varying and often questionable status. Dress (1966) in his treatment of cultivated species indicated the need for such a revision and Danin (1975) has noted that the genus has been poorly collected. In my examination of regional accounts published since 1920 (Academia Sinica 1987, Arènes 1941, Danin 1975, Eig 1942, El-Karemy and Zahreh 1991, Feinbrun-Dothan 1977, 1978, Franco 1976, Hossain and Aziz-Al-Sarraf 1982, Meikle 1985, Mouterde 1983, 1984, Murbeck 1921, Pérez de Paz 1981, Pignatti 1982, Polunin and Stainton 1984, Rechinger 1979, Sierra *et al* 1992, Sventenius 1960, Tamamshian 1963 and Valdes *et al.* 1987) the need for clarification of some species and their relationships has become acutely obvious.

The intentional use of *Onopordum* as the heraldic or Scotch thistle has undoubtedly led to its inclusion in gardening publications and catalogues. An examination of such publications (Anonymous 1825, Anonymous 1857, Bailey 1901, 1916, 1947, Bailey and Bailey 1941, 1976, Donn 1845, Francis 1859, Fraser and Hemsley 1917, Hellyer 1952, Huxley 1992, Johnson 1852, Loudon 1872, and Stuart and Co. of London and Nice 1911) shows that seventeen species under the names given in Table 1 have been cultivated and indeed some still are.

Occurrence outside Eurasia and North Africa

All species names so far recorded in Australian floras (Willis 1972, Jessop and Toelken 1986, Harden 1992) are included in this list, namely *O. acanthium*, *O. acaulon*, *O. illyricum*, *O. leptolepis* and *O. tauricum*, to which may be added *O. arabicum* collected in central Victoria in 1962. The three latter

Table 1. *Onopordum* species listed with appropriate synonyms and areas of origin. Dates of introduction into the horticultural world are given after some of the names according to Fraser and Hemsley (1917).

Onopordum spp.	Date	Area of origin
O. acanthium L., including var. *alba* Hort. and the cultivar Robert Bruce		South-western Asia
O. acaulon L. (syn. *O. pyrenaicum* DC., *O. uniflorum* Cav.)	1739	South-western France and Spain, north-west Africa
O. alexandrinum Boiss.		Egypt
O. algeriense (Munby) Pomel		Algeria
O. anatolicum (Boiss.) Eig		North-western Turkey and Anatolia
O. arabicum L., sometimes as *O. nervosum* Boiss. which I consider to be a synonym.	1686	Southern and central Iberian Peninsula
O. armenum Grossh.		Armenia, Anatolia, Caucasus, Iran
O. bracteatum Boiss. and Heldr. (syn. *O. insigne* Holmboe)	1901	Southern Balkan Peninsula and Aegean region
O. caulescens D'Urv. (syn. *O. sibthorpianum* Boiss.)		Aegean region
O. heteracanthum C.A. Mey.		Iraq, Iran, Caucasus
O. illyricum (syn. *O. graecum* Gouan, according to Rouy (1896), *O. elongatum* Lam., a superfluous name)	1640	Southern Europe
O. leptolepis DC.		Iraq, Iran, Caucasus, Afghanistan, Pakistan, central Asia, north-west China
O. macracanthum Schousboe	1798	Iberian Peninsula and north-west Africa
O. murbeckii H. Lindberg		Morocco
O. polycephalum Boiss.	1904	Turkey
O. salteri Hort.	1909	Unknown
O. tauricum Willd. (syn. *O. elatum* Sm., *O.virens* DC., *O. viscosum* Schrad.)	1816	South-eastern Europe and south-western Asia

species may still occur as casuals in Victoria.

The three species *O. acanthium*, *O. illyricum* and *O. tauricum* have also been recorded from disturbed sites in California (Hickman 1993). *O. acanthium* is sparingly naturalized over much of the United States and southern Canada (Gleason and Cronquist 1991) and is one of two species recorded for Argentina (Cabrera 1971) the other being *O. arabicum* (Hauman 1928). *O. acanthium* also occurs in Chile (Matthei and Marticorena 1990) and New Zealand where *O. tauricum* has been collected only once (Webb *et al.* 1988). For brief information on the history of *Onopordum* in Australia, accounts are given under *O. acanthium*, *O. illyricum* and *O. acaulon* in Parsons (1973), Parsons and Cuthbertson (1992) and Kloot (1986).

Taxonomy of the most common species.

Occurrences of *O. acanthium* in Australia according to Jessop and Toelken (1986) and Harden (1992) are of *O. acanthium* spp. *acanthium*, but no one has yet examined a wide range of specimens from Australia to see if other infraspecific taxa are involved. Similarly *O. acaulon*, whose occurrences cover the widest distance in Australia, from Western Australia to the New England region of New South Wales, has not yet been examined in detail to see whether subspecies recorded for Europe are also here.

As indicated in the introduction, the main problem concerns *O. acanthium* and *O. illyricum* and forms having affinities with either or both of these species. The use of *O. acanthium* in the floras or treatments already referred to offers few difficulties in interpretation. There are many good illustrations of it in the literature—for example Parsons and Cuthbertson (1992), Cabrera (1971), Jessop and Toelken (1986), Rechinger (1979) and Polunin (1969). It is the species best known in Europe and has been typified by Danin (1975).

With *O. illyricum*, however, there are difficulties which must be resolved in order to understand the plants occurring so abundantly in southern New South Wales. Following the advice of W.T. Stearn, Danin (1975) chose as lectotype the illustration in L'Obel (1581) referred to by Linnaeus (1753), presumably because he could find no satisfactory herbarium specimen to meet the criteria demanded. I have not seen the particular illustration but have seen an earlier one in L'Obel (1576) which is identical with that in Dodoens (1616). There is also a similar illustration in Bauhin (1651), published posthumously. Bauhin (1651) describes how the seed of the plant was procured in Slavonia by Valérand Dourez, and grown in Bauhin's garden in Lyon in France where L'Obel first saw it. There is a later and similar illustration of the plant in Morison (1699).

I believe that all these reproductions clearly represent the same taxon and give a good idea of what the plant in a number of Linnaeus' citations actually looked like. Many plants in southern Australia and in Europe with heads with broad phyllaries, 5 mm or more at their widest part and sharply reflexed and which are called *O. illyricum* today—for example, those illustrated in Parsons and Cuthbertson (1992) and Polunin (1969)—belie this typification.

Accordingly, I believe that these plants with such phyllaries cannot legitimately be called *O. illyricum* L. This does not mean, however, that the name must be abandoned in New South Wales for it seems to be appropriate to use it for many of the plants that appear to have affinities with *O. acanthium* and / or *O. illyricum*. They certainly fit the Latin diagnosis given by Linnaeus (1753)—*O. calycibus squarrosis, foliis laciniis pinnatifidis*. Dodoens (1616), Bauhin (1651) and Morison (1699) also refer to the deeply dissected leaves. The leaves are to be contrasted with those of *O. acanthium* which are much less so, sometimes almost sinuate.

I believe that the error in the application of *O. illyricum* may well be of long standing. When Lamarck (1779) separated his *O. elongatum* (a superfluous name for *O. illyricum*) from *O. acanthium* on the basis of the flowering stems having little development of wings beneath the heads, he probably confused other species from southern France which were similar in this respect. It may be argued that Linnaeus who gave as locality for *O. illyricum* the vague S. Europe, may have had a wider view of the species than I have presented. Morison (1699) however wrote that the plant was spontaneous in Dalmatia, Illyria and Slavonia, areas which can be taken to include the far northern part of the Balkan Peninsula and part of the eastern Adriatic coast, certainly S. Europe to Linnaeus.

Conclusion

What then are we to do with the plants left over? It is important to examine thoroughly the existing literature relating especially to those species which have been cultivated, collect more material where required and to continue close study of specimens. Inspection of authentic material from European and other appropriate herbaria is indispensable. Such studies may well lead to the discovery of taxa not yet recorded for Australia.

There may well be some hybridization within the genus in Australia as there has been reported for Europe (Danin 1975), but I believe that before we invoke hybridization limits must be set on the variation we allow in each species. *Onopordum* is unusual in our thistles and close examination of its many special characters is important. In addition to the obvious features of leaves and phyllaries and the nature of the whole inflorescence, a close study is necessary of the complex corolla consisting of a long more or less S-shaped tube expanding into a campanulate limb variously incised to give rise to five narrow segments. The campanulate base of the limb and the segments may or may not be glandular. Absolute and relative proportions of the structures vary according to species. Pappus hairs may be scabrous, shortly barbed or plumose. The honeycomb-like receptacle may also be worthy of study, not to mention the apical appendage of the anthers and the various features of the achenes.

Without a surer knowledge of the identity of the plants we are working with, how can we communicate with other workers in the field in ecology, control, genetics, serology or whatever study we care to name.

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Longevity of soil based seeds of *Onopordum illyricum*

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Summary

Seeding was prevented for eight years, in a paddock containing a dense population of *Onopordum illyricum*, initially by grazing with mature bush goats for five years, then by chemical/mechanical means. The population of residual soil based seeds was monitored annually following autumn germination. Initially the soil based seed population was estimated to be 5 million seeds per hectare. After four years of seeding prevention, the soil based seed population decreased to 1.6 million seeds per hectare and maintained a steady state at that level. Seedling counts following germination reflect the decline in population of soil based seeds. After five years of seeding prevention in a 2.8 hectare paddock the area was reduced to 0.5 hectare. Within two years of no seeding control the soil based seed population in the foregone 2.3 hectares increased to levels commensurate with the population when monitoring began. Plant counts after seven years were 0.05 and 9 plants m^{-2} in goat and 'no-control' (sheep grazed) paddocks respectively.

Introduction

Longevity of the residual soil-based seed population is an important determinant in devising control or eradication strategies for weeds. Populations of *O. illyricum* are increasing and traditional attempts at control have been thwarted by recurring populations after several years of apparent control of seeding. As a component of an experiment investigating control of *O. illyricum* by grazing with goats (Campbell and Holst 1990), residual soil seed populations were monitored.

Materials and methods

A description of the experiment can be found in Campbell and Holst (1990). Specifically, mature domesticated feral goats at 14 per hectare in a 2.8 hectare paddock successfully prevented any seed replenishing the residual soil based seed population. The experiment commenced in 1988 and was maintained until 1996. In 1993 the paddock was reduced to 0.5 hectare and the goats removed. However, prevention of seeding was continued by spraying and chipping the thistle.

Soil samples were collected following the autumn break in each year; cores to 7 cm depth being taken randomly across the paddock. The number of cores collected each year was modified over the duration of the experiment, but ranged from 150 in the 2.8 hectare paddock to 300 in the 0.5 hectare paddock from 1993 onwards. An adjoining paddock grazed by sheep was also monitored for soil based seeds of *O. illyricum*. The seeds, collected by wet sieving the cores, were cut and their viability determined by the presence of an embryo. Seedling counts were made from random 0.25 m^2 quadrats across the paddock following the autumn break.

Results

The initial viable soil based seed populations in sheep and goat grazed paddocks were 12 and 5 million seeds per hectare respectively. The soil based seed populations of the goat grazed paddock quickly declined over the initial four years to a steady state around 1.6 million seeds per hectare. In the adjoining sheep paddock, where no control was exerted on the flowering thistle, seed populations fluctuated but were significantly higher than the goat grazed paddock (Table 1). Within two years of removing goats from part of the original experimental plot in 1993 and where subsequent ineffectual control was exerted on the thistle, soil based seed populations increased to 11 million seeds per hectare. (Table 1).

Table 2. Seedlings per square metre following the autumn break in goat and sheep grazed paddocks.

	Sheep	Goat
1990	7.7	8.0
1991	22.8	1.5
1992	20.6	2.5
1996	77.0	0.5

Table 1. Viable soil based *Onopordum illyricum* seed (million per hectare) from goat (seeding controlled), ex-goat (seeding controlled for first five years, then ineffective) and sheep (seeding not controlled) grazed paddocks.

	1989	1990	1991	1992	1994	1995	1996
Sheep	12	30	32	17	19	43	23
Goat	5	3.5	4.0	1.6	1.2	1.8	1.6
Ex-goat					11.0	19.0	7.0

Seedlings

Counts of rosettes at the two leaf stage reflected the decline in soil based seed within the goat grazed paddock (Table 2).

The number of established thistle plants in May 1996 was 0.05 and 9 plants m^{-2} in goat and sheep grazed paddocks respectively.

Discussion

Soil based seeds populations of *O. illyricum* progressively declined over the duration of the experiment where replenishment of the soil reserve was prevented by grazing with goats. Little or no control was exerted in the paddock grazed by sheep and populations of the soil based seed were maintained at a high level producing significantly higher numbers of seedlings. The cessation of seeding in the goat grazed paddock has produced significant visible differences in frequency of *O. illyricum* when compared to the adjoining sheep paddock. Plants are still present in the goat grazed paddocks, however, at levels of 0.05 m^{-2}, the population is more manageable and pasture production greater than in the adjoining paddock where pasture had been greatly reduced due to thistle density (Allan *et al.* 1993).

After reducing the seed population in the soil for five years, it rose within two years of ineffective control of seeding to a level commensurate with the level at the start of monitoring. This has direct implications for the development of control programs which must annually prevent seeding. Also, because soil based seeds have a strong dormancy characteristic (Young and Evans 1972), a management strategy would need to be implemented over a long period to be successful (Campbell *et al.* 1991).

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Impact of seed reducing natural enemies on weediness of thistles

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Summary

The impact of biological control agents introduced around the world to control thistles has resulted in some success with seed-reducing agents contributing to this process. This short paper reviews the knowledge on seed-losses to endophagous insects for Australian thistles in an attempt to suggest where such insects may have a role in future biological control programs. It also illustrates how, in addition to direct seed losses, natural enemies can affect the spread and long-term viability of seeds that escape destruction, thereby reducing regrowth potential of declining thistle infestations.

Introduction

Causing high seed loss is the dominant strategy of most thistle control, as thistles tend to reproduce only by seed, generating soil seed banks that generally determine the outbreak potential of these weeds (Sindel 1991). Biological control applies this strategy by attempting to duplicate in Australia the seed losses to natural enemies found in the native range. This strategy is built on the assumption that control agents, if similarly destructive, should reduce a thistle's status in Australia to at least that found in the native range. This assumption is supported by example: the successful control of nodding thistle (*Carduus nutans*) in parts of North America (Harris 1984, Kok and Surles 1975), where seed losses to the control agent (approximately 50%) were comparable with the native range. This case history however belies explanation on two counts. First, simple models (Lashley 1969, Shea 1996) fail to explain how control was achieved, and second, control has not been replicated in other countries despite similar seed predation levels (Woodburn and Cullen 1993, Kelly and McCallum 1995).

This paper explores the general applicability of the seed loss strategy in biological control of Australian thistles described above by reviewing the potential for seed loss to candidate control agents. It then explains how direct seed-losses to biological control agents can have non-linear effects on both short and long distance seed dispersal capability. This is used, together with other ways that seed-reducing agents may indirectly reduce the growth rate of thistle infestations, to suggest why some such agents may contribute more to thistle control than is at first apparent.

Seed predation

If the introduction into Australia of seed-reducing insects on thistles is going to contribute to thistle control, then it is important to know their likely destructive capacity. Figure 1 shows the levels of seed-loss per plant recorded for thistles known to occur in Australia from both inside and outside (not necessarily Australia) the native range. The data from the native range have been collected from a number of studies (Sheppard 1996). Information is still unavailable for several thistles in regions where agents have been only recently or have never been introduced. However two features come out of this figure. Firstly, general seed losses in the native range are far less than 50% for most species; nodding thistle, Illyrian thistle (*Onopordum illyricum*) and artichoke thistle (*Cynara cardunculus*) being the exceptions. This begs the question as to whether releasing seed-reducing biological control agents against thistles other than on these three will be of any value. Secondly, in four out of five cases where data are available, insects released as biological control agents have caused more seed loss outside their native ranges; nodding thistle being the exception. While acknowledging the first feature, this is in general encouraging for biological control and probably results from relative differences in the ease with which capitula are located between the native and introduced regions (thistle abundance) and the fact that most biological control agents are released without any of their parasites/predators (Sheppard and Woodburn 1996).

Mathematical models used to predict the likely impact of seed reducing agents in biological control usually indicate that very high levels of seed loss (>90%) are necessary to cause weed populations to become sufficiently seed limited to force the net growth rate below 1 (Lashley 1969, Forrester 1995, Paynter *et al.* 1996). Only one nodding thistle model suggests that observed seed losses (at least those in the native range, Figure 1) might be sufficient (65%, Shea 1996). None would have successfully predicted the control of nodding thistle achieved in North America. This leads to two questions addressed in the remainder of this paper:

i. what features not included in these models might explain why lower levels of seed loss can contribute to thistle control (e.g. the case of nodding thistle)? and
ii. is the strategy of introducing seed-reducing biological control agents against thistles still justified in most cases?

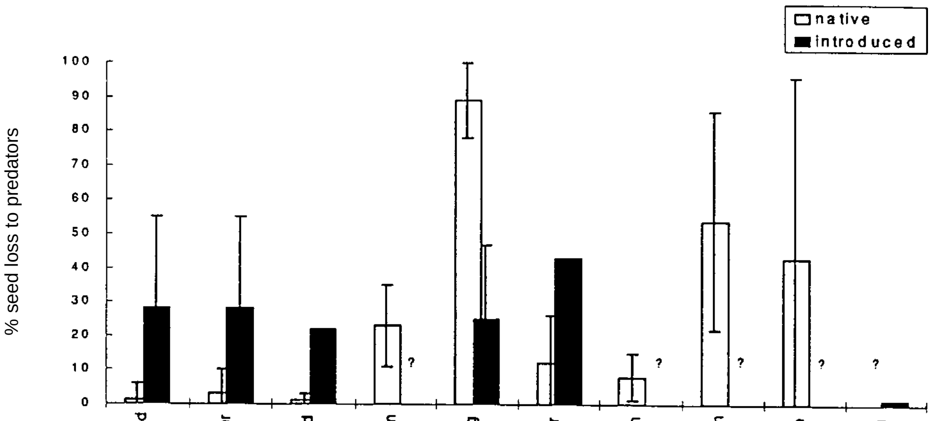

Figure 1. Seed loss (mean ± range) to seed reducing insects for ten Australian thistles both in the native range (white) and elsewhere where they have been introduced and subjected to biological control programs (black).

Seed dispersal

Thistles depend on three general types of dispersal for invasion and the establishment of new infestations:

i. local dispersal, where seeds are dropped directly from or remain in the capitulum,
ii. wind-born dispersal involving a pappus that varies in effectiveness between species, and
iii. long distance dispersal, where seeds are fortuitously carried a greater distance by some vector (animal, man or vehicle).

In some species, dispersal types one and two are associated with different seed morphs (Olivieri *et al.* 1983). In all types, the slope of the seed dispersal profile (any relationship of seed rain (y, usually log transformed) against distance (x)) will be shallower the further the seed are dispersed. There are two conceivable ways that seed predators can affect such relationships and thus influence the ability of a thistle to spread.

Firstly, direct seed losses will have a greater impact on long distance spread than they will on local dispersal because of the slope of the dispersal profile (Figure 2, Lonsdale 1993). This is because seed loss will affect the intercept, but not the slope of the profile and with a lower profile there will be a greater reduction in distance dispersed. To expand this, a thistle species with a well developed pappus will have a greater dispersal capability, but it will also be more prone to having that capability curtailed through seed-loss, assuming equal levels of seed production. This is the simple way seed-reducing insects can limit the invasibility of a thistle species.

Secondly, seed-reducing insects may be able to steepen the slope of the seed dispersal profile, particularly for wind-born dispersal, by reducing the proportion of viable seed leaving a capitulum with an intact pappus as a result of their disruptive feeding activities in the capitulum. While this has never been tested, seed dispersal profiles generated, for example, from data collected by Kelly *et al.* (1988) for nodding thistle appear to have a steeper profile in a year when the receptacle weevil was more abundant (these data were too few and unsuitable to test such a hypothesis).

Seed longevity

The activities of seed reducing agents in capitula may also reduce long-term viability of seeds that escape destruction and thereby reduce regrowth potential of declining thistle infestations. Viable seeds that drop from capitula that have had their receptacles bored out by insects are less likely to be either the same mean weight or as perfectly formed as seeds from undamaged capitula. Such seed may well be shorter-lived than normal seed and as such may contribute little to a long-lived seed bank. This hypothesis was tested when seed from damaged capitula of nodding thistle were sown into both a cultivated pasture (5000 m^{-2}) and buried in muslin bags (100 seeds per bag) at different depths in the native range. Seeds of similar weight from unattacked capitula imported from Australia (as nearly all capitula in the native range are attacked by insects), were buried in identical muslin bags as part of the same experiment (Meyer 1991). The Australian seed also had the same viability and germinability (results from tetrazolium and germination tests) as the seed from attacked heads (Meyer 1991). The sown seed bank in cultivated pasture had disappeared within 12 months of sowing (Sheppard unpublished data), whereas a seed bank of this size in Australia has much greater longevity (T. L. Woodburn personal communication). After 120 days, the seeds in the muslin bags from damaged heads had significantly lost viability by 15% while the seeds from intact heads were all recovered and viable (Meyer 1991).

Conclusions

In the last two sections of this paper I have attempted to outline subtle and rarely considered ways in which seed-reducing biological control agents can reduce the invasive ability of their host thistles. Such effects may partially explain the differences between successes worldwide in the biological control of thistles and the predictions of ecological models designed to explain them. Together with the observations that seed-losses are often greater following biological control attempts than in the native range (Figure 1), these effects offer optimism for the continued use of such insects as agents against thistles as yet untested. The equal success of other sorts of insects as biological control agents should also not go ignored and careful ecological consideration should take place before any agent type is introduced against thistles.

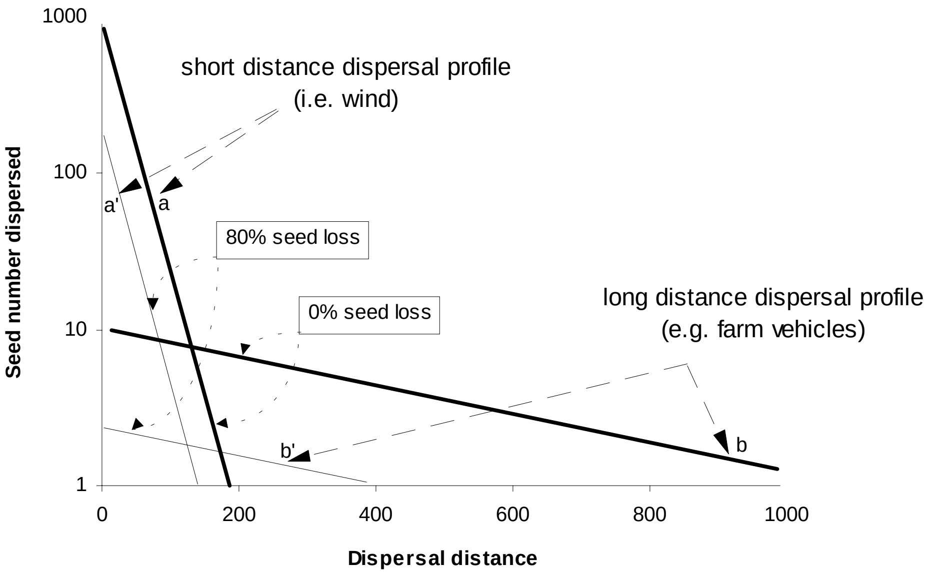

Figure 2. Effect of seed losses on potential dispersal distance. Given two types of dispersal (short and long distance), a similar percentage of seed loss will cause a much greater reduction in dispersal distance for long distance dispersal strategy (b → b') than for a short distance dispersal strategy (a → a'), because of the lower seed dispersal profile (adapted from Lonsdale 1993, Figure 9).

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Ecology of *Cirsium vulgare* and *Silybum marianum* in relation to biological control

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Summary
Spear thistle (*Cirsium vulgare*) and variegated thistle (*Silybum marianum*) are two of the most widespread thistles which infest pastures in temperate southern Australia. A biological control program targeting these thistles was commenced in 1985. No specific ecological studies of these thistles and their predators in the area of origin aimed at the selection of insects for release in Australia, have been carried out. Insects have been released in Australia, based on data from biocontrol programs against these thistles elsewhere in the world. This paper reviews the literature on ecological studies of these thistles and the effects of their predators. Additional studies from Victoria are summarized. Progress towards the classical biological control of these weeds in Australia is outlined and conclusions are drawn on the chances of success using the agents currently available.

Introduction
Spear and variegated thistles (*Silybum marianum* and *Cirsium vulgare* respectively) are two of the most widespread thistles in temperate eastern Australia (Briese 1988, Parsons and Cuthbertson 1992). In an extensive review of the ecology and control of thistles in Australia no comment was made on the implications of this information for their successful biological control (Sindel 1991). Biological control programs, commenced in Australia in 1986, are opportunistic in that they utilize insect species already introduced into other countries. There are considerable European ecological data on spear thistle and the effects of general predation on population dynamics (van Leeuwen 1983, de Jong and Klinkhamer 1988a,b, Klinkhamer *et al.* 1988, Klinkhamer and de Jong 1993) as well as the insect fauna associated with spear thistle (Redfern 1968, Zwölfer 1965, 1972). Detailed European ecological data are lacking for variegated thistle, but its insect fauna has been documented (Zwölfer 1965, Goeden 1976). This paper compares European and Australian information on plant population dynamics of spear and variegated thistle, outlines progress in the biological control of these two weeds in Australia and elsewhere and discusses this information in relation to successful biological control.

The ecology of spear thistle
Spear thistle is an annual or biennial herb, depending on its time of germination. Although seed can germinate at any time of the year, there are two main germination times in late-summer to autumn and late winter to spring (Bruzzese and Heap unpublished). Because of this, infestations can consist of plants of different size and ages. Seedlings develop into rosettes, up to 60 cm diameter, which generally require vernalizing before flowering can occur. Plants resulting from autumn germination become winter annuals and flower the following summer (6–9 month life-cycle). Plants that germinated in late winter-spring act as biennials, growing as rosettes through summer, autumn and winter and flowering the following summer (12–15 month life-cycle). A small percentage of plants which germinate in summer become summer annuals, flowering in autumn. Flowers appear in December to February and later in higher rainfall areas. Plants die after flowering and dead plants can remain standing for one or two years.

Seed production
Three populations of spear thistle were studied at grazed sites in Victoria in 1986–87. Seed production per plant (Table 1) at the three sites (2668, 4207 and 19 343) was much higher than that recorded in coastal sand dunes in Holland (246–2500 over a five year period on plants undamaged by predation (Klinkhamer and de Jong 1993)). It was however comparable to Australian values reported by Forcella and Wood (1986).

Soil seed bank
Soil seed banks in Victoria (Table 1) show a yearly pattern of replenishment after seed dispersal, followed by a marked decrease throughout the following year. The most important decrease, which ranged between 83 and 99%, was caused by germinations following the autumn rains. From the results, seed input occurs from December to March indicating a very long flowering and seed set period for spear thistle. Seed banks were lower during the second year of monitoring.

Victorian results are comparable to those obtained by Roberts and Chancellor (1979) in England who found that more than 90% of all seeds germinated within one year after production. Klinkhamer and de Jong (1993) estimated that less than

1% of seed produced is still viable the following winter and suggested that there is no persistent seed bank. Victorian studies did not include observations on seed longevity in the soil but Roberts and Chancellor (1979) found a few seeds dormant after five years. Extrapolations on our seed bank indicated that without seed replenishment only one to two viable seeds 100 m^{-2} would remain after five years.

Table 1. Spear thistle seed production, soil seed bank and plant density over time at three sites in Victoria.

Site	Lang Lang	Derrinallum	Wodonga
Seed production January 1986			
Flowering plants m^{-2}	2.8	6.1	2.6
Heads per plant	53.8	9.3	115.9
Seeds per head	78.2	286.9	166.9
Seeds per plant	4207	2668	19343
Seeds m^{-2}	11779	16274	50291
Soil seed bank (viable seeds m^{-2})			
March 1986	4260	3496	2355
May 1986	716	302	37
September 1986	180	175	35
April 1987	647	1389	–
October 1987	21	748	42
Plant density (plants m^{-2})			
March 1986	2.2	2	4.7
May 1986	33.6	390.5	68
August 1986	24.8	27.5	11.2
November 1986	2	11.2	0.2
January 1987	0.5	6.2	0.5
April 1987	12.1	6.7	–

Table 2. Insect/mite predators and fungal pathogens of spear and variegated thistles in Victoria.

Name	Plant part	Host
Insects and mites		
Hemiptera:		
Nysius clevelandensis	flowers	*Silybum marianum*
Capitophorus elaegni	leaves	*Silybum marianum*
		Cirsium vulgare
Brachycaudus helichrysi	leaves	*Cirsium vulgare*
Myzus persicae	leaves	*Silybum marianum*
Coleoptera:		
Arsipoda chrysis	leaves	*Cirsium vulgare*
Stegobium paniceum	dry seedhead	*Silybum marianum*
Lasioderma sp.	dry seedhead	*Silybum marianum*
Cortinicara hirtalis	dry seedhead	*Silybum marianum*
Edusella lineata	leaves	*Cirsium vulgare*
Corticaria japonica	dry seedhead	*Silybum marianum*
Teretrius sp.	flowers	*Cirsium vulgare*
Desiantha caudata	leaves	*Silybum marianum*
Phlyctinus callosus	leaves, stems	*Cirsium vulgare*
Melanophthalma sp.	leaves	*Cirsium vulgare*
Sericoderus sp.	leaves	*Cirsium vulgare*
Lepidoptera:		
Tebenna bradleyi	leaves	*Cirsium vulgare*
Epiphyas postvittana	leaves	*Silybum marianum*
Heliothis punctigera	leaves	*Cirsium vulgare*
Vanessa kershawi	leaves	*Cirsium vulgare*
		Silybum marianum
Acarina		
Tetranychus urticae	leaves, stem	*Cirsium vulgare*
Halotydeus destructor	leaves	*Cirsium vulgare*
Fungal pathogens		
Alternaria sp.	leaf spot	*Silybum marianum*
Ulocladium sp.	leaf spot	*Silybum marianum*
Trichoderma piluliferum	stem rot	*Silybum marianum*
Septoria silybi	leaf spot	*Silybum marianum*
Puccinia cnici	rust	*Cirsium vulgare*

Seed, seedling and plant survival to flowering

In Holland, losses in the seed stages were severe (97%), with losses in the seedling stage accounting for 67% of seedlings (Klinkhamer and de Jong 1993). When seed production was compared to the seed banks in Victoria (Table 1), losses between 64 and 95% were found to occur between January to March 1986. In the ACT, Forcella and Wood (1986) found average losses in the seed stage ranged between 85 and 90% while losses in the seedling stage were extremely high ranging between 99 and 99.8%. Losses in the rosette stage were 49% in grazed and 51% in ungrazed pastures.

In Victoria the major increase in thistle density in 1986 occurred in May at all sites (Table 1). The decrease in thistle density from May to November ranged between 94 and 99% indicating that survival from seedling to flowering ranged between 1 and 6%. Although individual plants were not tagged, observations at the three Victorian sites indicate that the proportions of plants is winter annual>biennial>summer annual.

The natural enemies of spear and variegated thistle in Victoria

Before a biological control program against thistles commenced, a survey of the natural enemies of thistles was undertaken to establish if specific natural enemies of thistles were present in Victoria. Table 2 lists insects, mites and fungal pathogens collected and identified on spear and variegated thistle. Inspections were carried out during the seedling (autumn), rosette (winter), cabbage (spring) and flowering/seeding (summer) stages of the thistles' life-cycle. Of the insect predators collected on spear and variegated thistle, only the larvae of the moth *Tebenna bradleyi* was considered damaging. It was found to skeletonize leaves of spear thistle at all sites during the flowering period.

Of the fungal pathogens collected, further studies were carried out on the spear thistle rust *Puccinia cnici* (Bruzzese *et al.* 1988) and the variegated thistle leaf spot fungus *Septoria silybi* (Bruzzese and Predebon 1987). Both fungi are specific to their host and very widespread. *Puccinia cnici* was found to have little effect on above ground biomass of spear thistle in the laboratory (Bruzzese *et al.* 1988) and has little effect in the field. *Septoria silybi*, which is highly virulent to variegated thistle, causes considerable foliar damage in the field and has potential for development as a mycoherbicide.

Table 3. Variegated thistle seed production, soil seed bank and plant density over time at four sites in Victoria.

Site	Euroa	Penshurst	Omeo	Maryborough
Seed production December 1985				
Flowering plants m^{-2}	27	5	40.5	134
Heads per plant	2.1	8.8	1.5	1.2
Seeds per head	76.9	100	65.5	35.9
Seeds per plant	160	876	100	42
Seeds m^{-2}	4329	4382	4060	5664
Soil seed bank (viable seeds m^{-2})				
February 1986	2191	2662.7	6058.4	2111.4
April 1986	509.2	1236.1	4970.9	318.3
July 1986	355.4	933.7	4090.2	620.7
October 1986	376.6	880.6	4334.3	578.2
December 1986	286.4	822.3	3368.7	275.8
March 1987	530.5	1331.5	4058.4	748.0
June 1987	53	1082.2	4286.5	212.2
Plant density (plants m^{-2})				
February 1986	53.2	3	77.2	6.5
April 1986	475.7	382	153.5	2136
July 1986	144.5	1.7	247.7	450
October 1986	64.7	1.2	65.2	347
December 1986	49.7	0.5	2.5	178.5
March 1987	2.9	21	259.2	39
June 1987	7	1.3	48	10.4

Importation of natural enemies from the area of origin of spear thistle

Spear thistle has been the subject of biological control programs in Canada, USA, South Africa and New Zealand (Julien 1992). The insects which attack the weed in its area of origin are known (Zwölfer 1965). No specific ecological studies of the weed and its predators in the area of origin, with regard to with potential impact in Australia, have been carried out. Based on evidence of establishment in other countries, three insects are currently being released on spear thistle in Australia. These are the spear thistle gall fly (*Urophora stylata*), the thistle receptacle weevil (*Rhinocyllus conicus*) and the thistle crown weevil (*Trichosirocalus horridus*).

The spear thistle gall fly

In Europe the gall fly attacks between 20 and 60% of flower heads resulting in seed destruction of between 10 and 60% (Zwölfer 1972). The larvae induce the plant to form woody galls in the flower heads which become physiological sinks for plant nutrients, thus redirecting plant resources from seed production. This insect has been successfully released in Canada, USA and South Africa (Julien 1992). *U. stylata* from south western France was released in southern Victoria in December 1994 in the high rainfall, temperate coastal area. Gall formation occurred at all release sites and the insect successfully overwintered, emerging as adults in early December 1995. At this stage it is too early to confirm establishment. An additional 11 releases were carried out in December 1995, extending releases into drier, Mediterranean type climates.

The thistle receptacle weevil—spear thistle strain

Larvae of *R. conicus* destroy the receptacle of a number of thistle species in Europe. It has been released in a number of countries, including Australia (Woodburn and Cullen 1995) for the control of *Carduus* thistles and in Canada and South Africa for the control of spear thistle (Julien 1992). Zwölfer and Preiss (1983) suggested that an ecotype of *R. conicus*, known to attack 80–100% of spear thistle flowerheads in western France, could be a successful biological control agent. Based on this information, insects from western France are established in South Africa (Zimmermann 1991).

Adults collected in south western France were screened for the debilitating microsporidian disease *Nosema* (Woodburn and Cullen 1995) which commonly attacks *R. conicus* in France. Their progeny were first released at a coastal site near Geelong in 1990 but establishment failed. A release in 1994 at a coastal site in Victoria resulted in recoveries of ovipositing adults in 1995. Releases at an additional five sites occurred in December 1995 increasing the climatic range of releases to colder and drier areas. At this stage it is too early to confirm establishment.

The thistle crown weevil

Larvae of *T. horridus* are known to attack the crowns of rosettes of spear thistle during the winter months (Kok 1975, Jessep 1989). This insect, used for the control of *Carduus nutans* in New Zealand (originally from Germany), is now well established at *C. nutans* sites in New South Wales (Woodburn and Briese 1996). It was first released on spear thistle in Victoria and New South Wales in March 1996. This insect has the potential to reduce the vigour of the weed in the rosette stage.

The ecology of variegated thistle

Variegated thistle is predominantly an annual herb which reproduces by seed and therefore relies on a soil seed bank for population survival. The main germination in temperate, predominantly winter rainfall climate of southern Australia occurs after the first autumn rains, with some emergence in late winter-spring and after summer storms (Bruzzese and Heap unpublished). The majority of plants behave as winter annuals with some plants acting as summer annuals and (rarely) as biennials. Infestations can therefore consist of plants of different sizes and ages. Seedlings develop into rosettes and 'cabbage like' plants which can grow to 1 m diameter before flowering stems develop in spring. Flowering commences in October and is normally finished by early summer, continuing into summer and early autumn in wetter, more temperate areas. Plants die after flowering and dead stems can remain standing for several months.

Seed production

Four populations of variegated thistle were studied in grazed sites in 1986–87. Head and seed production per plant (Table 3) was variable between sites and ranged from 1.2 heads producing 42 seeds to 8.8 heads producing 876 seeds. This is much lower than the per plant estimate recorded in Western Australia of 55 heads producing 6390 seeds (Dodd 1988).

Seed bank

Soil seed banks (Table 3) show a yearly pattern of replenishment in the summer period from December to March followed by a steady decrease in autumn, winter and spring. At all sites, the highest seed levels were in February 1986 and these levels were not reached again during the study. Seed banks ranged from 2111 to 6058 seeds m^{-2}. When seed production was compared to the seed bank, losses of between 39 and 62% were found from December to February. The reduction from February to December 1996 ranged between 44 and 87%. These differences are due to seed predation and seed germination in autumn. Variegated thistle seeds are large and palatable and are eaten by birds and rodents. Evidence of this was observed at all sites. In spite of these losses, large seed banks were maintained at all sites. Michael (1968) found that the soil seed bank decreased by 85% over nine years, from 351 to 48 m^{-2}. In contrast, at a site in central eastern Spain over a two year period, Groves (personal communication) found a seed bank of 25 and 0 m^{-2}.

Seedling survival to flowering

In Victoria, thistle density at all sites increased markedly in March 1986, coinciding with the autumn rains. There was great variability in seedling numbers between sites, ranging from 153 to 2136 m^{-2} (Table 3). From April to December 1986, thistle density decreased between 89 and 99% indicting that only 1–11% of seedlings reach flowering stage. The decrease is due mainly to intra and interspecific competition plus factors such as the presence of red legged earth mites and *Septoria* leaf spot during the seedling stage.

Seedlings were found at all sites in spring and at three sites in summer. The former is contrary to findings by Michael (1968) who found no spring germination. Spring seedlings usually survive but result in small flowering plants in early summer. Summer seedlings survive only if sufficient moisture is available and result in large rosettes which overwinter and flower the following spring, usually having multiple flower stems. In contrast, at a site in central eastern Spain in 1992–95 Groves (personal communication) found an average range of 2.5 to 12.9 seedlings m^{-2} in autumn resulting in 1.6 and 0.5 flowering plants m^{-2} in spring.

Importation of natural enemies from the area of origin of variegated thistle

Variegated thistle has been the subject of a biological control program in the USA (Julien 1992). As with spear thistle, no specific ecological studies were carried out in the area of origin to select agents with the potential to have the maximum impact in Australia. Based on evidence of establishment in the USA, the thistle receptacle weevil, *R. conicus*, is currently being released on variegated thistle in Australia. Two defoliating European rust fungi, *Puccinia mariana* and *P. cruchetiana*, were considered, but not introduced into quarantine because the funding organization recommended that the project concentrate on the field release and establishment of insects already approved for release. Recently, Groves (personal communication) concluded that *P. mariana* was not a strong candidate as a biological control agent, based on his observations in Mediterranean Europe.

The thistle receptacle weevil, variegated thistle strain

Goeden (1976) suggested that an Italian strain of *R. conicus* was the only promising insect candidate for the biological control of variegated thistle in California. It was released in 1972, attacking up to 94% of heads after three years (Goeden and Ricker 1977). This strain was transferred to Texas in 1978 and where it became established (Boldt and DeLoach 1985). Zwölfer and Preiss (1983) suggested that an ecotype of *R. conicus* from southern France had a preference for variegated thistle, and after being screened for *Nosema*, this strain was released at two sites in 1988–89, Omeo in December 1988 but did not establish. Releases in 1994 at Maryborough and Penshurst resulted in recoveries of ovipositing adults in 1995. Four extra releases sites were seeded in November 1995. At this stage it is too early to confirm establishment.

Conclusions

Spear and variegated thistles rely on seed production, adequate autumn / winter soil moisture and lack of competition from other vegetation to maintain populations from one season to the next. A soil seed bank is also important to both species to re-infest areas after soil disturbance. Both species can be managed with appropriate cultural practices; pasture competition during the main germination periods; grazing management to increase competition at critical times; chemical control to reduce dense infestations (Sindel 1991). The aim of biological control of annual and biennial thistles is to reduce seed production either by direct destruction in the flower head or by weakening the plant so that it dies before flowering or produces less seed. European data available on the plant population dynamics and the effects of general predation on spear thistle (van Leeuwen 1983, de Jong and Klinkhamer 1988a,b, Klinkhamer *et al.* 1988, Klinkhamer and de Jong 1993) are of little use in trying to predict which predators will be the most effective in the control of spear thistle in temperate Australia, as they were not collected in comparable climates and grazing regimes which result in the dense Australian infestations. European data on the insects associated with spear and variegated thistle (Goeden 1976, Redfern 1968, Zwölfer 1965, 1972), give an indication of which insects may be of use in Australia, but again were not collected with the aim of predicting which agents may have the greatest impact on plant populations in another part of the world.

Populations of these weeds can be diminished if seed production is reduced from the current level to well below the soil seed bank level just before the main autumn germination period, and preferably to the level after the autumn germination. From Victorian data, spear thistle seed reduction would have to be at least 78% and preferably 96% while variegated thistle seed reduction would have to be at least 50% and preferably 84%.

There is no information on either the impact of *U. stylata* and *R. conicus* on spear thistle in South Africa, or the impact of *T. horridus* in Canada and New Zealand. However, *U. stylata* is capable of reducing seed production in Canada by between 57–62% (Harris and Wilkinson 1981). Assuming that *U. stylata* will result in a similar reduction in southern Australia, *R. conicus* and *T. horridus* will need to reduce seed production by at least an additional 18% to achieve a reduction in plant populations. Establishment and evaluation of the impact of these three insects in Australia is recommended before considering the search for additional agents for spear thistle in its area of origin.

Variegated thistle results from USA indicate that *R. conicus* cannot achieve successful biological control alone. In a personal communication to R. Amor in 1978, Goeden reported that '*Rhinocyllus* is all that we have on *Silybum*, and it is not all that effective here' while Boldt and DeLoach (1985) state that while it caused significant damage to flowerheads in Texas, it did not appear to reduce the weed population. While it is too early to determine the impact of *R. conicus* on seed production in Victoria, the USA experience leads to the conclusion that, although a different ecotype free of *Nosema* was released in Victoria, it is unlikely to achieve successful biological control by itself and additional natural enemies will have to be found. Goeden (1976) concluded from southern European surveys that *R. conicus* was the only promising agent and suggested south western Spain and north west Africa as suitable locations for exploration for additional candidate agents. The fungal pathogens of variegated thistle in Europe have not been carefully surveyed for potential biological control agents and recent observations of the rust fungus *P. mariana* have discounted it as a candidate (Groves personal communication). Another defoliating rust fungus (*Puccinia cruchetiana*) is mentioned by Wapshere (1984) and may be worth investigating. Detailed plant population studies coupled with predator / pathogen impact studies in suitable climatic areas of Europe / North Africa are suggested to maximize the chances of finding candidate agents for Australia.

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The contribution of biological control to the management of thistles

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Summary

CSIRO Division of Entomology has two major projects on the biological control of carduine thistles, one against nodding thistle (*Carduus nutans*) and another for scotch and Illyrian thistles (*Onopordum acanthium* and *O. illyricum*). The strategies for biological control of these target thistles are similar, although the agents used are different. Since thistle populations depend solely on seedling establishment for recruitment, the priority area in both projects is to limit seeding, with the ultimate aim to reduce the soil seed banks found in Australia to the much lower levels found in Europe. Both projects include insects that attack the capitula and thus have a direct impact on seeding; both also have insects that attack vegetative parts of the plant and thus indirectly limit seed production. The role of biological control in an overall management strategy for these two groups of thistles is briefly discussed.

Introduction

CSIRO Division of Entomology is currently conducting two biological control projects on carduine thistles. The targets are nodding thistle, *Carduus nutans*, and Scotch and Illyrian thistles, *Onopordum acanthium* and *O. illyricum*. Other countries have mounted biocontrol projects against nodding thistle, with varying degrees of success (Julien 1992), but this is the first time that a project has been undertaken for *Onopordum* (Briese 1990). These two projects have progressed in a similar manner with both having European and Australian components. The European phase of each had two major objectives; the obvious one of identifying potential biocontrol agents and conducting studies on their biology and impact, and a second, perhaps not so obvious, but of prime importance, involving basic research into the population dynamics of the weed in its native range. Both projects have also collected base line plant population data on the weeds in Australia before the releases of any agents were undertaken. Results of these pre-release studies show that the soil seed banks in Australia are generally several orders of magnitude greater than those found in Europe (Pettit *et al.* 1996, Woodburn and Sheppard 1996). Since the thistles involved in both of these projects rely solely on seedling germination and establishment for recruitment to their populations, the underlying philosophy for control has been to limit seed production and thus over time to bring about a reduction in Australian soil seed bank levels to the levels that are found in the plants' native ranges.

The proposed biocontrol agents

A list of the insects identified during the European studies as having most potential as biological control agents is presented for *C. nutans* and *Onopordum* spp. (Table 1), along with a brief description of the damage caused to the plant and a timescale for their release.

The agents chosen limit seed production either directly by attacking the flowering capitula, (*Rhinocyllus conicus* and *Urophora solstitialis* for nodding thistle, and *Larinus latus* and *Tephritis postica* for *Onopordum* spp.) or they reduce plant vigour and thus have an indirect impact on seed production (the remaining agents listed in Table 1). If heavy attack is sustained by some of these remaining agents, the flowering plant population can be directly limited by plant death in the rosette stage, as in the case of *Trichosirocalus* spp. All of these potential agents have been chosen because they are considered to complement one another by attacking different parts of the weed, e.g. receptacle and rosette feeders utilize completely different plant resources. When the same part of the plant is targeted for attack, the chosen agents either attack at different times, for example *Trichosirocalus* sp. nov. attacks *Onopordum* spp. from autumn to early spring whilst

Table 1. Candidate agents for the biological control of two thistles groups in Australia.

Agent	Type	Damage inflicted on target weed	Actual or proposed year of field release
Nodding thistle (*Carduus nutans*)			
Rhinocyllus conicus	receptacle weevil	larvae consume both receptacle tissue and developing seed, limiting seed production	1988
Urophora solstitialis	seed fly	larvae induce the plant to produce a lignified gall, acts as a metabolic sink and destroys seeds, lowers seed production	1991
Trichosirocalus horridus	rosette crown weevil	larvae feed on rosette meristems, reducing vigour and hence lowering seed production, can cause death of plant	1993
Cheilosia corydon	stem / root fly	larvae mines the elongating stem, and eventually mines way down to the root stock, reduces vigour of plant	1997?
Scotch and Illyrian thistles (*Onopordum* spp)			
Larinus latus	seed weevil	larvae destroy seed in the thistle head and reduce seed production	1992
Lixus cardui	stem-boring weevil	larvae mine the stem and can reduce plant vigour and size	1993
Tephritis postica	seed fly	larvae destroy seed in the thistle head and reduce seed production	1995
Tettigometra sulphurea	sap-sucking bug	adults and nymphs suck sap from plant and can reduce vigour and kill rosettes	1996 or 1997
Trichosirocalus sp. nov.	rosette crown weevil	larvae feed on rosette meristems, reducing vigour and hence lowering seed production, can cause death of plant	1996 or 1997
Botanophila spinosa	crown fly	larvae feed on rosette meristem or branch axils and deform plant growth	1998

Table 2. Structure and current status of tasks leading to the introduction and establishment of biological control agents in Australia (as of June 1996).

Carduus nutans

Agent	*R. conicus* seed weevil	*U. solstitialis* seed fly	*Trichosirocalus horridus* crown weevil	*Cheilosia corydon* stem / root fly
Exploration and selection of potential agents	Selected	Selected	Selected	Selected
Biology and impact of agent studied in Europe	Completed	Completed	Completed	Completed
AQIS / ANCA permit to introduce into Australia	Permission given	Permission given	Permission given	Permission given
Host-specificity testing in quarantine in Australia	Completed	Completed	Completed	Completed
AQIS / ANCA permit to field release in Australia	Permission given	Permission given	Permission given	Application pending
Field releases made at selected study sites	Releases made in November 1988	Releases made in December 1991	Releases made in May 1993	
Agent established in field	First recovery November 1989	First recovery October 1992	First recovery November 1993	
Evaluation studies commenced	November 1990	October 1992	April 1994	
Distribution of agents throughout infested areas	No redistributions made	Redistributions made 1993 / 96	Redistributions made 1994 / 96	

***Onopordum* thistles**

Agent	*Larinus latus* seed weevil	*Lixus cardui* stem borer	*Tephritis postica* seed fly	*Tettigometra sulphurea* sapsucker	*Trichosirocalus* sp. nov. crown weevil	*Botanophila spinosa* crown fly
Exploration and selection of potential agents	Selected	Selected	Selected	Selected	Selected	Selected
Biology and impact of agent studied in Europe	Completed	Completed	Completed	Completed	In progress	In progress
AQIS / ANCA permit to introduce into Australia	Permission given	Permission given	Permission given	Permission given	Permission given	
Host-specificity testing in quarantine in Australia	Completed	Completed	Completed	Imported into quarantine	Imported into quarantine	
AQIS / ANCA permit to field release in Australia	Permission given	Permission given	Permission given	Application submitted	Application submitted	
Field releases made at selected study sites	Releases made in Nov. 1992	Releases made in Nov. 1993	Releases made in Nov. 1995			
Agent established in field	First recovery Nov. 1993	First recovery Nov. 1994	Not yet recovered			
Evaluation studies commenced	Nov. 1996	Nov. 1996				
Distribution of agents throughout infested areas	Redistribution made 1993 / 96	Redistribution made 1994 / 96				

Botanophila spinosa attacks the rosette / developing stem from spring to early summer, or there the available evidence suggests there is no interspecific competition between agents, such as in the case of *R. conicus* and *U. solstitialis* for *C. nutans* (Möller-Joop and Schroeder 1986).

Current status of projects

The progress of research to date for both projects has been substantial (Table 2). An exception is *Cheilosia corydon* which severely damages nodding thistle in Europe. However it has proved impossible to rear this insect under artificial conditions, and the question of whether to release this insect in Australia remains to be resolved.

A separate project involving the redistribution of the biocontrol agents by CSIRO and NSW Agriculture (as well as KTRI Victoria for *Onopordum* spp.) was funded (by IWS / MRC) to speed up availability of the agents to the farming community. All agents for the two projects are or will be redistributed, with the exception of *R. conicus* (see Evaluation below).

Redistribution of agents

In the IWS / MRC funded project, primary nursery sites are established in strategic areas of the weeds' infestations in New South Wales and Victoria by the co-operating partners, using starter colonies provided by CSIRO. From these initial colonies local redistribution networks are set up and co-ordinated by the partners but utilizing the officers of local community groups such as Landcare and District Noxious Weed Officers. A broad summary of the releases made to date is shown in Table 3 (for further details see Briese *et al*. 1996).

Initial agent impact

It is essential in any biocontrol program that the research effort continues after release and establishment of the agent has occurred (Briese 1993). Funding bodies need to recognise the importance of this phase of any project. The only way to quantify the impact of the agents is to undertake studies on the population dynamics the weed as influenced by the insects. To date the nodding thistle project has made greater progress in this regard and it will be used as the example in this section.

Table 3. Summary of redistributions made for biological control agents for *Carduus nutans* and *Onopordum* spp.

	C. nutans		*Onopordum* spp.	
Year	*U. solstitialis*	*T. horridus*	*L. latus*	*L. cardui*
1993	3		14	
1994	5	2	20	14
1995	22	4	5	69
1996		36		

Impact of R. conicus

This insect was successfully used to control populations of *C. nutans* and closely related thistles in North America (Harris 1984, Kok and Surles 1975), and similar results were initially expected in Australia, where it was released in 1988 (Woodburn and Cullen 1995). However, while *R. conicus* very successfully destroys the vast majority of seed in the primary capitula, its impact rapidly declines as the season progresses (Woodburn and Cullen 1993, 1996). Despite their larger size, the contribution of primary capitula to the total seed production is minimal, for most seeds set are formed in the large number of smaller capitula produced in the middle of the flowering season. The timing and extent of renewed attack by a small partial second generation of weevils is of minimal importance. Estimates of the reduction in total seed set due to the activity of *R. conicus* have varied between 7 and 20% (Woodburn and Cullen 1993, 1996). Seed destruction in New Zealand, where this weevil has been released for over 20 years (Jessep 1975), range between 3 and 49% without apparent long-term reduction in thistle population densities. However, in North America where thistle populations have been controlled by this weevil in ten years or less, the reported declines in seeding are about 50% (Kelly and McCallum 1995).

Impact of U. solstitialis

Urophora solstitialis was identified by Sheppard *et al.* (1994) as a potentially important seed predator because it undergoes a well defined partial second generation and should therefore attack capitula throughout the flowering season. The literature on competitiveness between this agent and *R. conicus* was equivocal; there being both evidence that the seed fly might out-compete the weevil (Zwölfer 1973) and that the two agents could coexist in the same capitula (Möller-Joop and Schroeder 1986, Sheppard and Vitou personal communication).

The seed fly was released in Australia in 1991 (Woodburn 1993) (and in New Zealand and Canada in 1990 (Julien 1992)). It established strongly, thereby enabling evaluation of its impact on thistle population dynamics to commence in the following year. As anticipated, there was a partial second generation under Australian conditions, leading to attack on capitula throughout the total flowering period, and a measured reduction in number of seed of 45% one year after release. However, at the beginning of the season emergence of the flies from diapause is not in phase with the capitulum development of the thistle and the majority of the insects do not succeed in finding oviposition sites. It is expected that this asynchrony in fly emergence should, by natural selection, become attuned with the phenology of thistle flowering in Australia, thus increasing the effectiveness of this biocontrol agent (Woodburn 1996a).

Combined impact of R. conicus and U. solstitialis

As indicated above, it was expected that there would either be minimal interspecific competition between these two capitula-feeding insects or that the seed fly would out-compete *R. conicus* in its introduced environment. Research to date indicates that, in fact, *R. conicus* is the superior competitor in Australia, at least at the beginning of the flowering period when the primary immature capitula (the site of oviposition for both species) are in short supply. These capitula are heavily attacked by *R. conicus* (more than 150 eggs per capitula—which is much greater than egg densities in Europe) and they either abort, or the receptacle tissue is completely mined. *U. solstitialis* requires this tissue to form a vascular connection and induce gall formation. When thistle densities are high competition is not as severe because there are more early immature capitula for the insects to utilize. At one such site, the insects together reduced seeding by 70%, but with the major contribution being made by the seed fly (Woodburn 1996b). Due to adverse competition between these insects, it has been decided not to assist the spread of *R. conicus* through the redistribution network.

Impact of T. horridus

Field evaluation of this insect is still at a preliminary stage, with no data having been collected at the thistle population level. Impact on individual plants was monitored in the field, using plants sprayed with insecticide at fortnightly intervals throughout the weevil's oviposition period as controls. Ten per cent of the attacked plants died as a result of attack by *T. horridus*. The final rosette diameter of plants that had survived attack was 50% less, and capitula production 70% less than that of the controls (Woodburn unpublished). Assessment of attack by this insect on a plant population basis commenced in the autumn of 1996.

Expectations of biocontrol and time scale needed

Biological control of weeds has a relatively long history, and during this time there have been some quite spectacular successes, as well as many that were not so spectacular (Crawley 1990). The community is generally well aware of the successes, e.g. prickly pear and more recently salvinia, where plant populations have been decimated by the control agents. For practitioners in this area this is a two-edged sword in that the farming community is convinced of the worth of this approach but also expects that they will see similar rapid and dramatic results with their particular weed. In the case of the thistle species under consideration here such spectacular success in the short term is remote. Even if seeding were halted immediately, thistles would remain at unacceptably high levels for many years to come, due to the soil seed bank which is both relatively long lived and, compared to Europe, is very large (Pettit *et al.* 1996, Woodburn and Sheppard 1996). The essential message that needs to be delivered to the rural community is that biocontrol is a long term approach to reducing weed densities, though in the shorter term the spread of weeds may be limited by a reduction in seed output. An indication of the size of the task comes from a long term ongoing experiment conducted on Illyrian thistle, where seed production is reduced by mechanically removing 100, 90, 50 and 0% of capitula produced on experimental field plots. The size of the soil seed bank is monitored each year. After four years a significant reduction in the seed bank is only detectable in the 100 and 90% removal plots, and at 90% seed destruction, the more realistic level, the half-life of the seed bank is estimated at four years.

Role of biological control in overall management strategies

Given that biological control of thistles is a long-term solution, it becomes essential to maintain other forms of control to minimize the impact of these weeds in the shorter term. Overall management strategies can be developed in two stages. A first approach would be to determine the appropriate control method for a particular situation, e.g. cultivation and cropping on arable land, broadacre herbicide use on high-value improved pastures, biological control on non-arable rangelands of lower value and in weed refuge areas etc. Such spatial stratification of different control treatments could then lead to a truly integrated approach where biocontrol occurs together with cultural and chemical control methods. Such integration, however, would require careful planning to ensure that the increase in population of biological control agents and their impact is not inhibited by methods such as herbicide use and grazing management. Evidence exists that the use of insects and herbicides are compatible, if attention is given to the timing of application of chemicals relative to the insects' life-cycle (Trumble and Kok 1982). Once biocontrol agents start to modify the dynamics of thistle populations, changes will pass through to other components of the pasture environment, such as availability of germination microsites and interspecific plant competition. There is thus the potential for synergism between biocontrol and other methods such as grazing management in reducing impact.

The future of biological control of thistles lies as one component, albeit a key one, in an overall management system. The challenge to the CRC for Weed Management Systems is to develop such strategies for the different major thistle groups as they infest different land-types and land-uses.

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Potential of native pathogens for control of saffron thistle

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Summary

Saffron thistle (*Carthamus lanatus*) is a widespread weed of cropping and pastoral areas throughout the wheat belt of Australia. It causes economic losses in both of these agricultural systems. Isolates of *Phomopsis* spp. have been collected from the field from both attacked thistles, and from seed from disease free plants. Data for pathogenicity tests on 23 isolates are presented, which suggest that five highly virulent strains have potential for development as bioherbicides.

Introduction

Saffron thistle (*Carthamus lanatus* L.) is an important winter growing annual weed of cropping and pastoral areas throughout the wheat belt of Australia, causing a yield reduction in cereals of up to 70% (Watson 1990). Contamination of grain with saffron thistle seed leads to downgrading and financial dockage. In pasture, the thorny nature of the thistle reduces livestock access to palatable pasture. Spines of saffron thistle cause damage to the eyes, mouth and hooves of livestock, and predispose stock to diseases such as scabby mouth and pink eye (Watson 1990).

Current control methods aim to exhaust seed reserves in the soil by using a combination of mechanical, chemical and cultural practices (Fromm 1990). Saffron thistles seed can remain viable in the soil for up to eight years (Quinlivan and Peirce 1968). To achieve effective control it is important to prevent seed set over several years. The delayed germination of saffron thistle within seasons adversely effects the outcome of any applied control strategy. This paper outlines the failure of current control strategies to impact on saffron thistle populations and investigates the potential for biological control.

Saffron thistle distribution

In 1995 a questionnaire was sent to 53 New South Wales (NSW) district agronomists requesting information on saffron thistle:

- the presence of infestations,
- the presence of infestations which are considered to be a problem,
- the crop / pasture situation in which it was considered to be a problem, and
- the need for control.

Of the 89% response, 85% reported infestations, which occurred in all cropping / pasture situations. The highest incidence was in pastures (82%), followed by cereal crops (46%), lucerne (29%), oilseed crops (24%) and grain legume crops (24%) (Crump *et al.* 1996a). Control of saffron thistle was considered to be warranted in 63% of the surveyed districts.

An earlier survey (Briese 1988) concluded that saffron thistle was the most economically important thistle in NSW. The results from the current survey show that its significance has not altered, indicating that current control strategies do not lead to a long term reduction in the population of the weed. Possible reasons for this failure include:

- The timing of herbicide application. The majority of the control methods have to be carried out at the most susceptible growth stage to provide effective control. For example, once stem elongation occurs the phenoxy herbicides do not provide reliable control.
- The damage to non-target species. Many herbicides used to control saffron thistle can cause damage to non-target species.
- The cost associated with control. The seed of saffron thistle can remain viable for up to eight years, therefore control strategies need to be implemented for three consecutive years in order to reduce the seed reserves in the soil (Watson 1990). The cost associated with control can be expensive especially in low value crops such as pasture in inaccessible areas.
- The pattern of germination. The germination of saffron thistle is staggered within a season, therefore there is a need to repeat control strategies throughout a season.

The failure of current control strategies to reduce thistle populations highlights the need for alternative control strategies, such as biological control.

Biological control of saffron thistle

The classical biological approach involves the 'introduction of an exotic beneficial organism into an area where an exotic pest has become established in the absence of the natural enemies that existed in its original home' (Burge 1988). If conditions are favourable the biocontrol agent becomes established and flourishes in its new habitat. The major constraint to the application of classical biological control for saffron thistle is its genetically similar background with safflower (*Carthamus tinctorius* L.). The discovery of suitable biocontrol agents which are specific to saffron thistle and not damaging to safflower has been limited to date (Wasphere 1984).

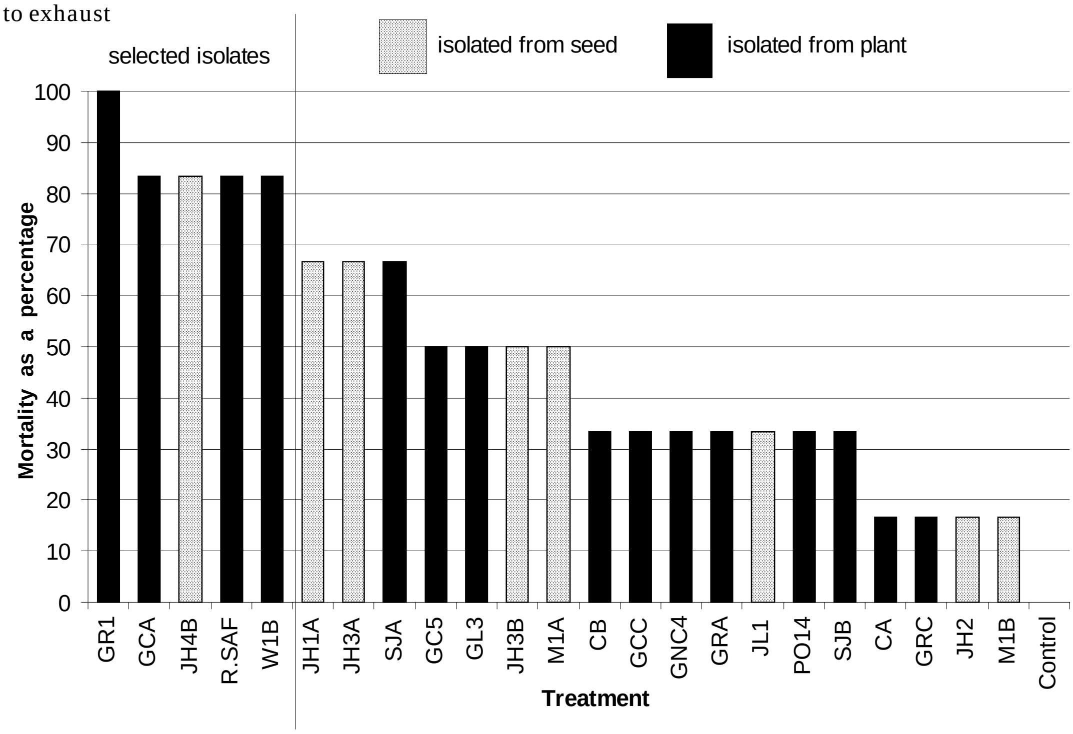

Figure 1. The variation in pathogenicity of *Phomopsis* spp. isolates on saffron thistle. Note only isolates which cause mortality are presented.

The adoption of an inundative approach to biological control overcomes some of the constraints applied to classical biological control. The inundative approach, which includes the bioherbicide technique, utilizes organisms with poor means of dispersal, therefore, reduces the spread to non-target species. The bioherbicide tactic can utilize indigenous pathogens eliminating the quarantine requirement and the risk involved in the introduction of foreign organisms associated with traditional approaches to biological control. Bioherbicides rely on the application of the pathogen in high concentrations to create a disease epidemic (Charudattan 1988). After infection the pathogen is reduced to low levels or does not survive. The use of the bioherbicide tactic to control saffron thistle has several advantages in comparison to conventional control:

- Bioherbicides are cheaper to develop and register than conventional herbicides, resulting in a lower cost to the user. This would be particularly advantageous in low-value pasture situations where current control methods are uneconomical.
- Bioherbicides can be targeted to provide control without damaging non-target species.
- The sustainable management of saffron thistle with bioherbicides has the potential to reduce chemical usage with associated environmental benefits.

Overseas explorations have identified several plant pathogens including *Septoria* spp. and *Puccinia* spp. (Evans 1995). The impact that these pathogens would have on thistle populations in Australia requires investigation. Research on indigenous fungi is complementing these international research investigations. The Australian isolates of *Phomopsis* spp. were collected from diseased plant material from sites in NSW. *Phomopsis* spp. were also obtained from seed collected from apparently disease free plants from Junee (47.5%), Mangoplah (10%), Warren (5%) and Barabba (0%) (Crump *et al*. 1995). Pathogenicity tests conducted on 45 isolates of *Phomopsis* spp. have shown plants could be killed in 4-10 days (Crump *et al.* 1996b). The most virulent isolates have been selected for further investigations (Figure 1). Preliminary results indicate that these isolates are suitable for the inundative biological control of saffron thistle in Australia.

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The use of pathogens native to Europe to control thistles in southern Australia

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Summary

Foliar pathogens of European thistles that have become significant weeds in southern Australia are listed and the potential for some of them to be classical biological control agents is discussed. Particular attention is paid to pathogens of slender, variegated and saffron thistles. In the case of the slender thistles, the current status of two recently released strains of *Puccinia cardui-pycnocephali* is presented. Control programs for variegated and saffron thistles are less advanced. Results of recent studies of *P. mariana* in Europe have thrown doubt on its suitability as a control agent for variegated thistle. In contrast, a survey of pathogens on saffron thistle has shown *P. sommeriana* to have some potential for biological control. Several pathogens in Europe may have potential to add to the effectiveness of biological control of certain thistles in southern Australian pastures, but only if their effects can be integrated with other methods of control, including biological control by insects.

Introduction

The CSIRO Divisions of Entomology and Plant Industry have been researching thistle control for over a decade. The program has emphasized classical biological control, using insects and fungi, in relation to the taxonomy and ecology of the major thistle groups as they occur in both Mediterranean Europe and southern Australia. The research has been jointly funded by CSIRO and also, for various periods, by both the International Wool Secretariat and the Meat Research Corporation. The program has been centred both in Canberra and Montpellier, France, the latter being the Mediterranean base of the CSIRO European Laboratory.

This paper reviews progress made on the thistle research program as it relates to:

i. the occurrence of certain foliar pathogens in Mediterranean Europe,
ii. the release in southern Australia of two strains of the pathogen *Puccinia cardui-pycnocephali* for control of the slender thistles *Carduus pycnocephalus* and *C. tenuiflorus*,
iii. the potential of several other pathogens to biologically control populations of variegated thistle (*Silybum marianum*) and saffron thistle (*Carthamus lanatus*) in southern Australia.

We review the foliar pathogens from Europe that are known to attack the introduced thistle groups that are the worst weeds in southern Australian pastures. These include nodding thistle (*Carduus nutans*), the slender thistles (*Carduus pycnocephalus* and *C. tenuiflorus*), Scotch, Illyrian and stemless thistles (*Onopordum acanthium, O. illyricum* and *O. acaulon* respectively), variegated thistle (*Silybum marianum*), spear thistle (*Cirsium vulgare*) and saffron thistle (*Carthamus lanatus*).

Thistle pathogens in Mediterranean Europe

The pathogens which have been recorded for the various thistles are listed in Table 1. This table draws on existing information (S. Hasan personal communication), supplemented by some recent records of pathogens from *Onopordum* and saffron thistle (Groves unpublished). It is obvious that there are many pathogens recorded for thistles in Europe, of which the rusts form the largest group; the rusts are also one of the most specific of all groups of fungi. It is not surprising, therefore, that research on the potential of fungi for biological control has tended to concentrate on the rusts.

Control of the slender thistles by the rust *Puccinia cardui-pycnocephali* in southern Australia

The closely-related taxa *Carduus pycnocephalus* and *C. tenuiflorus* both occur as short-season winter annuals in southern Australian pastures (Parsons 1977, Groves and Kaye 1989). Both species have a wide distribution in Europe and were introduced early to Australia. During this introduction stage, at least one strain of *Puccinia cardui-pycnocephali* was also introduced accidentally, but it has had little effect on the weediness and spread of slender thistle populations throughout southern Australia.

Research on the biological control of the slender thistles has fallen into three phases. The first was conducted at Montpellier, southern France, where the insects and fungi most damaging to populations of the thistles throughout their native range were identified. None of the insect species appeared to limit slender thistle populations (Sheppard *et al.* 1991); however, the rust *P. cardui-pyncocephali* was identified as having the most potential for biological control. Two of a total of 38 isolates of the pathogen collected in four European countries were selected for further testing, based on their capacity to inflict greater damage on accessions of the thistles collected in southern Australia than the relatively benign strain(s) already present in Australia (Chaboudez *et al.* 1993a). These isolates were each virulent on a different species of slender thistle; they reduced height, dry weight and seed production significantly under glasshouse conditions (Table 2) and also in a garden experiment. The specificity of these two aggressive strains (one for *C. tenuiflorus* from Italy and the other for *C. pycnocephalus* from France) was then exhaustively tested to ensure that economically important species (such as artichoke) or species native to Australia were not vulnerable to attack.

Table 1. Fungi recorded on thistles in Mediterranean Europe with potential for biological control (in part from S. Hasan, unpublished).

Fungal species	Known hosts
Ophiobolus cirsii (Sphaeriales)	*Carduus* spp., *Cirsium* spp.
Phyllosticta cirsii (Coelomycetes)	*Cirsium* spp.
Puccinia acanthii	*Onopordum acanthium*, *O. acaulon*
P. cardui-pycnocephali	*Carduus pycnocephalus*, *Carduus tenuiflorus*
P. carduorum	*Carduus* spp. (incl. *nutans*)
P. carthami	*Carthamus* spp.
P. cirsii	*Cirsium* spp.
P. cnici	*Cirsium* spp.
P. cruchetiana	*Silybum marianum*
P. mariana	*Silybum marianum*
P. sommieriana (Uredinales)	*Carthamus lanatus*
Ramularia cardui	*Carduus* spp.
R. cirsii	*Cirsium vulgare*
R. onopordi (Hyphomycetes)	*Onopordum acanthium*
Septoria cardui	*Carduus nutans*
Septoria centrophylla	*Carthamus* spp.
Septoria cirsii	*Cirsium* spp.
Septoria onopordonis	*Onopordum* spp.
Septoria silybi (Coelomycetes)	*Silybum marianum*
Ustilago cardui	*Carduus* spp., *Cirsium* spp., *Silybum marianum*
U. onopordi (Ustilaginales)	*Onopordum* spp.

The second phase of the program began in 1992 with the granting of quarantine approval to introduce pathogen isolates into high security quarantine facilities on the CSIRO Black Mountain site, Canberra. Host specificity was tested on a total of 46 species, and in September 1993 permission was jointly obtained from the Australian Quarantine and Inspection Service and the Australian Nature Conservation Agency to make field releases (Chaboudez *et al.* 1993b).

The third phase of the project focused on field releases of the rust and the continuous generation of inoculum in the glasshouse to cope with the demand for spores from co-operating agencies and collaborators. Field releases were made subsequently in all southern Australian States, albeit at a time of severe drought in the region. Once the drought broke (in autumn 1995), monitored releases in southern New South Wales showed good pathogen establishment and spread to uninoculated thistle stands more than 800 m away. At this site disease levels failed to build up sufficiently quickly to prevent normal growth or to reduce seeding of infected plants. However, verbal reports suggest that, at some release sites in south-western Victoria, the rust has established well, has spread by as much as 20 km and has reduced plant vigour and seeding. Although funding for the project has formally ceased, new releases continue to be made through Landcare groups and other collaborators.

We conclude that, except in particularly favourable localities, the main contribution of the recent release of the two strains of this pathogen will be through a general reduction in the vigour and seed production of the two slender thistle taxa known to occur in southern Australia.

Is *Puccinia mariana* a potential biological control agent for variegated thistle in southern Australia?

Variegated thistle (*Silybum marianum)* is widely distributed in Mediterranean Europe and north Africa, where it occurs primarily on disturbed and nutrient-enriched land. The species has been introduced to other regions with a Mediterranean climate, such as California, Chile and southern Australia where it is a weed of grazing lands.

While based at the CSIRO European Laboratory, Montpellier, Groves investigated populations of variegated thistle in Spain and southern France for the incidence of the pathogens listed in Table 1, especially *Puccinia mariana.* We considered that the effects of this rust may complement those of a host-specific strain of the seed-eating weevil *Rhinocyllus conicus,* which had already been introduced to California (Goeden and Ricker 1977) and for which several attempts at introduction have been made in Victoria (Bruzzese 1996).

At one site in southern Spain, a rust was found on both variegated thistle and on *Notobasis syriaca*, an annual thistle similar to and co-occurring with variegated thistle at the site. This fungus, tentatively identified as *Puccinia notobasidi*, was able to infect variegated thistle seedlings in the field and the glasshouse, but always at a level insufficient to control seeding. Spores were not carried over from one season to the next. In an annual species such as variegated thistle, seeding must be significantly reduced and year-to-year survival of the spores must occur if biological control is to be at all effective.

Subsequently, a further two isolates of the fungus were obtained—one from *N. syriaca* from Turkey, and one from *S. marianum* from Greece—but the same result was obtained (Hasan and Groves unpublished). The same fungus was also consistently ineffective on seedlings of *S. eburneum*, the only other species known in the genus. It is concluded that *P. mariana* may be a strain of the wider taxon *P. notobasidi*. The two fungal taxa are most likely two extremes of the one species, despite having been given different names, probably because of the two different hosts on which they have been recorded. On the basis of results of our pathogenicity tests, the taxon *P. mariana* may represent a less aggressive strain of *P. notobasidi.* The two *Puccinia* species are separated on the basis of spore size. More collections are needed to determine dimensions of spores collected from the two hosts over a range of site conditions. In conclusion, the chances of finding a strain of this fungus suitable for biological control of variegated thistle in regions such as southern Australia are slight.

A second fungus, *Septoria silybi* (Table 1), also occurs commonly on variegated thistle in Europe as well as in California and southern Victoria, where it was apparently accidentally introduced. The fungus commonly occurs on older rosette leaves only. Consequently, it hastens leaf senescence, but has little effect on plant growth or seed production (Moscow and Lindow 1989). Thus, it does not seem a suitable candidate for biological control of variegated thistle.

Is control of *Carthamus lanatus* by fungi possible?

Saffron thistle (*Carthamus lanatus)* is closely related to the crop congener, safflower (*C. tinctorius).* It is the thistle that will be most difficult (and / or most expensive) to control biologically because of its close taxonomic affinity to an economically important crop in Australia. Furthermore, surveys over a number of years in France and Spain of the entomofauna associated with both safflower and saffron thistle have yielded only one record of a sufficiently host-specific arthropod that may be able to control the weed species without affecting in some way the crop species (J-P. Aeschlimann personal communication). The effectiveness of this insect (*Botanophilla turcica*, a crown fly) is being tested currently (J. Vitou personal communication). Whilst the rust fungi are sometimes highly specific to taxonomic variants of a host, no strain of *Puccinia carthami* (Table 1) has yet been identified which is specific to the weedy species. Are there other fungi that may fill this apparent gap?

The result of a recent survey commissioned by CSIRO (Evans, 1995) shows that *Puccinia sommieriana* may fulfil some of the requirements of a potential biological control agent for saffron thistle. Evans surveyed sites in southern Greece where the two recognised subspecies of saffron thistle and their hybrids overlap at a time when this annual thistle was present mainly as a rosette. Evidence of damage to young rosette leaves of saffron thistle as a result of infection by *P. sommieriana* was found, despite this taxon not being listed among the fungi recorded from Greece. Little is known about the biology of this pathogen and its biology, especially its possible effect on reduction of seeding.

Evans also found *Septoria centrophylla* to be damaging on saffron thistle in Greece, although he considered ‘that the actual host range may turn out to be wider than that of the rust *Puccinia sommieriana*’ (Evans 1995). These two pathogens seem to be the only possible candidates from Europe for biological control against saffron thistle in Australia. Given our limited knowledge of pathogen biology and the

Table 2. Effect of *Puccinia cardui-pycnocephali* infection on plant height (cm), dry weight (g) and production of viable seeds of the slender thistles, *Carduus pycnocephalus* and *C. tenuiflorus* (from Chaboudez *et al.* 1993).

	Control	Inoculated
C. pycnocephalus (*n*=20)		
Height	87.3 ± 4.5	38.8 ± 2.7
Dry weight	19.4 ± 1.1	11.3 ± 0.8
Seed production	174 ± 23	32 ± 10
C. tenuiflorus (*n*=21)		
Height	52.9 ± 3.7	25.4 ± 4.0
Dry weight	16.9 ± 0.8	7.3 ± 0.6
Seed production	84 ± 12	21 ± 8

Means + standard errors are presented. All pairwise means differ at the 1% level, based on one-way ANOVA.

economic importance of saffron thistle, these pathogens warrant further study.

Conclusions

Host-specific fungal pathogens occurring in Europe may be effective biological agents that contribute to the control of at least some of the major thistles introduced to southern Australia. Slender thistle growth in Mediterranean Europe was more limited by the incidence of the rust than it was by the occurrence of more than 20 species of insects (Sheppard *et al.* 1991). Though it is still too early to predict the effectiveness of two strains of that same fungus on slender thistle populations in southern Australia, it seems probable that release of the rust will be insufficient on its own to control seeding of these annual thistles in any but the most favourable of environments. Such a conclusion may apply even more appropriately to the control of other thistle species.

Bendall (1973) found that a deferral of autumn grazing of pasture containing slender thistle was an effective control method, a result subsequently shown for some other thistles in pasture in other situations. A combination of deferred autumn-early winter grazing with application of an appropriate level of herbicide in early spring may achieve a greater level of control. If such a combined treatment is compatible with the continued effects of rust infection and the establishment of perennial pasture grasses, then even further control may be achieved and the weediness of at least one group of thistles reduced thereby. The challenge to research is to demonstrate the effectiveness of such integrated control methods in the field not only for slender thistle but also for other thistle groups with either annual or biennial life-cycles.

In conclusion, there is a role for imported fungal pathogens in thistle control, but only in an integrated weed management system. Pathogens operating in isolation are likely to be ineffective at controlling thistle populations in southern Australia.

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The potential of the fungus *Sclerotinia sclerotiorum* as a biological herbicide for controlling thistles in pasture

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Summary
Research is reviewed on the development of *Sclerotinia sclerotiorum*, isolated form Californian thistle (*Cirsium arvense*) as a biological herbicide for controlling thistles in pastures. It has been shown, in glasshouse tests, to be virulent against two other thistles (*C. vulgare* and *Carduus nutans*), but not against *Carduus tenuiflorus*. In field trials against *C. arvense* it causes high mortality of vegetative shoots, thus reducing the cover of the thistle foliage. Only 8% of treated shoots survived to flowering compared to 28% on untreated plots. Root biomass is also reduced, resulting in lower shoot growth in the season following treatment. The fungus did not infect the key pasture species *Lolium perenne* or *Trifolium repens*. The potential for the development of *S. sclerotiorum* as a mycoherbicide against *Cirsium arvense*, *C. vulgare* and *Carduus nutans* is discussed.

Introduction
Many weeds impede pastoral farming in New Zealand and one of the most important is Californian thistle (*Cirsium arvense*), a perennial widely distributed in the temperate agricultural zones of both hemispheres (Holm *et al.* 1977). In New Zealand it occurs in pastures and crops (Cockayne 1917, Bascand and Jowett 1982, Bourdôt and Kelly 1986) where population increase occurs by recruitment of adventitious shoots from the creeping root system, and by the establishment of seedlings on open land. Despite recommendations involving cultivation, herbicides and grazing (Hartley and Butler 1984, Hartley *et al.* 1984, Meeklah and Mitchell 1984), Californian thistle is rarely adequately controlled. Furthermore, the herbicides commonly used against the weed in pastures (MCPA, 2,4-D and dicamba) remove nitrogen-fixing clovers from the treated sward, reducing pasture production. As a consequence of the tenacity of this weed, the “classical” biological control approach has been attempted. To this end three exotic phytophagous insects (*Urophora cardui*, *Lema cyanella*, and *Altica carduorum*) have been released in New Zealand over the last 21 years (Jessep 1989). Unfortunately *L. cyanella* only has established but to date has not controlled the thistle (Jessep 1989). An alternative biological approach was first investigated about 12 years ago in the USA when a soil-applied mycelial / whole wheat grain preparation of *Sclerotinia sclerotiorum* (Lib.) de Bary, a common fungal pathogen of Californian thistle, many other weeds, and several important crop species (Pennycook 1989), was field-tested as a mycoherbicide against the thistle in Montana (Brosten and Sands 1986). However, because of the variable results in the field, and the very high application rates as a consequence of using whole seeds as the food source / carrier for the fungus, commercial interest in the USA declined and a mycoherbicide based on *S. sclerotiorum* was not developed.

Research began in New Zealand on *S. sclerotiorum* and its use as a foliage applied mycoherbicide in 1989 following the success of greenhouse trials on Californian thistle using a mycelium-on-kibbled wheat formulation. In this paper we summarize the research published to date and discuss the potential and limitations of this broad-host-range pathogen for controlling Californian thistle and other thistle species in pasture.

Experiments on the pathogenicity of *S. sclerotiorum* on thistles
Waipara *et al.* (1993) reported the results of an experiment in which an isolate of *S. sclerotiorum* (S9) from a Californian thistle plant in Canterbury, was tested for virulence on four thistle species. Inoculum containing about 15 000 colony forming units per gram was prepared by growing the pathogen on kibbled wheat and milling to a fine granule. This was applied to pre-misted plants in a glasshouse at an equivalent rate of 50 g m^{-2}. Twelve plants (one per pot) of each of the following weeds were inoculated: Californian thistle, nodding thistle (*Carduus nutans*), winged thistle (*Carduus tenuiflorus*) and Scotch thistle (*Cirsium vulgare*). Mortality was assessed 12 days after inoculation. The *S. sclerotiorum* infected all species, but some were more affected than others with symptoms ranging from superficial lesions on leaf laminae to general necrosis and death of whole plants. Californian, Scotch and nodding thistles all had high levels of mortality whereas mortality was low in winged thistle (Table 1).

Table 1. Mortality in four thistle species following inundative foliage inoculation with a mycelium-on-wheat formulation of *Sclerotinia sclerotiorum* under glasshouse conditions. Plant mortalities were determined 12 days after inoculation. (Adapted from Waipara *et al*. 1993).

	Mortality (%)
Californian thistle (*Cirsium arvense*)	100
Scotch thistle (*Cirsium vulgare*)	75
Nodding thistle (*Carduus nutans*)	58
Winged thistle (*Carduus tenuiflorus*)	8

Evaluation of *S. sclerotiorum* for Californian thistle control in pastures
An experiment was conducted by Bourdôt *et al.* (1993) at three sites in *Lolium perenne* / *Trifolium repens* pastures at Templeton in Canterbury from October 1991 until September 1992. The pastures were 10 years old and supported extensive populations of *C. arvense*. The pastures were flood-irrigated several times during the summer and were rotationally grazed by sheep.

At site 1 three treatments were replicated four times: (i) untreated control, (ii) *S. sclerotiorum* applied on 12 October 1991 to the newly emerged spring cohort of adventitious shoots, (iii) *S. sclerotiorum* applied on 12 October followed by re-treatment on 15 November when stem elongation and flower bud initiation were occurring in the thistle. At sites 2 and 3 a fourth treatment on 15 November only was included. The treatments used the formulation described above which was broadcast by hand at 50 g m^{-2} onto small plots. Other experimental details are described by Bourdôt *et al.* (1992).

Within seven days of application, leaf and stem lesions caused by *S. sclerotiorum* were apparent on most of the thistle shoots in the treated plots. Typically lesions developed from the granules of inoculum adhering to the upper surface of lower leaves close to the junction with the stem. These lesions then increased in size and enveloped the stem. Shoot growth slowed markedly and the leaves which developed after treatment became chlorotic and whole shoots soon wilted and died.

Averaged over the three sites, all treatments significantly reduced the ground area covered by the thistle when measured on 28 January 1992 in the season of treatment but there were no significant differences between the treatments (Figure 1). Application in October reduced the area covered by thistle to 42%, in November to 55%, and in October and November to 32% of untreated. Root dry weights measured at the end of the growing season in late autumn revealed that roots had been affected to similar extent as the aerial shoots (Bourdôt *et al.* 1996).

The percentage of ground area covered by the thistle and the density of shoots on 14 December 1992 in the growing season

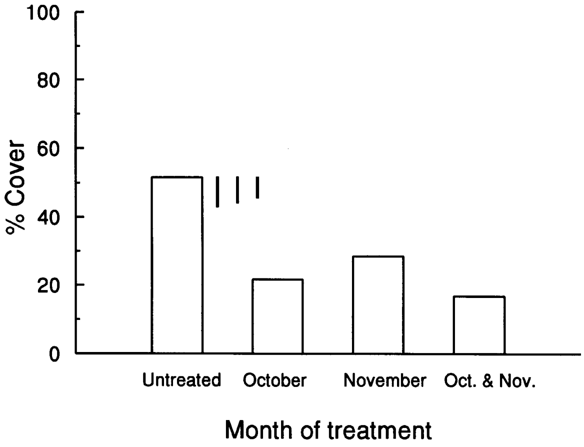

Figure 1. The effect of timing of applications of the experimental formulation of *S. sclerotiorum* in 1991 on the ground cover of *C. arvense* in January 1992. The data given are the means over the three sites. Vertical lines are LSD (P<0.05) values. The lefthand LSD is for comparing the October treatment with the double October/November treatment. The righthand LSD is for comparing the November treatment with untreated. The middle LSD is for all other comparisons. (From Bourdôt *et al.* 1993).

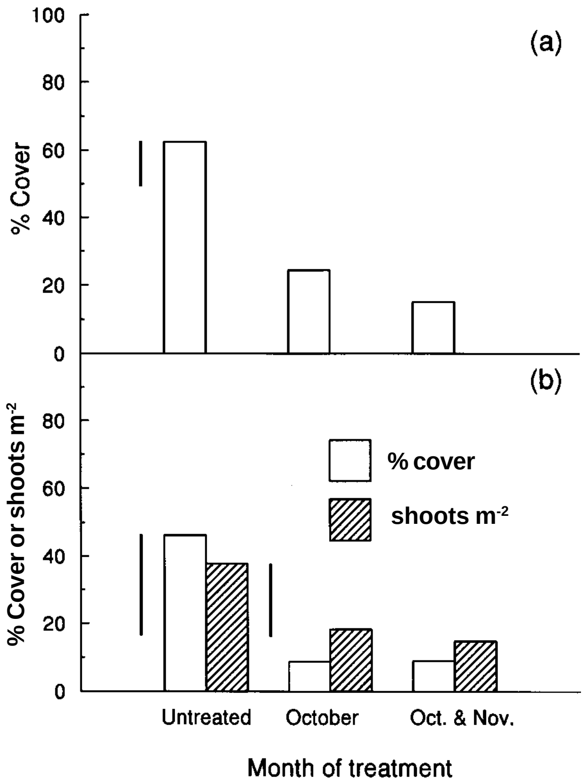

Figure 2. The effect of spring applications of the experimental formulation of *S. sclerotiorum* in 1991 on *C. arvense* at Site 1; (a) % ground cover of *C. arvense* shoots on 28 January 1992 and (b) % ground cover and density of shoots on 14 December 1992; the year after treatment. The vertical lines to the left of the lefthand bars in (a) and (b) are the LSD (P<0.05) values for comparing % ground covers between treatments; the line to the right of the lefthand hatched bar in (b) is the LSD (P<0.05) for comparing shoot densities between treatments. (From Bourdôt *et al.* 1993).

after treatment, is given for Site 1 in Figure 2. The effects on thistle ground cover in the year of treatment at Site 1 mimic the effects averaged over the three sites (Figure 2a cf. Figure 1). On 14 December, 14 and 13 months respectively after the October and November 1991 treatments, the ground cover of the 1992 population of thistle shoots on the treated plots was only 19% of untreated (Figure 2b). In addition the densities of the shoot populations in December 1992 on the plots treated in October and October plus November 1991, were 48 and 39% of untreated respectively. Since the proportional reduction was less for shoot density than it was for percentage ground cover, the shoots apparently had less leaf area on the treated plots than on the untreated in the year after treatment. These shoots were also less than half as tall as those on the untreated plots and flowered later and less profusely.

Demographic analysis of the treated and untreated populations was conducted by mapping all shoots in permanent sample areas with the plots. Three life history stages were recognised; vegetative shoots, shoots with flower buds and flowering/seeding shoots. This analysis revealed that the vegetative shoot stage to budding shoot stage was the most affected transition; only 13% of shoots surviving to become budders on treated plots, compared to 32% on untreated plots (Figure 3). A greater mortality also occurred at the flower bud stage on treated plots. The net effect of the treatment was that only 8% of adventitous shoots emerging during the season survived to flowering on treated plots compared to 28% on untreated plots. Most deaths due to the pathogen occurred within 35 days of treatment and all were restricted to shoots present at the time of application. Regrowth from axillary buds on stems below the ground rarely occurred; any regrowing shoots soon died as the pathogen invaded the new tissue from the dead parent tissue.

Selectivity of *S. sclerotiorum* in grasses/clover pasture

Hurrell and Bourdôt (1993) conducted an experiment on a Templeton silt loam in Canterbury to compare the effects of *S. sclerotiorum* and MCPA (the usual treatment for this weed) on pasture grasses and clovers. The pasture was 12 years old and contained perennial ryegrass (cv. Ellett) and white clover (cv. Huia); Californian thistle was absent. Two treatments were applied on 2 November 1992: (i) MCPA at 1.5 kg ha^{-1} (IWD MCPA, 375 g L^{-1}) and (ii) the mycelium-on-wheat preparation of *S. sclerotiorum* described above at 500 kg ha^{-1}. An untreated control was also included. Other experimental details are given in Hurrell and Bourdôt (1993).

Neither MCPA nor *S. sclerotiorum* reduced ryegrass yields. The dry matter yields of white clover and ryegrass on four harvest occasions are given in Figure 4. The yield of white clover was greatly reduced by MCPA at each time (as has been documented by others (Thompson 1956, Maclean 1957, Meeklah 1958, Meeklah and Mitchell 1984, Honore *et al.* 1980)). The percentage reductions were 85, 90, 74 and 71% at 23, 65, 118 and 168 days after treatment (DAT) respectively. By comparison there was no significant effect of *S. sclerotiorum* on clover yields. The effect of MCPA on the clover lasted almost the entire growing season.

Discussion

The term mycoherbicide is applied to fungal plant pathogens when used inundatively to control a weed population. The chosen pathogens are often already present in the country or region but affect the target weed only spasmodically as a result of natural constraints to epidemic development. This approach to biological weed control stands in contrast to the more conventional ‘classical’ biological control where the pathogen (or other agent e.g. an insect) is imported from another country or region and is released, after thorough testing, to build up population levels that eventually may suppress populations of the target weed.

The pathogen chosen as a candidate mycoherbicide for thistle control in New Zealand is *S. sclerotiorum*. Its advantages are the ease with which its mycelial phase can be cultured *en masse* and its naturally high pathogenicity towards several important thistle species. It appears from initial virulence tests with *S. sclerotiorum* (strain S9) that in addition to Californian thistle, from which this strain was obtained, both Scotch thistle and nodding thistle are also excellent targets (Table 1). Nodding thistle was hitherto unknown as a host of *S. sclerotiorum* (Pennycook 1989, Farr *et al.* 1989). To date only Californian thistle has been the subject of field evaluations and the results have been most

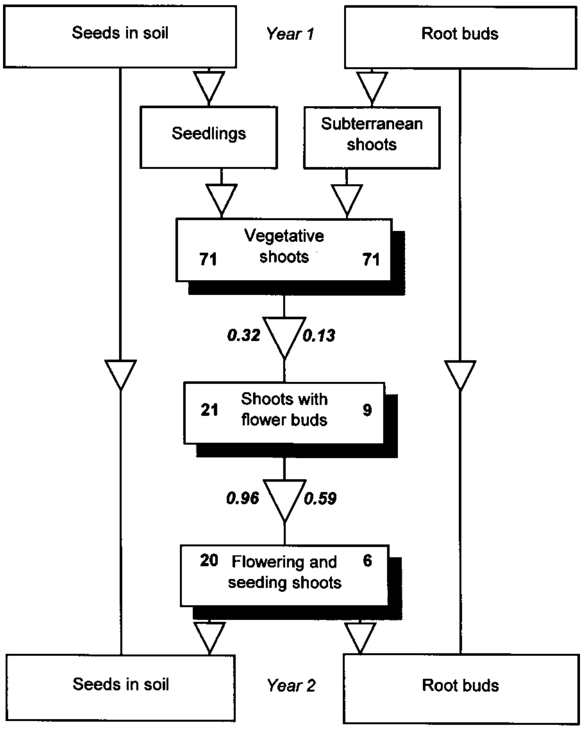

Figure 3. Life table for *Cirsium arvense* showing the impact of *Sclerotinia sclerotiorum* on transitions between two life history stages. Numbers on the right apply to a *C. arvense* treated with *S. sclerotiorum* and numbers on the left are for untreated *C. arvense*. Numbers in boxes are the number of shoots in each stage (shoots m^{-2}) and numbers beside the triangles are the probabilities assigned to the transitions between stages. (Modified from Bourdôt *et al.* 1996).

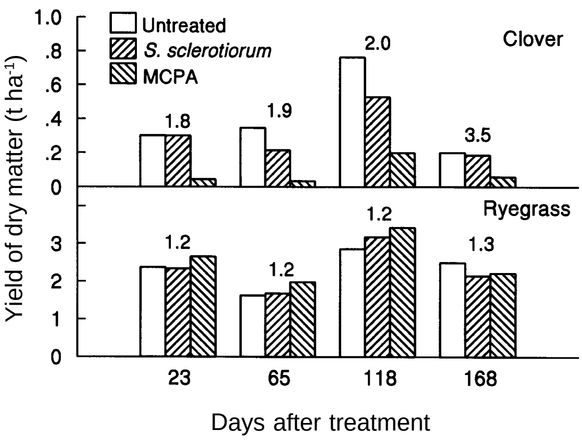

Figure 4. The effect of *Sclerotinia sclerotiorum* and MCPA on the productivity of ryegrass and clover on four occasions after treatment. Yields given as backtransformed means of the logarithms ($\log_{10}$) of the data. Values above each group of three treatments are the Least Significant Ratios (P<0.05). Treatment means are significantly different if the ratio between them is greater than the LSR (e.g. for the first occasion, one clover dry matter mean differs significantly from another mean if it is 1.8 times greater). (From Hurrell and Bourdôt 1993).

encouraging (Figures 1, 2 and 3). When applied as a mycelium-on-kibbled wheat formulation to the foliage of the thistle in spring, *S. sclerotiorum* (S9) was effective in reducing thistle cover in the year of application. It achieved this by killing a high proportion of the shoots present at the time of application. The effect of the pathogen was evident again in summer of the year after treatment when the treated shoot population consisted of fewer shoots. This was a direct consequence of a reduction in the size of the root system. This effect on the roots was probably due in part to the reduction in photosynthetic capacity of the thistle stands which would have resulted in reduced ability to support current roots and reduced ability to produce new roots. Additionally the pathogen invaded and killed roots down to a depth of at least 300 mm on treated plots (unpublished).

The shoots emerging on treated plots the year after treatment were developmentally delayed and several explanations seem possible for this. While root death provides an explanation for the lower density of shoots in the season after treatment, it is difficult to see how root death *per se* could result in smaller or developmentally delayed shoots in the year after treatment. A possible explanation is that the pathogen persisted in root tissue over winter, and weakened the spring shoots by continuing to destroy feeding roots in the year after treatment. New infections may also have occurred from over wintering sclerotia, weakening the developing shoots. There was however no evidence of shoot mortality due to *S. sclerotiorum* on the treated plots the year after treatment. The reason for reduced shoot vigour the year after treatment will remain obscure until more definitive studies.

The mycelium-on-wheat formulation was applied in the field at 500 kg ha^{-1} but this rate would not be commercially viable broadcast over large areas of pasture. However a food source must be applied along with the fungal mycelium in order to allow a period of saprophytic growth to facilitate eventual pathogenesis. Other food source/carriers are currently under investigation in a joint project between AgResearch and Crop Care Holdings Ltd., New Zealand.

The results from this first experimental use of a fungus as a biological herbicide in New Zealand show that *S. sclerotiorum* has potential for controlling Californian and other thistles in pastures. The lack of any substantial effect on pasture grasses and clovers contrasts with the debilitation of clovers which follows the use of MCPA (Figure 4). However, the pathogen's wide host range is a 'two-edged-sword' for whilst this widens its market potential as a bio-herbicide, it carries with it a possible increased risk of disease in adjacent or subsequent susceptible crops.

Two different approaches to this problem seem possible; risk avoidance and risk acceptance/management. Genetic modification to render the pathogen host-specific or incapable of spreading as ascospores from the treated thistles or surviving as sclerotia to infect later sown crops, is one approach (Sands and Miller 1993). This approach offers many scenarios of which auxotrophic and sclerotiumless mutants are two examples developed to date (Miller *et al.* 1989a,b, Sands *et al.* 1990). Because the chemical dependency of auxotrophs may be satisfied by naturally occurring nutrients on the leaf surfaces of some susceptible plant species (Sands *et al.* 1990), auxotrophs may not be completely safe. Furthermore, auxotrophs and sclerotiumless mutants tested to date have been less pathogenic than wildtypes (Sands and Miller personal communication) although Ford *et al.* (1992) showed that heterokaryons, produced by combining auxotrophic strains, are as pathogenic as wildtypes, and likely to segregate into 'safe' auxotrophs at ascospore formation (Ford personal communication). An alternative to using 'safe' mutants, is to use wildtypes in a risk acceptance/risk management approach. To this end, a risk analysis is being conducted in New Zealand in which the expected additional infection from a mycoherbicide source of *S. sclerotiorum* is being compared to the existing natural infection using techniques employed by de Jong *et al.* (1990). This approach accepts that there is a risk and attempts to quantify it so that the biocontrol agent may be used and managed to satisfy an acceptable level of relative risk.

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Estimating the impact of control efforts: models of population dynamics

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Summary
Population models can be used as a decision tool in the assessment of potential management plans, and can also improve evaluation of biological control and integrated pest management efforts. I illustrate this by discussing simple, data-based matrix models for the population dynamics of a thistle in New Zealand. Analyses and simulations indicate which are the most important state variables (thus facilitating efficient data collection), and which life history transitions are most crucial to population growth. This information can be used to investigate the potential of different control efforts. In this example, it seems that no one approach will control the weed, but that an integrated management approach has some chance of success. Models, used in conjunction with experimental studies, are a useful tool in planning and assessing pest control strategies.

Introduction: Population management
Population management as a general problem has three main aspects: conservation, harvesting and control. In the first case, a manager is interested in increasing the size of a population that is declining to extinction, in the second, the aim is to maintain the population of an exploited species at a productive level, and in the last, to cause a decrease in the numbers of a pest. The common thread is the regulation of population size and growth rate under some management regime. Yet, in spite of this, people often think about these three in very different ways (as the proliferation of books on 'conservation' and 'biocontrol', and the relative inaccessibility of the fisheries management literature will testify). All three areas have fairly strong theory already developed, with conceptual (and mathematical) models. In the work discussed here, the concern is control, but it is important to learn from the other two areas.

Why model?
A model is a representation of the structures and processes in a system, which is used to describe and understand that system. Mathematical models are just a more complex and detailed extension of the verbal and conceptual models we use every day. For example, even an idea such as 'I think this insect population will eat enough seeds to reduce plant densities in the future' is a model. Theory need not be expressed mathematically, but mathematical formalism is often the most precise way of conceptualizing an idea. The advantage of using mathematics is that it provides a common (and hopefully unambiguous) framework in which to express ideas, and which forces the investigator to be more exact. Writing a model down can often pinpoint aspects that are unclear, and forces consideration of the assumptions being made. So, in this respect, models are used to test our understanding, as well as to project into the future. This is extremely valuable in complicated situations: while it may be easy to guess what the effect of a single factor might be in a simple situation, when a great deal is going on, it can be very hard to separate the effects of different processes.

Why model in management?
The use of models is of particular importance in management situations. In order to implement a successful control strategy, information about the biology, life history and ecology of the target species (in the invaded, but also in the original habitat) has usually to be assembled (Waage and Mills 1992). Models can be useful in deciding which empirical data to collect. Control of pest populations has been achieved or attempted with a number of different approaches. Strategies include chemical means (including consideration of the timing and amount of applications), other classical agricultural practices and biological control, either separately, or together as part of an integrated pest management approach. The trouble is that there are so many potential factors to consider – armed with all this relevant information a manager has somehow to make a decision about which of several potential management strategies will make most impact on the pest species. What tools are available to help in that decision process. Experience helps, and ideally a series of experiments could be undertaken to test the options. However, this is not always practicable, and can be enormously greedy of resources. It is in such situations that models can be of outstanding use.

Models of intermediate complexity (Godfray and Waage 1991) can be developed relatively quickly (certainly on the time scale of an initial release project), and should ideally play a significant role in the development of control plans. Different plans can be tested in 'computer experiments' which, in tandem with field studies (resources permitting), can give a good idea of approaches that have the best chance of success. These projections provide information about the potential long term effects of different management strategies in a relatively short time. This is information that is not going to be generated by any other source, and while the answer should not be considered perfect, it does provide justification beyond guesswork for choosing a best option. Furthermore, the value of such studies is not purely predictive. They provide a 'summary' of knowledge about the system and how it is now, and they can be used to assess strategies already in use, as well as to investigate possible improvements.

Consider an example where a number of potential control agents have been assessed according to several criteria (e.g. degree of adaptation to pest, quick response to pest density changes, pest stage attacked). How are these to be ranked? How is the 'best' agent to be chosen? How many should be released and in what order? Inferior agents introduced first may affect the later establishment of better agents. There may be clear answers to these questions in the context of the ecology of the pest, but it would be hard to tease apart all the threads without the use of a model to help.

Early modelling attempts were fairly general, aiming to address broad issues and to make generalizations about suitable agents, or to explain, post hoc, success or failure of control efforts (Beddington, *et al.* 1978, Hassell 1980, May and Hassell 1981, Kakehashi *et al.* 1984). Recent advances include the use of stage-structured models, in which individuals are classified according to some state variable such as age or size. This increase in biological detail allows the researcher to think about, for example, control of the most economically damaging life history stage (e.g. Godfray and Waage 1991, Briggs 1993). Such models are similar to those used for other forms of management. For example, conservation models of endangered species aim to target efforts on the stage that will most increase population growth (e.g. models for turtles by Crouse *et al.* 1987, Heppell *et al.* 1996). Harvesting problems highlight issues of sustainability in the face of uncertainty (Ludwig *et al.* 1993, Rosenberg *et al.* 1993). It is important to keep abreast of these efforts as well.

Relatively few models have been developed as decision tools for specific pest control cases (but see Warwick *et al.* 1993) though there are rather more for other forms of management. There is a suite of host-parasitoid models that has been used to answer both general and more specific questions about biological control of insects (e.g. Beddington, *et al.* 1978, Hassell 1980, May and Hassell 1981, Murdoch 1990, Guttierez *et al.* 1988, Briggs 1993, Murdoch and Briggs 1996), but only a few models exist for weed systems (see Powell, 1988, Cloutier and Watson 1989, Lonsdale *et al.* 1995). So far, none really address the potential of other forms of control and integrated pest management. However, the work I summarize here is an example of the latter.

An example: *Carduus nutans* in New Zealand

Carduus nutans is a major weed of pastureland. In collaboration with Dave Kelly of the University of Canterbury, New Zealand, I developed simple, data-based, matrix population models of *C. nutans*, the nodding thistle (Shea and Kelly in press). The aim of the study was to understand the ecology and life history of this species in different parts of the country and to assess existing and potential future control strategies.

Matrix models are discrete-time, stage-structured population models. They provide analytical information about long-term growth rates and eventual stable stage and reproductive value distributions, as well as forming the basis for computer simulations. Data-based matrix models are relatively simple, but can be modified to include density-dependent effects and environmental variability. These models can be used to make predictions about the future, given certain assumptions (Caswell 1989). At the same time, they provide insight into the current state of the population.

The matrix models of *C. nutans* were used to investigate the potential success of its natural enemy, *Rhinocyllus conicus* (a receptacle weevil already released to provide control) as well as that of other management strategies. Elasticity analyses (de Kroon *et al.* 1986) indicate that transitions between the seedbank and small plant stages are more crucial to population growth than is the survivorship of larger plants, especially in drier areas where summer mortality is high. These seed-related transitions are heavily affected by *R. conicus*, but are unfortunately relatively insensitive to perturbation. Simulations using observed predation rates of about 36% (Kelly and McCallum 1990) indicate that, while the weevil may suppress the rate of population growth, at these predation levels it is not likely to cause a decline in the size of the thistle population. In fact, an estimated reduction in fecundity of about 65% would be required for success, and this is far larger than the largest recorded losses to this predator.

On the other hand, an integrated pest management approach may have more chance of success. For example, germination varies substantially from year to year, and stochastic versions of the model indicate that regular suppression of seedlings from new seed and the seedbank, in conjunction with a continued reduction in the input of seeds to the seedbank, could result in control of the thistle. In many areas, cultivation of dense pasture is common agricultural practice, but unfortunately this may not be practical in very arid regions. However, it is clear that these models can also be used to address other potential control measures, and to focus efforts appropriately.

Conclusions

Despite an increase in the use of models in biological control, it is still not always possible to explain the success or failure of a control attempt (Beddington, *et al.* 1978, Murdoch 1994). It must be remembered that models are not perfect descriptions of the system in question and a careful consideration of all assumptions, explicit and implicit, must always be made. Models are only as good as the information which goes into them: rubbish in will result in rubbish out. Clearly, most progress in understanding will be made when theory and experiment go hand in hand. Modelling, in conjunction with a thorough understanding of the processes occurring in the field, should provide a powerful tool for planning and assessing the success of biological control and integrated pest management efforts.

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Interference between pasture plants and thistles—a review

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Summary
The proposition that thistles may be controlled in pasture biologically by interference from neighbouring pasture plants is reviewed. Central to this approach is the hypothesis that the species composition and vegetation cover of a pasture influence birth and death rates in thistle populations, and hence also, population size. Experiments conducted mainly in New Zealand, Australia, USA and UK with species of *Cirsium*, *Carduus*, *Silybum* and *Onopordum* confirm that pasture grasses and legumes exert powerful inhibitory influences over seedling emergence and seedling and rosette survival in thistles. Pasture grasses, particularly perennial species, are generally more effective than legumes. This appears to be related mainly to their higher cover density, implicating competition as a mechanism, although there is some evidence that allelopathy may also operate. *Lolium perenne, Holcus lanatus* and *Phalaris aquatica* are particularly effective inhibitors of thistles. Pasture gaps play a key role in thistle seedling emergence and it is concluded that pasture management that promotes a dominant perennial grass component and an absence of small gaps is most likely to prevent thistle invasions. Research is needed on how grazing management and other factors including soil fertility and soil moisture influence the creation and closure of pasture gaps and the balance between grasses, legumes and thistles in pastures.

Introduction
Spatial and temporal variation in the size of thistle populations in pastures is commonly observed and often appears to be related to pasture cover and species composition. This observation has lead to the general hypothesis that interference from sown pasture species plays a dominant role in regulating population size in these weeds. Thistle control recommendations promoting interference from pasture species have arisen from this hypothesis for *Cirsium vulgare* (Scotch or spear thistle) (Anon. 1978), *Carduus nutans* (nodding or musk thistle) (Cregan and Scarsbrick 1977, Popay *et al.* 1979), *Carduus tenuiflorus* (slender or winged thistle) and *C. pycnocephalus* (slender winged or shore thistle) (Bendall 1973), *Onopordum acanthium* (Scotch or cotton thistle) and *Onopordum illyricum* (Illyrian thistle) (Gammie 1972), and *Silybum marianum* (variegated thistle) (Anon 1978, Michael 1968a). The ecological evidence supporting these control recommendations is reviewed in this paper and suggestions for the direction of future research on this topic are made.

Evidence for pasture interference from experiments in which pasture cover is manipulated

Cirsium spp.
Forcella and Wood (1986) investigated the effect of two levels of pasture interference on the demography of a natural population of the biennial *C. vulgare* in an annual pasture composed of *Bromus rubens*, *Lolium rigidum* and *Trifolium subterraneum* at Canberra, Australia, by leaving 1 ha of the pasture ungrazed for three years, and grazing 0.5 ha with sheep when forage was available. The thistle plants in the grazed pasture were, on average, larger, with more flower heads per plant and more seeds per head than plants in the ungrazed pasture. Significant population effects were evident by the second year. In the third year 14 times as many seeds were shed, and there were 18, 5 and 40 times as many seedlings, rosettes and adult plants respectively in the grazed pasture when counted in April or May. Estimates of the average annual transition probabilities between these life history stages for the three years showed about 50% of rosettes present in one year survived to become adults in the next year regardless of grazing. By contrast, the transition from seeds produced in one year to seedlings the next year was 1.5 times greater in the grazed pasture (0.149 compared to 0.098), but the transition most affected by pasture interference was that from seedling to rosette which was five fold greater in the grazed pasture (0.01 compared to 0.002). Seedling mortality began in the autumn in both grazed and ungrazed pastures, but proceeded at a greater rate during the winter in the ungrazed pasture in each of the three years.

Silverton and Smith (1989) planted seeds of *C. vulgare* in the winter into a permanent grass pasture in England under two levels of summer grazing (using sheep) and all combinations of some or no winter and spring grazing; these grazing regimes had been imposed for two years prior to the experiment. The percentage seedling emergence was determined during the next six months, and at the same time that the seedlings were counted for the final time in the summer, naturally-occurring rosettes were censused in each of the grazing treatments. Spring grazing increased the mean seedling emergence overall from 3.5 to 8.5%, and also resulted in a three fold increase in rosette numbers. Using seedling emergence as a covariate in the analysis of rosette numbers, 77% of the variance in rosette numbers was accounted for, indicating that the main effect of grazing on thistle rosette numbers was indirect, through a grazing-mediated interference with germination conditions. Possible mechanisms are alteration of light quality at the soil surface and / or changes in day / night temperature fluctuations (Phung and Popay 1981). Silverton and Smith (1989) concluded that the close relationship between emergence of sown seed and the number of rosettes established a year or more earlier indicates that seedling emergence is likely to be the most important transition in determining population size in *C. vulgare* in pasture.

Bullock *et al.* (1994) expanded the above demographic by determining the fates of individuals of *C. vulgare* in nine different life history classes over six years. Seed survival and seedling emergence were determined from sown seeds, and other life history stages were quantified by mapping and following the fates of naturally occurring individuals under the different grazing regimes. Heavier summer grazing, or grazing in the winter, increased seedling emergence 1.5 and 2.3 fold respectively, while winter grazing, in addition, increased seedling and small and medium-size rosette survival 2.7, 2.9 and 1.6 fold respectively. These effects were considered to have arisen through the relaxation of interspecific competition due to the preferential grazing of the pasture grasses. This hypothesis was supported by the finding that winter grazing, and heavier summer grazing, decreased the frequency of microsites in the pastures with a canopy, or with litter, by 20 and 80% respectively, and increased the frequency of sites with bare ground 1.5 fold. Matrix analysis of thistle life tables for the experimental paddocks showed that winter and spring grazing, and heavier summer grazing, increased the finite rate of population increase (λ), 3.1, 1.7 and 1.7 fold respectively. The hypothesis that the thistle populations had the capacity to grow faster as the level of pasture interference was reduced by increased grazing intensity, was supported by a significant correlation of λ values calculated for each of the 16 different grazing treatments (paddocks) with the six-year average population size for the paddocks. Five of these 16 λ values were <1, predicting that these populations should decline in size as a result of the level of interference from the pasture plants induced by the particular grazing regimes.

The effect of interference from pasture plants on the seedling emergence of *Cirsium arvense* L. (Californian or perennial thistle) has been investigated in dairy pastures in Victoria, Australia by Amor and Harris (1975). At one site seeds were sown in summer into plots of pasture consisting of *Lolium perenne* L., *Dactylis glomerata* L. and *Trifolium repens* L. that were either cut monthly to a height of 3 or 15 cm. Seeds were also sown onto, or shallowly into, pasture bared by a paraquat / diquat treatment. No seedlings emerged on pasture plots, but 13 and 3% of sown viable seeds emerged as seedlings from shallowly-buried and surface-sown seeds respectively on bared plots in the spring. Similar results were obtained in another dairy pasture in which seeds were sown either onto the surface of a *L. perenne* / *T. repens* pasture set stocked with 3.75, 4.25, 5, 5.75 or 6.5 cows per hectare, or into a lightly grazed pasture or into a wet pasture. Seeds were also shallowly buried or surface-sown on bared plots. Again there was no emergence in any pasture. However 7% of the shallowly buried seeds emerged as seedlings on the bare soil. These results suggest that pasture plants have a powerful inhibitory action against the germination of *C. arvense* seeds. The light requirement of the seeds (Bakker 1960), may not be fulfilled under pasture. Observations of patch size in the thistle in two lightly grazed pastures and two heavily grazed pastures suggested that the rate of vegetative spread was lower the higher the grazing pressure. It would seem that the reduced level of pasture interference which accompanies heavy grazing, while usually increasing population size in the biennial *C. vulgare*, is overshadowed in *C. arvense* by some opposing force, possibly that of being eaten (Mitchell and Abernethy 1993). However the dry matter production of *C. arvense* was relatively insensitive to increased interference from neighbouring pasture plants (compared to other weeds) in a Swedish study when the row spacing of pasture grasses and legumes was decreased from 50 to 10 cm (Hallgren 1976).

Together these studies provide good evidence that the presence of neighbouring pasture plants can limit population size in the biennial *C. vulgare* and that the life history stage most susceptible to pasture interference is the transition from seed to seedling (emergence) (Silverton and Smith 1989, Bullock *et al* 1994,). The seedling to rosette transition (Forcella and Wood 1986, Bullock *et al.* 1994) and the rosette to adult transition may also be sensitive, although perhaps to a lesser extent. These results support a control recommendation that maximizes pasture interference by maximizing pasture height or cover at the time of year when seedling emergence of *C. vulgare* is occurring. By contrast, population size in the perennial *C. arvense* may be much less affected by pasture interference (Amor and Harris 1975, Hallgren 1976). Population growth in this species depends entirely upon recruitment of shoots from adventitious buds on a creeping root system, and the initial reliance of these shoots on stored root reserves, rather than on current photosynthesis, provides an explanation for a lower sensitivity than seedlings to interference from pasture.

Carduus spp.

Feldman *et al.* (1968) sowed seeds of *C. nutans* in Nebraska, USA, in spring and summer, into 15-year-old pastures of four different types (species composition), each under three different grazing regimes (ungrazed, rotationally or continuously grazed). There was no overall effect of grazing intensity on seedling emergence, but the presence of more *C. nutans* plants on the grazed plots (relative to the ungrazed plots) in each of the two years after both sowings, was interpreted as a result of a higher survival rate of rosettes under a relaxed level of pasture interference. Medd and Lovett (1978) showed that the relative growth rate (RGR) of *C. nutans* seedlings is reduced by shading and concluded that the light compensation point (1.7% full daylight) may be reached for this species under a pasture canopy. Low RGR results in small size, and small *C. nutans* rosettes have higher mortality in pasture than larger rosettes (Popay *et al.* 1979). Thus relaxed competition for light is a possible explanation for the greater survival of *C. nutans* in grazed pasture. In Virginia, USA, Kok *et al.* (1986) sowed one or four *C. nutans* seeds per square metre with or without seeds of *Festuca arundinacea* (tall fescue) into cultivated soil. The growth of the thistles was greatly depressed in the tall fescue (relative to no tall fescue), as indicated by an 83% reduction in stem dry weight measured 10 months after sowing. Fecundity was also severely reduced as evidenced by an 89% reduction in seeds produced per plant, a consequence of reductions in the size and number of inflorescences per plant. These results were interpreted as the result of intense competition from the tall fescue. In a related study by these authors, seeds of *C. nutans* sown into the tall fescue pasture a year after it was sown, germinated poorly and all seedlings died before developing four leaves.

Studies in New Zealand in which the fates of *C. nutans* plants in pasture have been followed have revealed high mortality of seedlings and young rosettes during winter after emergence in the autumn (Popay and Thompson 1979, Popay and Thompson 1980). For example, Popay and Thompson (1980) found that of 200 rosette-stage thistles present in a pasture in autumn, 83% died during winter and spring before flowering began. The hypothesis that this mortality is due, at least in part, to interference from pasture species, is supported by studies showing greater survival in pastures desiccated by herbicide. Edmonds and Popay (1983) transplanted *C. nutans* seedlings into sheep-grazed pasture composed of the grasses *Lolium perenne*, *Cynosurus cristatus*, *Bromus mollis*, and *Anthoxanthum odoratum*, with and without prior desiccation by paraquat. Thirty five times as many seedlings from an early autumn planting survived to flowering in the desiccated pasture (relative to intact pasture).

Other studies in New Zealand in which pasture cover has been removed by herbicide indicate that the transition from seed to seedlings may also be influenced strongly by pasture plants. Popay and Kelly (1986) counted *C. nutans* seedlings emerging from intact pasture and pasture bared monthly by paraquat from autumn one year until the following autumn. Three times as many seedlings emerged on the bare pasture. In addition, there were both spring and autumn emergence peaks on the bare pasture, whereas all seedling emergence was confined to the autumn in the intact pasture. The results indicated that the presence of pasture prevented seedling emergence in the spring, and halved the numbers of seedlings emerging in the autumn. Martin and Rahman (1988) obtained similar results using the same experimental approach. When Kelly and McCallum (1990) sowed seeds of *C. nutans* into a pasture composed of *Lolium perenne* and *Trifolium repens* that was either kept clipped to a height of 1 cm or allowed to grow to a greater height under sheep grazing, they found that 6% of the seed emerged as seedlings in the clipped pasture but only 0.94% in the taller pasture. Thus the transition from seed to seedling was reduced 83% in the taller pasture. Furthermore, in related studies comparing life history transitions between two regions in NZ contrasting in susceptibility to the thistle, Kelly and McCallum (1990) found that the seed to seedling transition was an order of magnitude lower in the region where the thistle is not a problem, whereas other transitions differed little between the regions. This lead the authors to suggest that the seed to seedling transition is the single most important stage in the life-cycle of *C. nutans*, and that pasture interference during the time when this transition is occurring, will reduce population size.

By contrast, grazing experiments by Bendall (1973) in Tasmania, Australia, with *Carduus pycnocephalus* L. and *C. tenuiflorus* Curt. provide no evidence that pasture interference directly affects the demography of these thistles. While the survival of these thistles in *Lolium perenne*, *Bromus* sp., *Cynosurus echninatus*, *Trifolium repens* pasture grazed by sheep was significantly lower when winter grazing was not preceded by autumn grazing, when autumn grazing was withheld without being followed by winter grazing, there was no effect on thistle survival. The former results were explained by etiolation of the thistles in presence of ungrazed grass in the autumn, making them palatable and readily eaten (and killed) by the sheep during winter (or spring) grazing.

Overall, the above studies provide evidence of a powerful influence of pasture plants over the transition from seed to seedling in the annual / biennial / triennial *C. nutans* (Popay and Kelly 1986, Martin and Rahman 1988, Kelly and McCallum 1990). The transition from seedling to flowering plant is also significantly reduced in this thistle by interference from pasture plants (Edmonds and Popay 1983), probably by mortality at both the seedling (Kok *et al.* 1986) and rosette stages (Feldman 1968, Popay and Thompson 1980). Pasture interference can also reduce fecundity by depressing growth of surviving thistles (Kok *et al.* 1986). These results support control recommendations for *C. nutans* that maximize pasture cover especially during the seedling emergence phase. Direct effects of pasture interference on population size in the annuals *C. pycnocephalus* and *C. tenuiflorus* have not been proven, but etiolation in long grass facilitates death by grazing.

Pasture species composition effects

Cirsium vulgare

Forcella and Wood (1986) established two seedlings of *C. vulgare* with two of either *Lolium rigidum* or *Trifolium subterraneum* in pots under two nitrogen levels in glasshouse conditions, and imposed clipping treatments on the *L. rigidum* and *T. subterraneum* to simulate grazing. Pots containing four plants of *C. vulgare* only were included as controls. When the swards were not clipped, the dry weights of the thistle plants were the same in mixture with *L. rigidum* and *T. subterraneum* regardless of fertility, and by 10 weeks, were reduced 55% by interference from these pasture plants. However, when the competing grass and clover plants were clipped, differences occurred. Under low fertility, the dry weight of the thistle was 35 and 58% lower when *L. rigidum* was the competing species (relative to *T. subterranean*) when clipping occurred throughout or during the last five weeks of the experiment respectively. The *L. rigidum* was also the better competitor under high fertility and resulted in 61 and 48% lower thistle dry weights when clipping occurred during the first or last five weeks respectively. Fisher and Davies (1991) provide further evidence that pasture species vary in their abilities to interfere with *C. vulgare*. In a study to compare the effects of sown ground covers on invading weeds in set-aside fallows in the UK, they sowed swards of either *Lolium perenne*, *L. perenne* plus *Trifolium repens*, or *Festuca rubra* into an arable field. An unsown treatment was included. Both the frequency and cover of *C. vulgare* were lower in sown swards. Averaging over years 2, 3 and 4 of the study, the percentage ground cover of *C. vulgare* was reduced, in comparison to the unsown sward, 96, 94 and 85% by the three swards respectively. The frequency of occurrence of *C. vulgare* was reduced 86, 92 and 64% respectively. These results together suggest that *L. perenne* interfered more than *F. rubra* with population growth in *C. vulgare*.

Wardle *et al.* (1992) planted seeds of *C. vulgare* into 92 day old swards of the six grasses *Dactylis glomerata* L., *Phalaris aquatica* L., *Bromus catharticus*, *Lolium perenne* L., *Festuca arundinacea* Schreb, *Holcus lanatus* L. and the four legumes *Medicago sativa* L., *Trifolium pratense* L., *T. subterraneum* L. and *T. repens* under greenhouse conditions. *H. lanatus* had the most effect on the percentage emergence of *C. vulgare* seeds, reducing this to 35% from 53% on bare soil; a reduction of 34%. There was a significant negative correlation between the pasture cover of the 10 swards and the percentage emergence of the thistle seeds, implying that the mechanism of germination inhibition is related to foliage cover. Greater differences were found between these ten pasture species in their ability to reduce the growth of *C. vulgare*. In general the grasses, as a group, tended to reduce thistle growth more than the legumes, reducing shoot dry weight, measured 80 days after sowing, when the thistles were still rosettes, by 83 to 94% (relative to bare soil). The results suggested that *H. lanatus* and *L. perenne* are the most effective inhibitors of growth in *C. vulgare*, while *M. sativa*, *T. subterraneum* L. and *T. repens* are the least effective. In contrast to seedling emergence, there was no correlation between thistle growth (dry matter, plant diameter) and cover of the pasture species, suggesting that the mechanism of the inhibition of *C. vulgare* may not involve shoot competition.

Overall the evidence from these three studies suggest that grasses are better able to reduce the growth of *C. vulgare* plants, than are legumes.

Carduus nutans

Research in New Zealand has revealed that pasture species also vary greatly in their relative abilities to inhibit *C. nutans*. Nicholson *et al.* (1990) sowed *C. nutans* in replacement series with either *Lolium perenne* or *Trifolium repens* at two total densities under greenhouse conditions. Per plant dry weight of *C. nutans* declined in mixture with *L. perenne* but increased in mixture with *T. repens* suggesting that *L. perenne* had a competitive advantage over the thistle, whereas *T. repens* did not. Relative yield totals were not different from unity, implying competition between the pasture species and *C. nutans* for the same pool of limiting resources.

In the experiment described above for *Cirsium vulgare*, Wardle *et al.* (1992) also sowed *C. nutans* seeds into swards of the same grasses and legumes under greenhouse conditions. The total percentage emergence of *C. nutans* was reduced 55 and 61% (relative to emergence on bare soil) by *L. perenne* and *H. lanatus* respectively, whereas the other grasses and legumes had no effect on emergence. They concluded that this effect was probably due to a reduced red:far red light ratio under the canopies (Phung and Popay 1981, Black 1969); the difference between the species being explained, at least in part, by differences in their cover as measured by the point intercept method. There was no correlation between the emergence responses of *C. nutans* and *Cirsium vulgare* to these 10 pasture species, implying that the mechanism of emergence inhibition must vary between the two thistles. All ten pasture species reduced the seedling growth of *C. nutans* although the legumes exerted much less effect than the grasses, as was also the case for *C. vulgare*. The growth responses of *C. nutans* and *C. vulgare* were highly correlated, suggesting (in contrast to seedling emergence), that a particular pasture species will be equally effective in suppressing seedling growth in both thistles. *L. perenne* and *H. lanatus* were particularly effective.

Since there was no correlation between *C. nutans* seedling growth and canopy cover of the ten species, as was also found for *C. vulgare*, Wardle *et al.* (1992) suggested that competition for light was not the mechanism for thistle inhibition. They concluded that allelopathy is a more likely mechanism, at least for *C. nutans*, because they found strong positive correlations between *C. nutans* root growth (and root/shoot ratio) in a previous residual alleopathy study, and root and shoot growth, and seedling emergence in the current study. In the previous study Wardle *et al.* (1991) grew the same 10 pasture species separately in boxes for 3–5 months and then sowed *C. nutans* seeds into the soil from under each species at various times up until 162 days after removing the pasture plants. Residual allelochemical effects were identified for all six grasses in the 162-day-old soil. These effects ranged from 64 to 87% reduction in *C. nutans* shoot growth in the soil from beneath *D. glomerata* and *H. lanatus* respectively. Root growth was also significantly reduced in soil from some species and germination of *C. nutans* was reduced 50% by soil from beneath *L. perenne*. By contrast all four legumes demonstrated stimulatory effects, particularly in terms of thistle root and shoot growth.

In order to test the hypothesis that grasses have a greater capacity to interfere with seedling emergence and subsequent growth of *C. nutans*, Wardle *et al.* (1995) sowed monocultures of each of the six grasses and four legumes compared in previous studies, into a dairy pasture with a history of *C. nutans* infestation, after killing the existing pasture with herbicide. The experiment ran for 27 months from March (autumn 1990) during which time *C. nutans* seedlings were counted and removed two-monthly, regular point intercept (cover) estimates of pasture composition were made, and the fates of some tagged *C. nutans* plants were followed. Seedling emergence was generally lower in the grass than in the legume swards. These results are consistent with those of Wardle *et al.* (1992), showing that grasses inhibit emergence more than legumes. Across all swards, emergence was negatively correlated with the cover of grasses (sown or volunteer) and also with the cover of *Poa annua*, a species which invaded particularly in the grass-sown plots. Other measures of *C. nutans* performance also negatively correlated with the cover of grasses in the plots were the fraction flowering as annuals, plant diameter and capitulum number per plant. These correlations suggest, contrary to the conclusion made by Wardle *et al.* (1992), that shoot competition, at least from grasses, is an important interference mechanism under field conditions. The intense interference from the grasses prevented thistles from reaching sufficient size to flower in their first year, and resulted in a higher fraction of thistles dying as rosettes in the grass swards, relative to the legume swards.

The results of these glasshouse and field studies on interference between pasture plants and *C. nutans* reveal that grasses inhibit seedling emergence and subsequent growth and survival of rosettes to a significantly greater level than legumes. It also appears that pasture species vary in their abilities to inhibit emergence and growth of *C. nutans* by virtue of the amount of cover they produce. This implies that canopy cover alters the germination conditions, probably through reducing the ratio of red:far red light, and also that competition is involved in inhibiting growth and survival. Thus, while legumes may often be an essential component of pastures, it appears that newly-sown pastures should be grass dominant if control of *C. nutans* is an objective.

Silybum marianum

In an experiment in New South Wales, Australia, to measure the relative effectiveness of perennial and annual pasture species in preventing the establishment of the annual, *Silybum marianum*, Michael (1968a) sowed seeds of *Phalaris aquatica*, and *Lolium rigidum* with and without seeds of *Trifolium subterraneum*, *T. subterranean* alone and *Medicago sativa* alone into cultivated soil with a history of *Silybum marianum* infestation in preceding crops and pastures. When assessed in the first spring following autumn sowing the perennial species, *P. aquatica* had reduced the fresh weight and population density of *S. marianum* 74 and 39% respectively relative to the 'not sown' control. The other perennial, *M. sativa*, had completely prevented the occurrence of the thistle. By contrast the annuals, *L. rigidum* and *T. subterranean* had no effect. In the second spring after sowing, dry weights of the thistle were still lowest in the *P. aquatica* and the *M. sativa;* 98% reduction relative to the not sown treatment. The ability of *M. sativa* and *P. aquatica* to make rapid growth after late summer or autumn rains, at the time when *S. marianum* is germinating, was suggested as a mechanism for their success in controlling the thistle. Pook (1983) found that the light compensation point of *S. marianum* (and *Onopordum* sp.) was 2.4% full (cool season) daylight, and suggested that while this represents a degree of shade tolerance, heavy shading during the cool winter season by persistent pasture species could contribute to control of these thistles.

Onopordum spp.

The effects of pasture interference on *Onopordum acanthium*, *O. illyricum* and hybrids between these two biennial thistles appears to have received less attention by researchers than *Carduus* and *Cirsium* sp. Michael (1968b) sowed *Bromus inermis*, *Dactylis glomerata*, *Festuca arundinacea*, *Lolium perenne*, and *Phalaris aquatica*, (including not-sown controls) in the autumn (and spring) in New South Wales, Australia, into cultivated soil previously supporting a *Trifolium subterranean* pasture heavily infested with *Onopordum* sp. These five perennial grasses diverged significantly in their abilities to influence thistle population size with both times of sowing. Differences between the pastures appeared in the first year and persisted for at least seven years. In the spring of the seventh year after sowing, the population density of *Onopordum* plants that exceeded 100 mm diameter, and the dry matter yields of the populations, were lower in the *F. arundinacea* and *P. aquatica* pastures relative to the other three pastures (and the volunteer pasture) indicating that these two grasses had interfered more than the others with population size and plant growth in the thistle. Since both thistle population density and dry matter yield in spring were highly correlated to the cover of the grasses in the previous winter, differences in competitive abilities between the grasses probably explain the effects.

Pasture gap effects

Cirsium spp.

Gaps in pastures probably play a crucial role in the ability of pasture plants to interfere with the population dynamics of *C. vulgare*. Silverton and Smith (1989) found evidence for this by planting seed of *C. vulgare* into artificial gaps of varying diameter created in a mown grassland in England by cutting the sward to ground level. Percentage seedling emergence of sown seeds increased with gap diameter four fold from zero to 10 cm, but tended to decline with greater gap diameter. Panetta and Wardle (1992) found a similar relationship when they planted seeds of *C. vulgare* into gaps created in a *Lolium perenne–Trifolium repens* pasture on a dairy farm in New Zealand. In this case percentage seedling emergence increased 13 fold from a gap diameter of zero to 2 cm, and declined with increasing gap diameter up to 10 cm. Seeds sown into large (3 m^2) bared plots had a probability of producing seedlings similar to those sown into the intact pasture. There was however no response to gap size under glasshouse conditions, leading Panetta and Wardle (1992) to conclude that differences in diurnal temperature fluctuations or soil moisture content between gap sizes, rather than reductions in red:far red ratios of foliage filtered light (Black 1969), may control the gap size response of *C. vulgare*. This hypothesis is supported by the results of Phung and Popay (1981) which showed that increasing pasture cover, while reducing both germination and the red:far red ratio under fluctuating temperature conditions, did not reduce germination under constant temperature. These two studies suggest that there is an optimum gap size for seedling emergence in *C. vulgare*. Survival of seedlings may also be influenced by gap size. While there is no direct evidence for this with *C. vulgare*, Louda *et al.* (1990) found that the survival of transplanted seedlings of the native *Cirsium canescens* Nutt. in prairie grassland in Nebraska, USA, was reduced by 89% within nine weeks of planting, in 15–20 cm diameter gaps within clones of *Panicum virgatum* L. compared to survival in large open spaces between clones. Louda *et al.* (1990) suggested that competition between the thistle and the grass for water was the most likely mechanism for this effect, although they could not discount differences in the light levels and physical conditions.

Silverton and Smith (1989) explored the relationship between gap density and the population dynamics of *C. vulgare* by altering the gap density and seed aggregation parameters of a simple model which simulated the expected population density after 50 years, of a monocarpic perennial weed, capable, like *C. vulgare*, of establishing only in gaps of a specified size. The model showed the existence of a gap density threshold below which the population becomes extinct, and above which small changes in gap density lead to very large differences in population density. These results imply that sudden outbreaks of *C. vulgare* might be expected as gaps become more frequent through over grazing or through poor persistence of pasture plants.

Carduus nutans

Gaps in pasture have been considered to play a crucial role in the recruitment also of *Carduus nutans* seedlings (Ivens 1979). This was confirmed by the study of Panetta and Wardle (1992) in which the field emergence of sown *C. nutans* seeds increased with gap diameter up to 10 cm, above which it declined. This response was explained by a greater amplitude of temperature fluctuations experienced by seeds in medium size gaps promoting germination, and faster drying of soil after rainfall in larger gaps reducing germination. Reduced red:far red ratio of canopy filtered light may also partly explain the initial increase in germination with increasing gap size since Phung and Popay (1981) found *C. nutans* seedling emergence was increased on bare ground (relative to under a pasture canopy) under both fluctuating (glasshouse) and constant (growth room) temperature conditions.

Conclusions

The main conclusions that can be drawn from the studies reviewed here on the role of pasture interference in the population ecology of thistles are:

i. Pasture grasses and legumes can exert powerful inhibitory influences over seedling emergence and seedling and rosette survival in thistles, thereby regulating population size.
ii. Pasture grasses are, as a whole, more effective than legumes at inhibiting these demographic processes.
iii. Grasses (and legumes) vary in their inhibitory abilities and this seems to be determined largely by their foliage cover density although allelopathy may also operate.
iv. Perennial grasses exert greater inhibitory effects than annual grasses. *Lolium perenne*, *Holcus lanatus* and *Phalaris aquatica* appear to be particularly effective.
v. Pasture gaps promote thistle seedling emergence, and the optimum size appears to be in the range of 2–10 cm diameter.

The general rule that emerges, at least for the annual and biennial thistles, is that thistle population size will be limited most in pastures composed predominantly of perennial grasses that are managed in a manner that prevents the occurrence of small to medium size gaps particularly during times of the years when the seed to seedling (autumn) and seedling to rosette (winter / spring) transitions are occurring. Sindel (1991) reached a similar conclusion. The empirical evidence supporting this general rule for thistle control is very strong. Future research should focus on how grazing management and other factors including soil fertility and soil moisture (Sindel 1991), influence the creation and closure of pasture gaps and the balance between grasses, legumes and thistles in pastures.

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Targeted grazing of thistles using sheep and goats

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Summary
The diet of goats includes many plants not necessarily eaten by sheep and cattle. Hence we studied their use in control of Illyrian, nodding and variegated thistles. Goats ate Illyrian and variegated thistles in the rosette stage and all three thistles at the flowering/seeding stage. The amount eaten depended on the grazing pressure (both sheep and goats) and herbage mass (both thistles and pasture) so that season affected the outcome. Control of these thistles was achieved. Since goats ingest thistle seed it should be possible to significantly reduce thistle problems.

Introduction
The diet of goats includes many plants not necessarily eaten by sheep and cattle (Holst 1993, Leigh *et al.* 1993). This has encouraged the concept of mixed grazing—the practice of grazing more than one animal species either concurrently or sequentially—which is usually associated with an increase in animal production. However, a more important outcome is the effect on the pasture so that with an understanding of a plant's palatability to animals, it is possible for graziers to control most of the pasture weeds in eastern Australia (Allan *et al.* 1993).

Thistles provide a good example of dietary selection and the potential to use mixed grazing as a means of weed suppression (Rolston *et al.* 1981, McGregor *et al.* 1990, Sindel 1991). Despite good physical defences, thistles are highly palatable to goats at the flowering stage (Leigh *et al.* 1993). We wish to report on some grazing experiments conducted on Illyrian, nodding and variegated thistles. In an associated experiment we examined the possibility of seed transfer of the weeds Illyrian thistle, nodding thistle and scotch broom, by faecal droppings following their ingestion by sheep or goats.

Materials and methods

Illyrian thistle (Onopordum illyricum)
The experimental site was a degenerated pasture at Boorowa on the south-west slopes of New South Wales where the stocking rate was estimated to be 7 DSE per hectare. The experiment consisted of four plots, each of 2.8 ha with a sheep alone treatment (23 sheep), a goat alone treatment (30 goats) and two levels of sheep and goats combined (15 sheep and 10 goats, 20 sheep and 8 goats). The sheep and cashmere type goats were stocked at equivalent rates in terms of maintenance energy requirements. Measurements on the thistles were made in four sets of open and closed (3 × 3 m) quadrats within each treatment. Every 6–8 weeks, and more frequently at flowering, data were collected on thistle height, width and number; capitula and flowering stems eaten and not eaten; and seedling counts.

Nodding thistle (Carduus nutans L.)
The site was an arable, planar site at Crookwell on the southern highlands of New South Wales. Pasture consisted of demeter fescue, ryegrass, white and sub clover and some annual grasses. Thistle was uniformly spread across this paddock and occupied 22% of the area when assessed in mid winter. The experiment consisted of six 5.0 ha plots with two grazing treatments (2 levels of sheep and goats) and three replications. Initial stocking rate was equivalent to 3.5 DSE per hectare, but was increased to 14 DSE from mid Spring to late Autumn. Three open and two closed quadrats (3 × 3 m) were established in each of the six plots. From each of these, vegetative data were recorded every six weeks and more so at flowering. Counts of nodding thistle seedlings were conducted in Autumn.

Variegated thistle (Silybum marianum)
A degenerated barley grass dominant pasture located at Cowra in the central west of New South Wales provided nine plots each of 0.75 ha on which three treatments (100% sheep, 66% sheep and 33% goats, 33% sheep and 66% goats) were replicated three times. On each plot five random 0.25 m^2 quadrats were used for pasture estimation and a permanent 40 m transect for thistle measurements.

Seeds
Seeds were collected from mature capitula of nodding thistle and Illyrian thistle during the flowering period, approximately six months prior to the feeding experiment. Branches from scotch broom containing mature seed pods were harvested and pods allowed to open and seeds collected. All seeds were stored in paper bags at room temperature in a dark cupboard.

Immediately prior to feeding weed seeds, viability was determined by allowing seeds to germinate for 21 days and then cutting those remaining to determine the presence of an embryo. Viable seeds were determined as the sum of those germinating and containing an embryo. Four thousand five hundred viable seeds of scotch broom, 3460 viable seeds from nodding thistle and 3780 viable seeds of Illyrian thistle were combined into a single 'ration' just before feeding.

Animals
Six mature female cashmere type goats and four mature female Border Leicester × Merino ewes were housed in metabolism cages. All stock were conditioned to the feeding regime over a period of two weeks prior to the feeding of the weed seeds. All species of weed seeds were fed to goats, however only Illyrian thistle were given to the sheep. Intake of lucerne chaff was monitored for two weeks prior to feeding and on the day of feeding the weed seeds, 80% of the normal daily ration of lucerne chaff was combined with the weed seeds and fed in the early morning to sheep and goats. This reduction in chaff was undertaken to ensure complete consumption of feed.

Faecal collection
On each of the following five mornings faeces were collected from each animal. Seeds were collected by wet sieving, and were identified and separated into like species. They were then placed on filter paper moistened with fungicide, and allowed to germinate for 21 days.

Results

Illyrian thistle
Both sheep and goats grazed the thistle rosettes between August and October resulting in a reduction in diameter by

Table 1. Height of Illyrian thistle at flowering.

Treatment	Height (cm) Open quad	Closed quad	Reduction (%)
100% sheep	59	93	36
66% sheep 33% goats	50	108	53
33% sheep 66% goats	0	76	100
100% goats	3	100	98

Table 2. Percentage of Illyrian thistle flowering stems eaten.

Treatment	Month Nov	Jan	Mar
100% sheep	0	43	70
66% sheep, 33% goats	52	44	73
33% sheep, 66% goats	75	100	100
100% goats	34	100	100

20–40% in all plots. The effects of grazing were further reflected in the height of the thistles at flowering where height was reduced by 36% in the sheep alone plot and 100% in the goat alone plot (Table 1). Goats consumed significantly (P<0.001) more flowering stems than sheep (Table 2).

Nodding thistle

Sheep did not graze the nodding thistle rosettes and only occasionally the flowering capitula. Goats occasionally ate the larger (>30 cm) rosettes but had a significant impact on the capitula (Table 3).

Table 3. Per cent of nodding thistle grazed by sheep and goats and mean height (± s.e.) of grazed and ungrazed plants. Eaten P<0.001, height P<0.001.

	Sheep		Goat	
Month of year	Eaten (%)	Height (cm)	Eaten (%)	Height (cm)
December	0		22	
January	7	74.4 (4.5)	93	56.7 (33)
February	5	79.4 (2.9)	85	57.2 (46)
March	3	77.3 (2.3)	96	62.9 (2.2)
April	9	78.3 (2.5)	100	52.4 (6.4)
May	50	63.3 (5.2)	93	42.8 (7.5)

Variegated thistle

Sheep ate very little variegated thistle whereas goats readily ate the leaves and seedheads (Table 4, Figure 1).

Table 4. The effect of grazing on variegated thistle.

	Vegetative stage		At flowering	
Treatment	Diameter (cm)	Height (cm)	Height (cm)	Seedheads per plant
Sheep	54	31	162	27
Low goat	49	14	129	13
High goat	33	8	59	3

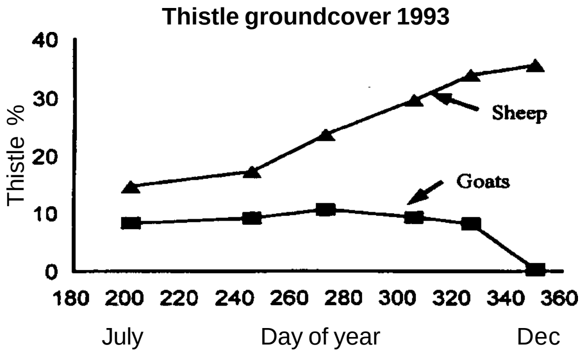

Figure 1. Variegated thistle groundcover in sheep and goat plots.

Seeds

Each species of the weed seed continued to be collected for the following five days after feeding. The greatest quantity of each species was recovered on days 2 and 3 after feeding and was not different between sheep and goats (Figure 2) for Illyrian thistle.

Differences existed between animals in recovery of seed. One particular goat accounted for 50.5, 73 and 37% of recovered seeds for scotch broom, Illyrian thistle and nodding thistle respectively. Less than 1% of the viable seeds fed for the thistle species, were recovered from the faeces. This contrasted with the average 10% recovery of seed from scotch broom (Table 5).

Table 5. Recovered seeds from goat and sheep faeces as a proportion of the number of viable seed fed.

		% Seeds recovered	
Species	Viable seeds fed	Goats	Sheep
Illyrian thistle	3780	0.16	0.13
Nodding thistle	3460	0.2	–
Scotch broom	4500	9.9	–

Germination of the recovered seeds was lower than the pre-feeding test (Table 6).

Table 6. Per cent germination of recovered seeds which contained an embryo.

	% germination of seeds which contained an embryo	
	Pre	Post
Illyrian thistle	7.7	0.1
Nodding thistle	46.8	0.01
Scotch broom	1.9	2.3

Some variation between animals was apparent in the number of seeds recovered. If data from the aberrant animal were removed, then the number of seeds recovered would be significantly less than that presented. Recovered seeds from scotch broom would amount to 1.8% of those fed.

Discussion

Goats readily included each thistle in their diet particularly at flowering and post flowering as the seed heads developed. Since there is a general linear relationship between amount eaten and number of goats, control could be effected by manipulating the number of goats and/or seedheads (by chemical). The result would be fewer viable seeds being added to the soil based population.

The number of recovered seeds from the thistle species indicates that rumen activity digested 99% of seeds ingested. This indicates that when the studied thistle seeds are consumed by goats (and sheep), that dispersal via the faeces will be a minimal factor contributing to spread of these weed species. Simao Neto *et al.* (1987) reported that increasing the time that seed were in the rumen increased the proportion of damaged seed. The period in the rumen, for the majority of seeds (36 hours), was sufficient to allow complete breakdown of the majority of the seeds.

The reason for a lack of germination of recovered seeds from Illyrian thistle and nodding thistle cannot be ascertained from this study. As some recovered seeds contained an embryo, they potentially are still viable. However, it is unclear whether any dormancy remains in the recovered seeds or rumen liquor has indeed killed the seed and rendered them non-viable. Notwithstanding unknown viability of the recovered seeds, following ingestion the majority of seeds disintegrated during mastication and passage through the rumen. Other studies have indicated that seed survival with passage through animals was related to the degree of hardseedness (Simao Neto *et al.* 1987, Blackshaw and Rode 1991). Grass and legume seed content in the faeces was highest between 24 and 72 hours post feeding (Simao Neto 1987) which is reflected in this study.

Both Illyrian thistle and nodding thistle may act as an annual or biennial plant, so that at any one time several generations may be present in a population. This reduces the efficiency of herbicides. However, this is not a problem with goats, who effectively accommodate a mixed generation, plants near fences and trees, non-arable areas and weather which is not suitable for chemical application.

Although goats clearly select thistles for inclusion in their diet, effective thistle control requires the presence of a vigorous pasture to compete with the weed. The ingestive behaviour of goats helps to achieve this objective (Gong *et al.* 1996).

Conclusion

Targeted grazing of thistles with goats and other farm livestock provides a useful technique to control thistle. Because goats

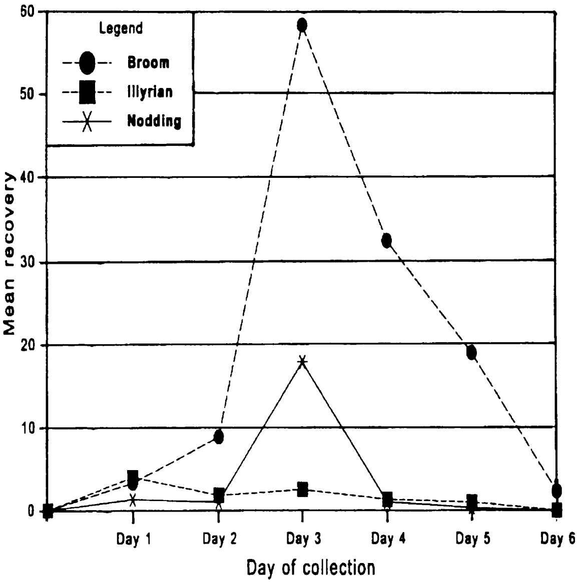

Figure 2. Average number of seeds of Illyrian thistle, scotch broom and nodding thistle, recovered from four goats.

can control the amount of seed entering the soil they represent an important technique and should be part of the integrated control of thistles.

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Herbicide management and thistle control—how to avoid resistance

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Summary

Applying phenoxy herbicides annually to thistles for many years can lead to herbicide resistance developing within thistle populations. Populations of nodding thistle have been located in Hawkes Bay which require six times more MCPA than normal to obtain adequate control. Such populations are known to exist on at least 12 properties in Hawkes Bay and Waikato. A comparison of past spraying practices on these properties and farms where resistance has not developed identified that resistance has occurred due to more frequent use of phenoxy herbicides on the former properties. Cross-resistance exists within these populations to 2,4-D, MCPA and MCPB. Thus such thistles can only be controlled by adding clopyralid to one of these herbicides, which is damaging to pasture legumes. Work with radio-labelled MCPA has shown that resistance is due to an increased rate of herbicide degradation within the plant rather than reduced uptake, so adding surfactants to the herbicide will not overcome the resistance.

Based on research results from a range of sources, the following recommendations could be made. Intense herbicide pressure can be justified on thistle species which are just establishing on a property. However, once populations have well established seed banks, a better strategy may be to rely mainly on good pasture management techniques to reduce the impact of weeds which are present. Sowing pasture species tolerant of dry conditions is probably the most useful pasture management strategy. Ensuring that these pastures are not overgrazed in summer and early autumn should help reduce establishment of the seedlings each autumn. Grazing paddocks with cattle rather than sheep can avoid overgrazing, and goats can reduce seed production by eating the seed-heads. Farmers may need to be more tolerant of low thistle numbers, and spray only in those years when densities are high. Thus resistance will be less likely to develop, so thistles will still respond to herbicides in those years when control is really necessary.

Introduction

Although it was once thought that herbicide resistance was unlikely to develop in weed species sprayed with phenoxy herbicides, work in New Zealand has shown that populations of nodding thistle (*Carduus nutans*) have become resistant to MCPA and 2,4-D through their continued use (Harrington 1990). The aim of this paper is to outline the work that has been conducted in New Zealand to study herbicide resistance in nodding thistle and to offer suggestions as to how farmers could avoid herbicide resistance developing in this and other thistle species growing in pasture.

Herbicide resistance in New Zealand thistles

Poor control of nodding thistle at Argyll in Hawkes Bay during the early 1980s prompted tests to be conducted to check whether resistance may have developed in the population. As the development of resistance to phenoxy herbicides had rarely been documented before this time, poor control was assumed to be due to environmental factors. However when nodding thistle from Argyll was grown from seed in a glasshouse beside nodding thistle from another site where satisfactory control was still being obtained, a significant difference in susceptibility was detected (Harrington and Popay 1987). Sizeable differences in susceptibility to MCPA were detected each time this comparison was repeated both in the glasshouse and in the field, and it was calculated that nodding thistle from Argyll was six times less susceptible to MCPA than normal (Harrington *et al.* 1988).

Nodding thistle seed was collected from a number of other sites in Hawkes Bay and Waikato where farmers had complained of obtaining poor control using 2,4-D. Plants from at least 12 of these sites showed similar levels of resistance to those plants at Argyll, showing that this resistance was not an isolated incident (Harrington 1989).

A range of different herbicides was applied at their recommended rates to field-grown plants of a susceptible and resistant population planted beside each other. Cross-resistance was detected to MCPA, 2,4-D and MCPB (Harrington 1989), the three herbicides normally used for selective control of nodding thistle in New Zealand pastures. Although there was no cross-resistance to herbicides such as dicamba, clopyralid or picloram, these herbicides all cause severe damage to clovers in pastures. The standard recommendation at present for controlling herbicide-resistant nodding thistles is to add a low rate of clopyralid to standard rates of 2,4-D or MCPA (Harrington 1993), though this can cause unacceptable levels of clover damage.

To determine whether resistance was due to poor herbicide absorption, ^{14}C-labelled 2,4-D was applied to the foliage of resistant and susceptible nodding thistle plants. No significant differences in penetration were recorded (Harrington 1992). However there were significantly lower levels of unmetabolized 2,4-D detected in resistant plants 7 days after application than in susceptible plants. It appeared that resistance resulted from 2,4-D molecules being converted into both water soluble and ether soluble metabolites more rapidly than in susceptible plants. Thus adding surfactants to increase uptake of the herbicide would be unlikely to overcome the resistance. Although surfactants might improve uptake of herbicides despite this, clovers are also likely to become more susceptible to the herbicide.

To determine why herbicide resistance developed in nodding thistle, the previous spraying histories for seven sites with resistance and seven sites free of resistance were studied. All sites with resistant populations had been sprayed at least annually every year for the previous 15 years or longer with 2,4-D or MCPA (Harrington 1990). The susceptible sites had also been sprayed in previous years, but they had all been sprayed much less frequently. Presumably this would allow susceptible plants to cross-pollinate with resistant plants in the years when herbicides were not applied, though perhaps even sites sprayed infrequently may eventually develop resistance in future years. No work has yet been done to determine whether resistance is caused by one or many genes, or whether the genes are dominant or recessive.

Likewise, few studies have been completed on whether resistant thistles are less 'fit' than susceptible thistles. A trade-off with fitness of plants is often noted when resistance develops to herbicides (Gressel and Segel 1982). However a preliminary trial in which resistant and susceptible plants grew beside each other in a 1:1 ratio under severe nutrient stress showed no significant differences between ecotypes in their reaction to this stress (Harrington 1990). Since that trial was conducted however, Bourdôt *et al.* (1996) have detected reduced growth from MCPA-resistant giant buttercup (*Ranunculus acris*) plants when grown at high densities with susceptible biotypes.

Avoiding development of herbicide resistance in other thistle populations

Since the development of resistance to 2,4-D in nodding thistle was recorded in Hawkes Bay, a similar phenomenon has been noted with resistance to MCPA in giant buttercup elsewhere in New Zealand (Bourdôt *et al.* 1989). Likewise resistance to MCPA appears to have developed in slender winged thistle (*Carduus pycnocephalus*) in Hawkes Bay, but further work is required to conclusively prove this (Harrington 1989). So there can be no doubt that farmers in New Zealand are able to exert sufficient selection pressure with phenoxy herbicides to develop herbicide resistant biotypes. Once this resistance has developed, these weeds can become very difficult to control. Thus it would be preferable to avoid resistance from developing initially.

Herbicides could be used less frequently if thistle densities could be kept low. Many studies have shown that thistle establishment is less likely if pastures remain dense throughout the year (e.g. Phung and Popay 1981, Popay *et al.* 1987). Many thistle problems occur as a result of pasture covers opening up during periods of dry weather, leaving bare soil where thistles can germinate when rain falls in autumn. However there are now a number of pasture species which are being successfully established in areas of New Zealand prone to summer drought, including 'Grasslands Wana' cocksfoot, 'Grasslands Maru' phalaris and 'Grasslands Roa' tall fescue (Milne *et al.* 1993). Establishment of such pastures make it easier for farmers to keep pastures dense throughout the year, making thistle invasion less likely.

Pastures will be more difficult to keep dense and competitive during summer if there is too much livestock on the property. Farmers need to carefully consider whether their stocking rate should be reduced over summer if thistle problems in the following season are to be avoided. Use of supplementary feed crops over summer to reduce the grazing pressure on pastures is another possible strategy. Cattle often do not graze pasture as close to the ground as sheep, so increasing the ratio of cattle on a property can help reduce thistle problems. One farmer in Waikato who had problems with herbicide-resistant nodding thistle completely changed his farming system from sheep to cattle and found nodding thistle was much less of a problem. Note however that ragwort (*Senecio jacobaea*) then became the dominant weed on his property. Goats can also be useful on properties with thistle problems as they often eat the seed-heads, reducing the quantity of seed produced each year (Rolston *et al.* 1981). Likewise biological control agents such as *Rhinocyllus conicus* should be encouraged as they can reduce seed production from some thistle species (Kelly *et al.* 1990).

Farmers also need to learn how to tolerate low densities of thistles and to only spray in those years when densities are particularly high. If MCPA or 2,4-D is used rather than MCPB for thistle control, animal production can suffer temporarily due to a reduction in clover production. Hartley (1983) showed that spraying thistles was not justifiable economically for densities below 1.7 m^{-2} because animal production was affected more by the herbicide than thistles below this density. Farms, where a policy of spraying only when really necessary had been adopted, had no herbicide resistance problems. Those where resistance had developed had been trying in vain for many decades to eradicate nodding thistle from their properties. Such eradication is apparently seldom achieved on properties where seed banks are well established. Intense herbicide pressure should probably only be applied when a new thistle species is just becoming established on a property. If densities of such a species are low enough that it is practical to kill survivors of a spraying operation each year by grubbing or spot-spraying with herbicides such as clopyralid, then eradication may be possible and development of resistance less likely. Noxious plants schemes should be designed to ensure that farmers are not being forced to attempt eradication of a thistle species from their property once seed banks are well established.

A meeting was convened in Napier during November 1995 at which invited farmers, advisors and scientists discussed what further research was required to assist Hawkes Bay farmers cope with thistle problems, including herbicide resistance. One of the main conclusions from this meeting was that scientists have a reasonable understanding of what needs to be done on farms to overcome thistle problems, but that farmers and often also the advisors are not aware of the research that has been completed over the past 20 years or the implications of these findings. Thus in the short term, improved extension activities were seen to be more important than further research. If farmers were more aware of the concepts discussed above, herbicide resistance would be less likely to develop on their farms. Note however that the lack of a testing service in New Zealand to confirm the presence of herbicide resistance in thistle populations can cause problems for advisors.

Conclusions

The development of herbicide resistance in thistle populations can and does occur. Once resistance is present, selective control of these weeds with herbicides is very difficult to achieve. Farmers should avoid resistance from developing at all by reducing the selection pressure applied by herbicides. They should try to keep their pastures competitive enough in late summer and autumn to prevent thistles establishing from seed. They should tolerate low densities of thistles and only apply herbicides in those years when densities are particularly high.

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Herbicide techniques for thistle management

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Summary

The thistle species causing major problems in the farming and pastoral areas of New South Wales are saffron thistle (*Carthamus lanatus*), black/spear thistle (*Cirsium vulgare*, variegated thistle (*Silybum marianum*), scotch and Illyrian thistle (*Onopordum* spp.) and nodding thistle (*Carduus nutans* ssp. *nutans*). Many other species are causing more localized problems. St. Barnaby's thistle (*Centaurea solstitialis*) is appearing as a more widespread problem. Herbicides when used in isolation and not as part of an integrated control program have generally given ineffective long-term control. Herbicides integrated into cropping and perennial pasture improvement programs, livestock grazing strategies (spray-graze technique) and selective control in establishing and established pastures are all important considerations for long-term effective control.

Introduction

The thistle species which are considered to be most widespread and causing concern in pastoral, cropping and non-agricultural land of New South Wales are *Carthamus lanatus* (saffron), *Cirsium vulgare* (black/spear), *Silybum marianum* (variegated), *Onopordum acanthium* (scotch), *Onopordum illyricum* (Illyrian) and *Carduus nutans* spp. *nutans* (nodding). In their references on widespread and troublesome thistle species, Groves and Kaye (1989), Medd (1981) and Sindel (1991) also include *Carduus pycnocephalus* (slender) and *Carduus tenuiflorus* (winged slender).

The biology of each species also varies considerably from short-season annuals, annual/biennials through to biennials (Groves and Kaye 1989). The response to herbicide control appears, to some extent, to be attributable to the annual or biennial growth habit of the species. Biennial species such an *Onopordum* spp. appear to be much more difficult to control (Dellow unpublished).

The essential part of any effective control program is the integration of control options based on perennial and competitive pastures (Sindel 1991, Popay and Medd 1995). This paper discusses herbicide application, as part of an integrated control program, either at lethal levels or sub-lethal levels as part of a spray-graze program.

Herbicide use

In New South Wales there are herbicides registered for all the thistle species discussed in this paper (Dellow 1995). However, one of the major factors affecting the efficacy of a herbicide is the time of application which is greatly dependent on the biology of the species. Popay and Medd (1995) observed in the case of biennials such as *C. nutans*, that a single herbicide application in spring was more effective than an autumn application; because of winter vernalization. Plants emerging in spring would remain vegetative until adequately vernalized during the following winter. Herbicide trials carried out in the Oberon district (Milne 1996) in spring 1995 demonstrated the efficacy of the relatively 'soft' herbicide MCPA on *C. nutans*. The success of the control is attributed to correct time of spraying, favourable seasonal conditions and correct herbicide choice. It confirms research conducted by NSW Agriculture on the Central and Northern Tablelands since 1983. *O. acanthium* and *O. illyricum* behave in a similar manner to *C. nutans* (Groves and Kaye 1989) and consequently, if a single herbicide application was undertaken, then a spring application would be considered the best option.

Annual thistles are more seasonal than the biennials (Sindel 1991) and are best controlled by herbicides in autumn after germination has occurred. Efficacy of herbicide is likewise very dependent on the growth size of the plant, growing conditions and stress factors caused by insects or disease. Once plants have passed the rosette stage and are commencing to elongate they become much more difficult to control. The choice of herbicide and application rate is greatly dependent on the thistle species, the plant's growth stage, the composition of the companion pasture and the density of the thistle population (Dellow 1995). Herbicides which are least detrimental to the legume component of a pasture are generally the least effective for thistle control; particularly the strongly perennial species such as *Onopordum* spp. (Dellow unpublished).

The consequence of non target herbicide damage (to companion pasture) is a very important management consideration. A manager who has a difficult control option such as the control of *Onopordum* spp. must first consider the choice of perennial pasture species which will not only afford long term thistle competition and quality livestock forage, but will also possess the capability of withstanding damage from the less selective and more highly efficacious herbicides. Strongly perennial and persistent pasture species such as *Phalaris aquatica* are the essence of effective weed control programs; particularly for perennial weed species (Campbell and McDonald 1979).

The effect of herbicides on the non-target pasture species is an important management aspect which is often little considered. Whether herbicide applications are single or repeated applications over several seasons, there is little data to demonstrate the long term effect. Graziers who have often repeated applications of non-selective herbicides such as dicamba for the control of *C. nutans* often report the long term detrimental affect on the legume component of the pasture (Dellow unpublished).

Spray graze technique

The technique of applying sub-lethal applications of phenoxy herbicides such as MCPA, 2,4-D amine and 2, 4-DB amine in conjunction with heavy stocking rates of grazing livestock (sheep) has been a long accepted control method (Dellow 1995). The spray-graze technique is registered in New South Wales for control of *C. lanatus*, *C. vulgare*, *C. pycnocephalus*, *C. tenuiflorus* and *S. marianum*. By using this technique the subsequent non-target damage to the legume component of the pasture is minimized. The spray-graze technique often does not have as wide an acceptance as it deserves. Factors which had been detrimental to its more widespread acceptance are that sheep are the only effective livestock, very heavy stocking rates are necessary for short periods (8–10 times normal stocking rate and often paddock size is inadequate to manage such stocking rates), or insufficient livestock numbers are available.

The technique, like all long term control programs relies on the presence of a competitive pasture to replace the weed. Often the grazier does not either have a sufficiently competitive pasture or the managerial ability to both control the weed and manage the pasture. Anecdotal evidence suggests the spray-graze technique would be equally effective on *C. nutans* and *Onopordum* spp.

Spray topping

Spray topping is generally considered a 'salvage' operation using a 'knock-down herbicide' (paraquat) to destroy flower heads and hence prevent seed set of *C. lanatus*. The herbicide application is made after the thistle has bolted and is timed to coincide with 10% of the flowers just commencing to show yellow flower colour (Dellow 1995). Preliminary trial work (Milne personal communication) in central west New South Wales indicates the technique is also effective on *Centaurea solstitialis.*

Discussion

As with all weeds, any one technique for the control of thistles, such as herbicide application, is ineffective if not used with other techniques and management strategies in an integrated program. For several thistle species such as *C. vulgare* and *S. marianum*, herbicides used in an integrated program provide satisfactory control. However, for the biennial species such as *Onopordum* spp. the effectiveness of herbicide is wanting. For species such as *C. nutans,* trial work (Milne 1996) has shown that herbicides can be extremely successful if the correct rate and timing is observed.

The philosophy of integrated weed control is generally little understood by many graziers and to a lesser extent by agricultural extension personnel. Many control programs are often unsuccessful because one single technique, such as herbicide application is used in isolation without consideration of a long term integrated strategy. Biological control is another important aspect of thistle control (Woodburn and Briese 1996) which requires research to fit it into an overall control program.

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The relevance of variation in thistles to herbicidal control

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Summary

Variation in thistles is the result of environmental, morphological and genetic factors. The success of any strategy for thistle control could depend on one or all of these factors and on the thistle species concerned. Seasonal rainfall and temperature patterns can have a significant bearing on the behaviour of many of the thistle species common to Australia. The intensity and frequency of rainfall events can markedly affect the emergence and establishment behaviour at the early part of the growing season and the amount and germinability of the seeds formed at the end of the season. The ability of some thistle species to form biennial and perennial plants that flower over a long period results in the production of large numbers of seeds. When these seeds germinate over an extended period in a single season, the seedlings pose a managerial problem and cause economic constraints through the cost of repeated herbicide or cultural treatments. In addition, the ability of thistles to produce seeds with the potential to remain dormant over several seasons adds to the cost of any control strategy. The presence of genetically distinct forms or 'ecotypes' in several of the thistles is well documented, but there have been very few studies of the responses of these forms to cultural and chemical treatments. Studies in future should consider the morphological and physiological features of the various thistles and investigate methods to improve herbicidal control without reduced production caused by damage to the infested pasture or crop.

Introduction

Research some years ago reported differential responses to 2,4-D of some ecotypes of Canada thistle *Cirsium arvense* (L.) Scop. from locations in North Western United States of America (Hodgson 1964). Although it was indicated that further investigations were to be initiated into herbicide responses, no reference to further work on this topic by that author has been found.

More recently intraspecific variation between populations of nodding thistles *Carduus nutans* L. ssp. *nutans* in the form of resistance to the phenoxy herbicides 2,4-D and MCPA has been reported from New Zealand by Harrington (1990) and Popay and Medd (1990). The resistant populations were deemed to be just as ecologically fit as the non tolerant populations. As a result of this, chemical control strategies had to be changed to apply herbicides that were more damaging to legume based pastures.

A review on ecology and control of thistles in Australia by Sindel (1991) mentions the variability within and between species but there were few references on the influence of this variability on control using herbicides. As a result of the limited information regarding the influence of variation within a thistle species on the success of herbicide treatments, much of this paper will deal with the obvious effects within and to a lesser extent between thistle species.

Morphological variation

Thistles can range in height from about 5 cm for stemless thistle *Onopordum acaulon* L. up to 180 cm for variegated thistle *Silybum marianum* J. Gaertn. (Parsons and Cuthbertson 1992). Variation in height either between or within a species poses a problem when applying herbicides by boom sprayers as the correct spray overlap cannot be achieved. This tends to lead to some strips being overdosed with chemicals while others receive sub lethal amounts. Additionally many of thistles are so tall that it is impossible to raise a conventional boom sprayer high enough to travel over the top of the infestation, and other methods for applying the chemical may be more appropriate.

The surface features of rosette and stem leaves and bracts surrounding the flowers could play an important part in herbicide retention and penetration. Evidence suggests that the droplet size has an important bearing on the amount of chemical taken in from various leaf surfaces (Hess *et al.* 1974). Small droplets are usually ineffective on very hairy plants because most of the droplets are retained on hairs with very little reaching the leaf surface. Larger droplets have a better chance of reaching the leaf surface of hairy plants because they shatter on the hairs, allowing some of the smaller droplets formed to contact the surface. The reverse can occur with smooth plant surfaces. Large droplets shatter and bounce or collect into larger deposits which can run off.

Translocated herbicides, such as glyphosate, 2,4-D or MCPA and contact herbicides such as diquat, paraquat and bromoxynil applied in small droplets (low volumes), may be more effective on the less hairy species, such as saffron thistle *Carthamus lanatus* L. and glaucous star thistle *C. leucocaulos* Sibth. and Sm. Higher volumes (larger droplets) may be required on hairy thistle plants such as African thistle *Berkheya rigida* (Thunb.) Bolus and Wolley-Dod, and the *Cirsium* and *Onopordum* species (Table 1).

Apart from some data from research on the effect of varying spray droplet diameters on control of grasses, there is limited information on broad leaved species such as thistles on the effect of droplet size, density and concentration of chemical as influenced by volume of application. Considerable work has been carried out on insects and it has been shown that volume of application / droplet size and chemical concentration have a pronounced influence on the effectiveness of control treatments (Smith *et al.* 1979). In addition to changing volumes of application and droplet sizes no information is available on the effect of various adjuvants, penetrants and anti-evaporants. Richardson (1981) reported that *S. marianum* showed no response to varying droplet sizes from 172–461 µm, but did have a minimum requirement of 10 droplets cm^{-2} for adequate control. The dose rate or the concentration of the chemical in the droplet applied to that thistle was shown to be more important than the other factors.

Differences in leaf area of the various thistles in the early rosette stage may determine the amount of chemical taken up. Rosette leaves of *Carthamus lanatus* have a very small surface area compared to *S. marianum*, *O. acanthium* L. and *Cirsium vulgare* (Savi) Ten.

Table 1. Texture of rosette and stem leaves of some thistles.

Rosette leaves		Stem leaves	
Hairy	None to slightly hairy	Hairy	None to slightly hairy
	Nodding thistle *Carduus nutans*	African thistle *Berkheya rigida*	Slender thistle
Star thistle *Centaurea calcitrapa*	Slender thistle *Carduus pycnocephalus*	Nodding thistle	Glaucous thistle
St. Barnaby's thistle *Centaurea solstitialis*	Saffron thistle *Carthamus lanatus*	Saffron thistle	Star thistle
Perennial thistle *Cirsium arvense*	Glaucous star thistle *Carthamus leucocaulos*	St. Barnaby's thistle	Perennial thistle
Spear thistle *Cirsium vulgare*	Variegated *Silybum marianum*	Spear thistle	Spotted thistle *Scolymus maculatus*
Artichoke thistle *Cynara cardunculus*		Artichoke thistle	
Scotch thistle *Onopordum acanthium*		Scotch thistle	
Stemless thistle *Onopordum acanthium*		Illyrian thistle	
Illyrian thistle *Onopordum illyricum*		Golden thistle *Scolymus hispanicus*	
Soldier thistle *Picnomon acarna*		Variegated thistle	

Table 2. Germination period for a range of thistles found in Australia.

	Autumn	Winter	Spring	Summer
Artichoke thistle	•*	•	•	•
Scotch thistle	•	•	•	•
Stemless thistle	•	•	•	
Illyrian thistle	•*	•	•	•
Soldier thistle	•			
Golden thistle	•	•	•	
Spotted thistle	•	•		
Variegated thistle	•*		•	
African thistle	•			
Nodding thistle	•	•	•	•
Slender thistle	•			
Saffron thistle	•	•		
Glaucous star thistle	•			
Star thistle	•			•
St. Barnaby's thistle	•			
Perennial thistle	•		•	
Spear thistle	•	•	•	•

* Main germination period.

Phenological variation

In most thistles, germination is staggered over a period of weeks / months (Table 2), so in any population there could be a range of plants at different growth stages. This creates two problems. Firstly any treatment early in the season to control rosettes may be only partially successful as there is the probability that further germinations will occur. The asynchrony in seedling emergence of *Carduus nutans* was recognised as a reason for delaying treatment until spring so that only one application in a year is needed (Medd and Lovett 1978). The extra treatments required to control the new germinations can make the treatment costly and time consuming, as well as causing further set backs to other pasture growth. Applying treatments after 'full' germination could result in more severe pasture damage because the dose rate of chemicals required to control large rosettes from early germinations is often higher.

Germination patterns of thistles can vary between locations and also between years, the latter being influenced by interactions of dormancy mechanisms, soil temperatures and rainfall patterns (Forcella and Wood 1986, Groves and Kaye 1989, Forcella and Randall 1994). This effect was shown on saffron thistle when seeds from one area were planted at two other locations to the north and south of its distribution in Western Australia. Seed planted in the north at a warmer site gave almost a single emergence pattern while at the cooler location in the south, emergence was staggered over several months (Peirce 1990).

Stem elongation in short-season annuals such as slender thistles, *Carduus pycncocephalus* L. and *C. tenuiflorus* Curtis, is delayed considerably as a result of delayed germination (Groves and Kaye 1989). Flowering in these two thistles was also retarded as the time of germination was delayed. In most other thistles, however, the variation in time of germination was not reflected in delayed stem elongation and flowering, hence any control measures to treat flowering plants should be successful, provided flowering of capitula was not spread over a long period of time. Control of *C. lanatus* at flowering has been quite effective in Western Australia (Peirce 1992), where full flowering was achieved within 14 days of the first capitulum reaching anthesis. Successful control at flowering of *C. lanatus* was also reported in South Australia by Fromm

(1990). However, in eastern Australia this successful method of treatment may not be applicable as flowering of *C. lanatus* can occur over 30–60 days at Canberra (Groves and Kaye 1989) and about 60 days at Wagga Wagga (Forcella and Wood 1986). This could be due to the higher summer rainfall which may permit treated capitula to recover or new capitula to form as the treatments are usually only causing severe damage to the capitula and not to the remainder of the plant structures.

Conclusions

The many studies on thistles both in Australia and overseas indicates that considerable variability does exist. The relevance of this to successful control strategies has not been fully investigated but could be a direction for any further research. More effective chemical application may be achieved by a better understanding of the behaviour of herbicides in combinations with the numerous additives that are now available. In addition some knowledge would be useful as to what effect the cuticle layer and other external structures on the leaf surface in the numerous thistles is having on the movement of herbicides into the plant.

The exploitation of the height difference between thistle and pastures may be utilized by more research into the techniques using wiping as a method to apply the herbicide.

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Practical problems with existing thistle control: Where is more research needed?

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Summary

Many practical problems exist with current thistle control techniques. Integrated control/management programs are necessary on properties, as well as continued research into alternative control methods. This paper summarizes problems with current thistle management, viewed from the perspective of a regional noxious plants control authority, and discusses some steps that are needed to improve the situation.

Introduction

The Southern Slopes Noxious Plants Authority (SSNPA) was established in 1992 and incorporates the Shires of Harden, Young, Yass and Boorowa in south-eastern New South Wales. The control area is located at Boorowa. The main objectives of the Authority are to:

- control noxious plants on all council lands
- enforce noxious plant control on privately owned land, reserves and crown lands
- advise and educate landholders
- initiate control programs for landholders
- provide a contract spraying facility.

One of four levels of control categories may be placed on declared noxious plants:

W1 – presence of the weed on land must be notified to the Local Control Authority and the weed must be fully and continuously suppressed and destroyed,

W2 – must be fully and continuously suppressed and destroyed,

W3 – must be prevented from spreading and its numbers and distribution reduced,

W4 – action specified in the declaration must be taken in respect to the weed.

Four species of thistle are currently declared noxious throughout the SSNPA area; scotch (*Onopordum acanthium*), Illyrian (*O. illyricum*) and stemless (*O. acaulon*) which have all been placed in the W3 category, and nodding (*Carduus nutans*) which has been placed in W2. Thistles are the most widespread of all the declared noxious weeds in our area with scotch and Illyrian thistles being the most prevalent. The Harden Shire, which takes in Jugiong, is heavily infested with these, and that is the reason for their W3 categorization. Stemless and nodding thistle are less abundant in the area.

Current control methods and problems in their application

The following control methods are used in the battle against thistles:

- herbicide spraying
- cultivation
- grazing/spray grazing
- pasture sowing as competition
- biological control.

A combination of several, if not all, of these methods are used by property owners to attempt to stop the spread of thistles. Unfortunately once the scotch/Illyrian thistles become established, it is difficult and expensive to eliminate them and programs are reduced to halting their further spread into clean country.

Practical problems with herbicide control
One potential problem is resistance to herbicides. Thistle control chemicals need to be rotated to avoid resistance build up by thistles, and new and improved chemicals are necessary to combat this. The application of herbicides on a broadacre scale to control thistles can be very expensive for the landholder. At an average cost of approximately $10 per hectare this can amount to a substantial sum on a large cropping / grazing property.

A third problem is the possibility of pasture damage. If not applied early in the season, the herbicides necessary for control of thistles can be very damaging to clovers and legumes. Finally, the chemicals used are environmentally hazardous. Although not classified as dangerous herbicides, the continual application of thistle control chemicals can cause soil residues and in turn livestock residues. Research in the areas of herbicides that do not require withholding periods and are more user friendly is possibly necessary.

Practical problems with spray grazing
High stock numbers, up to five times the normal rate, may be required to successfully use a low rate of herbicide and induce stock to graze thistles. This is not practical on a number of properties where paddocks are too large or livestock are not part of the operation. Overgrazing can also occur with this control technique which can be detrimental.

Practical problems with pasture establishment
Pastures are difficult to establish in steep, rocky terrain. In contrast, thistles thrive in these areas due to their remoteness and difficulty in growing pasture for competition. Stock are also selective in their choice of forage, and thistles are not their first choice for grazing unless spray grazing techniques are used. Research into compounds or supplements that could be applied to pasture to increase the palatability of thistles could provide an alternative to spray-grazing. Overgrazing can be a major problem, for the temptation of increasing stock numbers and maintaining stock numbers during dry periods can open up pastures, which allows thistles and general weeds to germinate and become dominant.

Practical problems with biological control
There appears to be a problem with agents adapting to extreme climatic conditions. From practical experience with the release and monitoring of biological control agents, it appears that the majority of agents released tend to control the target weeds in the immediate vicinity of release. From this point they seem to have difficulty in multiplying and spreading to new areas. The introduction of breeding cages with the scotch thistle agents has improved the breeding cycle, though there does still seem to be a problem with the agents adapting to the extreme climatic conditions such as frost and drought, resulting in a very slow build up of agent populations.

The interaction of agents with cropping and grazing programs needs to be investigated. When released on a mass scale over whole farm areas, will the agents survive the cropping rotations and transfer from uninfested to infested paddocks each year? How will the agents interact with herbicide application and continuous grazing of pastures?

The monitoring of biological control agents is also critical. At present, a number of organization staff and landholders monitor the progress of agent release sites and breeding cages throughout New South Wales. In the SSNPA area there are three separate organizations that establish and monitor agent releases. This process is ideal for release of agents and allows for interaction of organizations and landholder with hands on involvement. However, I feel that it would be beneficial if an officer from the Weed Management Program of CSIRO were to continually monitor all release sites. In so doing, accurate information would be obtained and practical problems with the agents would be readily discovered, allowing for rapid changes to sites and / or pinpointing areas that required further research.

Alternative control methods research
Research into alternative control measures for thistles may lead to the reduction in chemical application. The combining of products would cut down on application costs; for example, a pasture topdressing, superphosphate, could contain a herbicide additive that is released for the control of thistles. Chemical applications in the form of supplements or urea might have the same effect as MCPA and Lontrel in improving the palatability of thistles for spray-grazing purposes. Thistles that were allowed to grow to maturity could possibly be used as an alternative fuel source.

No doubt research is being carried out, with funding being a major factor. Government assistance is lacking, and there is insufficient funding for research and education. This will always be a problem with regards to thistle control and noxious weed control in general, as it is seems not to be considered a priority area of agriculture.

Funding for media releases and education programs directed at landholders is required. At present, if a cutback in spending is required on a property then noxious weed control is often the first targeted. Property owners need to be further educated in the implementation of long-term thistle control programs. Possibly more incentive should be given to Landholders to control thistles and noxious weeds.

A state-wide approach to thistle control programs is necessary involving co-operation and a further combining of resources between Departments such as ours and Landcare and NSW Agriculture.

Conclusions
Practical problems will always exist with regard to thistle control. This can be said for all aspects of agriculture. Continued research and education programs are imperative if landholders are to be successful in the battle against thistles. Coupled with this, a pooling of Government resources such as CSIRO, NSW Agriculture, Rural Lands Protection Boards, Noxious Weed Authorities and Landcare organizations is necessary to provide expertise, solutions, and assistance to landholders with thistle and general noxious weed problems.

Thistle control: A farmer perspective

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Abstract

There are a number of constraints placed on the landholder which affect the type and amount of weed control they are actually able to conduct. During this talk I will discuss a brief history of why thistles have got out of hand on the property. Black thistle was on the property but was not a major problem. This was followed by saffron thistle which was brought in from grain for drought feeding, and there was the odd Scotch thistle which was not a problem at the time. Twenty five years later I am battling a major Scotch thistle problem. Other land holders in the area have also not been as vigilant as perhaps they should have been in battling the problem and even if the problem on my property had been cleared the seeds from neighbouring properties would still have come in either wind blown or by birds etc. Other constraints include the time needed to battle other noxious weeds such as serrated tussock which is a major problem in the region. Nodding thistle and vipers bugloss are also becoming a problem along with St. Johns wort but not yet African lovegrass (*Eragrostis curvula*). Another major constraint is the decline in terms of trade. In the past I was able to employ a Station hand, then that was reduced to a casual hand, now I am battling to afford even casual labour and am now operating a one man 2700 acre property of mainly non-arable tableland country. Spraying has been conducted on open basalt country ten years ago and again there was no co-ordinated response from neighbours which raises the question of why persist when its still on the fence line all around you. Another land holder on a larger operation was conducting an annual aerial spray and concluded it was ineffective, repetitious and expensive. This lead to a number of financial contributions being made to the biological control program from various people in the district.

Landholder attitudes to *Onopordum* thistles and their control: A preliminary view

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Summary

Landholders participating in a redistribution network for biological control agents of *Onopordum* thistles were asked to complete a questionnaire on control methods currently being used, their cost and effectiveness. The 60 replies received to date provide an interesting insight into landholder perceptions of the impact of *Onopordum* thistles on their farming enterprises and of current thistle management. Overall, there is no uniform control strategy, and many landholders have devised their own management plans. While cultural methods such as rotational cropping or sowing improved pastures are important, herbicides form the key component of control measures. A variety of chemicals are used, alone or in combination, with MCPA and Dicamba being the main ones. The pattern and frequency of use of herbicides is quite variable, as is their overall effectiveness. Despite some local successes, the overall picture is that current control strategies are, at best, only preventing a worsening of infestations rather than reducing the problem.

Introduction

As part of a redistribution program for biological control agents of *Onopordum* thistles, CSIRO is providing co-operating landholders with an information kit on the agents and other forms of control. This kit includes a questionnaire designed to obtain information on the extent and cost of the problem caused by these thistles, as well as current control measures and their effectiveness, and landholder attitudes to the management of thistle infestations. The information will provide a baseline by which to evaluate the impact of biological control agents, once they have become well-established and have reached damaging population levels i.e. it will permit a measurement of the changes in other control methods due to biological control. In addition, the survey data provides an interesting picture of landholder attitudes to the management of thistle populations and, as such, should help in the task of determining what the gaps in knowledge are and what information is being sought by the client groups of research into thistle control. This paper summarizes the responses of 60 landholders in south-eastern New South Wales who have, to date, responded to the questionnaires. It therefore gives a preliminary overview of the management of *Onopordum* thistles in those areas that are worst affected by these noxious weeds.

Methods

The details of the redistribution scheme are described in detail by Briese *et al.* (1996), and comprised 15 separate release networks covering 13 shires in south-eastern New South Wales (Bombala, Boorowa, Cooma-Monaro, Cootamundra, Crookwell, Gundagai, Gunning, Harden, Snowy River, Tallaganda, Yarrowlumla, Yass and Young) where *Onopordum* thistles cause the most problems (Briese *et al.* 1990). Participating landholders were selected initially by District Agronomists, Shire or County Council Noxious Weeds Officers, and the Landcare group co-ordinators based on the extent of thistle infestations on their properties, availability of suitable release sites and ability to manage a release site.

The survey form comprised 26 questions, mainly requiring a tick or single number as a response. One set of questions related to details of the property concerned and the enterprises conducted on it, a second to the location and extent of *Onopordum* thistle infestations on the property and possible reasons for them, a third to detailing control methods currently used and their cost and effectiveness, and a final set of questions sought information on landholders views of the overall value of control.

Results

Impact of Onopordum infestations

Wool and meat production are the main industries affected by *Onopordum* thistles, with 82% of the landholders listing wool production as a major enterprise, and 85% listing meat production, with cattle slightly predominating over sheep. The size of moderate to severe infestations on individual properties ranged from 20 to over 2000 ha (mean of 280 ha). Most infestations occurred on non-arable improved pastures, followed by arable and non-arable unimproved land types. Very little infestation occurred in land that was cropped or irrigated. Landholders perceived a lack of competitiveness in pasture grasses as the main reason for infestation by *Onopordum* thistles. This is exacerbated

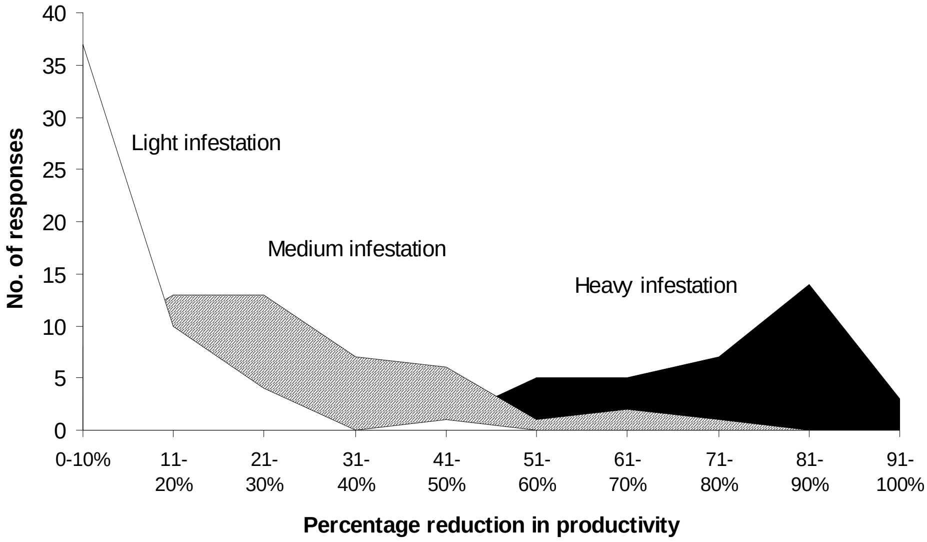

Figure 1. Estimated productivity losses due to different levels of *Onopordum* infestations.

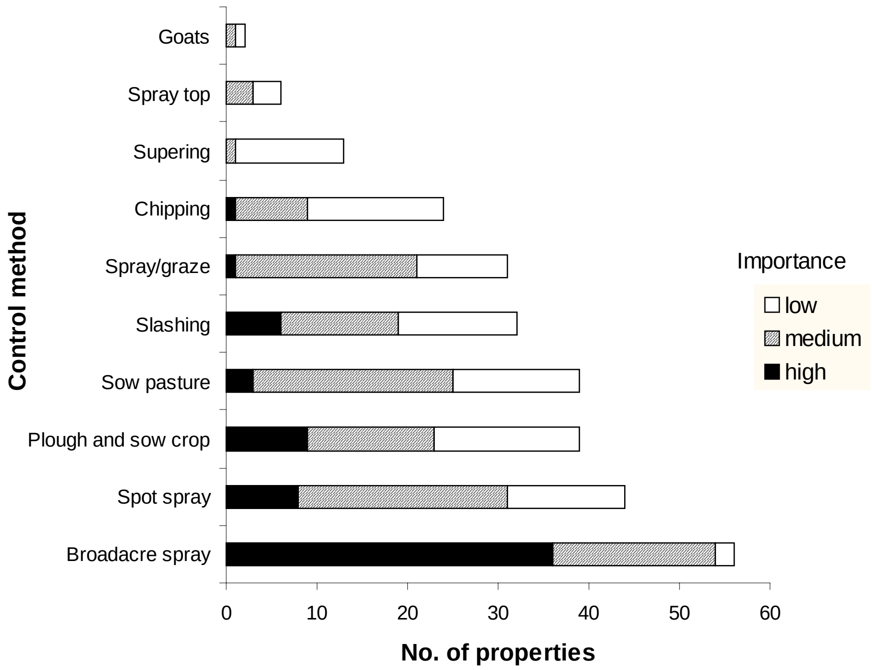

Figure 2. Control methods currently used for *Onopordum* thistles and their importance.

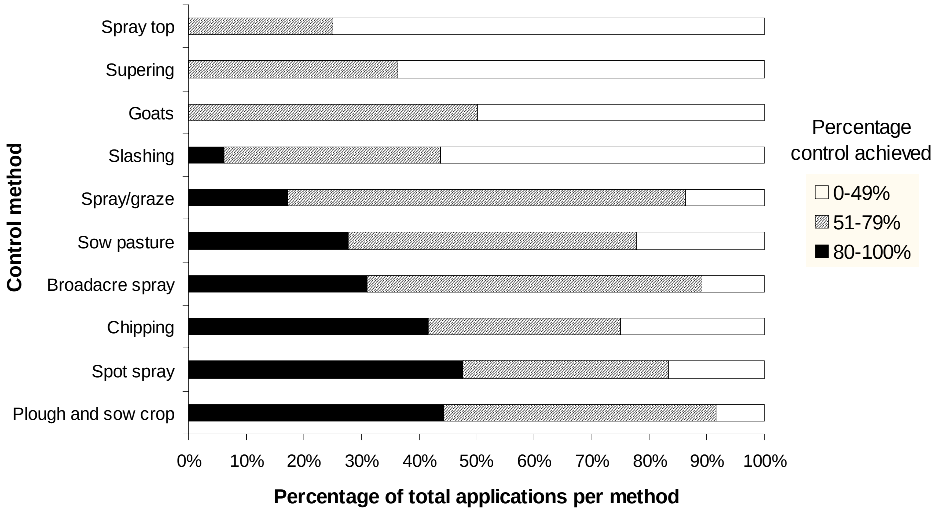

Figure 3. Effectiveness of current control methods for *Onopordum* thistles.

by the lack of grass cover at critical times (e.g. when thistles germinate), and the opening up of pastures by drought and, to a lesser extent, by overgrazing. In some cases the addition of fertilizer and pasture improvement programs have also led to a worsening of existing thistle infestations.

On most properties the problem has been a long-term one, with only 13% having been infested for less than 15 years. On half the properties there had been an increase in infestations over the past five years, while 30% reported a decrease and 20% indicated that there had been no change. The main detrimental effect of *Onopordum* thistles was considered to be a reduction in pasture and pasture access, and hence productivity. Reduced prices due to vegetable fault in wool, the impact of infestations on property values and difficulties in mustering were also considered to be problems caused by these thistles. Estimates of productivity losses are difficult to make and varied considerably between individual landholders (Figure 1), but the median losses were estimated at less than 10% for light, 21–30% for medium and 61–70% for heavy infestations of thistles.

Current control methods for Onopordum thistles

All 60 landholders have an active control program for *Onopordum* thistles, and have used a variety of measures (Figure 2). The landholders generally used combinations of these control measures, but clearly chemical herbicides form the basis of current management strategies, coupled with cultural control methods such as ploughing and cropping, sowing improved pastures and slashing. Combinations such as spray / graze are used to a lesser extent, while alternative techniques such as goat grazing are rarely employed. Control has generally increased over the last five years, with 33% of landholders doing more, 54 % the same or varying between years and only 13% claiming to have reduced control measures in that period. The median annual cost of control was $15–20 per ha, but this often did not include labour costs. Given that 60% of landholders spent between than 10 and 30+ man-days a year on control (Table 1), costs with labour included were as high as $50 per ha.

Table 1. Labour required to implement *Onopordum* thistle control programs.

No. of man-days	No. of properties
1–3	0
3–5	5
6–10	19
11–20	13
21–30	9
>30	14

The most effective form of control is to plough and sow to a crop (Figure 3), but this is only practicable on arable land. Methods aimed at isolated plants, such as spot spraying and chipping, are also effective but, because of the labour input, are limited to small patches or very light infestations. For more severe broadacre infestations, herbicide treatment and sowing to improved pasture and spray-graze are the most effective control measures, while slashing and related techniques had little effect on infestations (Figure 3). It needs to be borne in mind though, that the data refer to control over a single season and none of the methods provided consistently high levels of control on its own (Figure 3). The majority of landholders (55 out of 60) found that combining methods gave improved control, with the most common combinations being the use of chemical herbicides together with either pasture improvement, grazing management or cropping rotations.

A major factor influencing the success of control is the consistency with which it was practised. Only two of the 60 landholders claimed to treat all their infested areas every year, with a variety of treatment frequencies being applied to different proportions of infested areas by the remainder (Figure 4). Where chemical herbicides are used, the time of application also varies (Figure 5), while a total of 6 chemicals have been applied in 9 different combinations (Table 2). The bulk of herbicide treatments comprise MCPA and Dicamba either alone or in combination and MCPA / Lontrel® (clopyralid), and these chemicals seem the most effective, though timing of application is important. The seasonal spread of applications reflects, in part, the ability of *Onopordum* to germinate in all but the coldest months and, as a consequence, wide variability in plant age and size at any one time. Too often though, timing is dictated by other on-farm demands for labour.

There was a trend toward two distinct strategies of control; reduction and containment. The former was characterized by concentrating treatment on medium and heavy infestations with a view to lowering thistle numbers. Often this was done systematically, one paddock at a time. The containment strategy emphasized treatment of light infestations to prevent their development and limit spread, while leaving the more severe core infestations untreated. Often these core infestations are restricted to more inaccessible terrain.

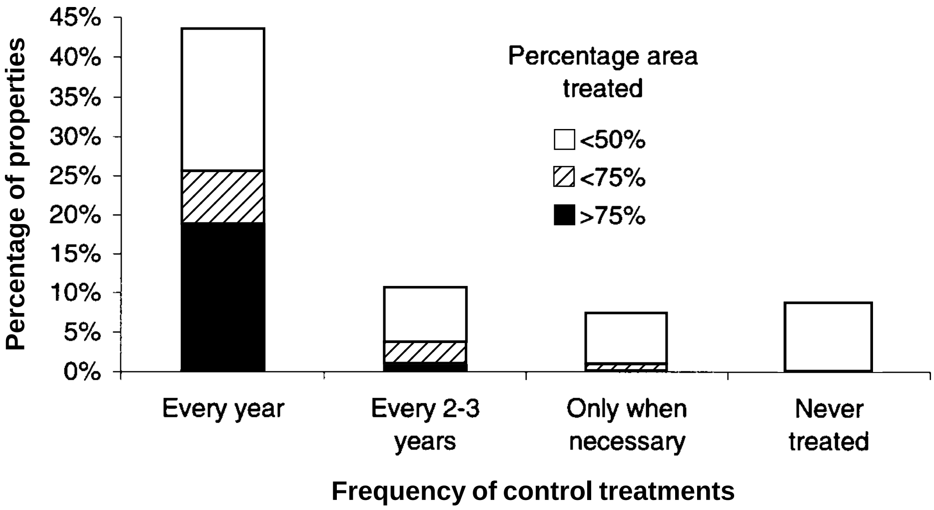

Figure 4. Frequency and extent of *Onopordum* infested areas treated for thistle control.

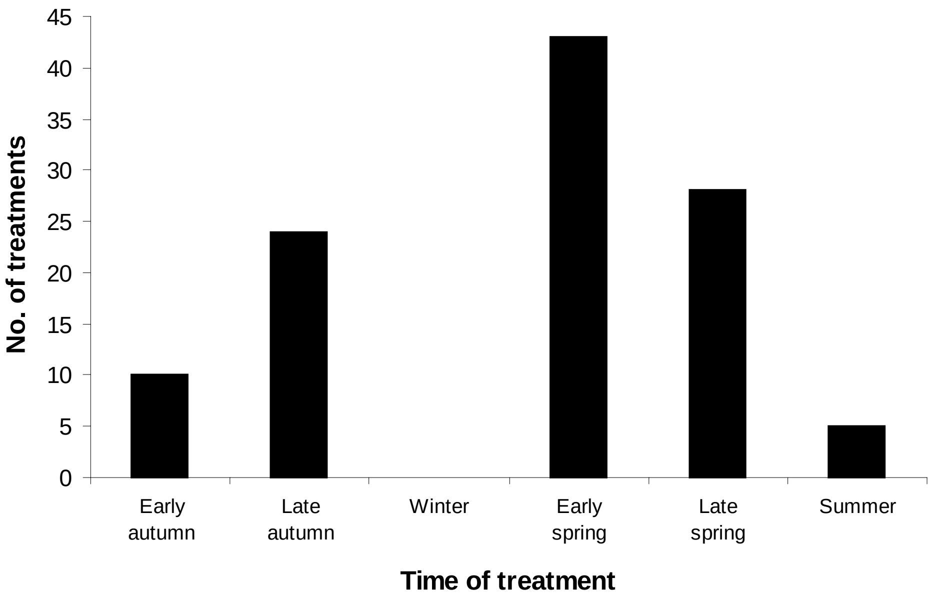

Figure 5. Time of spraying herbicides for the control of *Onopordum* thistles.

Does it pay to control Onopordum thistles?

Despite strong indications of variable responses by *Onopordum* to control methods, 52% of the landholders thought control very worthwhile, while 40% thought it only just paid for itself or were unsure of the value, and 8% thought it didn't pay. Seventy six per cent noticed an increase in productivity following control, while the remainder reported no difference. Most landholders have realistic expectations of control, with 85% viewing it as an ongoing process, 7% being uncertain and only 8% thinking that the problem could be controlled in 10 years or less.

The main disadvantage that landholders perceived in current control practices was the cost (principally of chemicals), while competition for time from other on-farm tasks made it difficult to maintain an effective control program in the long-term. A few felt that the herbicides available were not effective, and others were discouraged by the length of time needed to achieve satisfactory control. A major problem with the most effective herbicide, Dicamba, is its deleterious effect on legumes present in pastures (Keys 1987).

Discussion

Notwithstanding the small sample size, the overriding view of affected landholders is that some kind of management strategy for *Onopordum* thistles is

Table 2. Frequency of use of different herbicides against *Onopordum* thistles (alone or in combination).

Chemical	Broadacre	Spot spray
MCPA	32	14
Dicamba	23	21
Clopyralid	13	3
2,4-D	7	7
Glyphosate	1	6
Paraquat	1	0
Chemicals used	6	5
Combinations	9	9

essential. Many have devised particular plans for their properties, often with the guidance of local government advisors. However, the different competing needs of on-farm management and the general downward trend in real returns to landholders in Australia (Campbell 1991) means that few control programs are being maintained effectively. Because of the large and long-lived seed banks (Cavers *et al.* 1995), any disruption to a control program can nullify the gains of previous efforts. Thus, despite current control procedures there has been a trend toward an increase in the overall problem posed by *Onopordum* thistles.

Information from the questionnaires suggests that research is needed on more selective herbicides and the development or improvement of low input control methods such as grazing management and biological control. Most urgent, though, would appear to be the integration of methods appropriate to particular enterprises and extension support to ensure the coordination and maintenance of an overall strategy. The majority of growers clearly have no illusions concerning the difficulties of current control strategies, and accept that new methods such as biological control are long-term solutions, and must be viewed as part of an overall management package. The challenge of this workshop will be to develop appropriate guidelines and suggest what research is needed to improve methodologies so that such an effective package can be produced.

Acknowledgments

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Overview of thistle management in Australia

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Summary

Thistles have a high profile in the weed flora of Australia and are of particular concern to graziers in the temperate southern regions where they are often the dominant weeds of improved pastures. While thistles have morphological similarities and are closely linked taxonomically, they are nevertheless ecologically diverse, both between species and within species. Consequently, some management practices, e.g. biological control, may need to be aimed at specific ecotypic groups, while other management practices, e.g. pasture competition, may be able to be applied more unilaterally. This paper overviews the presentations made at the Thistle Management Workshop and synthesizes them into three broad categories—ecology/biology, management tactics, and farmer attitudes and constraints on control—and examines what is currently known about thistles, what is not known about them and where should research be aimed to yield results which will be of most practical use to thistle management in Australia.

Introduction

There is no other group of plants in Australia, and perhaps in the world, which better epitomizes weeds than the thistles. A cursory glance at some local sources of weed information confirms this idea. The brochure which describes the Co-operative Research Centre (CRC) for Weed Management Systems—'Weakening Weeds to Strengthen Australia'—has a photograph of *Carduus tenuiflorus* (winged slender thistle) on the front. The logo of the Weed Society of New South Wales, displayed prominently on its newsletter, A Good Weed, is of a thistle. The Australian weed books by Hyde-Wyatt and Morris (1980), Wilding *et al.* (1986), Auld and Medd (1987), Auld *et al.* (1987), Parsons and Cuthbertson (1992), and the new 'Crop Weeds of Northern Australia' by Wilson *et al.* (1995), all depict thistles of one type or another on their front covers.

What is it about thistles which gives them this unique standing? Is it their often sharp spines and prickles (for that is what partly defines a thistle in the family Asteraceae), their inherent beauty when in flower, or the combination and tension between these two features? Someone once said: 'Give me a thistle without thorns and I will give you a pasture plant'. Is technology now at the stage that we can genetically modify thistles to be spineless?

There are two postcards on my office pin board. Appropriately, the first is from Edinburgh, Scotland, and is of the 'Scottish thistle' (*Cirsium vulgare*). The second postcard, this time appropriately from the University of Oxford, England, says: 'The more I study the more I know; the more I know the more I forget; the more I forget, the less I know; so why study?'

The purpose of this synthesis paper is to draw together in broad terms the presentations from the Thistle Management Workshop and to ask 'what do we know about thistles', 'what don't we know about them', and 'what should we try and find out that will be of practical use in thistle management'. Do we already know the key to thistle management (if there is one) or are we still searching? If a key exists and we have not yet found it, does it lie in obtaining more information, securing more resources, developing new methods or in engendering greater commitment from those who attempt to control thistles?

This workshop produced some excellent presentations of current thinking and research in regard to thistle management and if I am to synthesize these papers then by definition I must put them together to make up a complex whole. And in some respects, weed management is necessarily becoming more complex as land managers negotiate the trend towards herbicide resistance, reduced cultivation and antagonism to pesticides. Ironically, the complexity of the thistle group is one of the over-riding themes that has been evident through the presentations from this workshop and one which I highlighted in my review of the ecology and control of thistles in Australia (Sindel 1991).

While thistles are often grouped under one broad umbrella (for some very good reasons, not the least of which are their morphological and taxonomic similarities), they are nevertheless a group of plants which are ecologically diverse—both between species and within species, as has been highlighted for saffron thistle (Peirce 1990). It might be concluded from Michael (1996) that part of the reason for this diversity in Australia is also due to the presence of taxonomic groups which are as yet unidentified, particularly in relation to the *Onopordum* thistles.

Peirce (1996) rightly emphasized that the variability in the behaviour of thistles must be taken into account when considering their response to herbicidal control measures. Biocontrol agents too can be very discriminating, even down to the level of thistle ecotype. For example, the ecology of saffron thistle (*Carthamus lanatus*) is quite different to many of the other thistles. Saffron thistle on one hand can be characterized as preferring regularly disturbed areas with coarse dry topsoil, but with good reserves of moisture in the deeper subsoil, whereas, most of the other major thistles reviewed at this workshop are typically dominant on soils rich in phosphate and nitrogen, and possibly regularly cultivated and / or irrigated areas (Doing 1972). As a result, saffron thistle is a major weed in both pastures and crops whereas many of the other thistles are a nuisance in pastures alone. So it is worthwhile stating again that we are not dealing with a homogenous group of weeds when we talk about the thistles. Consequently, many control measures will have to be aimed at individual species, and even ecotypes within species. Others, such as pasture competition, may act more unilaterally.

The factors that promote thistle invasion (often an increase in soil nutrient status combined with overgrazing and lack of reseeding) are also often responsible for changes in the relative abundance of individual thistle species. Such changes, which are continually occurring in the Australian weed flora (Kloot 1987), further complicate the already complex issue of thistle management. For example, McGufficke (1996) experienced changes on his property near Jindabyne, New South Wales, from dominance of spear (or black) thistle (*Cirsium vulgare*) to saffron thistle and then Scotch (*Onopordum* sp.) thistle. Similarly, over the course of 25 years on a property at Crookwell, New South Wales, an area that was once dominated by native redgrass (possibly *Bothriochloa macra*) changed to subterranean clover, then to variegated thistle (*Silybum marianum*) and finally to *Onopordum* sp. (Carter 1970).

Although management practices may alter the soil and pasture conditions and lead to changes in thistle dominance, the relative importance of different thistle species in Australian pastures has not been studied.

Significance

There can be little doubt that thistles are a major concern for graziers in the temperate regions of southern Australia. In a recent mail survey of grazier attitudes to weeds on the Northern Tablelands of New South Wales (Sindel 1996), graziers were asked to rank up to five major weeds in order of importance on their farms. A score of five was assigned to the top ranked weed in each case, a score of four to the second worst weed and so on down

Table 1. The most troublesome weeds among the graziers surveyed from the Tablelands of northern New South Wales (from Sindel 1996).

Weed	Presumed species	Number of respondents[A]	Score[B]
Saffron thistle	*Carthamus lanatus* L.	22	90
Blackberry	*Rubus fruticosus* L. s.lat.	12	38
Nodding thistle	*Carduus nutans* L. ssp. *nutans*	8	31
Bathurst burr	*Xanthium spinosum* L.	7	31
Spear thistle	*Cirsium vulgare* (Savi) Ten.	7	27
Thistles (generally)		6	20
Scotch thistle	*Onopordum* spp.	4	19
Horehound	*Marrubium vulgare* L.	7	18
Slender thistles	*Carduus pycnocephalus* L. *Carduus tenuiflorus* Curtis	5	12
Variegated thistle	*Silybum marianum* (L.) Gaertner	3	12
Rat's tail fescue	*Vulpia* spp.	3	12

[A] Number of respondents from the Tablelands who listed a particular species among their five worst weeds.
[B] Combined score of weed importance from rankings given by all 29 respondents from the Tablelands.

to one. Forty six weed species were listed in total by the 29 respondents. Table 1 lists those weeds which had a combined score of 12 or greater. It is clear that in this region at least, thistles, and particularly saffron thistle, are of major concern to growers.

Many of the thistles have become widespread and now often occur as the dominant weeds of improved pastures where annual rainfall ranges from about 500–900 mm (Michael 1968). And yet there are other species, e.g. *Cirsium arvense* (perennial thistle) and *Carthamus leucocaulos* (glaucous star thistle) which are present in Australia but which currently have a limited distribution and are of only minor importance (Parsons and Cuthbertson 1992). Do such species have the potential for further colonization and to fill niches left by the demise of other thistles in the future?

Dellow (1996) identified the five thistle species or groups which he considers are currently causing the major problems in the farming and pastoral areas of New South Wales. These are saffron thistle, spear thistle, variegated thistle, the Scotch (*Onopordum acanthium*) and Illyrian (*O. illyricum*) thistles and nodding thistle (*Carduus nutans*). To this list he adds St. Barnaby's thistle (*Centaurea solstitialis*) and others would also add the slender thistles (*Carduus pycnocephalus* and *C. tenuiflorus*) as being significant.

There can be little doubt that these particular thistles are well adapted to the Australian environment as evidenced by the results from the study on *Carduus nutans* by Woodburn and Sheppard (1996) where they compared the life histories of the weed in five Australian localities with that in three native localities in Europe. Most thistles in Australia are of European origin and have probably reached the limits of their potential distribution (Medd 1981), the exception being *Carduus nutans* which, partly because of its more recent introduction to this country, continues to spread (Parsons 1973, Medd and Smith 1978).

At the farmer level, the question of significance might be 'When do thistles constitute weeds in my pasture?' Unlike many other pasture weeds, thistles are rarely a palatable source of feed for most classes of livestock, although goats are an exception, as emphasized by Holst and Allan (1996). The thistles have been classified as plants that occupy ground which could be utilized by more useful pasture species (Michael 1970). Because they are not usually grazed, it may be easier to estimate their impact on pasture yield and animal production (ignoring for the moment animal health issues) than that of other pasture weeds which can be utilized by livestock to some extent.

For example, in New Zealand, liveweight gain in sheep was shown to be negatively correlated with the density of *Cirsium vulgare* (Hartley 1983), and in north-eastern California in 1970, *Onopordum acanthium* infestations were estimated to result in an annual loss of production equivalent to over $25 per hectare (Hooper *et al.* 1970).

If data were readily available on the economic impact that thistle infestations were having on farms then that may be an incentive for some farmers to be more diligent in their control of thistles and may allow some economic thresholds to be set and economically rational decisions to be made about their control.

Most of the papers presented in this workshop have addressed one or more of three broad issues – thistle ecology / biology, management tactics, and farmer attitudes and constraints to control. While it would be unduly repetitive to summarize the findings of all these papers here, I will highlight important issues from each of these three areas.

Ecology/biology

Baseline data

There would be few of the defence force personnel who would not argue that it is essential that you first 'know your enemy' before you make an attack on them. Otherwise, your attack is likely to be ineffective and you will not be able to assess what damage you have caused once that attack has been carried out. In this regard, Pettit *et al.* (1996) have appropriately done their reconnaissance work on *Onopordum* and have now laid baseline data against which to assess the effectiveness of biological control.

Seed banks in the soil

Sheppard (1996) highlighted the fact that nearly all thistle species are relatively short-lived and reproduce entirely by seed and that this must guide the formulation of control strategies. As a result, the continued infestation of pastures and crops by thistles depends largely on the persistence of viable seeds on and below the soil surface. He concludes that causing high seed loss should be the dominant control strategy in most thistle control activities. This strategy is particularly suited for biological control and for new invasions, and despite their importance, the dynamics and ecology of thistle seed banks have not been adequately investigated. The study by Allan and Holst (1996) is very helpful in this respect for *Onopordum illyricum*.

But the strategy has less relevance when substantial seed banks of the thistles exist and there is little possibility of weed eradication. Because of dormancy patterns in thistles and their long-lived nature in the soil, reducing seed numbers, often towards the end of the season, must go hand in hand with aggressive pastures (particularly at peak germination periods) which aim to impact on the germination, establishment and early seedling stages of the weed's life-cycle. Chipping or selective spot spraying may then be relied on to clean up isolated infestations that inevitably develop.

Dispersal

McGufficke (1996) raised an interesting biological issue when he says that 'even if the problem on my property had been cleared, the seeds from neighbouring properties would still have come in, either wind blown or by birds etc.' Despite the existence of scientific studies with evidence to the contrary such anecdotal views are widely held in the rural community. Thistle seeds are typically not spread far from the parent plant by wind. The relatively light seeds of *Carduus pycnocephalus* (Table 2) have been observed to spread to a distance of 8 m from parent plants in winds of 7.9–19.0 km h^{-1} (Harradine 1985) and *C. tenuiflorus* to nearly 7 m in one season (Auld 1988). Harradine (1985) concluded

Table 2. Seed and life-cycle characteristics of the major thistles (after Michael 1968).

Thistle	Life-cycle	Approx. seed weight (mg)
Carduus nutans (nodding)	Annual / biennial	3.5
Carduus pycnocephalus (slender)	Annual	5
Carduus tenuiflorus (winged slender)	Annual	3
Carthamus lanatus (saffron)	Annual	26
Cirsium vulgare (spear)	Biennial	4
Onopordum acanthium (cotton)	Biennial	11
Onopordum illyricum (Illyrian)	Biennial	15
Silybum marianum (variegated)	Annual	22

that the principal method of dispersal of *C. pycnocephalus* was movement across the soil surface, either by wind or animals, but that vegetation or litter cover restricted this movement. Studies by Smith and Kok (1984) and Kelly *et al.* (1988) indicate that seed of *C. nutans* also mostly falls close to the parent plant and that most wind-borne pappi have no seeds attached. Long distance dispersal of viable seed (>50 m) by wind is a rare event. Kelly *et al.* (1988) conclude that their findings 'may be reassuring to a farmer who is standing at her or his boundary fence, watching thistle pappi float onto the property'. Given the size of seeds of saffron, variegated and *Onopordum* thistles (Table 2), it is unlikely that wind would spread them very far either (see Auld 1988).

Granivorous birds such as goldfinches, sparrows and parrots are not candidates for the spread of thistles, since such birds husk the seed before ingesting it (e.g. goldfinches, McCallum and Kelly 1990). Fruit eating birds such as currawongs and blackbirds that do spread some weed seeds, are attracted to fleshy fruits, but do not digest the seeds as such. Importantly, Panetta and Scanlan (1995) suggest that for 90% of noxious weeds, spread is in some way aided by human activity. It is worthwhile noting then that we cannot hope to stop thistles spreading unless we know the main agents of dispersal.

Periodicity of germination

One of the areas which I see may be profitably pursued in thistle research is the subject of periodicity of germination on a regional basis as a means of determining if and when pasture competition or herbicides can be used to manage thistles when they are youngest and most vulnerable. If the emergence of thistles tends to be restricted to defined periods, as studies in Western Australia (Quinlivan and Peirce 1968) and parts of eastern Australia (Forcella and Wood 1986b) have shown (particularly for the annual thistles), then it is possible that control methods can be synchronized to improve their effectiveness, whether they be cultural, biological or chemical techniques. These studies have been carried out in essentially Mediterranean-type climates, but further work needs to be done across a range of environments. For example, in areas such as northern New South Wales where there is no distinct seasonal break following summer, there is controversy over when saffron thistle germinates. Such studies need to carried out over several seasons.

Scope also exists for work using either nitrogenous fertilizer or disturbance of the soil to help synchronize the germination of thistles and to improve the effectiveness of chemical control.

Management tactics

Pasture competition

The essential principle of any thistle control programme must be the provision of a dense, vigorous and competitive pasture, particularly in the autumn period which coincides with the bulk of thistle germination and seedling establishment. In general, thistles are weakest or most susceptible to control when at this early seedling stage or when passing from the seedling to rosette stage. For example, the percentage of spear thistle seedlings surviving through to the rosette stage was only 1.0% under grazed conditions and 0.2% in ungrazed pastures (Forcella and Wood 1986a). The facts that thistle seedlings are often found only on bare ground (Doing *et al.* 1969), that some species require light for germination (Bakker 1960, Medd and Lovett 1978), and that their growth is systematically reduced by shading (Medd and Lovett 1978, Pook 1983), indicate that control through competition for light is possible. Bourdôt (1996) has helpfully raised our awareness again of this most important management tactic.

Grazing management

Grazing management is related to pasture competition. It can influence the ability of thistles to invade pastures (George *et al.* 1970) primarily by altering the competitiveness of the desirable pasture species. By reducing competition from neighbouring plants, sheep grazing increased the survival of spear thistle seedlings as well as their growth, flowering and seed production (Forcella and Wood 1986a). Because thistle seedlings are vulnerable to competition soon after the autumn rains, stock should be temporarily removed from infested paddocks to increase thistle mortality. This deferred autumn grazing (until winter or spring) was found to reduce populations of *Carduus pycnocephalus* and *C. tenuiflorus* in Tasmania (Bendall 1973) and is recommended as a method of thistle control in pastures.

If goats can be incorporated into the production systems of individual farms then, likewise, their inclusion in a program for the control of thistles certainly warrants investigation, as Allan and Holst (1996) have shown. Goats have the ability to reduce plant numbers and prevent seed production and will often preferentially graze thistles over more palatable species.

The challenge confronting grazing management research is to determine how different grazing techniques can be used to suppress the undesirable thistles while maximizing the persistence and productivity of desirable pasture plants (Medd *et al.* 1987).

Chemical control

Even with the establishment of improved pastures, herbicides may be required to control thistles which establish with the sown species or which infest the pastures in particularly bad thistle years. However, repeated annual applications of chemicals aimed at exhausting the soil seed reserves in heavily infested paddocks may weaken the pasture, making it more liable to future re-invasion, and encourage the development of herbicide-resistant biotypes, as found by Harrington (1990) in New Zealand with nodding thistle.

The application of herbicide to thistles after they have bolted, commonly referred to as 'spray topping', can substantially reduce the number of viable seeds set by plants, for example in nodding thistle (McCarty and Hatting 1975) and saffron thistle (Fromm 1985), but due to the wide variation in flowering times between species, this management tactic would only seem to be valid in monospecific thistle stands.

Soil fertility

Thistles are often considered to be indicators of increasing soil fertility (Michael 1972). For example, increased fertility probably contributes to the occurrence of thistle infestations around dams and rabbit burrows and on stock camps. Similarly, anecdotal evidence suggests that changes in soil nutrient status is one factor which may cause a change in thistle dominance in a pasture. However, despite these apparent relationships, very little work appears to have been done on controlling thistles by altering the level of soil fertility, such as through cropping. The technique may be less effective with spear and saffron thistles which are thought to be rather indifferent to soil fertility. Alternatively, fertilizers can also be used to increase the competitive ability of pasture and reduce weed establishment. Timing of application in this case is critical.

Biological control

In Australia, biological control has become an important tactic for the control of many weeds, including the thistles, as indicated by various authors at this workshop, and has particularly high potential for extensive grazing industries on intractable terrain (Menz *et al.* 1984). But most scientists now believe, and this was re-emphasized by Groves and Burdon (1996), that biocontrol needs to be incorporated into an approach which integrates a variety of methods, even the integration of bioherbicides with classical biological control agents.

With the promising results which have been presented for both exotic and native pathogens of various thistles at this workshop (Bourdôt and Harvey 1996, Crump *et al.* 1996, Groves and Burdon 1996) it is disappointing that after several years of concerted research, bioherbicides have failed to attract the interests of multinational companies. This lack of interest is a major constraint to the future adoption of this type of technology.

Farmer attitudes and constraints

Many years ago, Mill (1848) wrote: 'In every department of human affairs, Practice long precedes Science: systematic inquiry into the modes of action of the powers of nature is the tardy product of a long cause of efforts to use those powers for practical ends.' In the context of this workshop, we can conclude from Mill's observation that farmers have had a long history of dealing with the practical issues of thistle management, so why not ask them what works best for them? Some have labelled this idea 'bench marking' or 'best practice'. Essentially, the idea is to survey farmers, identify those who have overcome their thistle problems, determine their management practices and then extend their successful techniques to other farmers in the district. This approach has considerable potential, particularly for tackling thistle management on a district by district basis.

There are many practical problems associated with current thistle control techniques (Minehan 1996), and it is important to be aware of what impediments there may be to the adoption of control strategies that researchers may devise. However, it is doubtful whether such constraints, if they are not universal, should change the ideal towards which researchers work. One of the advantages of an integrated approach to thistle management is that it provides a variety of techniques so that at least some will be applicable on any individual farm. I have already alluded to the advantage of biological control in pastures of difficult terrain.

To the list of innovative ideas for alternative research compiled by Minehan (1996), I would add the investigation of thistles to be harvested for the production of allelochemicals. Several thistle species are known to have allelopathic properties (Woodward and Glenn 1983).

Conclusions

What then is the key to improving thistle management – is it more studies in the ecology and biology of thistles, biological control, herbicide use or pasture competition? All of these elements must be addressed so that they can be combined to give a workable weed management approach, however, there are no easy solutions to thistle management. The data provided by Allan and Holst (1996) on the persistence of *Onopordum illyricum* over a six year period and the ease with which the problem flared again when management was allowed to lapse is evidence of the tenacity of thistles. Against these odds, it is pertinent that *continuous* and *vigilant* monitoring and control of weeds (usually by chipping and spraying) was given by graziers as the main reason for having either a static or declining weed problem (Sindel 1996). Equally, farmers have said before that the most successful weed management strategy is 'obsessive persistency'. Given the persistency of thistles themselves, it is reasonable to presume that this strategy will remain a key ingredient for any thistle management program to be successful in the future.

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Workshop outcomes – a blueprint for research into the management of thistles

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Introduction

There are more than a dozen species of thistle in Australia and New Zealand that are weeds of pastures and crops, and several of these belonging to the genera *Carduus*, *Carthamus*, *Cirsium*, *Onopordum* and *Silybum*, are key weeds in particular situations. Considerable effort has gone into their control, but this has usually been done by a number of different organizations acting in relative isolation. In 1995, the CRC for Weed Management Systems was set up with the purpose of co-ordinating research and fostering collaboration between groups to promote more effective weed management. As part of this aim, the CRC sponsored this Thistle Management Workshop, held at CSIRO Division of Entomology, Canberra, on June 12 and 13, 1996. It brought together over 40 researchers from Australia and New Zealand, representing expertise in thistle ecology, grazing and pasture management, herbicide use and biological control, as well as extension workers involved directly in thistle control and end-users, such as landholders and representatives of Landcare groups. The target for this group was to establish a set of research priorities for the CRC to develop integrated approach to the management of thistles.

The first day was dedicated to a series of research talks on ecology/biology (including modelling), biological control, grazing management (including goats), herbicide use and the potential for herbicide resistance, and summaries of the expectations and needs of control practitioners and landholders for thistle management. These papers have been edited and are now presented in these proceedings.

Armed with the information provided in the papers, group discussions were held on the following day. Initially, workshop participants were divided into four groups, according to their particular expertise, to discuss specific areas of research; namely, ecology, grazing management, biological control and herbicides. The groups were asked to discuss and identify:

- gaps in our knowledge of particular areas of weed biology and current management practices
- specific research projects that would provide the knowledge required
- future directions for research.

Following a plenary discussion of recommendations from these groups, they were reformed in order to have participants from each expert group in four new discussion groups, and asked to:

- examine the feasibility of integration of the various management strategies
- identify any drawbacks associated with integration
- suggest specific research projects that might allow evaluation of the interaction and integration of control methods.

The end result of these discussions was a list of 31 proposals for different research topics. During the final session, workshop participants were given the opportunity to rate each proposal according their attractiveness (to what extent the results would improve thistle management) and their feasibility (the probability of actually achieving the results). Proposals were rated as low, medium or high for each category. The results were then averaged and graphed (feasibility vs. attractiveness) to produce a picture of the combined view of workshop participants. This graph provided a useful means of prioritizing the 31 proposals, and served as a tool for generating a series of recommendations for future research on thistle management.

Outcomes

One difficulty with defining the topic as 'thistles' is that this comprises over a dozen species in Australia. No attempt was made to prioritize species as targets for control, but from the contents of papers and recommendations for research it was clear that particular species are of greater regional concern. These include nodding (*Carduus nutans*), Scotch and Illyrian (*Onopordum* spp.), and saffron thistles (*Carthamus lanatus*) in New South Wales, spear (*Cirsium vulgare*) and variegated (*Silybum marianum*) thistle in Victoria, saffron thistle in Western Australia, and nodding and perennial (*Cirsium arvense*) thistle in New Zealand.

The majority of the 31 research proposals suggested by the discussion groups could be applied to any one species or group of thistles. Several were sufficiently overlapping to be combined, while some addressed general issues rather than specific research questions. Omitting these left a set of 24 recommendations for future research. The prioritization exercise (Figure 1) separated out these recommendations into four groups: highly attractive and highly feasible, attractive but with lower feasibility, highly feasible but not very attractive, and with low feasibility and attraction. Table 1 lists the recommendations according to these categories.

There was a general consensus amongst workshop participants that integration of different control methods was essential for the long-term management of thistles. This created an urgent need for improved transfer of existing and new technologies to the end-users, and this need is reflected in the fact that three of the four recommendations in the highest priority group concern the implementation of such extension programs for herbicide use, the delivery of biological control agents and training in the integration of control techniques.

The highest priority research proposal again reflected the workshop's desire to see more integration of control methods. This recommendation was to carry out experiments to clarify the interactions between biocontrol agents and grazing or herbicide use, to optimize the use of the former in an integrated approach to weed management. A need was also perceived for more information on interactions between thistle populations and other pasture species, particularly in the area of thistle seed bank persistence and germination dynamics.

Such data could feed in to an iterative modelling / experimentation approach to test combinations of control methods and implement best bet strategies. While this latter approach was highly attractive, it was recognised that success would require considerable work input and

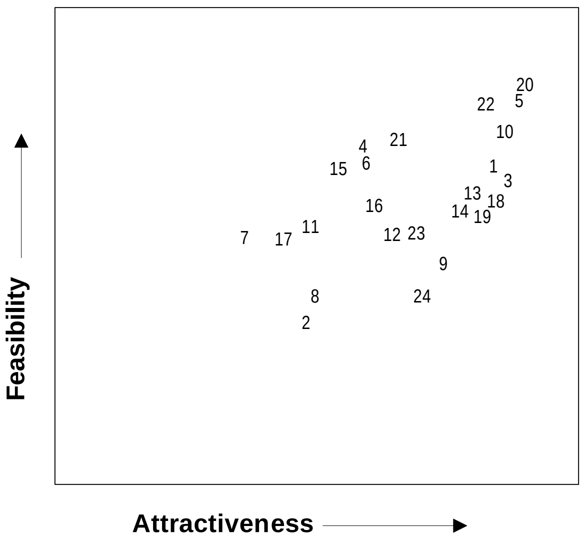

Figure 1. Ranking of research proposals with respect to their attractiveness and feasibility.

collaboration. A simpler proposal that could provide useful information in the shorter term would be to survey the cost and efficiency of current control practices and use the collated data to evaluate best-practice strategies.

One group of proposals were considered to be highly feasible, but were not as attractive, most likely because they addressed quite specific research questions, e.g. the use of spray / graze on *Onopordum* and *Carduus* thistles, the identity of populations of *Onopordum* and saffron thistles and technical aspects of herbicide use for *Onopordum*.

A basket of proposals were considered to have both low attractiveness and low feasibility. This does not necessarily mean that they should be dismissed as issues by the CRC. For example, even if it is considered 'dry' work and difficult to obtain the data there is an imperative to produce economic evaluations of weed problems and of the strategies developed to control them. Economic assessment not only provides an important measure of success or failure, but it is the measure most valued by decision-making and funding bodies. Some of the other lower priority ratings may also form part of wider projects aimed at integration, e.g. the effect of herbicides and grazing on pasture composition or the manipulation of pasture cover and thistle seed banks. While broad spectrum pathogens has been placed in the 'too hard basket' at the moment, they should not be dismissed from the potential range of control options in the long-term. A study of the problems that need to be overcome, such as legislative restrictions, the economics of commercial vs. cottage-industry production and non-target safety issues could help make an informed decision on their eventual suitability.

Some general issues to emerge in the discussions were that for any management strategy to work it would need to be geared to the specific requirements and practical limitations of the end-users. Farm practices that needed changing for integrated management to work would need to be identified, and the control of weeds would need to operate as part of a whole-farm management plan. Finally, it was strongly emphasised that whatever management models were developed, this would need to be done hand in hand with the extension links required for its implementation.

Quo vadis?

Thistles clearly comprise some of the most widespread and damaging weeds in temperate Australia. This workshop has drawn upon the expertise of Australasia to define current knowledge and future directions needed to improve their management. Both extension and research issues were viewed by workshop participants as important and we have grouped the overall recommendations into a number of categories for these two areas. The CRC for Weed Management Systems has been formed to tackle these problems. It has already recognised the gap in education and extension by establishing a program specifically addressed to the adoption of weed control technology.

Extension programs must initially be based on the current limited knowledge, but should subsequently include new information as it becomes available from the research projects listed in Table 2. While the appointment of two CRC positions, based in Canberra and Frankston, to co-ordinate biological control agent release networks goes part way to meeting the objectives, it is recommended that the CRC Adoption program look at mechanisms that will improve extension in all three areas. Finally, it is recommended that the Perennial Pastures Program of the CRC incorporate projects that address the three research areas. Success in tackling these particular issues should lead to substantial improvements in the long-term management of weedy thistles.

Table 1. List of individual proposals to improve thistle control and achieve integrated management.

No.	Research recommendation
High attractiveness – high feasibility	
20	Education of integrated control through simple messages to farmers
5	Improvement of herbicide extension
10	Development of a structured extension program for biological control
22	Timing of herbicides / grazing to aid biological control agents
High attractiveness – low feasibility	
1	Relationships to predict thistle impact on pasture production and composition
3	Seedbank maintenance and germination dynamics
13	Collation of data on cost and efficiency of current control practices
14	Evaluation of best-practice strategies identified by proposal 13
18	Iterative modelling / experimentation to test combinations of control methods
19	Implementation of best-bet strategies produced by proposal 9
Low attractiveness – high feasibility	
21	Spray / graze demonstrations for *Onopordum* and *Carduus*
4	Taxonomy of *Onopordum* and *Carthamus*
6	Timing, rates and types of herbicide needed for *Onopordum*
15	Timing of spray-topping / grazing etc. vs. seed predators
Low attractiveness – low feasibility	
24	Economic evaluation of strategies developed for different pasture systems
9	Potential synergy or antagonism between control agents
23	Manipulation of seed banks to reduce their seed
12	Manipulation of pasture cover and litter in perennial and annual systems
16	Effect of herbicides and grazing on pasture competition / composition
8	Investigation of potential for broad spectrum pathogens
2	Succession dynamics and niche overlap of thistles
7	Use of blanket wipers to reduce seed set
11	Relative palatability of thistles and pasture for different stock
17	Tactical application of fertilizers on pasture competition and control agents

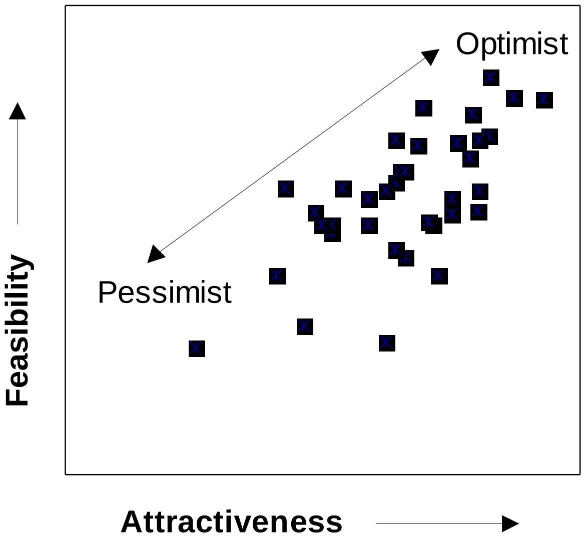

Figure 2. Ranking of individual workshop participants according to their assessment of the set of research proposals.

Postscript

The priority setting exercise permitted an interesting look at the psychology of people concerned with the problems of weedy thistles. By averaging all the responses for each survey, individual profiles could also be plotted on a graph summarizing their overall feeling as to whether the set of recommendations was attractive or feasible (Figure 2). This clearly showed a range from the very pessimistic to the highly

Table 2. Recommended areas of research and extension that need to be tackled to improve the management of thistles.

Area	Particular issues
Research	
Integrated practices	integration of grazing, biological control, herbicides and fertilizer usage into strategies for thistle management survey of current practices and evaluation of better-bet options specific studies on interactions between control agents and grazing, herbicides or the manipulation of pasture cover
Ecology	plant population dynamics (including modelling) thistle vs. pasture competition and seed bank dynamics the impact of specific biological control agents
Bioeconomic modelling	economics and modelling of current thistle management practices evaluation of better-bet strategies used by producers
Extension	
Integrated practices	education of land managers on integrated management practices through simple messages
Biological control	distribution of biological control agents and advice on their management
Herbicides	promotion of effective use of herbicides, including spray-graze demonstrations on *Onopordum* and *Carduus*

optimistic. Most participants, though, were optimistic that more can be achieved in the management of thistles. Hopefully, the sharing of these views at the workshop has presented a realistic, but challenging set of research objectives for the CRC.

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