A study of the biology and control of *Anthriscus caucalis* and *Torilis nodosa* in pyrethrum

by

Richard Rawnsley

B.Agr.Sc. (Hons.) University of Tasmania

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Richard Rawnsley

June 2005

Abstract

The Tasmanian pyrethrum industry has been operating on a commercial basis for 23 years and is now the second largest producer of pyrethrum (*Tanacetum cinerariaefolium* L.) for natural insecticides in the world. The industry, with a annual farm gate value in excess of $7 million, makes a significant contribution to the rural economy of Tasmania (Australia). Currently, production involves 120 contracted growers and 1300 hectares of land. To maintain its position as a world leader in the production of pyrethrum, the Tasmanian industry must continue to improve production technologies and efficiencies. An emerging area of concern is the management of weeds, with some weed species in pyrethrum being particularly difficult to control. This includes weeds that are commonly found in vegetable crops which are grown in rotation with pyrethrum as well as relatively uncommon species; such as *Anthriscus caucalis* and *Torilis nodosa*. This study investigated the biology and control of both *A. caucalis* and *T. nodosa* which belong to the Apiaceae family.

A morphological examination highlighted easily distinguishable characteristics for the identification of these relatively unfamiliar species. *Anthriscus caucalis* seedlings are identifiable by their tri-pinnate compound leaves which are glabrous on top with scattered hairs beneath. The fruit of *A. caucalis* is ovoid in shape and 2.5 to 3.5mm in size with distinguishing hooked spines and a short beak. The pedicels have a ring of hairs at the top. *Torilis nodosa* seedlings are identifiable by their deeply bi-pinnate compound leaves and narrow linear lobes. The fruit of *T. nodosa* is ovoid in shape and 2.5 to 3mm in diameter and composed of 2 distinct dimorphic mericarps. The outer mericarp has barbellate spines with the inner mericarp tuberculate.

A survey of pyrethrum crops revealed that the occurrence of these species was high, occurring in 30% of pyrethrum crops, with *A. caucalis* being the more prevalent species. As pyrethrum is a perennial crop which can be grown for up to five years, it was also found that the frequency of occurrence of Apiaceae species increased with increasing crop age.

Investigations into the germination characteristics of *A. caucalis* and *T. nodosa* revealed that *A. caucalis* possessed an innate seed dormancy which was overcome by seed scarification and dry storage at 20°C. *Torilis nodosa* displayed no innate seed dormancy. Both species, *A. caucalis* and *T. nodosa*, were found to behave predominantly as winter annuals, germinating in autumn and over wintering as small rosettes. Studies indicated that *T. nodosa* has a transient to short term persistent seedbank, while *A. caucalis* has a short to long term persistent seedbank. *Anthriscus caucalis* was found to undergo rapid vegetative stem development during late winter early spring with flowering commencing during mid spring. Seed maturation occurred in early summer. *Torilis nodosa* was found to produce procumbent stems in mid to late spring and flower approximately 6 weeks later than *A. caucalis* with seed maturation occurring in mid to late to summer.

Studies into the chemical control of *A. caucalis* and *T. nodosa* identified a small number of herbicides with potential for use in pyrethrum. Applications of dimethenamid at 3.6 kg/ha provided the most selective pre emergent control for both species, while clomazone applied at 120.0 g/ha provided very effective control of *T. nodosa*. Imazamox applied at 34 g/ha provided significant post emergent control of both species with excellent selectivity for use in pyrethrum. A number of other herbicides were identified as having activity on *A. caucalis* and *T. nodosa*, however lower levels of selectivity limited their potential adoption for use in pyrhethrum.

This thesis has provided significant information to the pyrethrum industry on the biology and competitive nature of the relatively unknown weed species *A. caucalis* and *T. nodosa*. The thesis has also provided immediate short term weed control strategies and enhanced the weed management options available for the industry.

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I dedicate this work to the people dearest to me

    My wife Kasee

    and My Parents Philip and Victoria

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Chapter 1 Introduction

1.1 Pyrethrum production and weed management

Pyrethrum is an important horticultural crop of Tasmania, with an annual farm gate value in excess of $7 million. Pyrethrum production is a relatively new industry to Tasmania and in a short time Tasmania has become the world's second highest producer of pyrethrum, supplying 30% of the world market. The industry has undergone major advancement in production techniques since its commercialisation in 1981. These techniques have included the use of direct seeding to establish crops, improved efficiencies in mechanical harvesting, improvement in plant breeding, integrated management of diseases, development of water and nutrient management strategies and effective weed control in seedling and established pyrethrum. All of these developments have been beneficial to the industry. However, there remains a need for further research to support the production of higher and more reliable yields. One of the areas of particular concern is weed management.

Development of an effective weed management strategy is important in the establishment of herbaceous perennial crops in new production locations (Calkins *et al.*, 1996) as any new management practice ultimately has its own complement of weeds (Aldrich and Kremer, 1997). The weed management program developed for pyrethrum in northern Tasmania is heavily reliant on herbicide use. One consequence, of increasing concern in the current program, is the unintentional selection of plant species that were not commonly viewed as being agricultural weed species of this area. The establishment of new weeds is a serious concern to the pyrethrum industry due to yield losses and increased costs of control. Production of pyrethrum involves a non-tillage system following seedling establishment and this has led to development of an intensive chemical control weed management program. Because the canopy of the pyrethrum crop is relatively open from the time of harvest in January/February to commencement of flowering in November, weeds are able to establish and subsequently compete with the crop for much of the year (Plate 1.1). Weed control in pyrethrum by use of herbicides in Tasmania has had minimal success on certain "hard to kill" weeds such as *Trifolium repens* L. (White Clover) and *Galium aparine* L. (Cleavers). Although many common weeds have been

successfully controlled, new emerging weeds are more difficult to control due to the difficulty in finding a successful selective herbicide and low competition from pyrethrum. Two weed species identified as being of greatest concern to pyrethrum production are the Apiaceae weeds; *Anthriscus caucalis* M. Bieb (burr chervil) and *Torilis nodosa* (L.) Gaetn. (knotted hedge parsley). Little is known about the biology of *A. caucalis* and *T. nodosa* in agricultural situations and there are no known reports in the literature of prior research into the management of these plants as crop weeds of agricultural importance. Current indications are however, that these two species have the potential to significantly reduce the productivity of pyrethrum crops and increase costs of production.

Plate 1.1 An established pyrethrum field in autumn illustrating an open canopy and poor competitive ability of the crop at this growth stage.

1.2 History of the pyrethrum industry

Commercial pyrethrum production was introduced into Tasmanian in 1981 when a subsidiary of British Oxygen Company (BOC), Commonwealth Industrial Gases (CIG) founded the industry. In 1996 Botanical Resources Australia Pty. Ltd., (BRA) was formed following a management buy out from BOC. Today BRA contract

growers produce in excess of 8000 tonnes per annum of pyrethrum flowers from the fertile soil of Tasmania's North and North West. The production of pyrethrum peaked in the year 2000 with the total area of production in Tasmania of 2000 hectares, involving 188 contracted growers (Anon., 2000a). Tasmania's pyrethrum industry has had a reduction in production since the year 2000 as a result of high world stocks and strong competition from synthetically produced pyrethroids. Currently, there is a total area of production of 1300ha and 120 contracted growers.

Australia is the second-largest producer of natural pyrethroids in the world and has the enormous advantage of having the only production system that is completely mechanised and based on advanced growing, harvesting and refining technologies (Biggs, 1997). The world's other main producers of pyrethrum are Kenya, Rwanda and Tanzania, with Ecuador and Papua New Guinea being minor producers.

1.3 The Pyrethrum plant

Pyrethrum (*Tanacetum cinerariaefolium* L.) is a daisy-like plant with a rosette habit and is traditionally cultivated in temperate to semi temperate agroclimates (Sastry, 2001). It produces conspicuous white inflorescences with yellow centres and the flower heads contain pyrethrins that are insecticidal in nature (Sastry, 2001). The pyrethrins are extracted and refined to produce a natural insecticidal product. Pyrethrum grows to a height of 45-75cm with the flowers growing on long upright stems. It is most productive when grown in a well-drained soil and where the maximum temperature does not exceed 30°C (Anon., 1995a). Pyrethrum is a perennial plant and under commercial production is usually grown for four years but can still produce economic yields after seven years (Biggs, 1997). In Tasmania direct drilling of pyrethrum occurs between August and October with the first harvest occurring 16 months later in January and February. Subsequent annual harvests occur in this period. Two varieties of pyrethrum are predominantly grown in Tasmania, *pioneer* and *piper*.

1.4 Tasmanian soil and climate

Tasmania is the most southerly, permanently inhabited island of Australia, lying 40° to 43° south in latitude. Pyrethrum production in Tasmania is restricted to the north of the island with production predominantly centred on the coastal areas around

Devonport. The crop is grown on the fertile red ferrosol soils (Isbell, 1996), previously referred to as Krasnozems (Plate 1.2). A small percentage of pyrethrum production also occurs in the North East and Central North of the island.

Tasmania has a mostly temperate maritime climate. A prevailing westerly airstream leads to a marked variation of cloudiness, rainfall and temperature. Consequently, the West Coast and highlands are generally cool, wet and cloudy, while the East Coast and lowlands are milder, drier and sunnier. Summers are mild, with any hot periods rarely lasting more than a few days. Rainfall is generally lower (in both amount and frequency) in summer, most notably in the west and northwest. Winters are not excessively cold, especially compared to places at similar latitudes in the northern hemisphere that do not have the sea's moderating influence. The mean annual rainfall and temperature for Devonport is 954.3mm and 16.8°C (Figure 1.1 and 1.2).
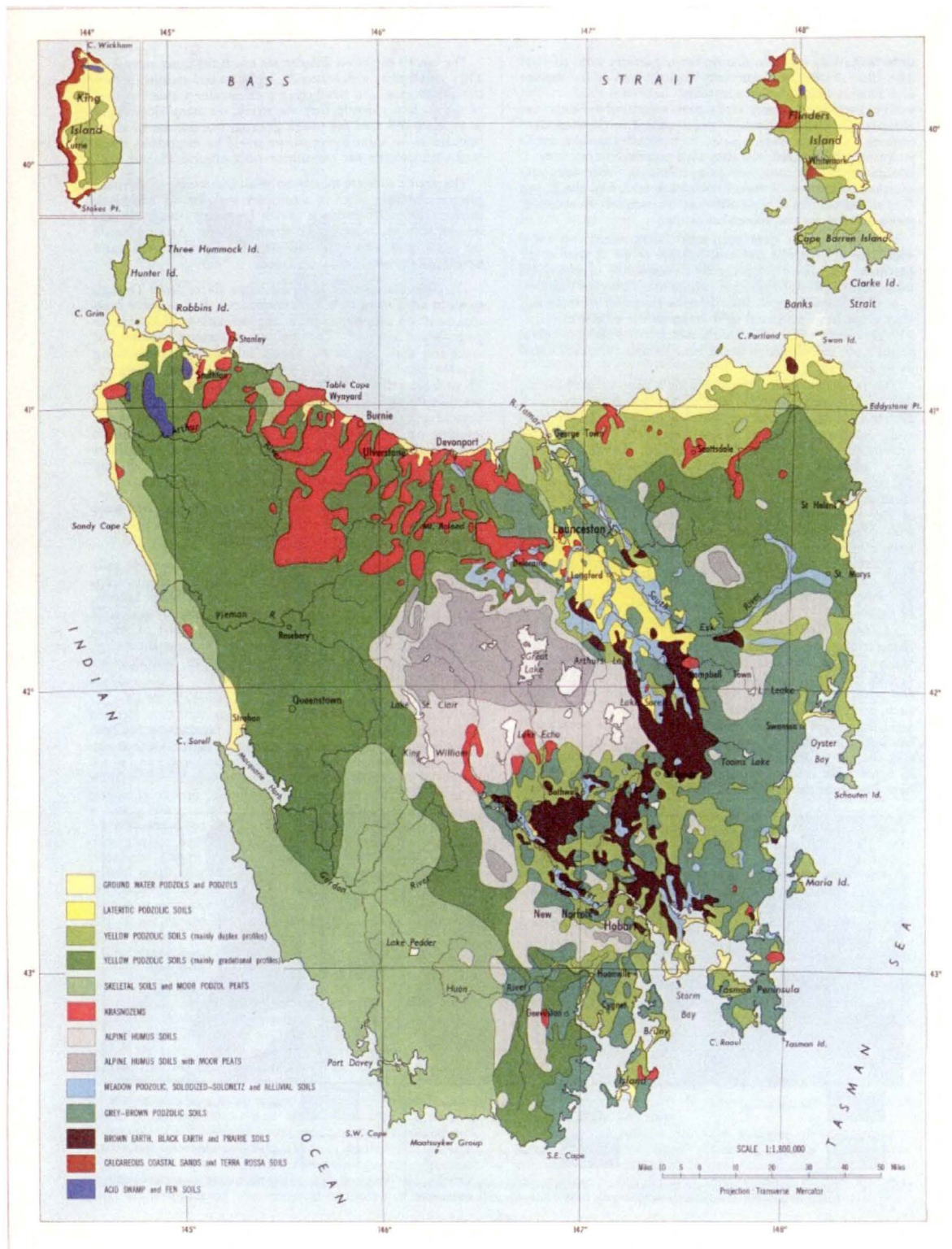
Plate 1.2 A map of Tasmania showing soil types distribution of red ferrosol soils (previously known as Krasnozems) shown in red (Source: Nichols and Dimmock, 1965).
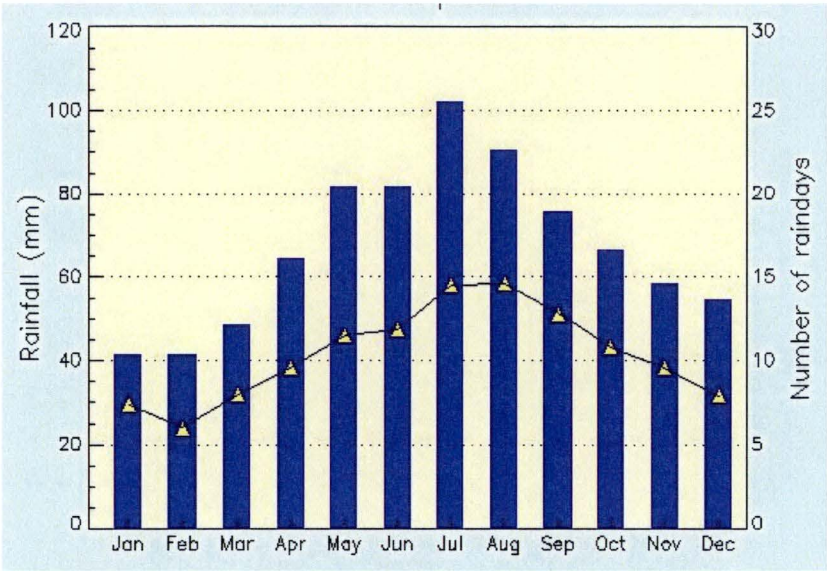
Figure 1.1 Mean monthly rainfall data for Devonport (41.2° South and 146.4° East). Source Tasmanian Bureau of Meteorology.
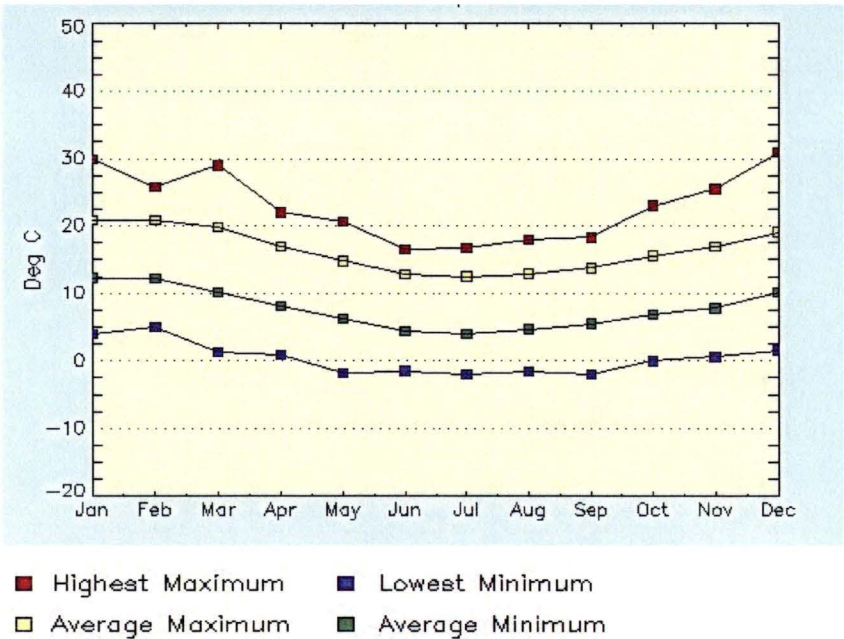
Figure 1.2 Mean monthly temperature data for Devonport (41.2° South and 146.4° East). Source Tasmanian Bureau of Meteorology.

1.5 Current weed control in Pyrethrum

In Tasmania weed control in pyrethrum crops is achieved predominantly by chemical use. Broadleaf weed control is achieved by the pre and post emergence application of Stomp® (a.i. Pendimethalin, 33%) alone or in combination with Totril® (a.i. Ioxynil,

25%). Other main herbicide applications include Linuron® (a.i. Linuron, 50%) in combination with Totril® (a.i. Ioxynil, 25%) and also Brodal® (a.i. Diflufenican, 50%) and Goal® (a.i. Oxyfluorfen, 24%). Control of grass weeds is predominantly achieved with Fulisade® (a.i Fluazifop-p, 21.2%) or Verdict® (a.i. Haloxyfob, 10.4%). Spot spraying for hard to kill weeds is achieved with Basta® (a.i. glufosinate-ammonium 200g/L) at a concentration of 1:75 (1 part Basta® to 75 parts water) or Basta® at 1:75 plus MCPA 500® (a.i. MCPA, 50%) at 1:200 to 1:300 where *Trifolium* spp. and *Sonchus* spp. are present (Anon., 2000b).

Concerns about the heavy reliance on chemical use and the efficacy of the current weed management program for pyrethrum production have been identified as two of the major deterrents to growing pyrethrum in Tasmanian. A survey of pyrethrum growers and also non-growers conducted by Falk (2001) found that three of the four highest perceived disadvantages of growing pyrethrum were; the amount of herbicides and fungicides required, the cost of managing weeds and the types of chemicals used which limit crop rotation. In addition to the costs of managing weeds, respondents were also concerned about the introduction of new weeds and the potential for carry-over effects into other crops. Falk (2001) summarised the weed concerns of growers and non-growers as follows:

> ➢ Cost of weed control in terms of labour and chemical inputs.
> ➢ Introduction of new weeds and their effects following pyrethrum removal.
> ➢ Colonisation of the bare ground created by the death of pyrethrum plants.
> ➢ Introduction of new weeds through contaminated seed.

Falk (2001) recommended three responses to the concerns identified in the survey:

> ➢ The investment in more research and development to find better ways (and chemicals) to manage weeds by BRA.
> ➢ The need to limit the risk associated with unclean seed.
> ➢ Improvement in farm hygiene standards to ensure weeds are not introduced through contamination from outside sources.

The results presented by Falk (2001) clearly indicated that not only are deficiencies in the current weed management strategies regarded as one of the major deterrents to

growing pyrethrum but also the introduction of new weeds was identified as a threat to the industry. *Anthriscus caucalis* and *Torilis nodosa* are two species that have been identified as of greatest concern to pyrethrum production and there is an urgent need to investigate the biology and control of these species in pyrethrum.

1.6 Study objectives and thesis structure

The project was initiated by the pyrethrum industry in Tasmania and therefore had an applied focus. The approach taken in the research was to use sound scientific knowledge of key aspects of weed biology and responses to herbicides to develop weed management strategies for industry adoption. The aims of the project were to provide information to the pyrethrum industry on the biology and competitive nature of *Anthriscus caucalis* and *Torilis nodosa* and to identify herbicide products that would be both effective and selective for use in pyrethrum. Part 1 of the study was focused on the biology of *A. caucalis* and *T. nodosa* and part 2 investigated the chemical control of *A. caucalis* and *T. nodosa* in pyrethrum.

The specific objectives addressed in part 1 of the thesis were:

i.   To provide a preliminary assessment of the threat posed by *A. caucalis* and *T. nodosa* based on the abundance, distribution and level of weediness of the species in pyrethrum crops.

ii.   To develop a diagnostic tool to facilitate accurate identification of seedling and mature *A. caucalis* and *T. nodosa* plants in the field.

iii. To investigate the factors affecting germination of *A. caucalis* and *T. nodosa* in order to identify strategies to reduce field emergence and facilitate control of the weeds.

iv.   To investigate the seedbank dynamics and emergence pattern of *A. caucalis* and *T. nodosa* under pyrethrum production.

v.   To examine the growth characteristics of *A. caucalis* and *T. nodosa* to assist in targeting of cultural and chemical management practices.

The following objectives were addressed in Part 2 of the thesis:

i.   To review the present chemical control program in pyrethrum, past attempts to control *Anthriscus caucalis* and *Torilis nodosa* in pyrethrum and identify

potential chemical control options based on control of related Apiaceae weeds.

ii.   To investigate the efficacy of a number of herbicides using pot screening trials.

iii.   To investigate the potential for use of identified herbicides in pyrethrum production.

The thesis is structured as a series of chapters, each covering experiments undertaken to address the specific objectives of the project. The third objective in Part 2 is addressed in three chapters incorporating data from field studies conducted over two years examining the following

a. The preemergence control of *A. caucalis* and *T. nodosa* in pyrethrum

b. The postemergence control of *A. caucalis* in pyrethrum

c. Pyrethrum response to combined applications of the most promising herbicides.

In each chapter the experimental work undertaken is described, results are reported and discussed in relation to the literature where appropriate. The major findings and the possible implications for industry are summarised in the final chapter in the thesis.

Chapter 2 Taxonomic and floral description of *A. caucalis* and *T. nodosa*

2.1 Introduction

A number of species of the Apiaceae, previously referred to as Umbelliferae, family have been observed to be present in pyrethrum fields in Tasmania. They include *Anthriscus cauc*alis M. Bieb., *Torilis nodosa* (L.) Gaertn., *Daucus glochidiatus* (Labill.) Fisch. & al., *Conium maculatum* (L.) and *Daucus carota* spp. *carota* (L). The correct identification of these species is of paramount importance as recommended chemical and cultural control strategies for any one species may not be effective for all species. The aim of the first part of this study was to identify all Apiaceae weeds found in pyrethrum and to determine easily identifiable and distinctive characteristics of each species. In addition, due to the paucity of published literature concerning the floral biology of *A. caucalis* and *T. nodosa*, a study was undertaken with the aim to provide information on the floral biology of both species and to compare their floral and growth characteristics in Tasmania with that recorded elsewhere.

2.1.1 The family Apiaceae

The family Apiaceae contains approximately 250 genera and 3,000 species (Harden, 2000). In Australia there are 42 genera with approximately 200 species occurring across all states (Harden, 2000). Species of the family are cosmopolitan in their distribution, but most abundant in the temperate regions of the northern hemisphere. A number of plants of the family are of economic importance, being cultivated for use as food and condiments. Examples include *Daucus carota* (carrots), *Pastinaca sativa* (parsnip), *Apium dulce* (celery), *Petroselinum crispum* (parsley), *Foeniculum vulgare* (common fennel) and *Coriandrum sativum* (coriander). Common weedy species of the family include *Conium maculatum* (poison hemlock), *Bifora testiculata* (bifora), *Eryngium rostratum* (blue devil) and *Hydrocotyle* spp.

Species of the Apiaceae family can be recognised by their characteristic umbel inflorescence, dissected pinnate leaves, inferior ovary and 2-celled, indehiscent dorsally or laterally compressed fruits which may be ribbed or winged (Bhellum and

Mangotra, 1996). They have hollow stems and alternate leaves, most often compound and usually swollen at the base. The small flowers appear in compound umbels and contain 5 sepals, 5 petals, 5 stamens and two styles. The fruit morphology is usually a key taxonomic feature used to identify most of the genera and species. The dry fruit of Apiaceae species consist of two parts (carpels), which separate at maturity along the midline into two one-seeded halves or mericarps (Curtis, 1963).

2.1.2 The genus *Anthriscus*

Anthriscus species are native to Europe, Asia and Africa (Clapham *et al.*, 1987). There are 23 *Anthriscus* species and although there are a number of taxonomic keys that include the genus *Anthriscus*, no one key includes all known species. Davis (1972) provides the following description of the genus *Anthriscus*;

"Annuals to perennials with 2-4 pinnate leaves, glabrous or not. Bracts present or absent. Bracteoles present, usually unequal. Pedicels often with ring of ± asperous hairs at top. Sepals very small or absent. Petals white, occasionally pink, sometimes radiant. Fruit glabrous or covered with antrorse ± tuberculate bristles, often shining, ovate to linear, usually tapering to apex. Mericarps ± terete. Ridges inconspicuous confined to apex. Dorsal vittae 4, very slender, inconspicuous; commissural."

Anthriscus caucalis has an upright growth habit with a main stem reaching a height of up to 80cm. The stems are hollow and glabrous with fine marked longitudinal lines. The bases of the stems are purplish in colour and thickened. The compound pinnate leaves are glabrous on top with stiff scattered hairs beneath. The fruit is ovoid and 2.5-3.5mm in size with distinguishing hooked spines and a short beak. The pedicels have a ring of hairs at the top.

Anthriscus caucalis has been introduced to both Australasia and North America (Clapham *et al.*, 1987). *Anthriscus caucalis* has a therophyte life form, germinating in autumn (Roberts, 1986) and flowering in late spring/early summer in Europe (Clapham *et al.*, 1987). According to records obtained from the Tasmanian herbarium, D.I. Morris collected the first recorded specimen of *A. caucalis* in

Tasmania in October 1967 in Sassafras and specimens have also been recorded at Molesworth (December 1967), Gretna (1987) and again in Sassafras (December 1998) in a pyrethrum field.

2.1.3 The genus *Torilis*

There are approximately 25 species of the genus *Torilis,* mainly in Europe but a few in Asia and Africa. There are a number of taxonomic keys that include the genus *Torilis* but no one key includes all known species. Curtis, (1963) provides the following description of the genus *Torilis;*

"Herbs with pinnate leaves. Umbels compound but usually with very short rays. Sepals 5, small; petals white or pinkish, with the apex inflexed. Fruit ovoid and slightly flattened laterally; mericarps densely covered with tubercles or spines".

Torilis nodosa has a trailing prostrate growth habit that is supported by surrounding vegetation where possible and grows up to a height of 50cm. The stems are procumbent and rigid with fine longitudinal lines. The compound leaves are deeply pinnate with narrow linear lobes. The flowers are borne in dense stalkless clusters resulting in a rigid compact umbel structure. The fruit is ovoid 2.5 to 3mm in diameter and composed of 2 distinct dimorphic mericarps. The outer mericarp has barbellate spines with the inner mericarp tuberculate.

Torilis nodosa is native to Africa, Asia and Europe (Clapham *et al.*, 1987) and has been introduced to Australia (Curtis, 1963). *Torilis nodosa* has been found to have a therophyte life form, germinating in autumn and spring and flowering in May and July (spring- summer) in Europe (Clapham *et al.* 1987). According to records obtained from the Tasmanian herbarium, L. Rodway collected the first recorded specimen of *T. nodosa* in Tasmania at Bellerive in November 1915. W.M. Curtis recorded *T. nodosa* at Low Head in December 1955, while more recent recordings have occurred on the Northwest coast of Tasmania in pyrethrum fields.

2.1.4 Floral biology of Apiaceae species

The inflorescence of Apiaceae species is distinctive in that the flowers are borne in a hierarchical arrangement. The inflorescence is usually made up of compound

umbels; these in turn are made up of umbellules (or umbellets), simple umbels that bear large numbers of small, closely packed flowers (Lovett Doust and Lovett Doust, 1982). Although there is variation in the flowering biology of species of the family Apiaceae some general features have previously been described. These features included a prominent stylopodium, exposed nectar, promiscuous pollination, perfect flowers, protandry, actinomorphic corollas, sexual reproduction and semi-compact umbels (Bell, 1971). The breeding system of this family is quite distinctive and according to Lovett Doust and Lovett Doust (1982), 49% of British Apiaceae species are andromonoecious with male and hermaphrodite flowers borne separately on the same plants, and almost all others have perfect flowers. In Apiaceae species that display dichogamy with the anthers and stigmas maturing at different times, 40% are protandrous with the pollen being released before the stigma is receptive (Lovett Doust and Lovett Doust, 1982).

Some floral features have been reported for the genera *Torilis* and *Anthriscus*. *Torilis leptophylla* is an andromonoecious species and exhibits variation in the proportion of hermaphrodite and staminate flowers in umbels of different orders (Koul *et al.*, 1984). The hermaphrodite flowers of *T. leptophylla* are protandrous as are the flowers of *T. arvensis* although only weakly protandrous in *T. arvensis* with dehiscence of anthers of the inner flowers and receptivity of the stigmas of outer flowers within the umbel overlapping (Koul *et al.*, 1993). Koul *et al.* (1993) reported that all flowers of *T. nodosa* are hermaphrodite flowers up until the quaternary orders of umbels, whereas in the quinary and senary orders, 1.7% and 39.0% are staminate, respectively. *Anthriscus sylvestris* is andromonoecious (Lovett Doust, 1980), with the hermaphrodite flowers being protandrous, although appearing only weakly protandrous (Darbyshire *et al.*, 1999). In general, however, little information is available regarding the floral biology of *A. caucalis* and *T. nodosa* and there is no reported study of their floral biology in the southern hemisphere.

2.2 Identification and description of Apiaceae species in pyrethrum

2.2.1 Materials and Methods

Fields of pyrethrum located in northern Tasmania were surveyed for the presence of Apiaceae species. Seedlings of the species found during the survey were removed and transplanted into 15cm pots with a standard potting mix (Appendix A.1). Following establishment, the transplants were grown under ambient conditions on outside benches at the University of Tasmania, Hobart (42° 90'S 147° 32'E) until completion of flowering and seed production.

During the growth and development of these species key taxonomic features were recorded and a simple key was constructed based on the main distinguishing features. In addition, photos of relevant features were taken and a coloured technical note produced to assist agronomists and pyrethrum growers in the correct identification of each species in the field.

2.2.2 Results and Discussion

An examination of pyrethrum fields identified five Apiaceae species; *A. caucalis*, *T. nodosa*, *Daucus glochidiatus* (native carrot), *Daucus carota* ssp. *carota* (wild carrot) and *Conium maculatum* (hemlock). All pyrethrum fields were surveyed and the results of this survey with respect to the presence and severity of infestation of these species are given in Chapter 3. This survey described the observed Apiaceae species as significant weeds of pyrethrum because of the competitive nature of these plants and the potential impact on the economic yield of pyrethrum. The similar leaf structure of *A. caucalis*, *T. nodosa* and *D. glochidiatus* and their scarcity in agricultural situations previously has resulted in difficulties in correctly identifying these species. To aid in the correct identification of Apiaceae weeds in pyrethrum fields the following technical note and key were prepared.

Identification of Apiaceae Weeds Commonly Found in Pyrethrum Fields in Tasmania

R. P. Rawnsley
School of Agricultural Science, University of Tasmania, GPO Box 252-54, Hobart 7001

Introduction

The current weed management program for pyrethrum production is heavily reliant on herbicide use and has unintentionally selected for a range of common plants eg. *Trifolium repens* (white clover) and *Galium aparine* (cleavers) and two new weed species, *Anthriscus caucalis* (Burr Chervil) and *Torilis nodosa* (Knotted Hedge Parsley). Although *A. caucalis* and *T. nodosa* are the most frequently observed species of the family Apiaceae other Apiaceae weeds have also been identified. These include *Daucus glochidiatus* (Native Carrot), *Daucus carota* ssp. *carota* (Wild Carrot), *Daucus carota* ssp. *sativus* (Cultivated Carrrot) and *Conium maculatum* (Hemlock).

Common Features of the Family Apiaceae

The family Apiaceae previously known as Umbelliferae consists of annual, biennial or perennial herbs. Species of Apiaceae are most easily recognised by their characteristic hierarchical arrangement of flowers, dissected pinnate leaves, inferior ovary and 2-celled, indehiscent dorsally or laterally compressed fruits, which usually separate from each other.

Apiaceae weeds of pyrethrum

Anthriscus caucalis (Burr Chervil)

Annual herb, 30-70 cm tall. Leaf surface smooth above, hairy below. Leaflets are arranged on the third branch of the compound leaf. Stems are hollow with marked parallel lines and often dark purple in color at the base. Petals white less than 1 mm, occasionally pink. Sepals are very small or absent. Umbels of inflorescence expanded, usually with 4-7 flowers per umbellet. Fruit 3 mm in size, dark green in color and clothed with hooked spines.
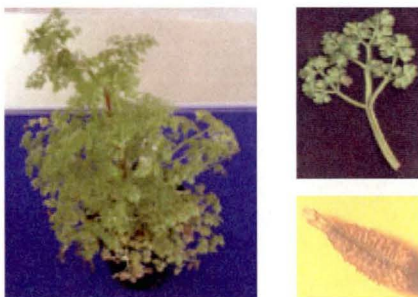
Plate 1 Burr Chervil: a, Flowering plant; b, A 3-pinnate compound leaf; c, Mature fruit.

Torilis nodosa (Knotted Hedge Parsley)

Annual herb up to 60 cm tall. Highly branched with stems trailing loosely along the ground and not rooting. Leaflets are arranged on the second branch of the compound leaf. Sparsely hairy. Petals white less than 1 mm. Umbel of inflorescence compact, usually with 6-11 flowers per umbellet. Fruit with two differing seeds, outer seed spiny, inner seed warty. Seeds ovoid in shape, 2.5-4 mm long.

Plate 2. Knotted Hedge Parsley: a, Flowering plant; b, Seedling; c, Mature seed.

Daucus glochidiatus (Native Carrot)

Annual herb variable in size, 5-60 cm tall, usually more prostrate then erect. Highly branched with a dense covering of stiff bristle like hairs and a stout taproot. Leaflets lobed with toothed like segments and arranged on the second branch of the compound leaf. Petals crimson less than 1 mm. Seeds ovoid 3-5 mm long, with rows of hooked spines.
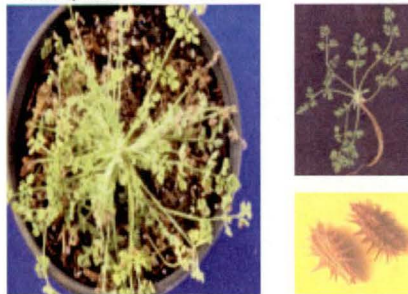
Plate 3 Daucus Glochidiatus: a, Flowering plant; b, Seedling; c, Mature seeds.

Daucus carota

Erect biennial herb, primary stem bristled with parallel lines or ridges. Leaflets distinctively pointed and deeply lobed. Leaflets arranged on the second and third branch of the compound leaf. Petals white or pinkish. Seed 3-4 mm long with stiff spines, apical spine barbed causing fruit to cluster.

ssp. *carota* (Wild carrot) – Root whitish not swollen. Leaves with a covering of hairs and usually grey-green in appearance.

ssp. *sativus* (Cultivated carrot) –Root orange, swollen in 1st year. Leaves usually bright green.

Conium maculatum (Hemlock)

A biennial herb up to 1-2 m high, with erect hollow stems. Compound leaves triangle in outline with leaflet arranged on the second and third branch. Fruit nearly circular with 5 prominent wavy scalloped ribs. Easily distinguished by absence of hairs, purple blotched stem and acrid odour similar to that of mice.

Taxonomic Key for the identification of Apiaceae weeds in pyrethrum

1	Plants with a general carrot like appearance. Leaves pinnately dissected, alternate, stem base scarious. Inferior ovary and 2-celled, indehiscent dorsally or laterally compressed fruits, which usually separate from each other.	(2)
2	Stems with purple blotches.	(3)
2	Stems without purple-blotches.	(4)
3	Glabrous with distinctive mouse like odour.	***Conium maculatum***
3	Plants not as above.	(4)
4	Leaves 1-2 pinnate, occasionally 3 pinnate	(5)
4	Leaves 3 pinnate only	(8)
5	Stems erect and ascending or prostrate, leaflets toothed. Fruit with spines, homomorphic.	(6)
5	Stems much-branched, procumbent or sometimes ascending. Plant sparsely hairy. Leaflets deeply pinnately divided into narrow linear lobes Fruit heteromorphic, tuberculate and with spines.	***Torilis nodosa***
6	Plants annual, densely hairy, usually prostrate growth habit. Fruit with reflexed spines	***Daucus glochidiatus***
6	Plants biennial erect, stout taproot. Spine of fruit barbellate causing fruit to cluster	(7)
7	Taproot swollen in 1st year, usually orange; leaves usually bright green, sparsely pubescent.	***D. carota*** ssp. ***sativus***
7	Tap root not swollen, whitish, leaves usually grey-green, hispid to pubescent.	***D. carota*** ssp. ***carota***
8	Leaves glabrous above, stiff scattered hairs beneath. Leaf segments somewhat rounded.	***Anthriscus caucalis***

Glossary

Barbellate: Finely or minutely barbed

Glabrous: Without hairs

Heteromorphic: Having different forms

Homomorphic: Of similar size and structure

Procumbent: Trailing loosely along the ground but not rooting

Pubescent: Having fine short hairs

Scarious: Having a dry membranous appearance, but fairly stiff

Tuberculate: Covered with small wart-like protuberance

Hispid: Covered with rough or stiff hairs

Pinnate: Leaflets are arranged in two rows, one on each side of the midrib

Indehiscent: Not opening

2.3 Floral biology of *A. caucalis* and *T. nodosa*

2.3.1 Materials and Methods

Twelve plants of both *A. caucalis* and *T. nodosa* were grown in a standard potting mix (Appendix A.1) in 15 cm diameter pots. Plants were grown under natural environmental conditions at the University of Tasmania, Hobart (42° 90'S 147° 32'E) and were watered daily to replace evapotranspiration losses. Following flowering, umbles from three plants of each species were destructively harvested every 5 to 6 days, which allowed sufficient time for each umbel order to be examined in detail. Due to the large number of secondary, tertiary and quaternary umbels only a random sample of each were assessed. Following this assessment, plants were allowed to set seed on those umbels that had not been destructively harvested, allowing for seed morphology to be examined.

2.3.2 Results and Discussion

Umbels up to the septenary order were produced in *A. caucalis*, and up to the senary order in *T. nodosa*. The mean number of umbels per plant was 199 ± 35 and 106 ± 13 for *A. caucalis* and *T. nodosa*, respectively. The highest percentage of umbels was in the quaternary order (28.4%) and quinary order (26.8%) for *A. caucalis*. In comparison, the highest percentage of umbels was found in the tertiary (36.7%) order and the quaternary (33.8%) order for *T. nodosa*. The mean number of flowers per umbellet of *T. nodosa* was between 7 and 9 and this was significantly higher ($P <$ 0.001) than the mean number of flowers for *A. caucalis*, which was between 5 and 7 for all umbel orders (Table 2.2). Both *A. caucalis* and *T. nodosa* produced between 3 and 4 umbellets per order (Table 2.3). The potential number of seed propagules for *A. caucalis* was approximately 7500 per plant while that of *T. nodosa* was approximately 6000 per plant.

Table 2.1 The mean percentage of umbels per plant of different umbel orders of *A. caucalis* and *T. nodosa*

	Umbel Order						
	Primary	Secondary	Tertiary	Quaternary	Quinary	Senary	Septenary
A. caucalis	**0.57**	**7.02**	**20.17**	**28.43**	**26.78**	**13.66**	**3.37**
	(0.10)	(1.22)	(3.90)	(2.57)	(0.83)	(4.33)	(2.33)
T. nodosa	**0.98**	**17.54**	**36.71**	**33.80**	**9.04**	**1.93**	-
	(0.12)	(3.36)	(3.67)	(3.25)	(2.98)	(1.11)	

s.e. shown in parentheses.

Table 2.2 The mean number of flowers per umbellet in each umbel order of *A. caucalis* and *T. nodosa*

	Umbel Order					
Species	Primary	Secondary	Tertiary	Quaternary	Quinary	Senary
A. caucalis	**6.07**	**6.20**	**6.09**	**5.70**	**5.39**	**5.03**
	(0.15)	(0.08)	(0.07)	(0.12)	(0.07)	(0.16)
T. nodosa	**8.63**	**8.50**	**8.61**	**7.60**	**7.33**	-
	(0.23)	(0.11)	(0.15)	(0.23)	(0.29)	

s.e. shown in parentheses

Table 2.3 The mean number of umbellets in each umbel order of *A. caucalis* and *T. nodosa*

	Umbel Order					
Species	Primary	Secondary	Tertiary	Quaternary	Quinary	Senary
A. caucalis	**3.67**	**3.78**	**4.04**	**4.15**	**3.85**	**3.70**
	(0.17)	(0.10)	(0.20)	(0.14)	(0.11)	(0.15)
T. nodosa	**3.67**	**3.92**	**4.05**	**3.67**	**3.00**	-
	(0.17)	(0.10)	(0.14)	(0.14)	(0.00)	

s.e. shown in parentheses

Both *A. caucalis* and *T. nodosa* were found to bear hermaphrodite flowers only. No staminate flowers were observed on the quinary umbels of *T. nodosa* in contrast to the observation of Koul *et al.*, (1993), who reported that 1.7% and 39.0% of flowers of *T. nodosa* from the quinary and senary orders were staminate. In this study a small proportion of flowers developed on the quinary umbels and no flowers were observed from the senary order. All flowers of *T. nodosa* examined from the quinary order were found to be hermaphroditic.

Both *A. caucalis* and *T. nodosa* produced flowers with five petals, which were white in colour and less than 1mm in length. There were also five stamens that were alternating with the petals. The filaments of both species were white and the anthers were versatile, attached to the filament such that the anthers could move relatively freely. The pistils of *A. caucalis* and *T. nodosa* were bicarpellary and syncarpous and the ovary was inferior and capped by a stylopodium. The stigmas were subsessile and emerged from the stylopodium.

The umbellets of *A. caucalis* fan out in sequence to produce an expanded umbel structure. The rays of *T. nodosa* were short causing the umbel structure to be compact in contrast to the open umbel structure of *A. caucalis*. For both species the flowers of the primary umbel were first to open, followed by those of the secondary, tertiary and quaternary. The development of the stigmas indicated that the flowers of both *A. caucalis* and *T. nodosa* were weakly protandrous (plate 2.1-2.4), although self-fertilisation did not appear restricted. Following maturation of the stamens and loss of pollen from the anthers of *A. caucalis* the pistils were observed to increase in size and the sub-sessile stigmas lengthened and divided from each other, becoming receptive to pollination. In *T. nodosa* following maturation of the stamens and loss of pollen from the anthers the pistils increased in size and the sub-sessile stigmas lengthened and divided from each other. The division and extension of the stigmas for *T. nodosa* was not as distinctive as for *A. caucalis*.
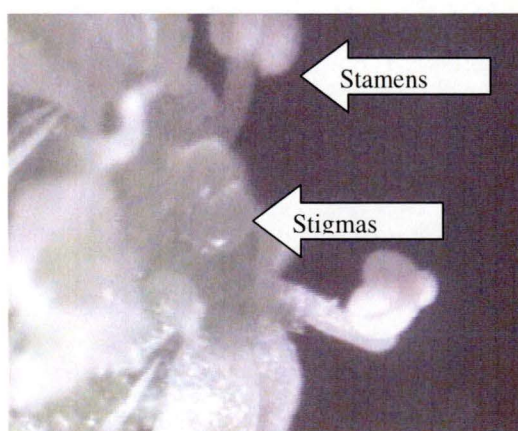
Plate 2.1 – Maturation of stamens showing the production of pollen and immaturity of the stigmas of *A. caucalis*.

Plate 2.2 – Lengthening and dividing of the receptive stigmas of *A. caucalis* and desiccation of the stamens, although some anthers remain with the flowers being weakly protandrous.
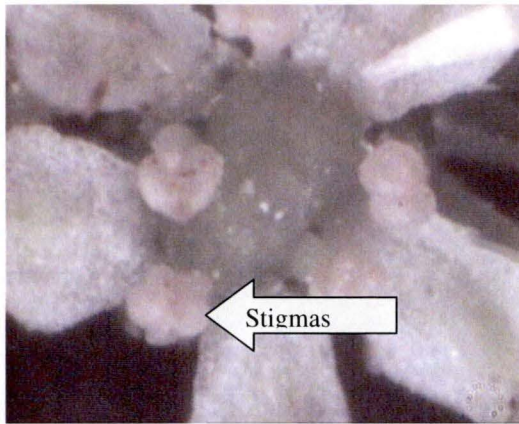
Plate 2.3 - Maturation of stamens showing the production of pollen of T. *nodosa*. The stigmas are also developing and becoming receptive.
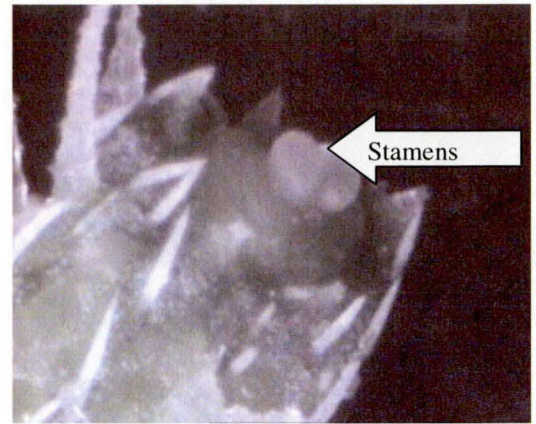
Plate 2.4 The stigmas of *T .nodosa* lengthening and slightly dividing from each other.

The fruit of *A. caucalis* was ovoid in shape, approximately 3 mm in length, dark green in colour with hooked spines and a short beak, and with a ring of short hairs at the top of the pedicels. The fruit of *T. nodosa* was ovoid in shape and 2.5-3mm in length. Fruit was heteromorphic consisting of an outer mericarp with long spines arranged in obscure rows with the inner mericarp tuberculate. The seed description for *A. caucalis* and *T. nodosa* was consistent with that reported previously (Davis, 1972; Curtis, 1963).

2.4 Conclusion

The results of this investigation suggested that both *A. caucalis* and *T. nodosa* are likely to have very similar breeding systems, with both species bearing hermaphrodite flowers only. Development of the stigmas of *T. nodosa* and *A. caucalis* species indicated that the flowers were weakly protandrous with protandry more evident in *A caucalis*. The developmental pattern observed is consistent with both species being in general, self compatible, as are many Apiaceae species (Bell, 1971). *Anthriscus caucalis* produced more umbels per plant and to a higher order than *T. nodosa*. In contrast *T. nodosa* produced more flowers per umbellet than *A. caucalis*. There was no significant difference in the number of umbellets per umbel between species with both species producing between 3 to 4 umbellets per umbel. *Torilis nodosa* was observed to produce heteromorphic mericarps, while the mericarps of *A. caucalis* were homomorphic. Seed morphology and floral arrangement of both *A. caucalis* and *T. nodosa* were consistent with that reported in

the northern hemisphere although no staminate flowers were found in high umbel orders for *T. nodosa*. The potential number of seed propagules for *A. caucalis* was approximately 7500 per plant while that of *T. nodosa* was approximately 6000 per plant.

The results of this study provide a quantitative prediction on the potential number of seed propagules for both *A. caucalis* and *T. nodosa* and well as providing taxonomic information of the weeds and their breeding systems. *Anthriscus caucalis* seedlings are identifiable by their tri-pinnate compound leaves which are glabrous on top with scattered hairs beneath. The fruit of *A. caucalis* is ovoid in shape and 2.5 to 3.5mm in size with distinguishing hooked spines and a short beak. The pedicels have a ring of hairs at the top. *Torilis nodosa* seedlings are identifiable by their deeply bi-pinnate compound leaves and narrow linear lobes. The fruit of *T. nodosa* is ovoid in shape and 2.5 to 3mm in diameter and composed of 2 distinct dimorphic mericarps. The outer mericarp has barbellate spines with the inner mericarp tuberculate.

This information increases the level of knowledge on these relatively unfamiliar species and is likely to assist in better identification and understanding of *A. caucalis* and *T. nodosa* in Tasmania. There is also a need to document the level of occurrence of these species.

Chapter 3 Occurrence and distribution of *A. caucalis* and *T. nodosa*

3.1 Introduction

Although *A. caucalis* and *T. nodosa* have been observed in pyrethrum crops for approximately 7 years, no quantitative data were available on the severity and distribution of these species within pyrethrum growing districts in Tasmania. Both *A. caucalis* and *T. nodosa* have been observed to germinate predominantly in autumn and to over-winter as rosettes. In spring *A caucalis* grows rapidly with flowering commencing during October and seed maturity and dispersal taking place in early summer. *Torilis nodosa* also grows rapidly in spring, producing procumbent stems and commences flowering in late October/early November. In contrast to *A. caucalis* the seeds of *T. nodosa* are slower to mature and dispersal of seeds of *T. nodosa* does not occur until late summer/early autumn at which time the parent plant has completely senesced. Both species have been observed to grow in very dense mats, which have the ability to compete strongly with pyrethrum plants.

Weed mapping is an important process where the assessment of the level of a weed problem is sought and is a critical component in the development and monitoring of successful and economically sound weed management (Welsh, 2000). The objective of this two year study was to survey and assess the occurrence and severity of Apiaceae species in pyrethrum crops in northern Tasmania. The data will provide a baseline of information that can be used in future comparisons and as a means to determine the level of research and extension needed to investigate and manage these species. This study also aimed to integrate the results of the survey with the geographic distribution and agronomic history of pyrethrum crops to provide valuable information in determining strategic procedures to reduce the impact and spread of *A. caucalis* and *T. nodosa*.

3.2 Materials and Methods

Pyrethrum growing districts in northern Tasmania are divided into eight geographic agricultural areas (Figure 3.1) for production and extension purposes. The eight districts are: Burnie/Table Cape (1), Penguin/North Motton (2), Ulverstone/Kindred

(3), Forth/Barrington (4), East Devonport/Wesley Vale (5), Latrobe/Sassafras (6), Deloraine/Cressy (7) and North East (8).
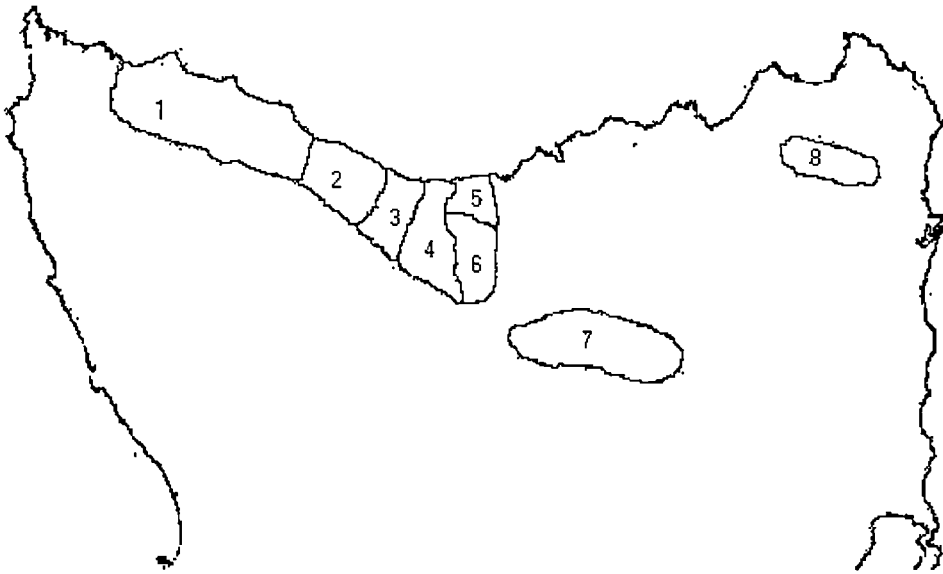
Figure 3.1 The geographic distribution of pyrethrum growing districts in northern Tasmania.

All pyrethrum crops were surveyed in collaboration with district field agronomists and consultation with pyrethrum growers. The survey of the paddocks entailed a complete field walk of each pyrethrum crop by following an inverted W pattern. The field surveys were undertaken during a six-week period in mid June to early August in 2001 and 2002. This time frame was chosen for several reasons. Firstly, the main germination and emergence period of *A. caucalis* and *T. nodosa* had already occurred. Secondly, visual assessment was made relatively easy due to the open canopy of the crop during the slow growing winter period. Thirdly, the completion of the survey prior to the spring period permitted sufficient time for growers to implement control options for their removal.

The presence or absence of *A. caucalis* and *T. nodosa* was recorded and where present the level of infestation was ranked as low (sparsely distributed and not forming dense patches), moderate (weeds forming dense patches), severe (weeds

growing in numerous dense patches) and very severe (high level of weed infestation leading to the recommendation that production immediately cease).

A total of 388 and 338 pyrethrum crops were surveyed in 2001 and 2002 respectively. Of these, 230 crops were examined in both years. These data were treated as individual data sets for each year for comparative analysis between seasons. In addition, due to the cessation in production of a number of crops in 2001 and the establishment of new crops in 2002, a third data set was established combining those fields assessed in both seasons. Data assessment was undertaken for the frequency of occurrence of each species and their level of infestation. These data were analysed in relation to paddock location and crop age.

3.3 Results

Both *A. caucalis* and *T. nodosa* were shown to be significant weed problems in pyrethrum. It was found that one in three pyrethrum crops had the presence of either or both these species. *Anthriscus caucalis* was more prevalent than *T. nodosa*. In 2001 and 2002, *A. caucalis* was present alone in 24.5% and 22.8% of pyrethrum crops respectively, while *T. nodosa* was present alone in only 6.2% and 2.4% of the crops (Table 3.1 and 3.2). *Anthriscus caucalis* and *T. nodosa* were found together in 5.4% and 7.4% of pyrethrum crops in 2001 and 2002, respectively.

Of the 108 pyrethrum crops newly planted in 2001, 21.3% (23 crops) were found to have Apiaceae weeds (Table 3.2). Of these crops, two were located on paddocks that had previously grown pyrethrum and where the presence of *A. caucalis* had been observed. These two sites had a severe and a moderate level of infestation of *A. caucalis*. Of the remaining 21 sites 19 had a low level of infestation of *A. caucalis*, one with a low level of infestation of *T. nodosa* and one with a moderate level of infestation of both *A. caucalis* and *T. nodosa*. Seven sites were located on properties where neighbouring pyrethrum crops on the same property contained the Apiaceae weeds at the time of assessment. The other 14 crops were located on properties where the weeds had not been previously recorded.

Table 3.1 The number of pyrethrum crops with the presence of Apiaceae weeds, *A. caucalis* and *T. nodosa*, in 2001 for each year of pyrethrum planting.

	Year Planted					
	1996	**1997**	**1998**	**1999**	**2000**	**Total**
A. caucalis present	9	12	29	33	12	**95**
T. nodosa present	0	1	7	13	3	**24**
A. caucalis and *T. nodosa* present	5	7	8	1	0	**21**
A. caucalis and *T. nodosa* absent	0	10	65	79	94	**248**
Total pyrethrum crops surveyed	14	30	109	126	109	**388**

Table 3.2 The number of pyrethrum crops with the presence of Apiaceae weeds, *A. caucalis* and *T. nodosa*, in 2002 for each year of pyrethrum planting.

	Year Planted					
	1997	**1998**	**1999**	**2000**	**2001**	**Total**
A. caucalis present	0	16	30	12	19	**77**
T. nodosa present	0	1	5	1	1	**8**
A. caucalis and *T. nodosa* present	1	11	9	1	3	**25**
A. caucalis and *T. nodosa* absent	0	20	42	81	85	**228**
Total pyrethrum crops surveyed	1	48	86	95	108	**338**

Twenty-three crops of pyrethrum were found to have a severe or very severe infestation of Apiaceae weeds in 2001 (Table 3.3). Due to the removal of a number of these crops from production in 2002 the number of pyrethrum crops with a severe or very severe infestation of Apiaceae weeds fell to six in 2002.

Of the 95 pyrethrum crops where *A. caucalis* was present in 2001, 60% had a low level of infestation, 25.3% moderate and 14.7% severe. 70.8% of the pyrethrum crops, where *T. nodosa* was present, had a low level of infestation, 20.8% moderate and 8.3% severe. Where *A. caucalis* and *T. nodosa* were found together, 28.6% were low, 38.1% moderate, 23.8% severe and 9.5% very severe. A similar level of infestation was observed in 2002. Of the 110 pyrethrum crops with Apiaceae weeds, 72.7% had a low level of infestation, 21.8% moderate and 5.5% severe. No infestation of any field assessed in 2002 was considered very severe.

Table 3.3 The severity of infestation as a percentage of Apiaceae weeds recorded in all pyrethrum crops in 2001 and 2002.

	Assessed year 2001				Assessed year 2002			
	Low	Moderate	Severe	V severe	Low	Moderate	Severe	V severe
A. caucalis	60.0%	25.3%	14.7%	0.0%	77.9%	15.6%	6.5%	0.0%
	(57)	(24)	(14)	(0)	(60)	(12)	(5)	(0)
T. nodosa	70.8%	20.8%	8.3%	0.0%	62.5%	25.0%	12.5%	0.0%
	(17)	(5)	(2)	(0)	(5)	(2)	(1)	(0)
A. caucalis and *T. nodosa*	28.6%	38.1%	23.8%	9.5%	60.0%	40.0%	0.0%	0.0%
	(6)	(8)	(5)	(2)	(15)	(10)	(0)	(0)
Total	**57.1%**	**26.4%**	**15.0%**	**1.4%**	**72.7%**	**21.8%**	**5.5%**	**0.0%**
	(80)	**(37)**	**(21)**	**(2)**	**(80)**	**(24)**	**(6)**	**(0)**

Number of crops shown in parentheses.

Due to removal of a number of crops from production in 2002 and new crop planting in 2001 only 230 pyrethrum crops were assessed in both years. Of these 230 pyrethrum crops, 125 remained free of Apiaceae weeds, 50 had Apiaceae weeds present in both years, 18 had Apiaceae weeds present in 2001 only and 37 had Apiaceae weeds present in 2002 only (Figure 3.2). Of the 50 crops where Apiaceae weeds were recorded in both 2001 and 2002, the severity of infestation from 2001 to 2002 had increased in 14 crops, remained unchanged in 28 and decreased in 8. Of the 37 pyrethrum crops where Apiaceae weeds were recorded for the first time in 2002 *A. caucalis* was found in 36 of these crops.
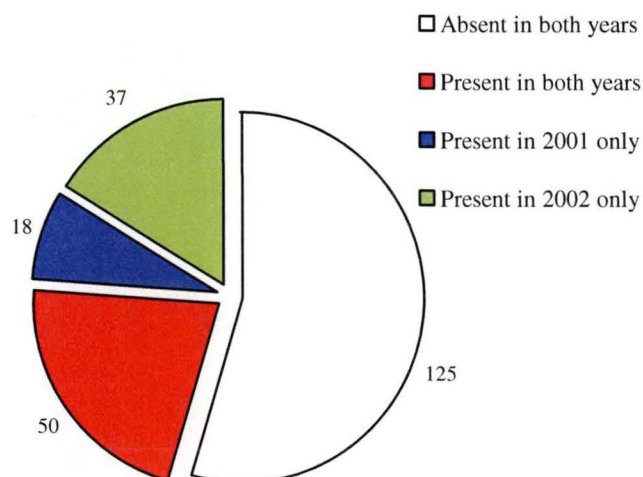
Figure 3.2 The frequency of occurrence of Apiaceae weeds in pyrethrum crops in 2001 and 2002.

The presence of *A. caucalis* at high infestation levels in pyrethrum crops re-sown into old pyrethrum fields provides anecdotal evidence that the seeds of this species have the ability to persist in the soil under the current crop rotational system. The high incidence of occurrence of *A. caucalis*, and to a lesser extent *T. nodosa*, in newly established crops of pyrethrum where these species have not previously been observed indicated that these species may have been contaminants in pyrethrum seed lots or have been introduced during crop establishment. Although assessment has only been undertaken over two seasons, it is clear that these species are widespread and of the two species, *A. caucalis* has spread more rapidly.

The severity of infestation was generally low, although older crops were found to have a higher level of infestation than newly established crops (Figure 3.3). All pyrethrum crops, which had undergone 4 harvests (i.e., 5 year old), were found to have Apiaceae weeds present. Of these, 20% had a low level of infestation, 40% moderate and 40% severe. In comparison, crops that had not undergone a pyrethrum harvest (i.e., 1-year-old), 82.5% were without Apiaceae weeds and 15.2% had a low level of infestation.
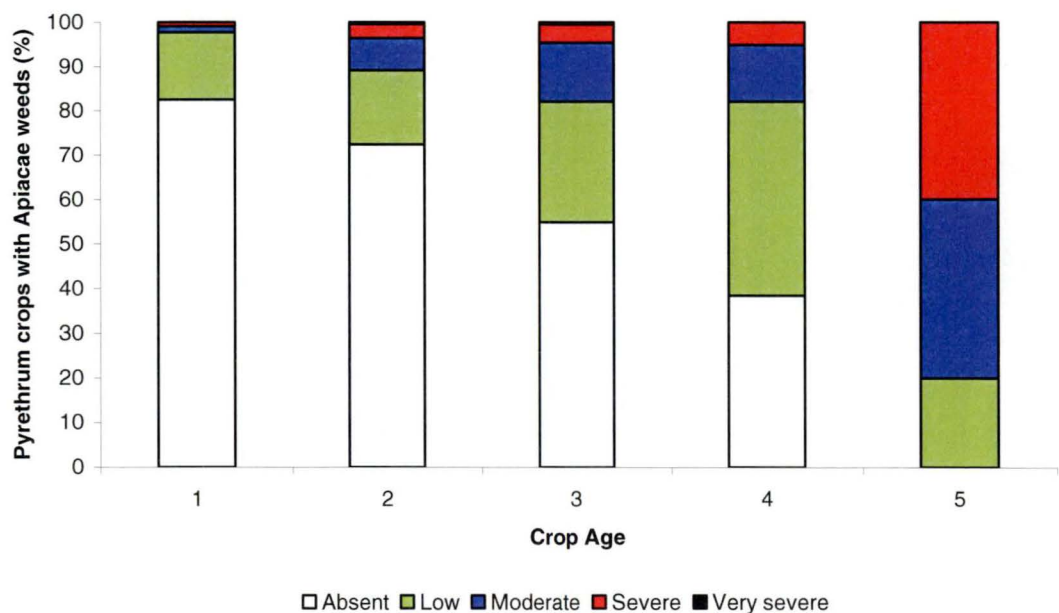
Figure 3.3 The severity of infestation of Apiaceae weeds in pyrethrum against age of the crop expressed as a percentage of the number crops.

The frequency of occurrence of Apiaceae species varied among pyrethrum growing districts, with the growing districts of Latrobe/Sassafras and Penguin/North Motton having the highest occurrence in 2001 (Table 3.4). The highest level of occurrence of *A. caucalis* (51.0%) was recorded in the Latrobe/Sassafras district. The Penguin/North Motton district had the highest occurrence of *T. nodosa* (20.5%).

Table 3.4 The percentage of occurrence of *A. caucalis* and *T. nodosa* in pyrethrum fields across eight regional growing districts

	% Pyrethrum crops with Apiaceae weeds	
Growing district	*Year 2001*	*Year 2002*
Burnie/Table Cape	36.1 (61)	30.8 (39)
Penguin/North Motton	54.5 (44)	64.9 (37)
Ulverstone/Kindred	34.7 (75)	26.9 (67)
Forth/Barrington	30.3 (66)	27.6 (58)
East Devonport/Wesley Vale	28.1 (57)	34.0 (47)
Latrobe/Sassafras	55.1 (49)	23.8 (63)
Deloraine/Cressy	8.3 (24)	40.0 (15)
North East	23.1 (13)	25 (12)

Number of pyrethrum fields shown in parentheses.

3.4 Discussion

This survey represented the first quantitative evidence of the extent of *A. caucalis* and *T. nodosa* as weeds of pyrethrum. The ability of these plants to reach high levels of infestation demonstrated their threat to the pyrethrum industry and their broader potential to become significant weeds in agricultural areas in northern Tasmania.

The high frequency of occurrence of *A. caucalis* and *T. nodosa* in pyrethrum crops and their absence in agricultural crops prior to the establishment of the pyrethrum industry provides quantitative evidence that these species should be classified as problematic weeds of pyrethrum. Many plant species have the ability to establish themselves as problematic weeds of crops and their success is determined by an ecological relationship between the species, the desired crop, the natural environment and human beings (Aldrich and Kremer, 1997). A major weed problem usually develops from a minor one following a modification to management practices

(Perrins *et al.*, 1992) and the weed flora of any given farm or field changes with time. Production practices are the most important contributing factor to these changes in terms of extent and time period over which the changes occur (Aldrich and Kremer, 1997). The results of this survey where these species were found in more than 30% of pyrethrum crops suggest that the changes in production practice associated with the establishment of pyrethrum has led to the development of *A. caucalis* and *T. nodosa* as significant agricultural weeds. Changes in production practices as a result of the commercialisation of pyrethrum in northern Tasmania include; a shift to a non-tillage production system: a system which favours the production of small seeded annuals (Ball and Miller, 1990), an over reliance on a small number of chemicals to control many common broadleaf weeds, and the introduction of new commercial seed lots.

No cultural control of weeds through cultivation is available following the establishment of pyrethrum, with the productive life of pyrethrum usually lasting four years. Both *A. caucalis* and *T. nodosa* have been observed to behave predominantly as winter annuals. Under the conventional cropping systems of northern Tasmania, where a large number of spring sown crops are produced, significant control of winter annual weeds is provided by the means of spring cultivation. In addition to the lack of cultural control methods, no effective chemical control options are available in pyrethrum for *A. caucalis* and *T. nodosa*. Broadleaf weed control in pyrethrum is heavily reliant on repeated applications of pendimethalin and as a result has unintentionally selected for species that are tolerant of pendimethalin. A number of newly planted pyrethrum crops were recorded as having the presence of Apiaceae weeds for the first time on the farm property. This may have occurred through contamination of the pyrethrum seed or planting machinery used for sowing the crop. A further possibility is that, due to the observed winter annual behaviour of *A. caucalis* and *T. nodosa,* their presence previously on farm properties has gone unnoticed as a result of intensive annual spring crop production.

The likely occurrence and severity of Apiaceae weeds are increased with increasing crop age. This is indicative of plants with a seed dispersal mechanism, as newly sown pyrethrum crops have not been subjected to a regular harvest program and

therefore the risk of transport of these weed species seeds from an infected paddock into a clean new paddock is minimal. *Anthriscus caucalis* was more prevalent than *T. nodosa*. A biological factor likely to contribute to the wider spread of *A. caucalis* is that seeds of this species are easily dispersed from the compound umbel inflorescence. In contrast, seeds of *T. nodosa* are held tightly within compact umbels. The seed dispersal mechanism of *A. caucalis* would assist in its spread by aiding attachment to harvesting machinery. Increases in weed seedbank levels due to seed propagule production from adult plants that elude cultural or chemical control will lead to high levels of infestations in older crops.

In 8% of crops, Apiaceae weeds were recorded in 2001 and not in 2002. This indicated that effective control of these weeds is possible. Hand removal or spot spraying small areas of Apiaceae weeds from crop rows has been used in the majority of situations where there was only a low level of infestation. Hand removal and or spot spraying were viewed as being economically feasible approaches to the removal of Apiaceae weeds in pyrethrum crops. The benefits gained by this approach are that the build up of a weed seedbank is prevented and any carryover effect into following crops is removed. If this control approach is not undertaken then the development of a more severe weed infestation will occur and the relationship observed between the severity of weed infestation and crop age provided evidence of this. In addition, of the crops where the weeds were present in both 2001 and 2002, 28% increased in severity, 56% remained unchanged and only 16% decreased. Reasons for this carry over effect could be the result of ineffective removal prior to seed maturity or the presence of a persistent seedbank. Reports on the longevity of the weed seedbank of *Anthriscus caucalis* are variable. Roberts, (1986) reported that the longevity of *A. caucalis* seeds was greater than 5 years while Levassor *et al.*, (1990) found it to be transient. The seedbank longevity of *T. nodosa* has only been reported as being transient (Maranon and Bartolome, 1989). The longevity of weeds in the soil is influenced strongly by its environment and can vary between regions (Thompson *et al.*, 1997). Although this survey has not investigated the seedbank dynamics of *A. caucalis* and *T. nodosa* it was found that *A. caucalis* was able to re-establish in newly planted pyrethrum crops that had been sown into fields that had been pyrethrum crops in the past. This, in addition to the large number of fields with the presence of *A. caucalis* in both years, provided anecdotal evidence to suggest that

the seed longevity of *A. caucalis* was greater than 1 year. Differences in seedbank longevity between the two species may also contribute significantly to the recorded higher frequency of occurrence of *A. caucalis* than *T. nodosa.*

With the emergence of new weed species solutions are required to suppress their spread and reduce their impact. This study has highlighted the need to review the present chemical control program such that effective and selective options are available for the control of *A. caucalis* and *T. nodosa.* In the short term a number of hygienic and strategic approaches can be adopted. This would include ensuring that pyrethrum seed is clean and free of unwanted weed seeds, avoiding the transportation of weed seeds onto farm machinery by removal of *A. caucalis* and *T. nodosa* prior to flowering and/or develop a strategic harvesting procedure. First year clean crops (Apiaceae weeds absent) could be harvested prior to older pyrethrum crops or alternatively a single harvester could be devoted only for use in newly established pyrethrum crops, free of Apiaceae weeds. Sowing of new pyrethrum crops in old pyrethrum fields where severe infestations of *A. caucalis* or *T. nodosa* have been recorded previously should also be avoided until such time that an effective chemical control program has been developed.

3.5 Conclusion

Apiaceae species *A. caucalis* and *T. nodosa* are problematic weeds of pyrethrum and pose a potential threat to the industry. The results of this survey have determined the extent of the weed problem. It is suggested that the presence of *A. caucalis* and *T. nodosa* in pyrethrum has resulted in response to changes in production practices associated with the establishment of pyrethrum as a horticultural crop in northern Tasmania. The over-reliance on a small number of chemicals for weed management, the no-till production system, the timing of crop harvesting and the possible contamination of planting material have most likely contributed in some way to their increase in the area. This study has highlighted the need to investigate the seed and plant biology of these Apiaceae weeds and to develop a selective and effective chemical program such that an integrated approach to their control can be achieved.

Chapter 4 Seed dormancy of *A. caucalis*

4.1 Introduction

There is a paucity of information on the seed biology of *A. caucalis*. In preliminary studies undertaken at the commencement of this project, the mean initial germination percentage of freshly collected viable seeds of *A. caucalis* was less than 30% when germinated at a constant temperature of 20°C and illuminated for a 12 hour period per day. This indicated that there was some level of seed dormancy associated with seeds of *A. caucalis*. Seed dormancy is the failure of seeds to germinate because of factors associated with their embryo, seed coat and/or environment (Anderson, 1996). Seed dormancy is a very common attribute of many weed species and contributes to the persistence and survival of the individual species (Aldrich and Kremer, 1997). Seed dormancy is a survival and persistent mechanism because is ensures germination occurs when conditions are favourable for seedling survival and also regulates germination of the weed seed population, ensuring a reservoir of ungerminated but viable seed for later seasons.

Dormancy classification

There are many different types of seed dormancy and dormancy classification is quite complex. Dormancy may be of the enforced type in which case the seed is being deprived of its requirement for germination. Examples of such requirements include moisture, oxygen, a suitable temperature and light. Innate dormancy, sometimes referred to as primary dormancy, is that present in the seed when released from the parent plant (Aldrich and Kremer, 1997). There are three recognised groups of primary dormancy; exogenous, endogenous and combinational (Hartmann *et al.*, 1997). Exogenous dormancy is imposed by factors outside the embryo, endogenous dormancy is related to dormancy factors within the embryo and combinational involves both exogenous and/or endogenous dormancy mechanisms. The following classification of dormancy is adapted from a review by Geneve, (1999).

Exogenous dormancy can be categorised into:
1. Tissue covering factors that can inhibit water or oxygen movement (a physical exogenous dormancy)

2. Tissue covering factors that restrain embryo expansion (mechanical exogenous dormancy)

3. The presence of embryo inhibitors or by preventing the leaching of inhibitors from the embryo (chemical exogenous dormancy) (Bewley and Black, 1994).

Chemicals that accumulate in fruit and seed covering tissues during development and remain with the seed after dispersal can act as germination inhibitors (Evenari, 1949). In general these chemicals are water-soluble, and they may be removed from the seed by leaching, a natural phenomenon in soils and they therefore act as "chemical rain gauges" (Anderson, 1996). Presence of inhibitors of germination in seeds of Apiaceae species *Foeniculum vulgare*, *Cumunum cyminum*, *Carum copticum*, *Daucus carota* and *Coriandrum sativum* has been demonstrated (Chaturvedi and Muralia, 1975).

Seeds with endogenous dormancy fail to germinate because of factors associated with the embryo. There are two types of endogenous dormancy: morphological and physiological (Geneve, 1999).

Morphological dormancy is where the embryo has not completed development at the time of seed dispersal. This dormancy is overcome by either warm or cold stratification, which allows the embryo to fully develop.

Physiological dormancy involves changes within the embryo that allows the radicle to escape the restraint of the seed coverings (Geneve, 1999). There are three types of physiological endogenous dormancy: non-deep, intermediate and deep. Non-deep physiological dormancy is the requirement for a period of dry storage to lose dormancy also termed "after ripening" and is the most common form of dormancy (Baskin and Baskin, 1998). Intermediate or deep physiological dormancy is broken by cold (1 to 10°C) stratification (Geneve, 1999) with the time period depending on the level of dormancy. Intermediate endogenous dormancy is broken by moderate periods (up to 8 weeks) of cold stratification and deep endogenous dormancy by long periods (> 8 weeks) of cold stratification.

Dormancy can be a combination of both physiological and morphological endogenous dormancy referred to as morphophysiological dormancy (MPD). There are two general types of MPD, simple and complex (Nikolaeva, 1977). In seeds with simple MPD, warm stratification, alone or in combination with cold stratification, promotes loss of physiological dormancy, and embryo growth (loss of morphological dormancy) occurs only during warm stratification (Baskin and Baskin, 1991; Baskin *et al.*, 1995). In seeds with complex MPD, cold stratification alone or in combination with warm stratification, promotes the loss of physiological dormancy, and embryo growth occurs during cold stratification (Baskin *et al.*, 2000; Baskin *et al.*, 1992). Other examples of combinational dormancy include exoendodormancy in which seed coat dormancy and intermediate physiological endogenous dormancy exist together. It is often difficult to distinguish between certain types of endogenous dormancy and some forms of exogenous dormancy, because removal of the seed coat often allows the embryo to germinate in seeds with endogenous dormancy (Geneve, 1999).

Seeds may lose or acquire dormancy in response to environmental stimuli, and their responses are highly habitat and species specific (Allen and Meyer, 1998). Loss of dormancy during dry storage (dry after-ripening) or while imbibed at high temperatures is common in broadleaf weed species (Baskin and Baskin, 1986) and grass species (Simpson, 1990) emerging in autumn. Many species emerging in spring have a chilling requirement for dormancy breakage (Baskin and Baskin, 1987) while chilling or high temperature imbibition may induce a secondary dormancy in some species (Forcella, 1998). There is a distinct light and temperature for alleviating photodormancy and seeds may lose their requirement for light after a period of dry storage or the requirements can be offset by cool temperatures and sometimes by alternating temperatures (Geneve, 1999).

Almost without exception seeds of weed species possess one or more factors contributing to seed dormancy (Anderson, 1996). Germination in members of the family Apiaceae is widely reported to be low as well as delayed (Chaturvedi and Muralia, 1975). The majority of Apiaceae species produce dormant seeds that fail to germinate unless dormancy is broken by stratification and/or enforced mechanism. Grime *et al.* (1981) reported that a chilling requirement was characteristic to the Apiaceae family. Morphological dormancy (undeveloped embryos) has been

reported in Apiaceae species *Apium graveolens* (Jacobsen and Pressman, 1979), *Conium maculatum* (Baskin and Baskin, 1990) and *Pastinaca sativa* (Baskin and Baskin, 1979). *Thaspium pinnatifidum* has been shown to have deep complex MPD (Baskin *et al.*, 1992).

There is a scarcity of information regarding the dormancy behaviour of *A. caucalis*. From the genus *Anthriscus* Baskin *et al.* (2000) reported that *A. sylvestris* requires a long cold stratification only for loss of physiological dormancy and for growth of the embryo (deep complex MPD). Since cold stratification is the only requirement for loss of deep complex MPD, both the physiological and morphological dormancy is broken during winter. Thus seed dormancy in *A. sylvestris* is overcome during winter and germination occurs in spring. During cold stratification the embryo of *A. sylvestris* grows to 10 times its original volume (Janiesch, 1973).

The dormancy of annual weed seeds is the principal factor contributing to their success (Anderson, 1996). Understanding seed dormancy of a weed species is essential information for successful forecasting of germination trends and the development of effective integrated control measures. The aim of this study was to complete a series of experiments investigating the dormancy behaviour of *A. caucalis* by examining the effects of surface leaching, stratification, scarification and dry storage as possible mechanisms for breaking seed dormancy.

4.2 Materials and Methods

Unless stated otherwise, individual treatments for all laboratory experiments consisted of 50 seeds placed on two sheets of Postlip filter paper moistened with distilled water in 85 mm petri dishes. Petri dishes were incubated in a Contherm™ incubator at a constant 20°C with an illumination period of 12 hours per day. A light intensity at seed level of approximately 140 μmol s^{-1} m^{-2} was produced by two 15-watt fluorescent tubes. A seed was considered germinated when the radicle protruded a minimum 1 mm from the seed coat (ISTA, 1996).

Surface leaching and stratification

Mature seeds of *A. caucalis* were collected in the summer of 2001 and dry stored for a period of 2 to 3 months at 4°C prior to use. Seed lot viability was determined using a tetrazolium test (TZ) (ISTA, 1999) in which three groups of 50 seeds were pre-soaked in deionized water for 8 hours at 20°C, bisected longitudinally, and stained in 0.1% TZ solution at 20°C for 16 hours. Mean seed lot viability was 51%.

Seeds of *A. caucalis* were either surfaced leached in running water for 24 hours, cold stratified at 4°C for a period of 4 weeks or remained untreated. In addition, 50 *A. caucalis* seeds were soaked in 30ml of distilled water for 24 hours to collect the seed surface leachate. The leached, stratified and untreated *A. caucalis* seeds were imbibed in either distilled water or seed surface leachate. Fifty *A. caucalis* seeds were used in each treatment and each treatment replicated four times. In addition seeds of *T. nodosa* were imbibed in the collected leachate or distilled water to examine the effect of the surface leachate from seeds of *A. caucalis* on the germination of another Apiaceae specie. Seeds were incubated for a period of 21 days and germination counts were conducted every 7 days after incubation (DAI).

The experiment was a completely randomised factorial design with mean germination percentages subjected to analysis of variance with Fishers protected LSD test (P = 0.05) for mean separation.

Dry storage and stratification

Seeds of *A. caucalis* from three differing locations (Table 4.1) were collected on 27th December 2001 and dried for 7 days at room temperature and then dry stored at 20°C for six differing durations (0, 7, 21, 42, 70 and 182 days). The viability of each seed lot was found to be between 75-85%.

Table 4.1 Mean seed lot viability as determined by a tetrazolium test (ISTA, 1999).

Location	Seed lot viability (%)
Cressy (516240E , 5376084N)	81.2 ± 6.2
Table Cape (390546E, 5466277N)	76.8 ± 6.3
North Motton (422179E, 5440187N)	80.8 ± 3.6

At each storage interval, germination was assessed. In addition, following drying, seeds were imbibed and stratified at 4°C for a period up to 16 weeks then incubated at 20°C with an illumination period of 12 hours per day. Seeds were incubated for 28 days and germination counts were conducted every 7 DAI.

Sufficient seed was collected allowing for a proportion of each seed lot to be dry stored at 4°C. After 182 days of storage the germination of these seed lots was also assessed and compared to those dry stored at 20°C.

Each germination test was replicated three times. Both the dry storage and cold stratification experiments were completely randomised factorial designs (Seed lot by days storage) with mean germination percentages subjected to analysis of variance with Fishers protected LSD test (P = 0.05) for mean separation.

Seed scarification

Anthriscus caucalis seeds collected for the dry storage and stratification experiment (Refer section above) were dry stored at 20°C and 4°C. Following 26 weeks of storage seeds were scarified with a motorized scarifier using 60 grit sandpaper. Seed lots of 500 seeds were scarified for differing durations; 0 (untreated control), 30, 60, 180 and 360 seconds. Only the seed lot collected from Cressy on the 27th December 2001 was examined. Following scarification 50 seeds of each treatment were incubated at 20°C with an illumination period of 12 hours per day with three replications. The experiment was a completely randomised factorial design (storage temperature by scarification duration) with mean germination percentages subjected to analysis of variance with Fishers protected LSD test (P = 0.05) for mean separation.

Storage temperature, scarification and light

Seeds of *A. caucalis* were collected on the 15th January 2003 from a commercial pyrethrum field at Don, Tasmania. The collection was made from the headlands area following pyrethrum harvesting at which time the seeds had matured to a level where the seed moisture content was 7.5% on a fresh weight basis. Seed viability as determined by a TZ test (ISTA, 1999) was 92%. Seeds were packaged into sealed zip lock plastic bags and dry-stored at constant temperatures of 4°C, 20°C and 30°C. Seed were also exposed to ambient daily temperatures by placing them in a nylon mesh envelope stored on top of a red ferrosol soil in a 9L container. A transparent cover was placed approximately 25cm above the seed such that light and air movement was not limiting but precipitation onto the seeds was avoided. Daily temperature for the duration of the study is given in appendix A.11.

Seed was scarified with a scalpel where the seed coat of *A. caucalis* seed was nicked to expose the endosperm. Scalpel scarification was chosen as the desired method as sandpaper, acid and mechanical scarification with a motorised scarifier was shown to be inconsistent due to the variability in seedcoat hardness within the seed lot. Although time consuming, scalpel scarification allowed for a standardised procedure to be adopted. Four replicates of 25 seeds were germinated for each treatment. Seeds were incubated in a contherm™ incubator set at 12-hourly alternating day/night temperatures of 15/10°C. The number of germinated seeds was recorded 14 DAI. Seeds were also germinated in complete darkness by applying a double wrapping of aluminium foil around the petri dish of the imbibed seeds. An untreated control was included in which the seeds were not scarified and were incubated at 12-hourly alternating day/night temperatures of 15/10°C. The experiment was a completely randomised factorial design (storage temperature by storage duration by seed treatment) with mean germination percentages subjected to analysis of variance with Fishers protected LSD test (P = 0.05) for mean separation.

To assess seed coat permeability 50 unscarified and 50 scarified seeds of *A. caucalis* were imbibed in crystal violet blue for a period of 7 days. Seeds were then dissected and the distribution of the dye assessed.

Embryo size assessment was undertaken 30 weeks after dry storage. The technique used to extract and measure embryo size was similar to that outlined by Gray and Steckel (1983). The lengths of 50 embryos from each storage temperature were assessed for comparative size. Following soaking of seeds in formalin acetic acid (FAA v/v; 50% ethanol, 40% water, 5% glacial acetic acid, 5% formalin) for a minimum of 48 hours, embryos were carefully extracted from individual seeds by removing the caruncle then pressing slightly on the back of the seed using the blunt side of a scalpel to extrude the embryo under a stereomicroscope The length of each individual embryo was recorded by measuring the distance from the base of the hypocotyl to the tip of the cotyledons after projecting the image onto a 30cm computer monitor. The magnification of the image was calibrated using a slide graticule. The differences between mean sizes were compared using a students t-test (P = 0.05).

4.3 Results

Surface leaching and stratification

There was no significant (P > 0.05) difference in the level of germination of *A. caucalis* seeds when surface leached, stratified for 4 weeks or imbibed in the surface leachate of *A. caucalis* seeds (Figure 4.1). There was no significant (P > 0.05) difference in the germination of *T. nodosa* seeds when imbibed in the removed seed surface leachate of *A. caucalis*. The mean germination of *T. nodosa* was significantly (P < 0.001) higher than that of *A. caucalis* (Figure 4.1).
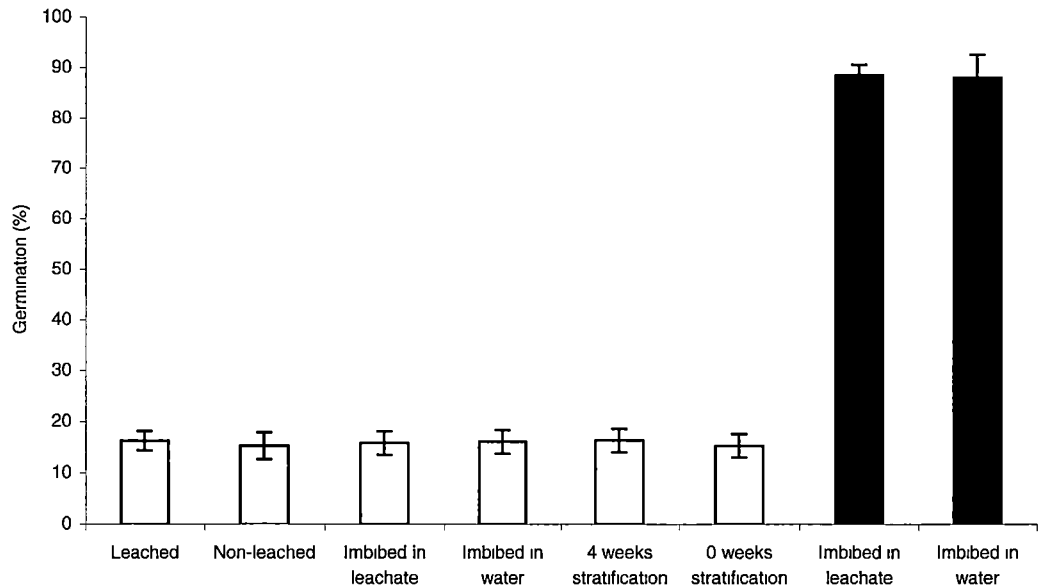
Figure 4.1 Effect of surface leaching, addition of seed surface leachate and stratification on the germination of *A. caucalis* (□) and *T. nodosa* (■). Mean values ± standard error of mean are shown.

Dry storage and stratification

There was no significant (P > 0.05) change in the germination of *A. caucalis* seed with dry storage at 20°C for the first 70 days. However, dry storage of *A. caucalis* seeds at 20°C for 182 days significantly (P < 0.001) increased germination (Table 4.2). Dry storage at 4°C for 182 days resulted in a slight increase in germination from the initial level although the mean germination of each seed lot was below 10% and was significantly (P< 0.001) lower than that from seed stored at 20°C for the same period.

At 182 days of dry storage the germination percentage of the Cressy seed lot was significantly (P < 0.001) higher than that of the Table Cape and North Motton seed lots, which were not significantly (P > 0.05) different to each other.

Table 4.2 Effect of dry storage duration at 20°C on the germination *A. caucalis* seeds collected from three field sites in Tasmania.

	Location		
Days Storage at 20°C	Table Cape	North Motton	Cressy
0.0	0.7 ± 0.7	0.0 ± 0.0	0.0 ± 0.0
7	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
21	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
42	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
70	0.0 ± 0.0	1.3 ± 1.3	1.3 ± 1.3
182	25.3 ± 4.4	20.0 ± 4.6	56.7 ± 5.5
Days Storage at 4°C			
182	2.0 ± 1.2	4.7 ± 2.7	6.0 ± 1.2

Cold stratification at 4°C for a period of up 16 weeks did not significantly (P > 0.05) change the germination of *A. caucalis* (Table 4.3).

Table 4.3 Effects of stratification duration on the germination of *A. caucalis*

	Weeks of Stratification at 4°C					
Location	0	2	4	8	12	16
Table Cape	0.7 ± 0.7	0.0 ± 0.0	0.0 ± 0.0	0.7	0.0 ± 0.0	0.0 ± 0.0
North Motton	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	1.3 ± 0.7	1.3 ± 0.7	1.3 ± 0.7
Cressy	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0

Seed scarification

Scarification using a motorised scarifier significantly (P < 0.05) affected the germination of *A. caucalis* seeds (Figure 4.2). Scarification for periods of 30 and 60 seconds resulted in a significantly higher (P < 0.05) germination than all other scarification durations. Scarification for 180 and 360 seconds significantly (P < 0.001) reduced germination. Seed dry stored at 20°C resulted in a significantly (P < 0.001) higher mean germination than seed dry stored at 4°C.
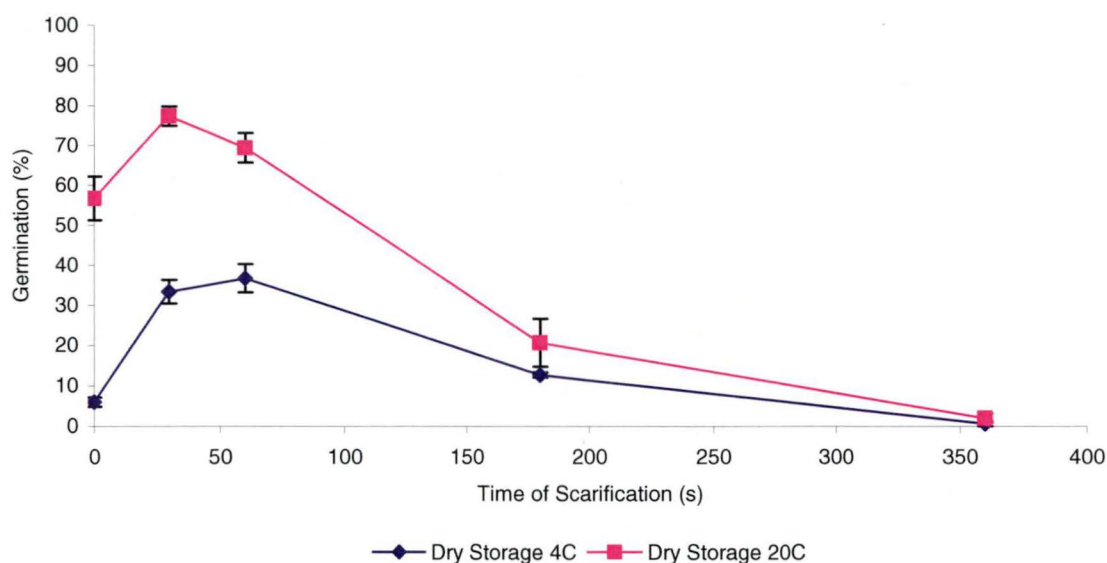
Figure 4.2 Effect of scarification on germination of *A. caucalis* seeds stored at 4°C and 20°C. Mean values ± standard error of mean are shown.

Storage temperature, scarification and light

There was a significant (P < 0.001) storage temperature, storage duration and seed treatment effect on germination, and a significant (P < 0.001) three way interaction between treatments. The mean germination of seeds stored at 20°C was 52.8%. This was significantly (P < 0.001) higher than the mean germination of seeds stored at 4°C, 30°C and ambient temperature (Table 4.4).

Table 4.4 The mean germination of *A. caucalis* seeds as affected by storage temperature.

Storage Temp (°C)	Germination %
4.0	22.3[d]
20.0	52.8[a]
30.0	45.2[b]
Ambient	41.0[c]
LSD (P = 0.05)	2.6

Each value is the mean of 4 replicates. Mean values within a column followed by differing letters are significantly different at P = 0.05

The initial germination percentage of the seed lot was 15.0% ± 4.7. This increased significantly (P < 0.05) with dry storage at 20°C with a positive response against time with germination reaching 91% after 52 weeks in storage (Figure 4.3). There was

also an increase in the percentage of seed germinating in complete darkness following storage at 20°C. The germination in darkness was significantly (P < 0.05) lower than the untreated at all storage durations except at 12 and 16 weeks after storage. Scarification significantly (P < 0.05) increased germination, which was significantly (P < 0.05) higher than the untreated at all storage durations prior to 39 weeks of storage.
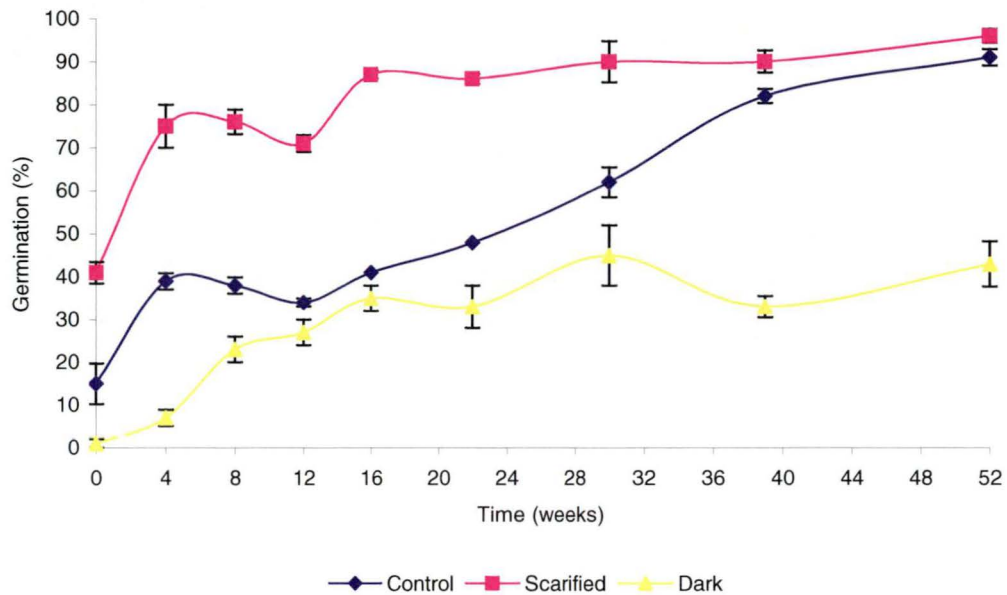
Figure 4.3 Germination response of *A. caucalis* seeds dry stored at 20°C for differing periods up to 52 weeks and germinated at 15/10°C. Seeds treatments were scarification, incubation in completed darkness or untreated control. Mean values ± standard error of mean are shown.

Storage at 4°C resulted in no discernible pattern of change in germination percentage over the duration of the storage (Figure 4.4). Under complete darkness seeds failed to germinate or were restricted to germination levels below 5%. The initial germination of scarified seeds was 41% and this did not significantly (P > 0.05) change with storage duration at 4°C. Similarly for the untreated seeds there was no significant (P > 0.05) change over the first 38 weeks of storage although there was a significant (P < 0.05) increase after 52 weeks of storage.
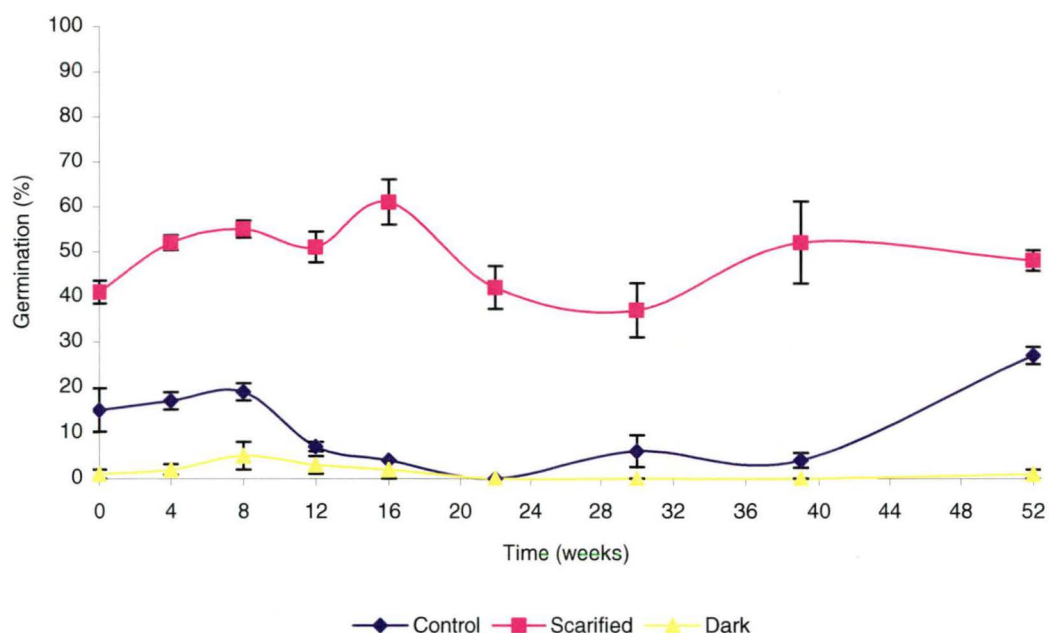
Figure 4.4 Germination response of *A. caucalis* seeds dry stored at 4°C for differing periods up to 52 weeks and germinated at 15/10°C. Seeds treatments were scarification, incubation in completed darkness or untreated control. Mean values ± standard error of mean are shown.

After 4 weeks of storage at 30°C, there was a significant (P < 0.05) increase in the germination response of scarified and untreated seeds of *A. caucalis* (Figure 4.5). Germination of scarified seeds did not significantly (P < 0.05) change with storage duration following this initial increase. For the untreated seeds however there was a significant (P < 0.05) decrease in germination at 12 weeks and this lower response was also observed at 16, 22 and 30 weeks. After 39 weeks of storage there was a significant (P < 0.05) increase in germination. It appears that there was a cyclic germination response of *A. caucalis* with storage duration at 30°C. In contrast the light requirement for germination of *A. caucalis* seed stored at 30°C diminished during the first 22 weeks of storage and displayed no cyclic response.
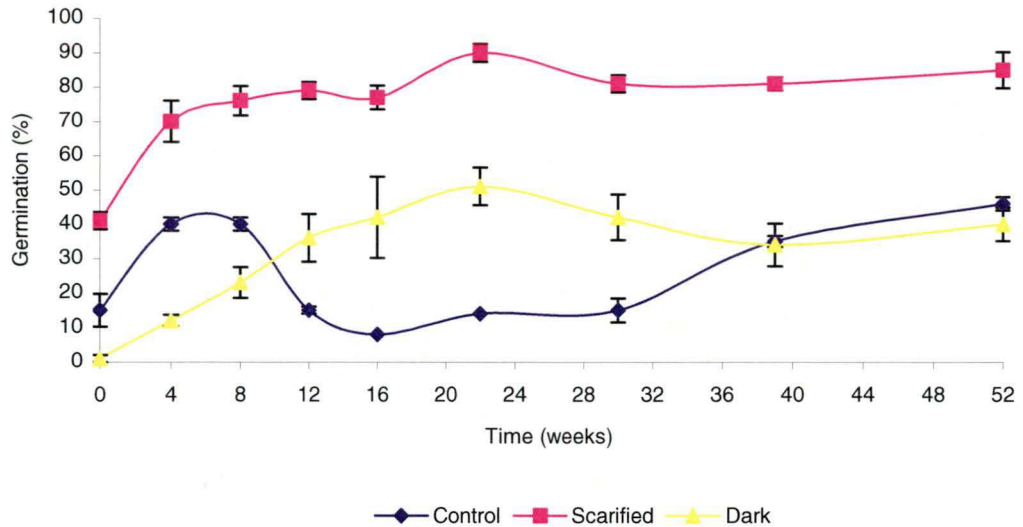
Figure 4.5 Germination response of *A. caucalis* seeds dry stored at 30°C for differing periods up to 52 weeks and germinated at 15/10°C. Seeds treatments were scarification, incubation in completed darkness or untreated control. Mean values ± standard error of mean are shown.

There were fluctuations in the germination of *A. caucalis* in response to exposure to seasonal day and night temperatures (Figure 4.6). The germination of scarified seeds of *A. caucalis* significantly ($P < 0.05$) increased during the first 22 weeks of storage and then significantly ($P < 0.05$) decreased in the weeks following. Similar cyclic responses were shown for seeds incubated with and without light stimulus. During the first 8 weeks of storage there was a significant ($P < 0.05$) increase in the germination of seeds incubated in the dark and light and in the following 8 weeks there were significant ($P < 0.05$) decreases. Following this 16 week period of storage there were no discernible change in the light requirement of *A. caucalis* seeds, while the germination response of seeds incubated in light increased.
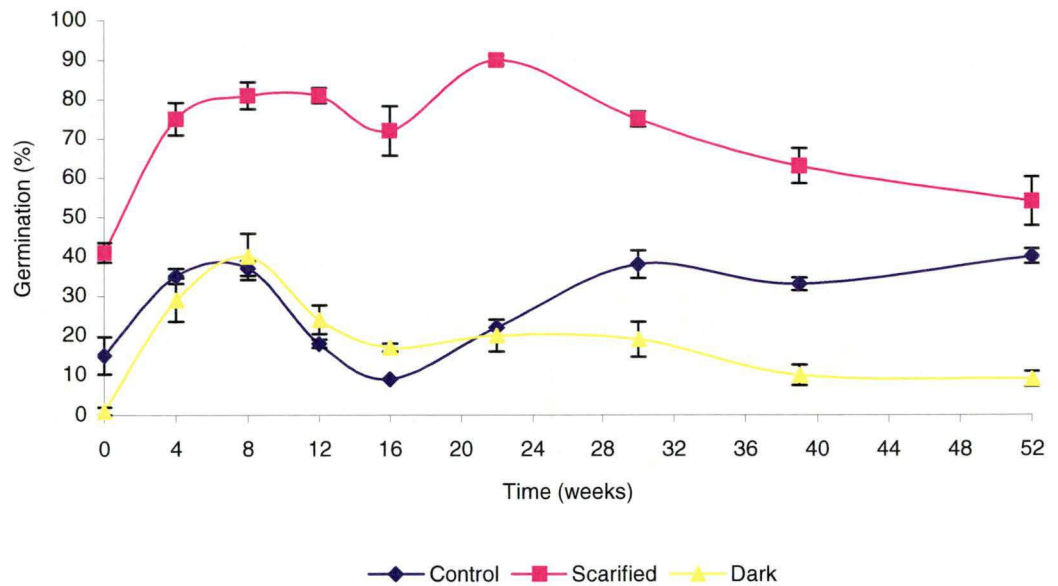
Figure 4.6 Germination response of *A. caucalis* seeds dry stored under ambient temperature for differing periods up to 52 weeks and germinated at 15/10°C. Seeds treatments were scarification, incubation in completed darkness or untreated control. Mean values ± standard error of mean are shown.

The endosperm of all scarified seeds imbibed in crystal violet were found to be stained after 7 days whereas only a low percentage (14%), comparable to the germination percentage of unscarified seeds, were stained (Plate 4.1).

Plate 4.1 A comparison of the staining of the endosperm of scarified (left) and non-scarified (right) seeds of *A. caucalis* imbibed in crystal violet for 7 days.

There was no significant (P < 0.05) difference in the embryo sizes of *A. caucalis* after 30 weeks of dry storage (Table 4.5).

Table 4.5 Embryo length (mean ± s.e.) of seeds of *A. caucalis* at 30 weeks after dry storage under differing temperatures

Dry Storage Condition	Embryo length (mm)
4°C	0.519 ± 0.008
20°C	0.534 ± 0.008
30°C	0.516 ± 0.012
Ambient temperature	0.532 ± 0.007

Plate 4.2 Extracted embryo of *A. caucalis* (length = 0.520mm).

4.4 Discussion

The results of this series of germination experiments on the seeds of *A. caucalis* showed that there were no germination inhibiting substances that can be extracted with water on the surface of the seeds, that short periods of cold stratification did not result in the breakage of the seed dormancy and that there was a non-deep physiological endogenous dormancy that was overcome by dry storage and an exogenous dormancy that was overcome by seed scarification.

There was no response in germination of seeds stratified at 4°C and therefore no intermediate or deep endogenous physiological dormancy associated with *A. caucalis*. Cold stratification is generally the requirement for the breakage of dormancy for many summer annuals germinating in spring. The results of this study

were consistent with the observed autumn/winter germinating behaviour of *A. caucalis*. It is unknown whether there is an inducement of a secondary dormancy in *A. caucalis* by stratification as the initial germination percentage was very low (< 5%).

Scarification of *A. caucalis* for 30 seconds improved the germination of dry stored seeds by 20%. A scarification requirement for the promotion of germination has been previously reported for species of the family Apiaceae (Hassell and Kretchman, 1997). Longer periods of scarification resulted in a decrease in germination and following examination of the scarified seed under a stereomicroscope it was found that the endosperm of the seed had been noticeably damaged.

The differences in germination response to scarification from the seed lots dry stored at 20°C and 4°C indicated that there is combinational seed dormancy associated with *A. caucalis*. Exogenous dormancy is broken by scarification and endogenous dormancy is overcome by dry storage. This behaviour is consistent with the winter annual behaviour of *A. caucalis*. Maturation and seed dispersal occurred in early summer and emergence of seedlings was not observed until mid autumn/early winter. It is likely that during this dry warm period from seed dispersal to emergence that the requirements for after-ripening and some loss of seedcoat dormancy will occur.

The duration of the dry after-ripening period required to overcome the non-deep physiological endogenous dormancy of *A. caucalis* appears to vary with seed lot. The observed difference in germination at 182 days of dry storage indicated that the seed lot from Cressy was at the time of collection further advanced in satisfying it's after ripening requirement. Under field conditions this after-ripening requirement would be achieved during the summer period when temperatures are high and conditions dry. Dry storage at 20°C satisfied this after-ripening requirement. Dry storage at low temperatures (4°C) resulted in no after-ripening taking place. Hightemperatures (30°C) and seasonal alternating temperatures resulted in fluctuations in the germination and in the light requirements for germination of *A. caucalis*.

No morphological development of the embryo occurred during dry storage as shown by the embryo size assessment. The germination increase was therefore not in

response to a morphological development of the embryo but due to a physiological response. The results also showed that seeds of *A. caucalis* have an imposed seed coat dormancy and the non-staining of unscarified seeds when imbibed in the crystal violet solution indicated that the seed coat imposed dormancy was due to an impermeable seed coat.

Storage of *A. caucalis* seeds at 30°C diminished the light requirement up to period of 22 weeks of storage. This may however vary considerably for differing seed lots. It appeared that during the last two months of summer (first 8 weeks of storage) the requirements for light decreased when exposed to these higher temperatures but then returned in the periods following. Cyclic change in light requirements has also been shown to occur in other annual species, for example in *Lactuca* spp. (Evenari, 1984). This study has shown that there may be some photodormancy associated with *A. caucalis* seeds but the alleviating influence of the surrounding environment is not fully understood and requires further examination.

4.5 Conclusion

Seeds of *A. caucalis* displayed a physical exogenous dormancy that was broken by scarification and a non-deep physiological endogenous dormancy that was overcome by dry storage. Seeds of *A. caucalis* were photosensitive, but the light requirement varied with differing storage temperature. The results are consistent with the behaviour of *A. caucalis* as a winter annual species, which flowers and set seeds in spring to early summer. The results of this study indicated that the after-ripening requirements of *A. caucalis* can be satisfied during the summer and early autumn months. In addition, some possible breakdown in seed coat dormancy may also occur during this period. The seed coat dormancy together with different levels of after-ripening requirements help spread the germination of *A. caucalis* over the late autumn early/winter period as well as allowing for longer term seed survival.

The results provide valuable information on the germination behaviour and pattern of emergence of *A. caucalis* which would assist in the development of an integrated weed management approach to the control of *A. caucalis* by improving the timing of preemergence herbicide applications and by identifying the time frame in which

seedling emergence is likely to occur, such that postemergence herbicide applications can be applied prior to vegetative development. This information could also aid in the selection of choice of rotational crops so that the impact of these weeds can be reduced though cultivation practises. The majority of crops grown in rotation with pyrethrum are spring sown and cultivation occurring after the emergence of *A. caucalis* will substantially reduce the level of occurrence in following crops.

Chapter 5 Factors affecting germination of *T. nodosa* and *A. caucalis*

5.1 Introduction

There is a paucity of information regarding the factors involved in controlling seed germination of *T. nodosa*. Within the genus *Torilis*, seed of *T. japonica* has been found to be dormant at time of dispersal (Roberts, 1979; Grime *et al.*, 1981) and chilling was required to break dormancy (Grime *et al.*, 1981). In contrast, Baskin and Baskin (1975) found that seeds of *T. japonica* were non-dormant at time of dispersal and were induced into dormancy by low temperatures. Seeds of *T. japonica* that do not germinate in the year that they are dispersed undergo an after-ripening during summer allowing germination to occur during the autumn following (Baskin and Baskin, 1975).

Several environmental factors are known to affect weed seed germination and there is no relevant information regarding the environmental factors involved in controlling seed germination of both *A. caucalis* and *T. nodosa*. The objective of this study was to

1. Assess the level of seed dormancy of *T. nodosa*
2. Examine some of the major environmental factors affecting germination and emergence of *A. caucalis* and *T. nodosa* seed including: temperature, light, osmotic stress and seed burial.

An understanding of factors influencing the germination of *T. nodosa* and *A. caucalis* will provide an objective basis for successful forecasting of germination trends and the development of effective integrated control measures.

5.2 Materials and Methods

General Procedure

Seeds of *T. nodosa* and *A. caucalis* were collected in the summer of 2001 and 2002 respectively. Seed lots were cleaned and dry stored at room temperature and used within 6 months of collection. Seed lot viability as determined by TZ test (ISTA, 1999) was 96% and 82% for *T. nodosa* and *A. caucalis* respectively.

Unless stated otherwise, individual treatments for all laboratory experiments consisted of 50 seeds placed on two sheets of Postlip filter paper moistened with distilled water in 85 mm petri dishes. Petri dishes were incubated in a Contherm™ incubator at a constant 20°C, with two 15-watt fluorescent tubes producing a light intensity at seed level of approximately 140 μmol s^{-1} m^{-2}. Following each experiment, ungerminated seeds were examined and recorded as being fresh ungerminated seeds or empty seeds. Determination of fresh and empty seed was achieved by the application of slight pressure with forceps (Ball and Miller, 1989). A seed was considered germinated when the radicle protruded a minimum of 1 mm from the seed coat (ISTA, 1996). The number of days of incubation at which seed lot germination attained 50% of its maximum (T_{50}) and the final germination percentage were assessed in each experiment. *Anthriscus caucalis* seeds were scarified for the temperature response and seed burial study but remained unscarified for the osmotic study.

Seed dormancy of T. nodosa

Seeds of *T. nodosa* were tested for initial germination percentage with seeds directly transferred to 20°C with a 12-hour light/dark period. Moistened seeds of *T. nodosa* were also subjected to complete darkness at 2°C, 4°C or 10°C for eight days, after which they were transferred to a constant 20°C with a 12-hour light/dark period. Seeds were counted every 2 days following placement at 20°C and germinated seeds were recorded and removed. The experiment was terminated after 6 consecutive days of no germination.

Light and stratification effect on the germination of T. nodosa

Moistened seeds of *T. nodosa* were stored at 4°C for 0, 1, 2, 3, 4, 6, 8, 12 and 16 weeks with 12-hour light/dark period. Following stratification treatment seeds were transferred to a constant 20°C with a 12-hour light/dark period. Seeds were also kept in complete darkness for the pre-chilling treatment of 0, 2, 4, 8 and 16 weeks and following transfer to 20°C, by applying a double wrapping of reflective aluminium foil around each petri dish. Seeds incubated in light were counted every 7 days following placement at 20°C for 28 days and germinated seeds were recorded and removed. Seeds incubated in complete darkness were counted only once after

incubation at 20°C for 21 days. The effects of stratification and light on the germination of *A. caucalis* have been described in the previous chapter.

Temperature

A Terratec™ thermogradient table with 10 thermocouples was used to determine the effect of temperature on germination of *T. nodosa* and *A. caucalis*. The thermogradient plate had thermocouples spaced 15 cm apart resulting in regions with constant temperatures ranging from 0°C to 40°C. The temperature of each region was monitored daily. This experiment was not undertaken at the same time for the two species, resulting in temperatures at which the seeds of both *A. caucalis* and *T. nodosa* were exposed to being slightly different.

One hundred seeds of *T. nodosa* and 50 seeds of *A. caucalis* were exposed to each temperature treatment under constant light. Seeds were observed daily for 28 days and germination counts were recorded every 7 DAI. Temperatures above 25°C caused localised drying, and consequently seeds were re-moistened twice daily throughout the experiment.

Planting depth

A red ferrosol soil (Isbell, 1996) known to be free of *T. nodosa* and *A. caucalis* seeds was collected from northwestern Tasmania. The red ferrosol soil was chosen as it is representative of the soil type on which the majority of pyrethrum crops are grown. The soil was heat sterilised at 100°C for 24 hours to ensure that any weed seeds present were destroyed. The soil was then ground with a mortar and pestle, passed through a 5mm sieve and rewetted.

Forty-two 12.5cm diameter plastic pots were filled to one of seven soil depths: 0, 5, 10, 20, 30, 50 and 70mm from the top of the lip of the pot. Fifty seeds of both *T. nodosa* and *A. caucalis* were distributed evenly across the surface of the soil in separate pots. All pots were then filled to the level of the plastic lip with additional soil and watered thoroughly. Pots were placed in a glasshouse (20 ± 5°C) for period of 49 days and watered twice daily for 2 minutes to replace transpiration losses. Emergence counts were recorded weekly.

Osmotic stress

Solutions with osmotic potentials of 0.00, -0.25, -0.50, -0.75 and -1.00 MPa were achieved by mixing the appropriate amounts of polyethylene glycol 8000 (PEG 8000) in 40 ml of distilled water (Michel, 1983). The osmotic potential of the PEG was checked using an osmometer. The 0.00 MPa (distilled water) solution was used as the control treatment. Fifty seeds of both *T. nodosa* and *A. caucalis* were imbibed on two sheets of Postlip filter paper moistened with 5ml of each solution in separate 85 mm petri dishes. Germination counts were undertaken every 7 days for a period of 28 days.

Statistical analysis

All studies were arranged as randomised complete block designs. Four replications were used for each study except for the temperature and soil depth study, which were replicated three times. Percentage germination data were subjected to analysis of variance with Fishers protected LSD test (P = 0.05) for mean separation using the statistical analysis package SAS (SAS Institute, 1998).

5.3 Results

Seed dormancy of T. nodosa

Freshly collected seeds of *T. nodosa* exhibited no dormancy behaviour. The mean initial germination of *T. nodosa* seeds incubated at 20°C was 93%. Stratification of the seeds at 2, 4 and 10°C for 8 days resulted in no significant (P > 0.05) change in germination (Table 5.1). T_{50} was achieved 8 DAI at 20°C. Similarly seeds stratified at 2 and 4°C achieved T_{50} in 8 and 7 DAI respectively. In contrast seeds stratified at 10°C reached T_{50} in 3 DAI.

Table 5.1 Final germination percentage and time to 50% maximum germination of freshly collected seeds of *T. nodosa*.

Treatment	Germination (%)	T_{50} (days)
20°C	93 [a]	8.0[a]
Stratified 2°C	92[a]	8.0[a]
Stratified 4°C	93[a]	7.0[a]
Stratified 10°C	92[a]	3.0[b]

[a] Each value is the mean of 4 replicates. Mean values within a column followed by the same letter are not significantly different at P = 0.05

Light and Stratification effect on the germination of T. nodosa

In the absence of stratification, the germination of seeds of *T. nodosa* was 79% in complete darkness, which was significantly (P < 0.05) lower than with a 12 hour daily illumination period (Figure 5.1). There was a significant (P < 0.05) reduction in germination of *T. nodosa* seeds when stratified in complete darkness. Increases in the duration of stratification resulted in no significant (P > 0.05) difference in the germination for those seeds exposed to a 12 hour daily illumination period.
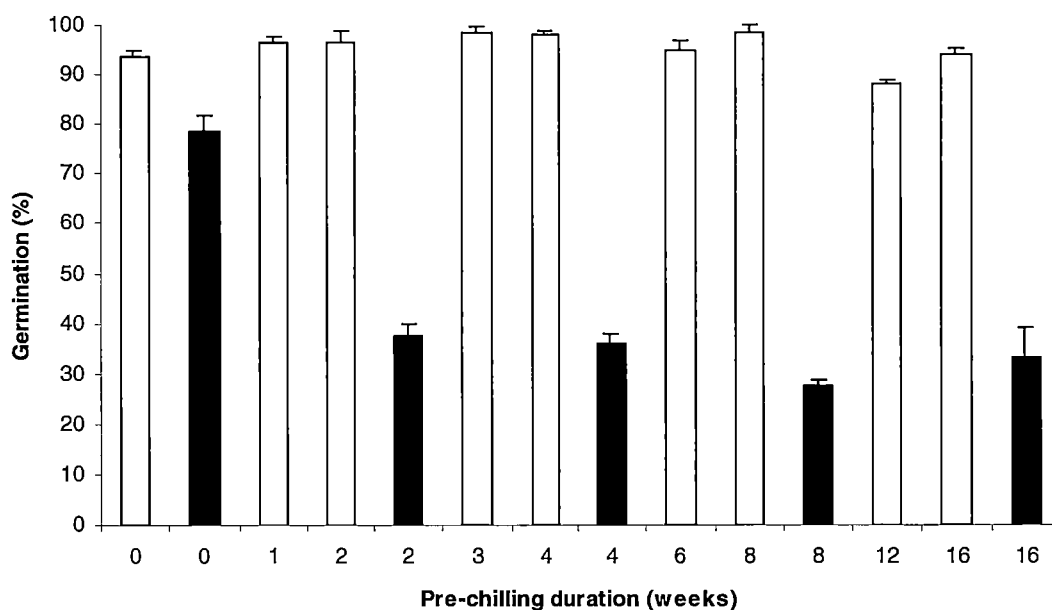
Figure 5.1 Effect of stratification (4.0°C) duration on the germination of *T. nodosa* incubated in complete dark (shaded bars) or with a 12 hour daily illumination period (clear bars). Mean values ± standard error of mean are shown.

Temperature

Torilis nodosa seeds required a temperature above 4.2°C but below 35.0°C to germinate (Table 5.2). The highest level of germination occurred at 18.2 and 23.4°C. At 28 DAI the mean germination for seed imbibed at 18.2 and 23.4°C was 91.0% and 94% respectively, which was significantly ($P < 0.05$) higher than all other temperatures. There were significant ($P < 0.05$) differences in the rate of germination of *T. nodosa* seeds at differing temperatures. For example, at 21 DAI the germination percentage of seeds imbibed at 7.8°C was 35.3%. This was significantly ($P < 0.05$) lower than the germination percentage at temperatures between 15.4°C and 25.5°C. At 28 DAI however the germination percentage of seeds imbibed at 7.8°C increased significantly to 83.3%. This was not significantly ($P > 0.05$) different to the final germination at 9.7, 15.4 and 25.5°C. The observed differences in germination rate of *T. nodosa* seeds and the lack of significant differences at final germination when exposed to differing temperatures was consistent with that reported previously for non-dormant seeds (Bewley and Black, 1982).

Table 5.2 Effect of temperature on the germination of *T. nodosa*

Temp (°C)	7 DAI	14 DAI	21 DAI	28 DAI
4.2	0.0e	0.0^d	0.0^d	0.0^e
7.8	0.0^e	0.7^d	35.3^b	83.3^c
9.7	0.0^e	73.0^b	84.3^a	84.7^c
15.4	13.0^c	84.3^a	87.3^a	87.3^{bc}
18.2	36.0^a	88.0^a	89.3^a	91.0^{ab}
23.4	39.0^a	86.3^a	88.0^a	94.0^a
25.5	27.7^b	80.7^{ab}	83.0^a	86.0^{bc}
30.8	1.0^d	9.3^c	19.0^c	43.0^d
35	0.0^e	0.0^d	0.0^d	0.0^e
36.8	0.0^e	0.0^d	0.0^d	0.0^e

Each value is a mean of 3 replicates. Mean values within a column followed by the same letter are not significantly different ($P < 0.05$).

Anthriscus caucalis seeds required a temperature above 2.0°C but below 29.5°C for germination. The maximum germination percentage occurred at 6.0, 10.5, and 14.5°C (Table 5.3). At 28 DAI the mean germination percentage at 6.0, 10.5 and 14.5°C was 66.7%, 71.3% and 74.7% respectively. Initially (7 DAI) the highest level of germination was achieved at temperatures of 14.5, 18.0 and 22.0°C, but at these temperatures the final germination at 28 DAI was only 56% and 42% at 18.0 and 22.0°C, respectively. Germination rate was significantly ($P < 0.05$) lower at 6.0°C than at 10.5°C, which was significantly ($P < 0.05$) lower than at 15.0°C. At 26.0°C the germination percentage at 28 DAI was 12.0% with germination totally restricted at temperatures of 29.5°C and above.

Table 5.3 Effect of temperature on the germination of *A. caucalis*

Temp (°C)	7 DAI	14 DAI	21 DAI	28 DAI
2.0	0.0^c	0.0^e	0.0^e	0.0^f
6.0	0.0^c	12.7^d	60.0^b	66.7^b
10.5	0.0^c	70.7^a	71.3^a	71.3^{ab}
14.5	53.3^a	74.0^a	74.7^a	74.7^a
18.0	51.3^a	56.0^b	56.0^b	56.0^c
22.0	39.3^b	42.0^c	42.0^c	42.0^d
26.0	0.7^c	8.0^d	11.3^d	12.0^e
29.5	0.0^c	0.0^e	0.0^e	0.0^f
34.0	0.0^c	0.0^e	0.0^e	0.0^f
38.0	0.0^c	0.0^e	0.0^e	0.0^f

Each value is a mean of 3 replicates. Mean values within a column followed by the same letter are not significantly different (P < 0.05).

Planting depth

The optimum planting depth of *T. nodosa* and *A. caucalis* seeds for seedling emergence occurred between 0mm and 30mm (Figure 5.2). At a planting depth of 50mm emergence of both species was significantly (P < 0.05) reduced with emergence totally inhibited at 70mm.

$$y = 0.0014x^3 - 0.1702x^2 + 3.951x + 62.352$$
$$R^2 = 0.9891$$

$$y = 0.001x^3 - 0.1019x^2 + 1.7266x + 52.017$$
$$R^2 = 0.9947$$
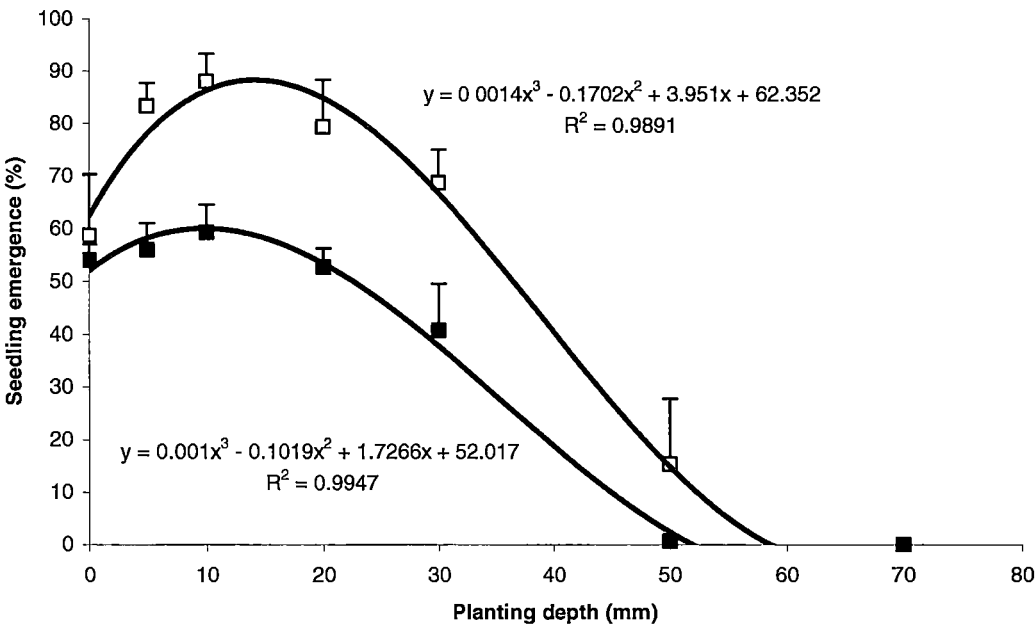
Figure 5.2 Effect of planting depth on the emergence of *T. nodosa* (□) and *A. caucalis* (■) seeds 7 weeks after planting. Standard errors of the mean shown as error bars.

Plate 5.1 Effect of planting depth on the emergence of *T. nodosa* seedlings. L to R, 0, 5, 10, 20, 30, 50 and 70mm planting depths.

Plate 5.2 Effect of planting depth on the emergence of *A. caucalis* seedlings. L to R, 0, 5, 10, 20, 30, 50 and 70mm planting depths.

Osmotic stress

There was no significant (P< 0.05) difference in germination of *T. nodosa* and *A. caucalis* at osmotic potentials between 0 and -0.5 MPa (Figure 5.3). However, there was a highly significant (P < 0.001) reduction in germination at an osmotic potential greater than -0.75 MPa for both species and germination was totally inhibited at an

osmotic potential of -1.0 MPa. The results indicate that both *T. nodosa* and *A. caucalis* are sensitive to osmotic stress.
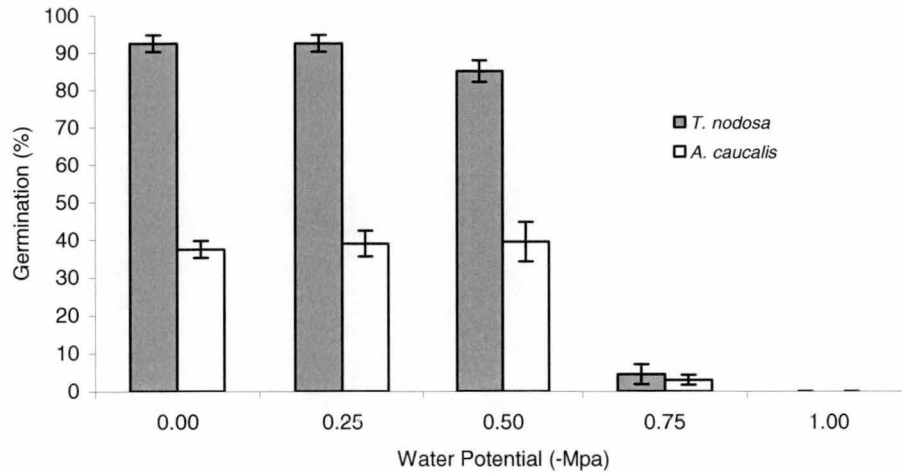
Figure 5.3 Effect of osmotic potential on the germination of *T. nodosa* and *A. caucalis* incubated at 20°C with a 12 hour daily illumination period for 4 weeks. Stand errors of the mean shown.

5.4 Discussion

The high initial germination (92 to 93%) of *T. nodosa* indicated that there was no innate dormancy in this species. This in contrast to the majority of Apiaceae species (Grime *et al.* 1981), although it was consistent with that reported by Baskin and Baskin (1975) for the closely related species, *T. japonica*. The innate dormancy behaviour exhibited in the majority of Apiaceae species is likely to be a survival mechanism to prevent germination at times of unfavourable climatic conditions.

An explanation for this finding could relate to the fact that *T. nodosa* seeds remain attached to the senescing adult plant until dispersal occurs in early autumn and it is conceivable that dormancy is unnecessary as conditions for germination are favourable at this time. Seeds collected prior to senescence of the parent plant have been found to be non-viable due to immaturity of the embryo and endosperm. Production of viable seeds of *T. nodosa* only occurs when the mature plant is left to senesce. This has also been reported in *T. arvensis* (Wilson, 1991). Cutting or removal of the parent plant prior to senescence will therefore reduce the number of viable seeds produced. Pyrethrum harvesting begins in late December and at such time senescence of *T. nodosa* is not complete. The harvesting procedure removes all

foliage down to a height of approximately 50 mm which limits the amount of viable seed produced and may account for the lower level of spread of *T. nodosa* in comparison to *A. caucalis*.

Germination of seeds of *T. nodosa* was unaffected by stratification at 4°C and inducement of dormancy over the winter period was therefore considered unlikely. This is in contrast to the related species, *T. japonica*, where field populations have been found to be induced into dormancy by low temperatures (Baskin and Baskin, 1975). Dispersed seeds of *T. nodosa* were not induced into dormancy by cold stratification and are unlikely to be exposed to dark conditions in a non-tillage production system like pyrethrum and therefore have the ability to behave predominantly as facultative winter annuals spreading their germination over autumn and spring.

Torilis nodosa showed a decrease in germination when a light stimulus was removed. For most Apiaceae species there is no light requirements for germination although Apiaceae species *Berula erecta*, *Conium maculatum*, *Daucus carota* and *Pimpinella saxifragae* have been reported to respond to light (Grime *et al.* 1981). Changes in light requirements under differing conditions have been observed for a range of species (Wesson and Wareing, 1969). *Torilis nodosa* displayed a stronger light requirement following cold stratification. Although germination was significantly (P < 0.05) reduced when a light stimulus was removed, germination was not totally inhibited.

Optimum germination of *A. caucalis* occurred over a narrower range of temperatures than for *T. nodosa*. The results, however, suggest that both *T. nodosa* and *A. caucalis* were capable of behaving as facultative winter annuals with some germination occurring in spring but with the majority taking place in autumn following seed dispersal. The optimum temperature for the germination of *A. caucalis* was lower than that for *T. nodosa*. *Anthriscus caucalis* may therefore behave more like a strict winter annual than *T. nodosa*. It would be conceivable that a mild spring would result in minimal germination of *A. caucalis*. Only the cool temperatures experienced during the winter periods in northern Tasmania would restrict germination of *T. nodosa*. Planting of pyrethrum takes place in early spring and germination of *T.*

nodosa and *A. caucalis* would be possible at this time. This has been observed to occur, although from the recorded response of germination to differing temperatures, it would be expected that the emergence of *T. nodosa* would be more prevalent than *A. caucalis* in this period due to its higher optimum temperature for germination.

The emergence of both *T. nodosa* and *A. caucalis* was prevented at depths greater than 50 mm. Light becomes a restrictive stimulus for germination at depths greater than 10 mm (Tester and Morris, 1987), however, germination was not significantly ($P < 0.05$) reduced at 20 and 30mm. Although it has been shown that both *T. nodosa* and *A. caucalis* germination is reduced under complete darkness, germination is not totally restricted and in this experiment a decrease in the light stimulus as a result of seed burial did not limit the emergence of either species. The restriction in emergence of *T. nodosa* and *A. caucalis* when planted at depths of 50 mm and 70 mm was concluded to be a result of the small seed size that restricted epigeal emergence from greater depths. As *T. nodosa* and *A. caucalis* have similar size seeds it was not surprising that their emergence response to planting depths was similar. The results suggest that a no-tillage production system such as that for a short lived perennial crop like pyrethrum would favour the germination of *T. nodosa* and *A. caucalis* through accumulation of seeds at or near the surface (Dorado *et al.*, 1999). Slight burial of *T. nodosa* and *A. caucalis* seeds just below the surface would most likely occur as a result of the movement of machinery, grazing animals and abiotic factors during the growing season, favouring the germination of these seeds. In attempts to reduce the impact of the seedling emergence in following crops, conventional tillage may bury a large proportion of the seed to depths that inhibit emergence.

Both *T. nodosa* and *A. caucalis* were found to be sensitive to moisture stress. During the summer period in northwestern Tasmania the upper 5cm of the red ferrosol soils becomes dry, especially under a non-tillage system, and soil water potentials commonly fall to levels near permanent wilting point (- 1.5 MPa) (McLaren, 1996). Germination of any newly dispersed *T. nodosa* and *A. caucalis* seeds at such time would be restricted and would be unlikely to occur until moisture availability increased in autumn. In addition to the initial germination of dispersed *A. caucalis* seeds being low due to an imposed seed coat dormancy and a requirement for after-

ripening, low levels of moisture availability during the summer period would also restrict emergence. Seed coat dormancy and a requirement for after-ripening are viewed as being survival strategies of *A. caucalis* in that they limit the number of false breaks that will occur during the summer period. Although *T. nodosa* has been shown to have no innate seed dormancy, susceptibility to false breaks in the summer is overcome by a delayed dispersal mechanism of the mature seeds which are held tightly in compact umbels and have been observed to remain on the parent until senescence has been completed, generally occurring in later summer early/autumn.

5.5 Conclusion

The optimum germination temperature for *A. caucalis* was between 6°C and 15°C and the optimum planting depth between 0 and 30 mm. *Anthriscus caucalis* seeds were sensitive to osmotic stress and failed to germinate at a water potential of - 1.0MPa. The germination responses of *A. caucalis* to differing temperature and osmotic stresses are compatible with its behaviour as a winter germinating annual species. During mid autumn and winter soil temperatures decrease and moisture availability increases allowing for environmental stimuli for germination of *A. caucalis* to be satisfied.

Dispersed seeds of *T. nodosa* displayed high initial germination (>90%) with optimum germination between 18°C and 24°C. Germination of *T. nodosa* was restricted by planting depths greater than 30 mm and osmotic stresses of less than - 0.75 MPa. Germination was reduced when a light stimulus was removed and following stratification at 4°C in complete darkness.

Immediately following seed dispersal from the senescing adult plant in late summer, mature seeds of *T. nodosa* are capable of germination. During autumn in northern Tasmania sufficient moisture and optimum temperatures for germination are likely to be reached. During winter low soil temperatures will slow or prevent the germination of *T. nodosa*, however no inducement into dormancy is likely and, therefore, germination will recommence during early spring until conditions, such as low moisture availability, become limiting. The results suggest that *T. nodosa* behaves

predominantly as a facultative winter annual with emergence favoured by the non-tillage production system associated with pyrethrum.

Chapter 6 Seedbank dynamics of *A. caucalis* and *T. nodosa*

6.1 Introduction

The soil seedbank is an indicator of past and present weed populations and reflects the cumulative effects of many years of crop and soil management (Cardina *et al.*, 1991). Weeds can emerge over an extended period each year and there is a typical periodicity, including a period (or periods) of high emergence, that is characteristic for each species (Chepil, 1946; Stoller and Wax, 1973). An understanding of the periodicity of emergence and seed longevity will elucidate the likely degree of interference to a crop and assist in the development of an integrated weed management programme.

The seedbank longevity of weed seeds is classified into three broad categories:

➤ Transient – Seeds that persist in the soil for less than one year

➤ Short term persistent - Seeds that persist in the soil for at least one year, but less than five years

➤ Long-term persistent- Seeds that persist in the soil for at least five years (Thompson *et al.* 1997).

The majority of Apiaceae species have transient or short-term persistent seedbanks (Thompson *et al.*, 1997). A small number of species in the family have been reported as having long-term persistent seed banks. *Daucus carota* seeds can remain dormant in the soil for up to 10 years (Harrison and Dale, 1966), *Bifora testiculata* seeds have been found to remain viable in the soil for at least 10 years in Southern Europe and for approximately six years in Northern Europe (Stephenson, 1992) and seeds of the annual *Aethusa cynapium* have also been found to form long-term persistent seed banks (Chancellor, 1986; Roberts, 1979).

The seedbank of *A. caucalis* has been reported to be transient (Levassor *et al.*, 1990), however Roberts, (1986) reported that the longevity of *A. caucalis* seeds was greater than 5 years. The seedbank longevity of *T. nodosa* has also been reported as being transient (Maranon and Bartolone, 1989).

Cropping history and cultivation influence the weed seed population of the soil. Crop rotation has a strong influence on herbicide use, the type and timing of tillage and the harvest date relative to crop and weed maturity (Ball and Miller, 1990). Particular conditions created by a narrow crop rotation or monoculture benefit weed species that have a niche similar to the crop, and these weeds can rapidly become abundant (Dorado *et al.*, 1999). The increase in prevalence and the dominance of Apiaceae weeds in pyrethrum indicates they are favoured by the current production system. The present herbicide program fails to control these weeds, and the maturity of these species coincides with crop harvest possibly aiding in their dispersal. In addition, the non-tillage system associated with production of pyrethrum following seedling establishment would favour the accumulation of small seeded annuals at or near the surface which has been shown to be the ideal conditions for emergence of both *A. caucalis* and *T. nodosa*. A more heterogenous vertical distribution of seeds within the seedbank has been reported to occur under a no-till system while the vertical distribution of seeds in the mouldboard plough layer is relatively homogenous within the plough horizon. (Dorado *et al.*, 1999).

To effectively manage *A. caucalis* and *T. nodosa* in pyrethrum more information is required on the timing of seedling emergence and seed bank distribution of these weeds. Both species have been observed to emerge in dense patches, with emergence predominantly occurring in autumn and winter. However, no quantitative evidence has been recorded on the level, longevity or timing of emergence. The aim of this study was to investigate the seedling emergence and seed survival of *T. nodosa* and *A. caucalis* and to examine the seedbank distribution of these species under pyrethrum production.

6.2 Materials and Methods

Timing of emergence of A. caucalis and T. nodosa

Two commercial pyrethrum fields were selected based on the high presence and density of *A. caucalis* and *T. nodosa*. On the 22ndAugust 2001, fifteen 0.09 m^2 soil sections, to a depth of 5 cm were carefully removed with minimal soil disturbance and placed in similar sized trays. Initial seedling density was determined by counting, and seedlings were removed by cutting the developing hypocotyl. Trays

were exposed to natural daily temperature and light conditions at the University of Tasmania, Hobart (42° 90' S, 147° 32' E) and newly emerged seedlings of *A. caucalis* and *T. nodosa* recorded and removed weekly. Daily temperature for the duration of the study is given in Appendix A.11. Soil was disturbed slightly in early January 2002 to mimic the event of harvests within a pyrethrum field. Trays were watered daily with overhead sprinkler irrigation to replace evaporation losses.

Field emergence of A. caucalis and T. nodosa

A pyrethrum field (440094E, 5439670N) with no previous history of occurrence of *A. caucalis* and *T. nodosa* was selected to examine the emergence pattern of these weeds under typical crop management conditions. The experimental layout was a block of 24 plots each 1.0 m² in area. Within each plot a permanent 0.25m² quadrat was located which provided an adequate buffer zone between plots. Mature seeds of *A. caucalis* and *T. nodosa* were collected during the summer of 2002. Allowing for differences in germination 250 and 500 seeds of *T. nodosa* and *A. caucalis*, respectively were spread evenly over the soil surface within the 0.25m² quadrats on the 18th February 2002. This resulted in 12 replicates for each species. After spreading, the soil surface was covered with pyrethrum stubble to mimic the occurrence of seed dispersal within a pyrethrum field. The area received the same commercial management as the remainder of the field with the exception of the absence of herbicide applications. Seedling emergence was recorded at 14 to 21 day intervals for a period of 23 months. On the dates of recording, the emerged seedlings were removed by defoliation below the cotyledons. Unwanted vegetation was also removed to eliminate variation from competition. Mean daily maximum and minimum air temperature and precipitation for this area are shown in Appendix A.12 and A.7.

Seedbank distribution of A. caucalis under pyrethrum production

A pyrethrum field was selected based on the high frequency and density of *A. caucalis*. Two 9 m² plots within the field where selected as being representative of a typical weed infested area. A total of 40 soil cores were extracted using a 7.5 cm diameter thread auger at depths of 0 to 5 and 5 to 10 cm. The seedbank was sampled on the 11th July 2001.

To extract weed seeds, flotation and deflocculation methods were used. Soil samples were combined in a beaker with 2L of water and stirred and passed through a series of sieves: 2 mm, 1 mm and 0.5 mm. Soil aggregates were then deflocculated with a solution containing sodium hexametaphosphate (50g/L) and sodium bicarbonate (25 g/L) (Dorado *et al.*, 1999) to obtain any remaining seeds. Soil was placed in a 2L beaker mixed with the deflocculating solution (1:2 by weight to volume) and stirred for 15 minutes. To retain weed seeds, samples were again passed through a series of sieves. Samples where allowed to dry and all weed seeds present counted and identified under a stereomicroscope. Only the seeds that were intact physically and resistant to slight pressure with forceps were counted as viable. Seedbank analysis was only performed for *A. caucalis* seeds as the selected field had no history of presence of *T. nodosa*.

6.3 Results

Periodicity of emergence of A. caucalis and T. nodosa

Emergence of *A. caucalis* occurred predominantly in autumn with increases in emergence occurring between March and April. Emergence of *A. caucalis* continued into the winter period with emergence slowing between August and December (Figure 6.1). Increases in emergence of *T. nodosa* occurred prior to that of *A. caucalis* with emergence of *T. nodosa* commencing during January. A more rapid increase in emergence of *T. nodosa* occurred from February to April. The emergence of *T. nodosa* slowed significantly during the winter period from June to August. There was some emergence during the spring period but this was substantially lower than that which occurred during the late summer and early autumn period.
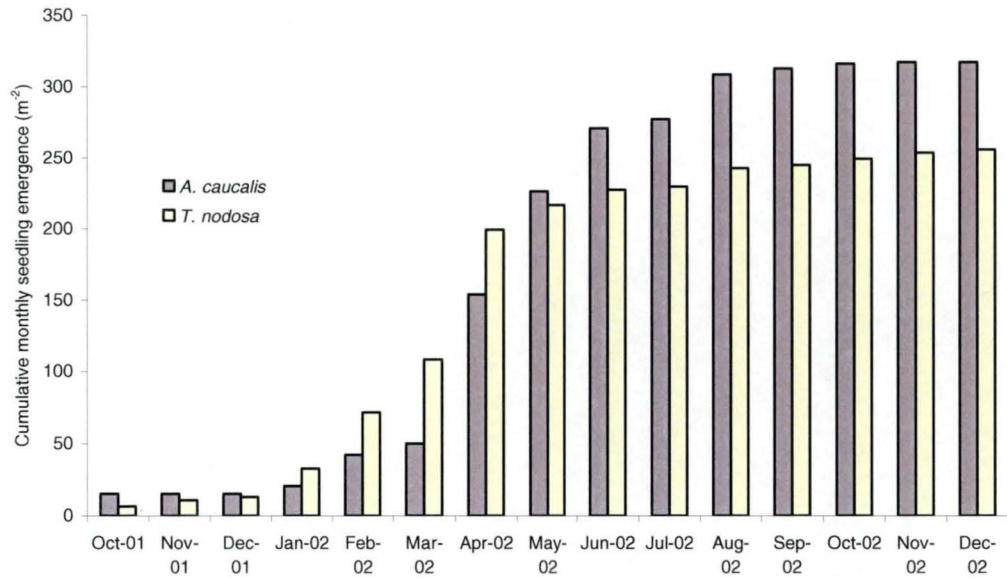
Figure 6.1 Cumulative monthly seedling emergence (m^{-2}) of *T. nodosa* and *A. caucalis.*

At the time of soil removal and placement into trays the initial mean number of weed seedlings was 4037 ± 368 m^{-2} and 5558 ± 519 m^{-2} for *A. caucalis* and *T. nodosa* respectively (Table 6.1). The total number of seedlings that emerged during this experiment was significantly ($P < 0.001$) lower than the initial seedling density for both species. In the 12-month period from September 2001 to September 2002 the number of emerged seedlings was 381 m^{-2} for *A. caucalis*, a 90.5% reduction from the initial seedling density from the previous year. Similarly for *T. nodosa* the number of emerged seedling was 249 m^{-2}, a 95.5% reduction.

Table 6.1 Rate of seedbank depletion of *A. caucalis* and *T. nodosa*, as shown by mean seedling emergence (m^{-2}) for a two-year period.

Emergence Period	*Anthriscus caucalis*	*Torilis nodosa*
Initial (Jan 01-Sep 01)	4037 ± 368	5558 ± 519
Sep 01-Sep 02	381 ± 67	249 ± 50
Sep 02 – Jan 03	9 ± 3	13 ± 6

Field emergence of A. caucalis and T. nodosa

There was a discernible pattern to the emergence of both *A. caucalis* and *T. nodosa* with the emergence virtually restricted to the autumn and winter period (Figure 6.2).
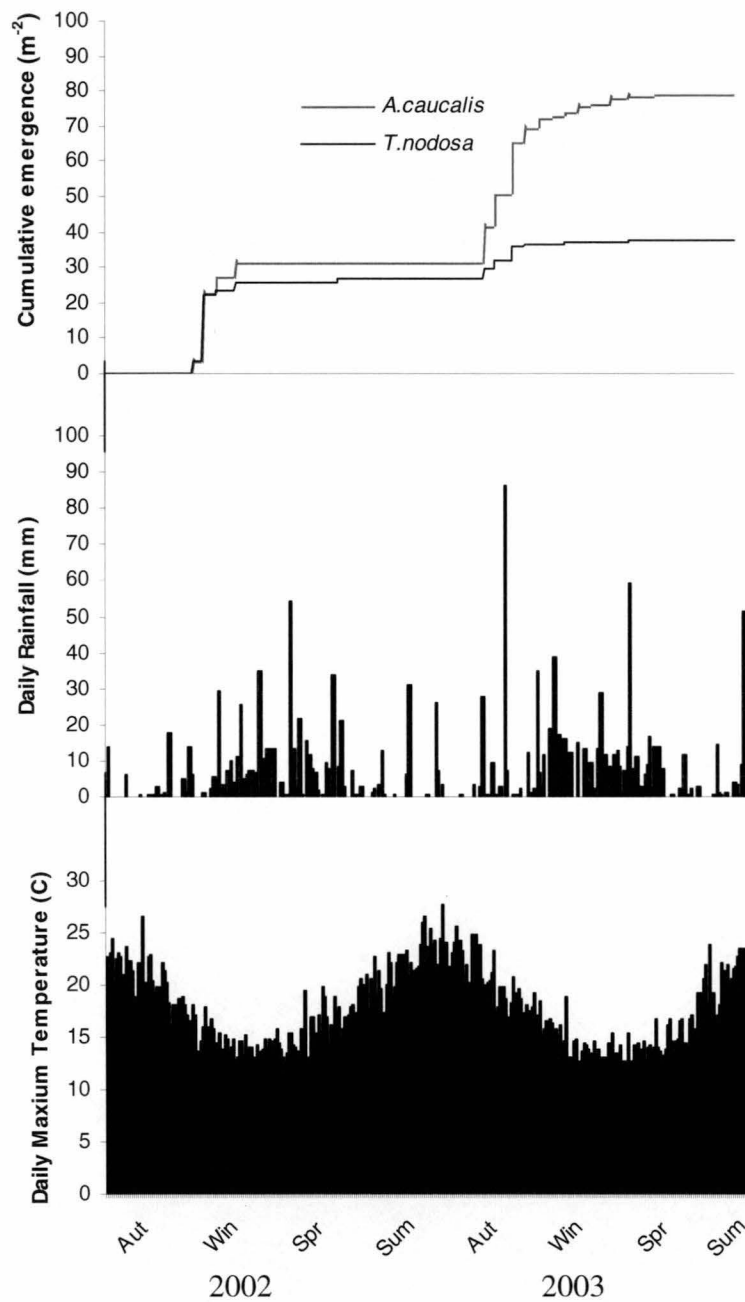
Figure 6.2 The cumulative emergence of *A. caucalis* and *T. nodosa* in relation to the daily rainfall and daily maximum temperature in 2002 and 2003.

A greater percentage of emergence of *T. nodosa* seeds occurred in 2002 than 2003. The mean number of emerged seedlings during 2002 was 73% of the total of

emergence for the duration of the study. In comparison the emergence of *A. caucalis* was more evenly spread over the two periods with 40% of the total emergence occurring in the autumn/winter period of 2002 and 60% in the same period in 2003.

Seedbank distribution of A. caucalis under pyrethrum production

The vertical distribution of *A. caucalis* seeds in the soil layer was heterogeneous with seeds predominantly accumulating in the 0 to 5 cm soil layer (Figure 6.3).
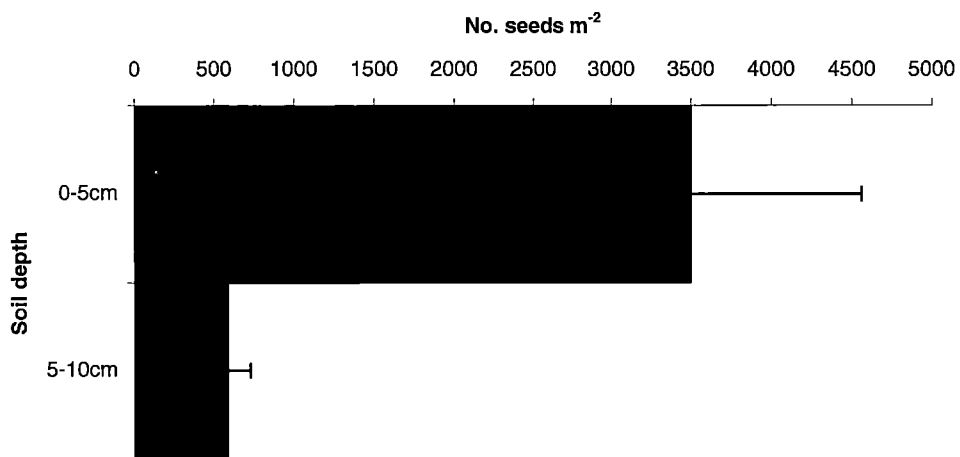
Figure 6.3 The vertical distribution of viable seed*s* of *A. caucalis* within the seed bank. Standard errors of the mean shown as error bars.

The number of *A. caucalis* seeds found within the seedbank was $3500m^{-2}$, although *A. caucalis* seeds did not completely dominate the actual seedbank and a number of more common small weed seeds were found in relatively high numbers (Figure 6.4). Seeds of *Coronopus didymus* (lesser swinecress), *Brassica rapa* ssp. *sylvestris* (wild turnip), *Raphanus raphanistrum* (wild radish), *Daucus carota* ssp. *carota* (wild carrot) and *Trifolium repens* (white clover) were the most prevalent weed seeds.
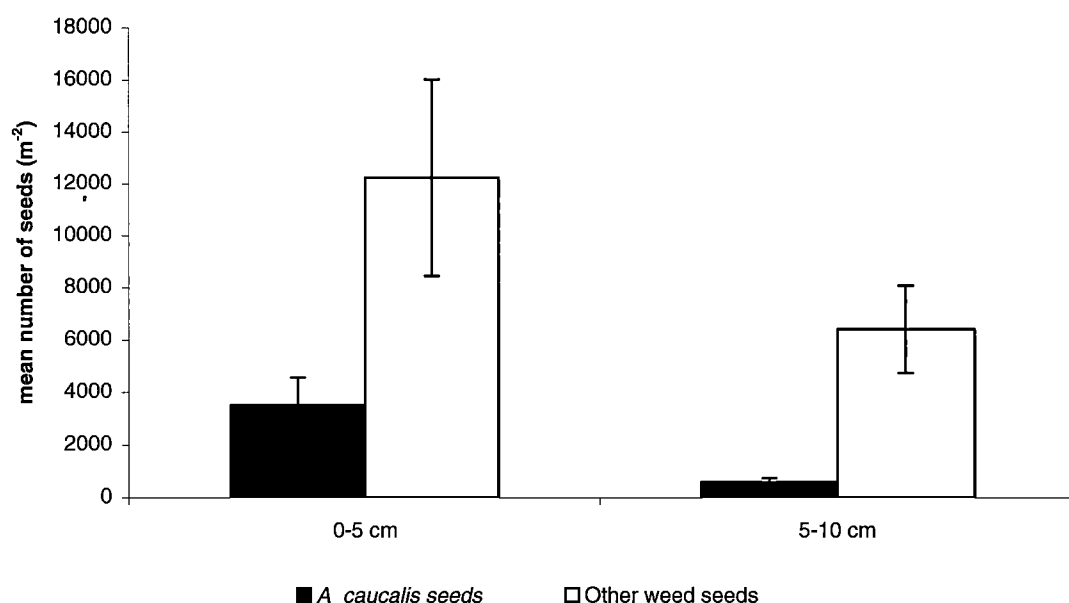
Figure 6.4 The mean number of *A. caucalis* seeds and the mean number of other weed seeds within the seedbank

6.4 Discussion

Depletion of *A. caucalis* and *T. nodosa* seeds capable of emerging from within the seed bank was quite rapid. This was consistent with the findings of Roberts (1979) for a number of other Apiaceae weeds. However, reports on the seed longevity of *A. caucalis* are variable. Levassor *et al.* (1990) reported that the seedbank longevity of *A. caucalis* was transient, while Roberts, (1986) reported that seeds were persistent, lasting longer than 5 years. From the study using removed soil sections, the seedbank longevity of *A. caucalis* appeared to be short-term persistent; however, the length of this persistence beyond 23 months was not determined. Due to variable levels of seed dormancy the persistence of the seedbank could be greater than 5 years. The study by Roberts (1986) involved artificial burial of seeds, a technique which tends to overestimate the persistence compared with data obtained from natural seedbank studies (Thompson *et al.*, 1997). The result of the seedling emergence of *T. nodosa* indicated that the seedbank was predominantly transient and this has been reported previously (Maranon and Bartolone, 1989). The initial seedling density of *T. nodosa* was 5558 and the total number of emerged seedlings in the 16 months following was only 4.5% of this. It is suggested that this small percentage of *T. nodosa* seeds failed

to initially germinate and emerge due to light restrictions from the competing weeds and also due to some small percentage of seed burial. A non-persistent seed bank is consistent with other members of the family Apiaceae (Roberts, 1979; Thompson and Baster, 1992).

The periodicity of emergence of *A. caucalis* and *T. nodosa* under field conditions was consistent with that observed in trays with both species emerging predominantly in autumn. Moisture availability strongly affected the emergence of both species. The early autumn of 2002 was dry and emergence of both species was not observed until substantial rainfall had occurred. The total rainfall for the months of March and April in 2002 was only 30.2mm and as a result moisture availability was low. The first substantial increase in emergence was recorded on 4th June 2002 which followed the 22.6 mm of rainfall on the 16th and 17th May 2002. In comparison emergence occurred earlier in 2003 with the first emergence occurring in early April in response to the 37.0mm rainfall on the 20th and 21st March 2003.

Although the emergence of *T. nodosa* occurred earlier than A. *caucalis* in the study using removed soil sections, moisture was not a limiting factor due to applied overhead irrigation. Under field conditions the emergence of both *A. caucalis* and *T nodosa* were similar and available soil moisture appeared to be the major environmental factor. The failure of *A. caucalis* and *T. nodosa* to emerge during the dry periods of March and April 2002 was consistent with the earlier results (Chapter 5) that both species are sensitive to water stress.

The longevity of seeds of *A. caucalis* under field conditions was in contrast with that observed in trays. In the study using removed soil sections it appeared that the emergence of *A. caucalis* occurred predominantly during the first year. Soil sections were directly removed from the field and the initial density count of the seedlings was assumed as emerging from seeds dispersed in the preceding summer. It is possible that the initial emergence of *A. caucalis* had actually occurred from *A. caucalis* seeds of varying ages and not solely from seeds dispersed in the previous summer. Consistent with the observation that emergence of *A. caucalis* is spread over more than 1 year was the result of the seed storage study. In this experiment it was shown that the germination of *A. caucalis* steadily increased with dry storage

duration at 20°C over 52 weeks. Following dispersal of *A. caucalis* in the current study after-ripening would have been satisfied during the late summer early autumn period, allowing a percentage of the seeds to germinate and emerge. Those seeds that failed to germinate were then exposed to lower temperatures during the winter and the requirements for dormancy may not have been broken during this period. In support of this conclusion, it was shown that seed germination of *A. caucalis* was not increased by periods of cold stratification at 4°C or by dry storage at 4°C. During the summer, low moisture availability restricted emergence of *A. caucalis* and a percentage of the remaining viable seed within the seedbank would then be capable of germinating in the proceeding autumn and winter as the dry warm periods of summer satisfy their after-ripening requirements. During autumn and winter environmental conditions become more conducive to germination, namely moisture and lower temperature allowing germination and emergence to proceed. The significant emergence of *A. caucalis* in the second year indicated that the seed dormancy of *A. caucalis* allowed emergence to be spread over a number of years.

The innate seed dormancy of *A. caucalis* allows it to have a more persistent seedbank than that of *T. nodosa*, which has no innate seed dormancy. Emergence of *T. nodosa* predominantly occurred during autumn although emergence during the spring period was not completely restricted. No inducement of dormancy was found with cold stratification of *T. nodosa* seeds and as a result *T. nodosa* is capable of emergence all year round as long as moisture and temperature are favourable. It has been shown that *T. nodosa* has a higher optimal germination temperature than *A. caucalis* and that both species are sensitive to low moisture stresses. This may explain why the emergence of *T. nodosa* was observed during the warmer autumn periods and not carried through into the cooler periods of mid to late winter.

The low percentage of emerged seeds for both *A. caucalis* and *T. nodosa*, compared to the number of seeds dispersed is realistic. According to Vanasse and Leroux, (2000) it has been estimated that only 0.3 to 9% of the weed seeds produced develop into seedlings in a given year. Contributing factors for this included: loss of seeds to diseases and pests such as insects and birds, false breaks and non-viable seed.

Prior to the establishment of this experiment, consideration was given to burying the seed slightly below the surface and that seed movement be constrained by the use of a screen similar to that described by Egley (1983). The burial of seeds was avoided as the trial was aimed at keeping the conditions as similar to those experienced under pyrethrum production as possible. Also the inclusion of any material that may influence the moisture availability to the weed seeds following precipitation was not desired. Dispersing the seeds amongst the pyrethrum stubble was also chosen as this not only occurs under pyrethrum production but crop residues have been found to influence soil moisture and temperature having a significant effect on the emergence of weed species (Guerif *et al.*, 2001).

The number of *A. caucalis* seeds found within the seedbank was high ($3500m^{-2}$) and when environmental conditions become favourable the level of germination would be expected to be high. If 10% emergence of the viable seed within the seedbank occurred in the following season the population density of *A. caucalis* would be 350 plants per m^2. This was consistent with the level of infestations observed in the field where *A. caucalis* has been seen to emerge in large numbers and form dense populations with seedling density in some pyrethrum fields exceeding 500 seedlings per m^2.

The heterogenous nature of the vertical distribution of seeds under pyrethrum production was consistent with that observed for other non-tillage production systems where the distribution of weed seeds have been reported to be heterogenous with the greatest proportion of seeds found in the upper soil layer (Dorado *et al.*, 1999). It is apparent that the non-tillage system associated with pyrethrum production favours the accumulation of small seeded annual weeds at or near the surface.

6.5 Conclusion

Both *A. caucalis* and *T. nodosa* behave predominantly as winter annuals. Moisture and temperature availability strongly affect the emergence of both species. Seeds of *A. caucalis* displayed seasonal cyclic emergence behaviour with emergence being strongly restricted to the autumn and winter period. Like *A. caucalis*, the emergence

of *T. nodosa* occurred predominantly during autumn although emergence during the spring period was not completely restricted.

The seedbank of *T. nodosa* was transient to short-term persistent. The seedbank of *A. caucalis* was more persistent than that of *T. nodosa*. The innate seed dormancy of *A. caucalis* allowed for the emergence of *A. caucalis* to be spread over a number of seasons. The actual period when viable seeds of *A. caucalis* remain in the seedbank is unknown due to the time restrictions of this study. A long-term study examining the persistence of *A. caucalis* and *T. nodosa* under field conditions is recommended to provide more evidence to accurately determine the periodicity of emergence and longevity of these seeds within the seedbank.

The results of the current study gave a strong indication of the likely emergence period of *A. caucalis* and *T. nodosa* under pyrethrum production and this information will be used to improve the timing of herbicide applications. It was also concluded that pyrethrum production favours the accumulation of Apiaceae weed seeds in the upper soil layer, resulting in continued germination and accumulation of viable seed within the seedbank.

Chapter 7 Seed development and growth of *A. caucalis* and *T. nodosa.*

7.1 Introduction

Although the growth of both *A. caucalis* and *T. nodosa* has been observed in the field, the timing of phases of vegetative growth, flowering and maturation of seeds have not been quantitatively recorded. This information is of importance with respect to new weed species as it can be used as a tool for improving control procedures. Determination of seedling and vegetative growth stages allows for the identification of periods in which chemical and cultural control methods can be applied. Determination of flowering time is an important characteristic as the removal of the weeds prior to flowering can significantly reduce the level of spread through the prevention of seed development. Identifying the periods of seed maturation and seed dispersal and comparing this to crop agronomic practice such as harvesting and crop seed collection can identify the possibility of seed transport and seed crop contamination. Previous chapters have examined the floral biology, level of occurrence, seed germination, seed dormancy, seedbank longevity, and periodicity of emergence of *A. caucalis* and *T. nodosa*. The aim of this series of experiments was to:

1. Monitor the growth changes of *A. caucalis* and *T. nodosa* and quantify periods of flowering and seed maturation.

2. Examine the growth rates of *A. caucalis* and *T. nodosa* and determine the characteristics of *A. caucalis* and *T. nodosa* contributes to weed competitiveness.

7.2 Materials and Method

Growth and development of A. caucalis and T. nodosa in pyrethrum

Eight commercial pyrethrum fields (four for each weed species) were selected from six geographic regions and on the presence of the weed species (Appendix A.4). Where *A. caucalis* and *T. nodosa* were found in dense communities (> 20 plants m^{-2}) a 5m by 5m plot was established and clearly identified to exclude any herbicide application. At 14-day intervals 20 individual plants were randomly selected and the

growth stage assessed and coded according to Table 7.1. A mean growth stage was then calculated and recorded. The code was constructed based on a modification of that described for lucerne (Kalu and Fick, 1981). The trial commenced on the 22nd August 2001 at which time the weed species were in their seedling stage of growth. Growth was monitored until the point of removal at the end of December 2001. Weed removal was necessary to allow pyrethrum harvesting to proceed without the risk of seed spread and further contamination of the field. One location for *A. caucalis* had to be removed from the study due to herbicide spray drift damage.

Table 7.1 Growth code of *A. caucalis* and *T. nodosa.*

Code	Stage name	Stage definition
0	Germination	Emergence of cotyledons and first true leaf
1	Early seedling stage	Cotyledons present more than one true leaf
2	Mid seedling stage	Loss of cotyledons less than 6 true leafs
3	Late seedling stage	More than 6 true leaf, no stems present
4	Early Vegetative	Stems length less than 10 cm
5	Mid Vegetative	Stem length 10-20 cm
6	Late Vegetative	Stem length >20 cm
7	Bud formation	Flower bud visible, no open flowers
8	Early Flowering	First open flowers
9	Mid Flowering	50% of flowers open
10	Late Flowering	> 90% or flowers open
11	Early seed development	Primary seeds mature
12	Mid seed development	50% seed mature
13	Late seed development	> 90% of seeds hard
14	Plant desiccation	

At the commencement of seed development, randomly selected plants were collected and seed maturity quantitatively assessed. Seeds were removed from each umbel position and a bulk seed sample was collected to determine mean seed fresh weight (FW), dry weight (DW) and DW percentage. At developmental stages where the seeds were undeveloped and not able to be differentiated within the inflorescence, umbels were removed directly above the peduncle and a mean FW and DW recorded. Dry weight percentage was determined following drying at 70°C for 48hr. Individual seed DW% for *T. nodosa* were not assessed as removal of fresh seeds prior to maturity resulted in discernible damage due to the compact umbel structure.

For removal of *T. nodosa* seeds for viability and germination assessments umbels were left to dry at room temperature for 14 days. Seeds of *A. caucalis* were air dried for 14 days at room temperature, removed from the inflorescence, cleaned and dry stored. The viability of seed lots for both *A. caucalis* and *T. nodosa* was assessed using the tetrazolium test (ISTA 1999). Germination of *A. caucalis* and *T. nodosa* was assessed by incubation at 20°C with 12hour light/dark period. Germination assessment of *A. caucalis* was undertaken following 30 weeks of dry storage at 20°C. Germination assessment of *T. nodosa* was undertaken within 1 month of collection.

Seed development of A. caucalis and T. nodosa in pots

A glasshouse trial was set up to complement the growth and development data obtained from the field trial. Eighteen plants of both *A. caucalis* and *T. nodosa* were established in 15cm pots in the early winter of 2001 on outside benches at the University of Tasmania. Flowering commenced in early spring. At 6, 8, 10, 12, 14 and 16 weeks following first open flower stage, umbels were destructively removed from the secondary umbels up to the youngest available umbel order. Primary umbels were also removed and examined but data not included in analysis due to the low sample size. Seeds were removed from each umbel position and seed DW determined. The experiment was arranged as a completely randomised design with 3 replicates.

Growth characteristics of A. caucalis and T. nodosa

Seeds of *A. caucalis* and *T. nodosa* were sown on 17th June 2002 into separate 9L (30 by 24 cm) tubs with a standard potting mix (Appendix A.1). Following emergence seedlings were removed to create densities of 1, 4, 16 and 64 seedlings per tub. The plants were then grown under shade house conditions at the University of Tasmania for the duration of the trial, watered daily and fertilised fortnightly with Hoaglands solution (Appendix A.3).

On the 23rd Aug 2002 (14 weeks after planting), a destructive harvest was undertaken in which the shoot biomass was assessed for the following parameters:

➤ Dry weight (DW) per plant

➤ Leaf DW per plant (leaf = all petiole and lamina material)

➤ Stem DW per plant

> ➢ Stem diameter

> ➢ Leaf area (LA).

Leaf area was assessed using a planimeter. Leaf area index (LAI), leaf weight ratio (LWR), stem weight ratio (SWR), specific leaf area (SLA) and leaf to stem ratio (L/S) was then calculated as follows:

LAI = leaf area/land area (cm^2/cm^2)

LWR = Leaf dry weight/total dry weight (g/g)

SWR = Stem dry weight/total dry weight (g/g)

SLA = Leaf area/leaf dry weight (cm^2/g)

L/S = Leaf dry weight/stem dry weight (g/g).

Plant material was also divided into five above ground stratums; 0 –10cm, 10-20cm, 30-40cm and 40-50cm and the above variables assessed. The trial was analysed as a factorial design with four replications. Non-stratified data was analysed as a two (species) by four (density) factorial design to compare differences in growth response between species. Stratified data was analysed individually for both *A. caucalis* and *T. nodosa.*

7.3 Results

Growth and development of A. caucalis and T. nodosa in pyrethrum

Anthriscus caucalis flowered earlier than *T. nodosa* and reached a higher level of maturity at the time of pyrethrum harvest than *T. nodosa* (Figure 7.1). At final assessment on 27 December 2001, *A. caucalis* plants had reached an advanced stage of late seed development for all three sites. In the same period, *T. nodosa* plants had reached a mid to late stage of seed development at Hagley and North Motton and early to mid stage of seed development at Kindred and Table Cape.
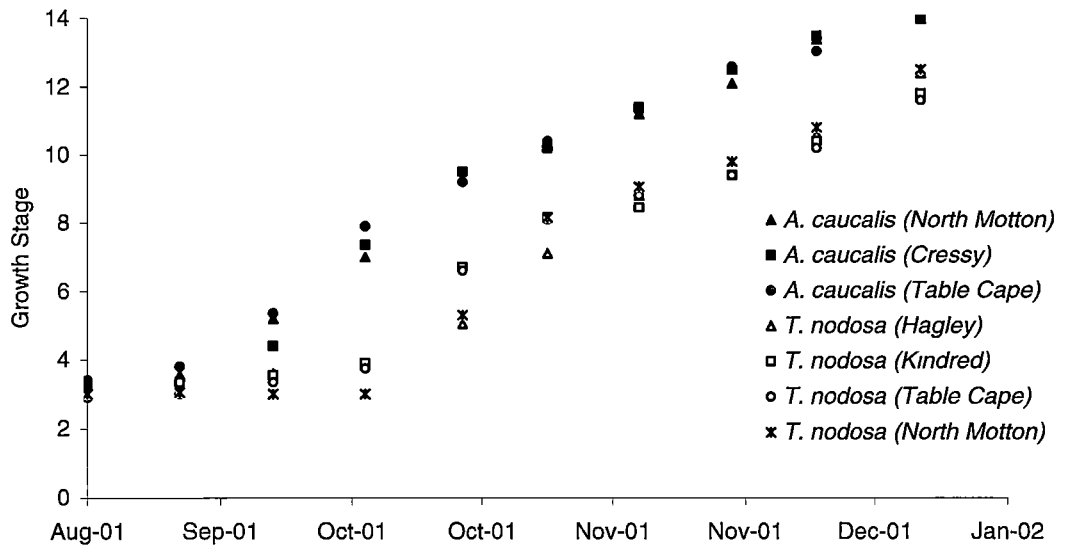
Figure 7.1 Changes in growth stages of *A. caucalis* and *T. nodosa* with time under the temperate climatic conditions of northern Tasmania.

There were significant ($P < 0.05$) increases in mean seed DW % with time for both species. *Anthriscus caucalis* reached a high level of desiccation with seeds from each umbel position having a DW% above 90% at final assessment (Figure 7.2). The DW% of umbels of *T. nodosa* was below 50% with the higher order umbels having a significantly ($P < 0.05$) lower DW% than the lower order umbels (Figure 7.3). The primary umbels of both species were the first to mature followed by the secondary, tertiary and lower order umbels.
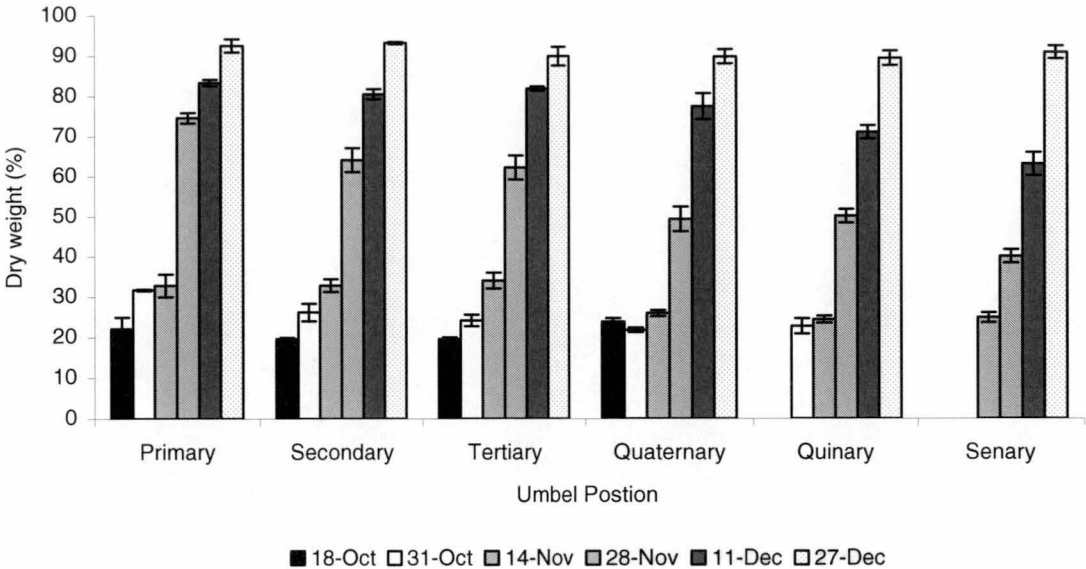
Figure 7.2 The mean seed DW% changes in time for *A. caucalis* for each umbel order averaged across the three locations. Standard error of means shown as error bars.
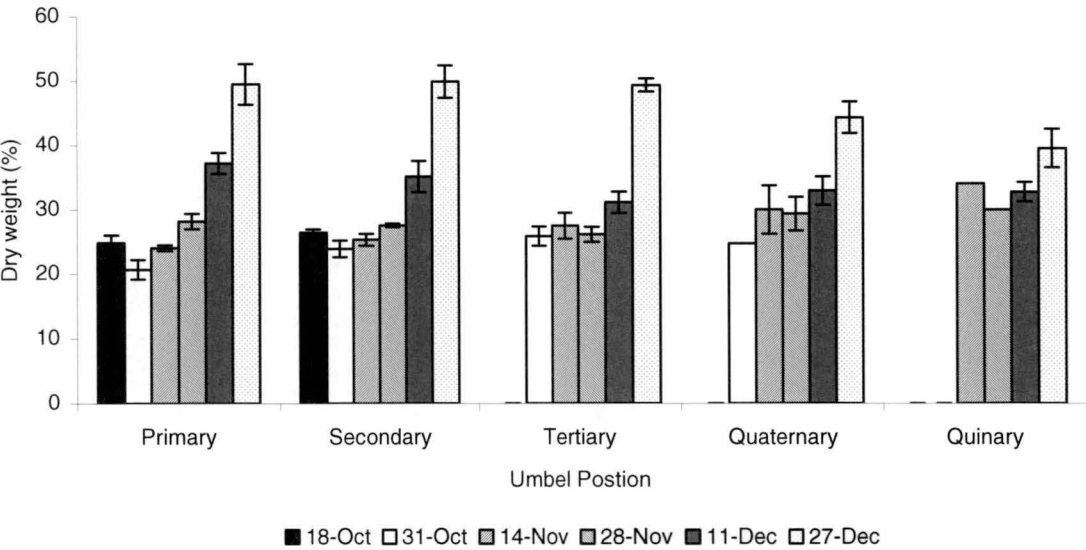
Figure 7.3 The mean umbel DW% changes in time for *T. nodosa* for each umbel order averaged across the four locations. Standard error of means shown as error bars.

Consistent with the changes in DW percentage it was found that seeds of *A. caucalis* became viable earlier than seeds of *T. nodosa* (Table 7.2). At final harvest date there was no significant (P > 0.05) difference in mean seed viability of *A. caucalis* among

locations. There was however a significant (P < 0.05) difference in the seed viability of *T. nodosa* among locations (Table 7.2) with the Hagley and North Motton locations having the highest mean viability of 95.3 and 87.3% respectively, which was significantly (P < 0.001) higher than Kindred (54.0%), which in turn was significantly (P < 0.001) higher than Table Cape (24.0%).

Table 7.2 Mean viability of *A. caucalis* and *T. nodosa* seeds as affected by harvest date

Species	Location	Harvest date			
		14/11/01	28/11/01	11/12/01	27/12/01
A. caucalis	Cressy	20.3 ± 4.2	58.9 ± 2.7	54.3 ± 2.1	81.2 ± 6.2
A. caucalis	Table Cape	18.7 ± 2.4	50.8 ± 1.9	49.3 ± 2.9	76.8 ± 6.3
A. caucalis	North Motton	18.6 ± 3.6	56.6 ± 3.4	60.2 ± 4.0	80.8 ± 3.6
T. nodosa	Hagley	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	95.3 ± 1.8
T. nodosa	Kindred	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	54.0 ± 2.3
T. nodosa	North Motton	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	87.3 ± 1.8
T. nodosa	Table Cape	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	24.0 ± 2.0

There was a significant difference (P< 0.05) in the germination of seeds of *T. nodosa* from different umbel positions (Figure 7.4). Seeds from secondary umbels were found to have a significantly (P< 0.05) higher mean germination than seeds from all other umbel positions. Seeds from the primary umbel had a significantly (P< 0.05) higher germination than seeds from umbels positions of lower orders except for seeds from the secondary order. At the two sites with the highest viability, Hagley and North Motton, there was no significant (P > 0.05) difference in mean seed germination percentage between the secondary and primary umbels. There were significant differences (P < 0.05) among the mean germination of seeds from all other umbel orders, with germination percentage decreasing with increasing umbel order.
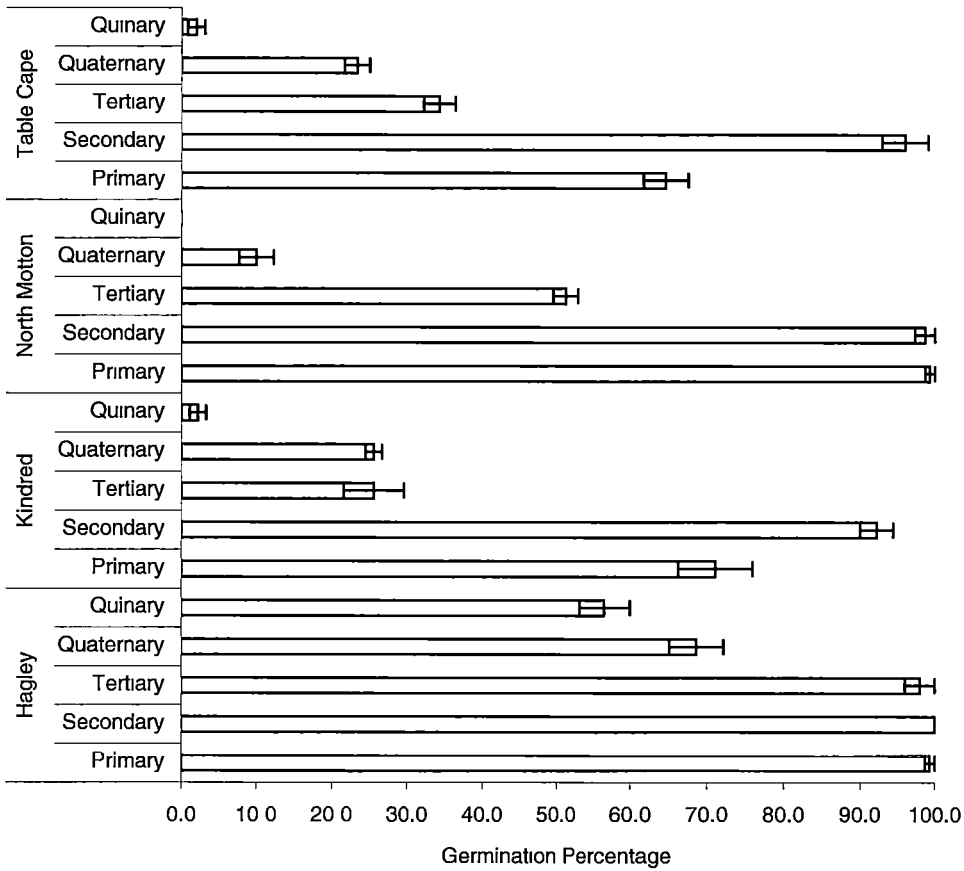
Figure 7.4 Mean germination percentage of seeds of *T. nodosa* collected on 27/12/01. Standard error of means shown as error bars. (LSD (P = 0.05) = 6.13).

A positive linear relationship was obtained between the mean germination percentage of *T. nodosa* seeds and the DW percentage of umbels (Figure 7.5).

The chart shows a scatter plot with trend line:
- Y-axis: Germination % of *T. nodosa*, ranging 0 to 100
- X-axis: DW% of umbels of *T. nodosa*, ranging 30 to 60
- Equation: $y = 3.6827x - 103.03$
- $R^2 = 0.7074$
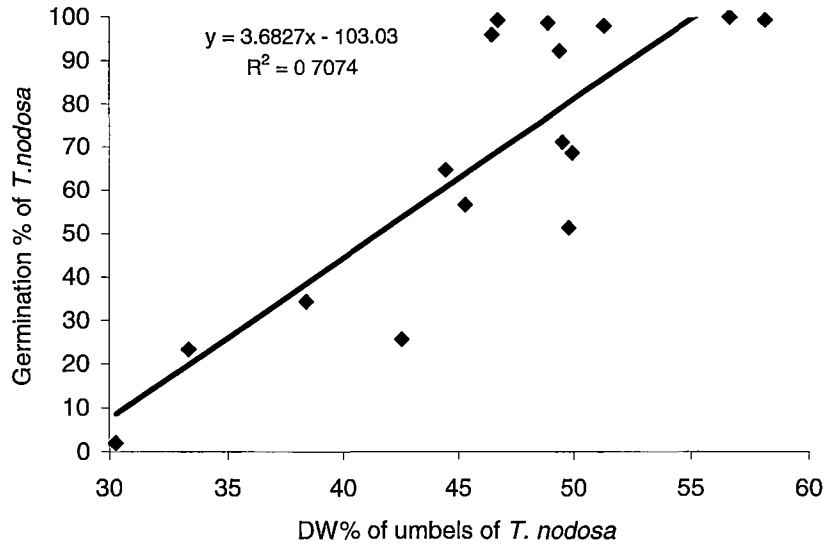
Figure 7.5 The relationship between germination percentage of *T. nodosa* and DW% of umbels.

There was a significant (P < 0.05) difference in the germination percentage of *A. caucalis* from different umbel order positions (Figure 7.6). Seeds from the primary umbel order had a significantly lower germination than seeds from all other umbel orders after 30 weeks of dry storage. Seeds from the senary umbel order produced the highest mean germination which was significantly (P < 0.05) higher than all other umbel orders. There was no significant (P > 0.05) difference in the germination of seeds from umbels secondary, tertiary, and quaternary, which were significantly (P < 0.05) lower than seed for quinary umbels. The germination percentage of *A. caucalis* seeds was significantly (P < 0.05) lower than that of *T. nodosa*.
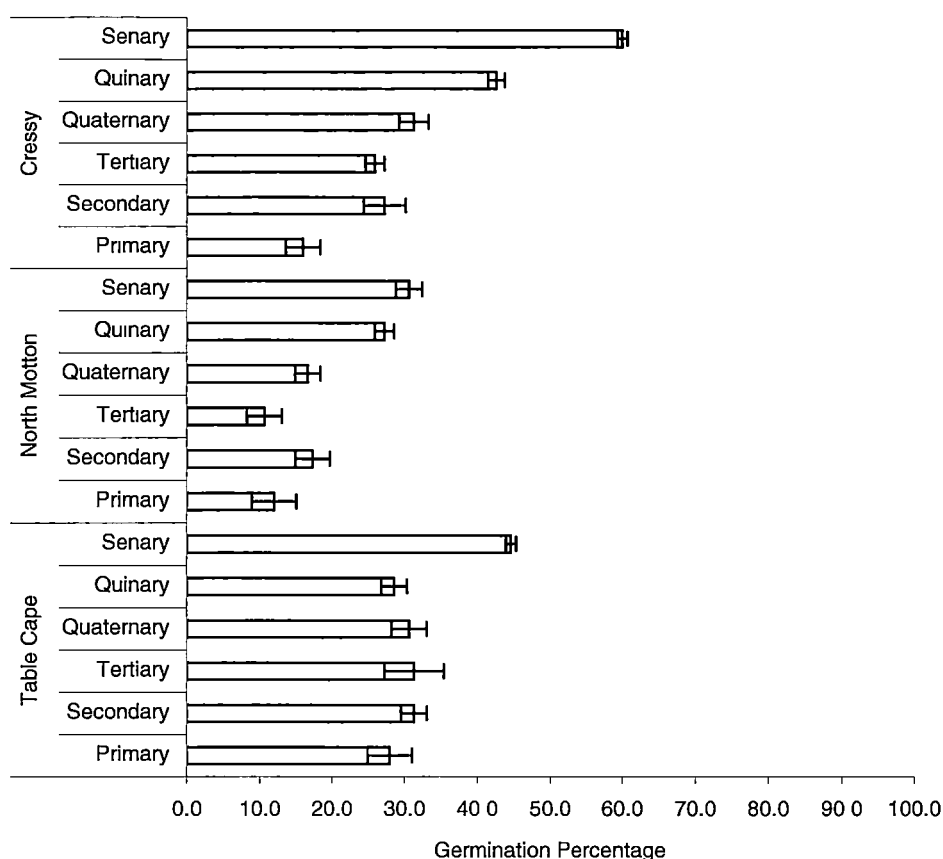
Figure 7.6 Mean Germination % of seeds of *A. caucalis* collected on 27/12/01. Standard error of means shown as error bars. (LSD (P = 0.05) = 6.45).

Seed development of A. caucalis and T. nodosa in pots

The results of the pot study were consistent with those recorded in the field. *T. nodosa* was found to flower approximately 4 weeks later than *A. caucalis* and seed maturity was also slower by 4 weeks. Only at 16 weeks after flowering had the seeds of *T. nodosa* matured sufficiently such that they could be dispersed from the umbel structure. At 16 weeks, seeds from the secondary umbel order had reached 82% DM (Figure 7.7). Seeds from the lower umbel orders had much greater variation in DW percentages and a lower mean DW percentage, indicating that the seeds had not yet reached a desired level of maturity for dispersal and germination.
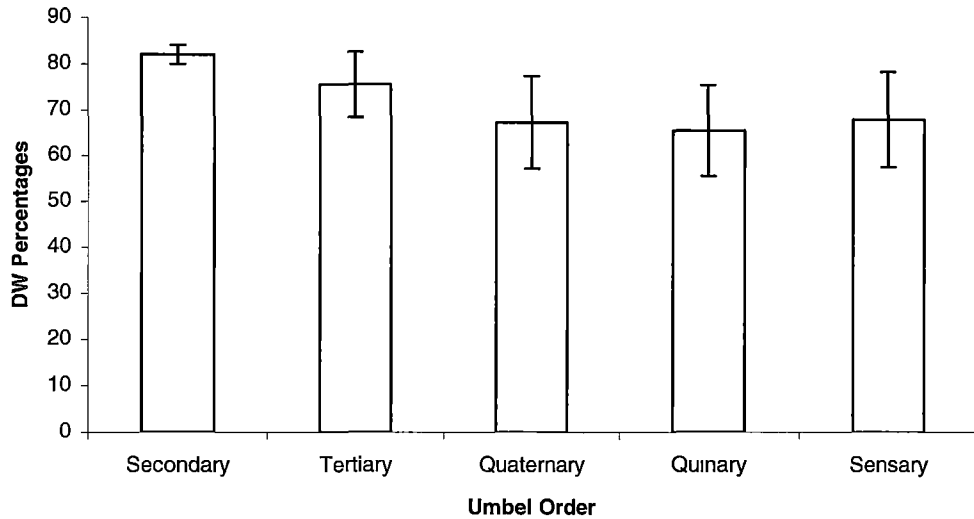
Figure 7.7 Mean seed DW% of *T. nodosa* 16 weeks after flowering. Standard error of mean shown as error bars. LSD (P = 0.05) = 10.4

At 12 weeks after flowering, seeds of *A. caucalis* from the secondary and tertiary umbel orders had undergone significant desiccation indicating a high level of seed maturity being achieved at this stage (Figure 7.8). At 12 weeks after flowering, seeds of *A. caucalis* from the secondary and tertiary umbel order had a mean DM percentage above 85%, while seeds from the quaternary, quinary and senary umbels had a significantly (P < 0.05) lower DW%. At 16 weeks, seeds from each umbel position had achieved a level of desiccation above 85% and there were no significant (P > 0.05) differences in seed DW% between umbel orders.
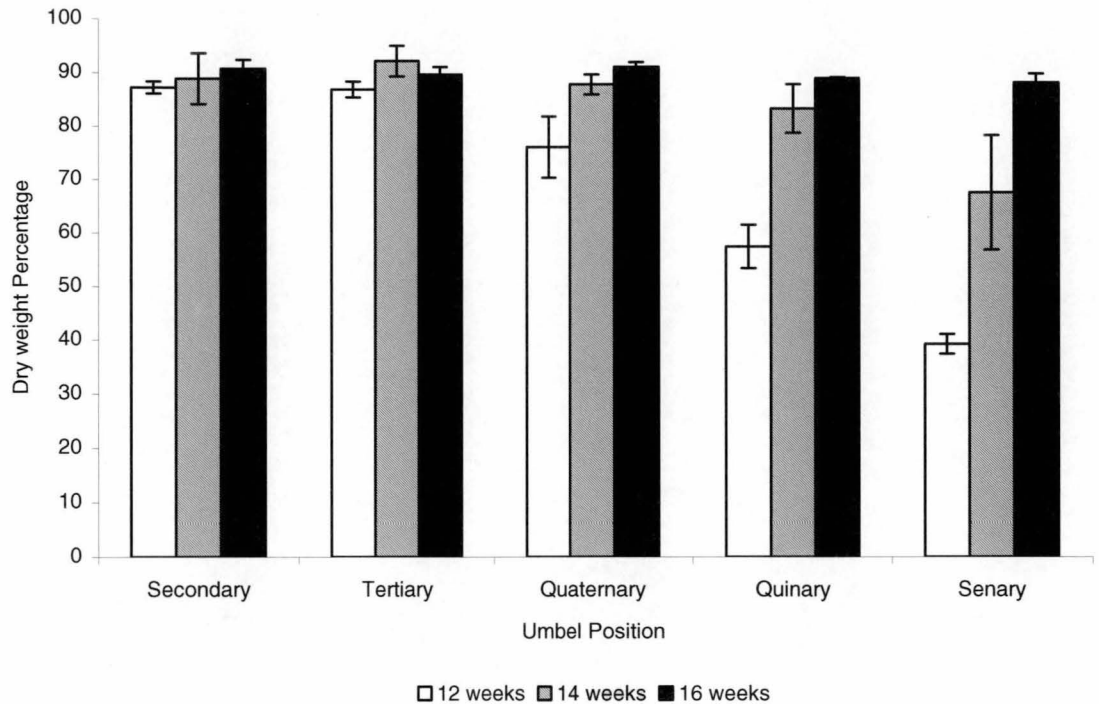
Figure 7.8 Seed DW% of *A. caucalis* seeds at 12, 14 and 16 weeks after flowering Standard error of mean shown as error bars.

The difference in seed maturity between *A. caucalis* and *T. nodosa* was similar in both the field and glasshouse trial. It was concluded that *A. caucalis* flowers approximately 4 weeks earlier than *T. nodosa* and that seed maturity of *A. caucalis* occurs 12-14 weeks after flowering while *T. nodosa* takes in excess of 16 weeks under temperate climatic conditions.

Growth characteristics of A. caucalis and T. nodosa

At 14 weeks after planting the mean plant DW of *A. caucalis* for all four densities was 2.84g, which was significantly (P < 0.001) higher than the mean plant DW of *T. nodosa*, which was only 0.44g. *Anthriscus caucalis* also produced significantly (P < 0.001) more leaf DW and stem DW per plant than *T. nodosa*. The mean LAI of *A. caucalis* was 6.77, which was significantly (P < 0.001) higher than that of *T. nodosa*, which had a LAI of 2.26. *Torilis nodosa* failed to produce any stem growth in the 14 weeks after sowing. In contrast, *A. caucalis* had a mean SWR of 0.34. The mean L/S ratio of *A. caucalis* was 2.16. There was no significant (P > 0.05) difference in SLA between the two species.

Table 7.3 Mean biomass of *T. nodosa* and *A. caucalis*, 14 weeks after planting.

Species	LAI	SLA (cm^2/g)	Total DW per plant (g)	Leaf DW per plant (g)	LWR	Stem DW per plant (g)	SWR	L/S
T. nodosa	2 26	283	0.437	0 437	1 00	0.0	0 0	n a
A. caucalis	6 77	320	2 842	1 938	0 66	0.903	0.34	2.16
LSD (P=0.05)	0 73	n.s.	0 662	0 403	0.03	0.279	0.03	n a.

There was a significant (P < 0.05) species by density interaction for all variables assessed. *Anthriscus caucalis* was found to produce a significantly (P < 0.05) greater amount of DW per plant at each density than *T. nodosa* (Figure 7.9). There was no significant (P > 0.05) effect of plant density on total DW per plant for *A. caucalis* at densities of 1 and 4 plants per tub, but total DW per plant decreased significantly (P < 0.05) as density increased to 16 and 64 plants per tub. There was no significant (P > 0.05) difference in the total DW per plant of *T. nodosa* between densities and the slow vegetative development of *T. nodosa* resulted in small insignificant differences in total DW per plant between densities.
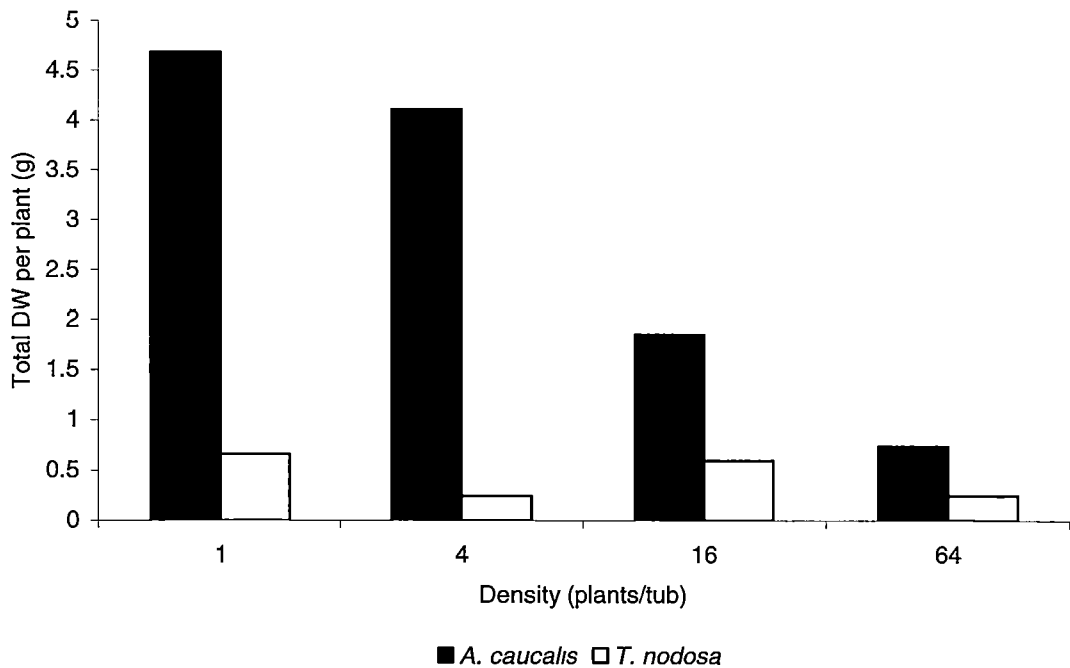
■ *A. caucalis* □ *T. nodosa*

Figure 7.9 The total DW per plant of *A. caucalis* and *T. nodosa* at 14 weeks after sowing as affected by plant density. LSD (P = 0.05) = 1.32

The mean leaf DW of *A. caucalis* decreased from 3.30g/plant at the lowest density to 0.41g/plant at the highest density (Table 7.4). Similarly the mean stem DW fell from

1.38g/plant to 0.33g/plant. The growth of *A. caucalis* was shown to be quite plastic in response to changes in densities. The LWR of *A. caucalis* was significantly (P < 0.05) lower at the highest density than at all other densities, which were not significantly (P > 0.05) different to each other. Similarly the L/S ratio of *A. caucalis* declined with increasing density. No such responses from *T. nodosa* to increasing densities were observed due to the slower growth rate and failure to produce any stem material in the 14 weeks after planting.

There was a significant (P < 0.05) increase in LAI with increasing densities for *A. caucalis* and *T. nodosa*. At the highest density, the mean LAI for *A. caucalis* was 12.1, which was significantly (P < 0.05) higher than at all other densities. Similarly for *T. nodosa* the mean LAI at the highset density was 5.46, which was significantly (P < 0.05) higher than all other densities but significantly (P < 0.05) lower than the mean LAI of *A. caucalis* at densities of 64 and 16 plants/tub. The difference between species is indicative of the rapid growth of *A. caucalis* and its observed greater ability to compete under field conditions in comparison to *T. nodosa*.

Table 7.4 Mean shoot biomass values of *T. nodosa* and *A. caucalis* as affected by plant density.

Species	Density (plants/720 cm²)	LAI	Leaf DW per plant (g)	LWR	Stem DW per plant (g)	SWR	L/S
T nodosa	1	0 17	0 660	1 00	0.000	0 00	.
T. nodosa	4	0 57	0 243	1 00	0 000	0.00	.
T. nodosa	16	2 85	0 595	1.00	0 000	0 00	
T. nodosa	64	5 46	0 245	1 00	0 000	0 00	
A. caucalis	1	1 36	3 300	0 73	1 380	0 27	2 83
A. caucalis	4	5.15	2 800	0 70	1 305	0 30	2 44
A. caucalis	16	8 54	1 249	0 67	0.598	0.33	2 07
A. caucalis	64	12.05	0 408	0 56	0 330	0 44	1 31
LSD (P = 0.05)		2.06	0 807	0 07	0 558	0.07	1.11

There was a significant (P < 0.05) strata effect on all variables assessed except SLA for *A. caucalis* (Table 7.5). Significantly (P < 0.05) more stem DW was produced in the lower stratum (0-10cm) than all other strata. The mean SWR for the 0-10cm strata was 0.51, which was significantly (P < 0.05) higher than for all other strata. The results highlighted the vertical growth habit of *A. caucalis*. As *A. caucalis* matures it reduced its leaf production closer to the ground in favour of stem production such that the vertical growth of the plant is increased and the

photosynthetic area is increased at greater heights. Consistent with this, the LWR and L/S ratio of *A. caucalis* increased with increasing plant height.

There was no significant (P > 0.05) difference in the amount of leaf DW per plant produced by *A. caucalis* between the 0-10, 10-20, 20-30 and 30-40cm strata while there was significantly (P < 0.05) less leaf DM produced in the highest strata compared to the lowest three strata. Significantly (P < 0.05) more leaf area and in turn a higher LAI of *A. caucalis* was produced in the 10-20, 20-30 and 30-40cm strata than the 0-10 and 40-50cm strata. The stem diameter of *A. caucalis* decreased with increasing height. At plant heights of 0-10 cm the mean stem diameter was 7.7 mm and this fell to 3.2 mm at a height of 40-50 cm.

Table 7.5 Mean shoot biomass values for each stratum for *A. caucalis* 14 weeks after planting.

Stratum	LAI	SLA (cm²/g)	Total DW per plant (g)	Leaf DW per plant (g)	LWR	Stem DW per plant (g)	SWR	L/S	Stem Dia (mm)
0-10	1 20[h]	315[a]	0 891[a]	0 473[a]	0.49[d]	0 417[a]	0.51[a]	1.13[e]	7 76[a]
10-20	1.59[ba]	334[a]	0 831[a]	0 566[a]	0 61[c]	0 266[b]	0 39[b]	2.27[c]	6.74[ba]
20-30	1 78[a]	335[a]	0 575[b]	0 429[a]	0.71[b]	0 146[c]	0 29[c]	2.64[c]	5.89[b]
30-40	1 40[ba]	318[a]	0.399[b]	0 334[ab]	0.80[b]	0 064[cd]	0 20[c]	6.09[b]	4 08[c]
40-50	0 81[c]	298[a]	0 146[c]	0.136[b]	0.89[a]	0.010[d]	0 11[d]	10.38[a]	3 17[c]
LSD (P = 0 05)	0 39	n.s	0.240	0.198	0 08	0.095	0 08	3 27	1.46

There was a significant (P < 0.05) density by stratum interaction in stem diameter for *A. caucalis* (Figure 7.10). At the lowest density the change in stem diameter with increasing plant higher was large. At a density of 1 plant/tub the mean plant diameter at the base was 9.3 mm and this fell to 4.5 mm at a height of 30-40cm. In contrast at higher densities the differences in stem diameter were not as discernibile. At a density of 64 plants/tub the mean stem diameter at the lowest strata was 4.6mm and this fell to 3.5mm at a height of 30-40cm.
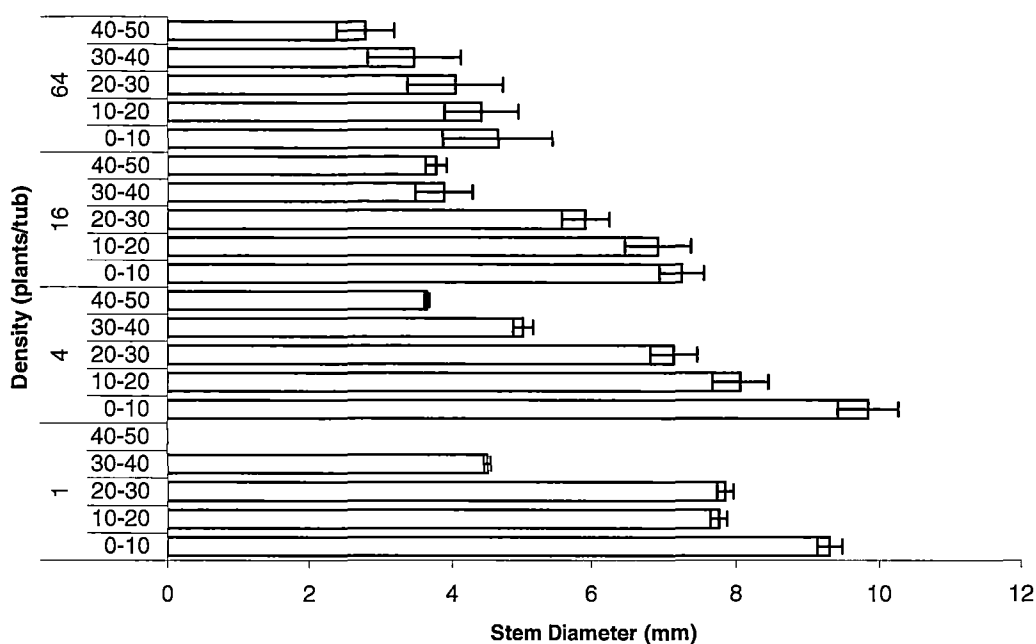
Figure 7.10 Effect of density and strata level on the stem diameter of *A. caucalis*. LSD (P < 0.05) = 1.10. Note Standard error of means shown as error bars.

Similarly there were significant (P < 0.05) density by stratum interactions in plant DW, leaf DW and stem DW per plant for *A. caucalis* (Table 7.6). The upright growth of *A. caucalis* provides the plant with the ability to compete vertically with crops and surrounding weeds as well as being able to colonise surrounding space with horizontal leaf development.

At the lower density vegetative stem development did not reach a height above 40cm and this was likely to be in response to the lower competition for light. As the density increased the stem diameter per plant was also found to significantly (P < 0.05) decrease, a characteristic plastic response to competition by producing thinner more elongated stems. As density increased *A. caucalis* produced less shoot biomass closer to the ground in preference to more erect growth with more shoot biomass being produced at greater heights. In contrast, when the density was low, individual plants of *A. caucalis* produced larger stems supporting a larger leaf biomass that could colonise the available space around them.

Table 7.6 Mean shoot biomass values on a per plant basis for each stratum for *A. caucalis* 14 weeks after planting.

Density	Stratum (cm)	Total DW per plant (g)	Leaf DW per plant (g)	Stem DW per plant (g)
1	*0-10*	1.62	0.92	0.70
	10-20	1.69	1.25	0.44
	20-30	0.67	0.49	0.18
	30-40	0.52	0.46	0.06
	40-50	0.18	0.18	0.00
4	*0-10*	1.33	0.68	0.65
	10-20	1.00	0.65	0.35
	20-30	1.04	0.83	0.21
	30-40	0.59	0.50	0.09
	40-50	0.15	0.14	0.01
16	*0-10*	0.40	0.21	0 19
	10-20	0.41	0.25	0.16
	20-30	0.37	0.27	0.10
	30-40	0.30	0.25	0.05
	40-50	0.13	0.11	0.02
64	*0-10*	0.16	0.06	0.10
	10-20	0.17	0.08	0.09
	20-30	0.17	0.10	0.07
	30-40	0.14	0.09	0.05
	40-50	0.09	0.08	0.01
LSD (P = 0.05)		0.48	0.40	0.19

At 14 weeks after planting, *T. nodosa* plants had grown to a height of less than 20cm and produced no stem material. Significantly (P < 0.05) more plant DW was produced in the 0-10cm stratum than the 10-20cm stratum (Table 7.7). The LAI was in turn significantly (P < 0.05) higher at the lower stratum. There was no significant (P > 0.05) difference in SLA between the two stratum levels for *T. nodosa.*

Table 7.7 Mean shoot biomass values for each stratum of *T. nodosa* 14 weeks after planting.

Stratum	LAI	SLA (cm^2/g)	DW per plant (g)
0-10	1.80	278	0.401
10-20	0.46	286	0.036
LSD (P = 0.05)	0.31	n.s.	0.131

There was a significant (P < 0.05) density and strata interaction for leaf area and plant DW for *T. nodosa.* No shoot material was produced in the 10 to 20cm stratum of *T. nodosa* at densities of 1 and 4 plants/tub. At the two highest densities some shoot material was produced in the 10-20 stratum although significantly (P < 0.001) lower than that produced at the lower stratum. This resulted in a significant (P < 0.05) interaction between stratum and plant density. At the lower density *T. nodosa* leaves were larger and more prostrate colonising the surrounding area. As the density

increased *T. nodosa* growth habit became slightly more vertical and the leaves produced from the crown of the plant spread out in a more upright arrangement. This plasticity in the growth habit of *T. nodosa* could give the plant some ability to compete for light when surrounding competition was high, however its ability to compete strongly could be limited by its prostrate nature and slow vegetative growth rate.

Table 7.8 Mean shoot biomass values of *T. nodosa* as affected by density and stratum level 14 weeks after planting

Density per tub	Height	LAI	SLA (cm^2/g)	Total DW per plant (g)
1	0-10	0 17 ±0.05	195 ± 12	0.67± 0.24
1	10-20	0 00 ± 0 00	N/A	0.00 ± 0 00
4	0-10	0 57 ± 0.06	466 ± 108	0 24 ± 0 04
4	10-20	0 00 ± 0 00	N/A	0 00 ± 0 00
16	0-10	2.29± 0.12	210 ± 16	0.50 ± 0 05
16	10-20	0 56 ± 0 21	281 ± 14	0.09 ± 0 04
64	0-10	4.19 ± 0.76	242 ± 13	0 19 ± 0 04
64	10-20	1 27 ± 0.31	291 ± 13	0.05 ±0 01
LSD (P = 0 05)		0 89	n s	0 26

In comparison to *A. caucalis*, *T. nodosa* failed to produce vegetative stem elongation even at the highest density and this resulted in no plant material being produced above 20cm. This distinct difference between the two species suggested that the competitive ability of *T. nodosa* was much lower than that of *A. caucalis* due to the more rapid stem development of *A. caucalis*. In comparison the vegetative development of *T. nodosa* was slow and the plant failed to grow upright to competing heights. However the procumbent stems of *T. nodosa* observed under field conditions compete for light with stems intertwining with the crop giving it the ability to intercept light at a greater height in the developing canopy.

7.4 Discussion

The occurrence of *A. caucalis* is more widespread than *T. nodosa*. A contributing factor to this distribution pattern is that at the time of pyrethrum harvest, which commences during the last week in December and continues through into February, *A. caucalis* has reached a level of maturity at which the majority of seeds have desiccated and are more readily dispersed from their umbel structure. The seed also can be readily attached to and transported via harvest machinery. The increases in seed DW% with time and the high level of desiccation achieved at each umbel

position at final assessment for *A. caucalis* supported this finding. In contrast *T. nodosa* has been observed to be more restricted in it is spread and newly germinated plants are often observed to occur within the close vicinity of *T. nodosa* stubble.

There was a difference in the viability of *T. nodosa* seeds between locations. At the final assessment the mean growth stage of *T. nodosa* was early seed to mid seed development for locations Kindred and Table Cape. At North Motton and Hagley the mean growth stage was mid seed development and this difference in the level of seed maturity between locations could have resulted in the seed viability differences.

The low viability of *T. nodosa* seeds at the earlier assessment dates was a result of low levels of maturation of the seed. On the 11th of December 2001 the mean growth stage of *T. nodosa* at each location was below early seed development and as such no seeds were fully mature. In comparison *A. caucalis* matured earlier and low seed lot viability in the earlier assessments was associated with undeveloped embryos. The viability of *A. caucalis* at final assessment was approximately 80% for each location. Damaged embryos and endosperm as well as a small percentage of embryolessness resulted in this 20% non-viability.

The difference in germination between umbel positions for *T. nodosa* was a result of immaturity of the developing seed as reflected by the low DW percentages at the time of assessment of seeds from the higher umbel orders. In support of this a positive linear relationship was obtained between the mean germination percentage of *T. nodosa* seeds and the DW percentages of the various umbels. A lower germination percentage was obtained for seeds from the primary umbels in comparison to the secondary umbels at Table Cape and Kindred and production of non-viable seed was found to be the causative factor.

In contrast to the observed difference in *T. nodosa*, differences in germination of *A. caucalis* seeds from differing umbel positions were not attributed to immaturity of the seeds. Seeds from each umbel position had reached a high level of desiccation, which were not significantly ($P > 0.05$) different to each other at final assessment. The results indicated that there are different levels of dormancy being displayed from differing umbel positions for *A. caucalis*. The seed dormancy of *A. caucalis* has been

shown to be a combination of both physical exogenous dormancy, which is broken by scarification, and non-deep physiological endogenous dormancy, which is broken by dry storage. The seed treatment in the current study was 30 weeks of dry storage at 20°C and this resulted in seeds from the senary umbel order having greater than 40% germination. Seeds from lower umbel orders did not reach above 35% germination. In addition, examination of the *A. caucalis* seed lots following scarification found that there was greater response with seeds from the primary umbels than from umbels of the high orders. The results of this study have demonstrated that *A. caucalis* produced seeds with different levels of dormancy with the seeds from the higher order umbels having a lower level of seed dormancy. Different levels of seed dormancy are an adaptive feature of some weed species (Stabell *et al.*, 1996), allowing their emergence to be spread over a greater time period. Similar responses have been reported with *Apium graveolens* from the Apiaceae family (Thomas *et al.*, 1979; Hassell and Kretchman, 1997). When seeds are harvested from one plant or a population at the same time, the population obtained will contain seeds of a range of sizes and weights. It is therefore expected that differences in dormancy and germination characteristics will occur in seeds from different umbel positions (Thomas *et al.*, 1979).

There were substantial differences in the vegetative development of the two species and their response to increasing seedling density. *Anthriscus caucalis* had a more erect growth habit when compared to the prostrate growth habit of *T. nodosa*. At flowering *T. nodosa* becomes reliant on the development of procumbent stems to compete for light resources. In contrast, *A. caucalis* had rapid vegetative stem elongation to compete vertically and its large compound pinnate leaves colonised surrounding ground when the density of the population was low. This behaviour of *A. caucalis* will allow it to compete strongly with other weeds in pyrethrum and also with the crop itself. During mid to late winter the pyrethrum crop is slow growing and weed seedlings emerge in the open spaces between pyrethrum plants. *Anthriscus caucalis* during this period has the ability to colonise this ground by producing large prostrate leaves and also rapid vegetative stem development. This allows *A. caucalis* to grow above pyrethrum suppressing crop growth and flowering during spring. When the plant density is high, *A. caucalis* compensates for this by producing smaller stems and less leaf material closer to ground in favour of more rapid upright

growth. Similarly *T. nodosa* has the ability to colonise surrounding bare ground with prostrate compound leaves but fails to compete vertically due to its slow vegetative development and more prostrate growth habit. *Torilis nodosa* overcomes this by relying on its procumbent stems to intertwine and grow vertically with the surrounding vegetation to complete its life cycle. *Torilis nodosa* would therefore not be expected to impact as strongly on pyrethrum yield as *A. caucalis*. However at high densities *T. nodosa* has the ability to colonise the surrounding ground and grow more upright which would result in a restriction to the early spring vegetative growth of pyrethrum.

7.5 Conclusion

From the examination of the growth of *A. caucalis* and *T. nodosa* in pyrethrum, it was clearly demonstrated that *A. caucalis* flowered and matured earlier than *T. nodosa* and that the maturity of *A. caucalis* coincided with that of the pyrethrum harvest. This could give *A. caucalis* a competitive advantage over *T. nodosa* in that it is able to mature and disperse seeds prior to pyrethrum harvest and that seeds that have not yet dispersed from the parent plant prior to harvest have reached a level of seed maturity such that their dispersal is aided by pyrethrum harvest. This would lead to increased spread throughout the field and also increase the likelihood of seed transport on harvesting machinery. The results of this study have also provided a quantitative assessment of the growth of *A. caucalis* and *T. nodosa* and highlighted the differing growth forms of both species which contribute to their ability to compete as weeds of pyrethrum. Both *A. caucalis* and *T. nodosa* are problematic weeds not only due there negative impact on production but due to their ability to produce and disperse propagules leading to a build up of weed seeds in the seedbank, which will impact more severely on production in following seasons and potentially on following crops. There is therefore an immediate need for control options to be developed.

Chapter 8 Chemical control of *A. caucalis* and *T. nodosa*.

8.1 Introduction

Pyrethrum is a perennial crop and as such the weed flora composition that inhabits this crop is different to the many annual crops that dominate the intensive cropping system in Tasmania. The atypical weed flora composition combined with the relative newness of the pyrethrum industry has resulted in the lack of reliable information on selective herbicides for use in pyrethrum and therefore limited the effectiveness of the current herbicide programme to control certain weed species.

In Tasmania, some weed species in pyrethrum have proven particularly difficult to control. These include weeds that are commonly found in vegetable cropping systems such as *Senecio vulgaris* (groundsel), *Galium aparine* (cleavers) and *Trifolium repens* (white clover) as well as the previously uncommon weeds *Anthriscus caucalis* and *Torilis nodosa*. Although the control of a wide range of weed species in pyrethrum requires further investigation, the scope of this research study was limited to *A. caucalis* and *T. nodosa* as these two Apiaceae species were identified by industry representatives as being the most problematic weeds. Due to the current paucity of information on how to control these weeds in intensive cropping systems it was considered imperative to develop a herbicide program for their control.

The previous chapters of this study covered the occurrence and severity as well as aspects of biology and ecology of *A. caucalis* and *T. nodosa* in pyrethrum. This chapter reviews the research literature covering the efficacy of herbicides with different modes of action to control the two Apiaceae species and their likely selectivity in pyrethrum. This review formed the basis of the selection of herbicide products for evaluation in glasshouse and field trials for the control of *A. caucalis* and *T. nodosa*.

8.2 Mode of action of herbicides

For a weed management programme to be effective the herbicides must be both selective and active. Herbicide activity describes the phytotoxic effects of a chemical on plant growth and development, while herbicide selectivity refers to the phenomenon where a chemical is lethal to target plant species in a mixed plant population without harming or only slightly affecting the other plants. The activity of a herbicide is also broadly classified as either systemic (translocated) or non-systemic (contact). Contact herbicides kill only parts of the plants they contact, and usually have little or no residual effect. Conversely, translocated herbicides are transported within the plant to parts remote from the point of application. Herbicide applications can be either foliage applied or soil applied. Soil applied herbicides are applied at pre-planting or pre-emergence, while the foliage applied herbicides are applied post emergence. Soil applications help prevent weed emergence and establishment, thus enabling the crop to grow in a weed-free environment from emergence, while foliage applied herbicides often ensure a better kill of deep-rooted weeds. Some herbicides are both foliage and soil applied.

Herbicide activity and selectivity is affected by many factors: the mode of action of the herbicide, the amount of herbicide applied, the formulation of the herbicide, the method of application, the stage of growth of the plant, the environmental conditions and cultivation operations. Mode of action is defined as the mechanism by which a herbicide kills a plant. In Australia, herbicides are grouped according to their mode of action (Table 8.1).

Table 8.1 Classification of herbicide group by mode of action in Australia.

Group	Mode of action
A	Acetyl coenzyme A carboxylase (ACC-ase) inhibitors
B	Inhibitors of acetolactate synthase (ALS inhibitors)
C	Inhibitors of photosynthesis at photosystem II
D	Inhibitors of tubulin formation
E	Inhibitors of mitosis
F	Inhibitors of carotenoid biosynthesis
G	Inhibitors of protoporphyrinogen oxidase (PPO)
H	Inhibitors of protein synthesis
I	Disrupters of plant cell growth
J	Inhibitors of fat synthesis
K	Multiple sites of action
L	Inhibitors of photosynthesis at photosystem I
M	Inhibitors of EPSP synthase
N	Inhibitors of glutamine synthetase

(Taken from Avcare, 2000).

Within each herbicide group there are a number of differing active ingredients (constituents), which are classified into chemical families. The active ingredient is that part of a commercially manufactured herbicide that is biologically active. Herbicides in the same family, generally, have the same site of action (Rao, 2000).

Acetyl coenzyme A carboxylase (ACC-ase) inhibitors

Group A herbicides are inappropriate for examination due to their activity being restricted to monocotyledon species and therefore having no potential activity on *A. caucalis* and/or *T. nodosa*.

Inhibitors of acetolactate synthase (ALS inhibitors)

Little effort has been made to examine the role of group B herbicides due to their perceived low levels of selectivity of use in pyrethrum. Eclipse® (a.i. 71.4% metosulam) has been investigated for the control of *Trifolium repens,* and shown to have selectivity for use in pyrethrum (Anon. 2003). Chemical families belonging to this group include the sulfonylureas, imidazolinones and sulfonamides. No chemicals

from these families are registered for use in carrot crops in Australia (Anon. 2000c), indicating that Apiaceae species may be susceptible to ALS inhibitors. There is a paucity of published information regarding the activity of this group of herbicides to Apiaceae weed species, although imazethapyr, an imidazolinone herbicide, is reported to provide control of *Bifora testiculata* (Black *et al.*, 1994).

Herbicides from this group may provide activity against *A. caucalis* and or *T. nodosa* and have some level of selectivity for use in pyrethrum. Three chemicals from this group were selected for examination based on their availability and unknown activity and selectivity for use in pyrethrum. They were imazamox, rimsulfuron and flumetsulam.

Inhibitors of photosynthesis at photosystem II

Group C herbicides; Totril® (a.i. 25% ioxynil) and Linuron® (a.i. 50% linuron) are currently used in pyrethrum, indicating that pyrethrum displays some level of tolerance to inhibitors of photosynthesis. This group of herbicides is large compared with other groups, with the majority of herbicide products belonging to the chemical families Triazines, Ureas and Nitriles. Metribuzin at a rate of 0.6 kg/ha, and bentazone and atrazine in combination (1:1) at 1.4 kg/ha have been shown to be selective for use in pyrethrum in Kenya (Wanjala, 1989). Metribuzin has displayed activity against Apiaceae species *Conium maculatum* (Jeffery and Robison, 1990), *Daucus carota* (Stachler and Kells, 1997), *Scandix pecten-veneris* (Pozuelo *et al.*, 1989) and *Bifora testiculata* (Black *et al.*, 1994). Bentazone has been reported as providing activity against *Daucus carota* (Stachler and Kells, 1997). Other group C herbicides which have displayed activity against Apiaceae species include cyanazine and simazine. Cyanazine has been reported as providing activity against *Daucus carota* (Stachler and Kells, 1997) and *Bifora testiculata* (Black *et al.*, 1994). Simazine has been reported as providing activity against Apiaceae species *Torilis arvensis* (De Prado *et al.*, 1990) and *Scandix pectin-veneris* (Fryer and Makepeace, 1972; Pozuelo *et al.*, 1989). Due to the potential selectivity of herbicides belonging to this group for use in pyrethrum and the cited activity of metribuzin, bentazone, cyanazine and simazine to Apiaceae species, these chemicals were identified as requiring examination for the control of *A. caucalis* and *T. nodosa* in pyrethrum.

Inhibitors of tubulin formation

At present there is an over reliance on pendimethalin, a group D herbicide, to provide preemergence control of most annual grasses and certain broadleaf weeds in pyrethrum. Pendimethalin controls weeds by inhibiting seedling development, but will not control established weeds. Pendimethalin (as Stomp® EC, 33%) is applied at rates as high as 1.98 kg/ha in pyrethrum and up to 3.96 kg/ha is applied over a growing season. Pendimethalin provides control of *Capsella bursa-pastoris*, *Polygonum aviculare*, *Chenopodium album* and *Stellaria media*. It also provides useful suppression of *Fumaria* spp., *Sonchus oleraceus*, *Solanum nigrum* and *Raphanus raphanistrum* (Anon. 2000c). Due to the high levels of application of pendimethalin in pyrethrum, complete suppression of these weeds is often obtained. No activity against *A. caucalis* or *T. nodosa* has been recorded with pendimethalin, which is consistent with its registration for use in Apiaceae crops (Anon. 2000c). Other dinitroaniline herbicides have also been found to provide little activity against Apiaceae weeds (Pozuelo *et al.*, 1989). The dinitroaniline chemical family of herbicides have a mode of action which is selective for use in pyrethrum, however they have low levels of activity against Apiaceae species and this will prevent their use for the control of *A. caucalis* and *T. nodosa*.

Inhibitors of carotenoid biosynthesis

Only a limited amount of work has been previously undertaken to examine the role of inhibitors of carotenoid biosynthesis for selective use in pyrethrum although diflufenican is currently registered for use. Diflufenican is a Group F residual herbicide belonging to the nicotinanalide chemical family. Brodal® (a.i. 50% diflufenican) is applied at rates of 200 to 400 ml/ha for the control of *Galium aparine* in pyrethrum and suppression of *Trifolium* spp. Diflufenican is also used for preemergence or early postemergence control of weeds in cereals. As a postemergence application it is used in Tasmania for selective weed control in lupins, field peas, clover based pastures and oilseed poppies. Selectivity between crop and weeds is primarily due to differential uptake and indirectly to translocation (Haynes and Kirkwood, 1992). The rooting region of the cereal plants occurs at a greater depth than those of the weeds and according to Haynes and Kirkwood (1992) "depth protection" is one of the major reasons for selectivity of soil-applied diflufenican. Residual activity can be expected for up to 8 weeks after application under

favourable growing conditions. Susceptible weeds germinate but show immediate chlorosis followed by a mauve-pink discoloration (Anon. 2000c). Diflufenican has been observed to induce chlorosis in pyrethrum (Groom, pers. comm. 2001) and this may potentially limit the use of diflufenican in the future if yield losses occur. There is a little information regarding the activity of inhibitors of carotenoid biosynthesis on Apiaceae species and as a result of this, and concerns about the selectivity of use of diflufenican in pyrethrum, alternative chemical inhibitors of carotenoid biosynthesis should be examined for their selectivity and weed spectrum activity. Two chemicals, clomazone and picolinafen, from this group were selected for investigation due to their availability, potential activity on Apiaceae species and unknown selectivity for use in pyrethrum.

Inhibitors of protoporphyrinogen oxidase (PPO)

The only product belonging to this group registered for use in pyrethrum is oxyfluorfen. Oxyfluorfen belongs to the diphenylether family of herbicides. Goal® (a.i. 24% oxyfluorfen) is applied at rates of 2.0 to 4.0 l/ha in pyrethrum for broadleaf weed control. It is primarily a soil-applied herbicide that is readily absorbed by the roots (Rao, 2000). Oxyfluorfen has a systemic mode of action and can be applied to the foliage as well but is generally not as effective (Rao, 2000). The activity of oxyfluorfen has been variable when applied to Apiaceae vegetable crops. Gorske (1981) reported that carrots generally tolerated oxyfluorfen but the wettable powder (WP) formulation of oxyfluorfen was safer than the emulsifiable concentrate (EC) and tolerance varied with plant age. Applications of oxyfluorfen in either a WP or EC resulted is varying degrees of leaf necrosis when applied to celery (Gorske, 1981). No reported activity of oxyfluorfen has been documented or observed on *A. caucalis* and *T. nodosa* when applied in pyrethrum. Due to oxyfluorfen's selectivity for use in pyrethrum and some level of activity against related Apiaceae vegetable crops, herbicides belonging to this group of chemicals should be further investigated. Herbicides selected for examination into their selectivity of use in pyrethrum and activity against *A. caucalis* and *T. nodosa* from this group were sulfentrazone, carfentrazone ethyl and flumioxazin.

Disrupters of plant cell growth

This group of chemicals, which include the phenoxy herbicides, was the first developed selective herbicide group. Only a minor amount of research effort has been undertaken on the use of this group of chemicals in pyrethrum due to their low level of selectivity (Frost, pers comm. 2001, Groom, pers comm. 2001). The relatively new quinoline carboxylic acid family of herbicides was identified as potentially providing activity against Apiaceae species. Quinclorac is a systemic herbicide that can be soil or foliage applied. It is used in direct-seeded and transplanted rice to control important annual grass weeds (Rao, 2000). Quinmerac, which is structurally very similar to quinclorac, has been shown to effectively control important broadleaf weeds such as *Galium aparine* and *Aethusa cynapium*, an Apiaceae weed in sugarbeet (Bartels, 1995). Due to the reported low levels of selectivity of herbicides within in this group for use in pyrethrum, only quinclorac and quinmerac were identified as warranting examination. Unfortunately quinmerac was not available in Australia for use in this study.

Herbicide with multiple sites of actions

This group of herbicides is quite large and includes the amide chemical family. A number of herbicides from the amide family have been examined for use in pyrethrum previously, however low levels of selectivity or poor activity against the target species have limited their use (Frost, pers comm. 2001). A small number of other chemical families which are also classified under alternative mode action are included in this group. This includes the nitrile and carbamate chemical families and herbicides belonging to these families have been identified as being non selective for use in pyrethrum (Groom, pers comm. 2001). Dimethenamid a recently developed amide herbicide was identified as requiring examination into its selectivity for use in pyrethrum and activity for controlling the emergence of broadleaf weeds.

Remaining Groups

Herbicides belonging to groups E, H, J, L, M and N were not investigated due to their low levels of selectivity for use in pyrethrum (Groom, pers comm. 2001). There are three chemical families of herbicides belonging to Group E; thiocarbamates, carbamates and organophosphorus. Herbicides belonging to this group have been identified as being non selective for use in pyrethrum. The same applies to Group H

and J which contain only one herbicide each, thiobencarb and 2,2 –DPA. Bipyridils are the only chemical family belonging to Group L (inhibitors of photosynthesis at photosystem I), provide only contact activity and has limited selectivity for use in crop situations. This group of chemicals is quite small and contains the herbicides paraquat and diquat. Group M (inhibitors of EPSP synthase) and Group N (inhibitors of glutamine synthetase) have only one registered herbicide each. Glyphosate is a non selective systemic Group M herbicide and glufosinate is a non selective contact Group N herbicide. These two herbicides have no selectivity for use in pyrethrum.

Past research

Control of *A. caucalis* and *T. nodosa* in pyrethrum has proven difficult due to the failure to determine a suitable herbicide regime for these weeds that is both active and selective. Many attempts in past have been undertaken and although a number of herbicides have shown activity against *A. caucalis* and *T. nodosa*, low pyrethrum tolerance has restricted their use. Examples of this includes Bromicide[®] (a.i. 20% bromoxynil,), MCPA[®] (a.i. 50% MCPA) and Diuron[®] (a.i.50% diuron) (Smith *et al.* 1997a; 1997b; 1997c).

Only a small number of herbicides are currently registered for use in pyrethrum; pendimethalin (Group D), diflufenican (Group F), ioxynil (Group C), linuron (Group C), oxyfluorfen (Group G) and fluazifop-P (Group A). Due to the high level of occurrence of *A. caucalis* and *T. nodosa* in pyrethrum it is likely that these herbicides provide little activity against these weeds. Related herbicides from the same groups may provide acceptable levels of selectivity for use in pyrethrum as they have the same mode of action but may provide some activity against *A. caucalis* and or *T. nodosa* by having a differing site of action.

8.3 Summary

It was concluded that chemicals that inhibit tubulin formation have low levels of activity on Apiaceae species and although selectivity for use in pyrethrum is high little effort should be applied to investigating their activity against *A. caucalis* and *T. nodosa*. Herbicides that inhibit photosynthesis may potentially provide activity against Apiaceae species although their selectivity for use in pyrethrum requires

substantial investigation due to reported crop phytotoxicity with low levels of application of the herbicides linuron and ioxynil. Herbicides selected for examination from this group include simazine, cyanazine, metribuzin and bentazone. Other modes of action with potential activity on Apiaceae species include PPO inhibitors and ALS inhibitors. Products from the PPO inhibiting group that had not previously been screened for use in controlling *A. caucalis* and *T. nodosa*, and that became available during this study were: sulfentrazone, carfentrazone ethyl and flumioxazin. Products from the ALS inhibitors group were imazamox, flumetsulam and rimsulfuron. Although no literature was cited regarding the activity of inhibitors of carotenoid biosynthesis on Apiaceae species, herbicides with this mode of action may provide some selectivity in pyrethrum as observed with the current use of diflufenican. Clomazone and picolinafen were identified as two herbicides that should be examined. New products, identified as likely to become commercially available for use in Australia, which have not been examined for use in pyrethrum were dimethenamid and quinclorac (Frost, pers comm. 2001). Other products, which appear to have activity against Apiaceae species, namely dicamba, clopyralid, diuron, bromoxynil and MCPA, are limited by having high levels of phytotoxicity (Groom, pers. comm. 2001) and as such their investigation is not warranted. Those herbicides identified from the literature as potentially having selectivity for use in pyrethrum and activity to control *A. caucalis* and or *T. nodosa* are examined in the following chapters.

Chapter 9 Herbicide efficacy

9.1 Introduction

Apiaceae species *A. caucalis* and *T. nodosa* had not previously been observed or viewed as agricultural weeds in northern Tasmania prior to the establishment of pyrethrum as a commercial crop in this area. With the emergence of new weed species, solutions were required quickly to suppress their spread and reduce their impact. No cultural control of weeds through cultivation is available following the establishment of pyrethrum, with the production life of pyrethrum usually lasting for at least 4 years. As a result, weed management in the short-term remained reliant on chemical use. It was critical for the continuing success of this industry to identify herbicides that were both effective and selective for use in pyrethrum to control *A. caucalis* and *T. nodosa*.

Identifying effective and selective herbicides provides contract growers of pyrethrum with more options and potentially allows for a reduction in chemical inputs by reducing the reliance on a small number of products. Herbicides identified from the literature as being potentially active on *A. caucalis* and/or *T. nodosa* were: flumetsulam, imazamox, rimsulfuron (Group B), cyanazine, simazine, metribuzin, bentazone (Group C), clomazone, picolinafen (Group F), carfentrazone-ethyl, sulfentrazone, flumioxazin (Group G), quinclorac (Group I), and dimethenamid (Group K). To determine the potential weed control efficacy of these products a number of preliminary pot trials were undertaken over two years. The soil behaviour of these herbicides is given in Appendix A.7.

9.2 Materials and Methods

General Procedures

All pot screening trials were undertaken using 12.5cm diameter pots. For foliage-applied applications a standard potting mix medium was used (Appendix A.1). For preemergence (soil applied) applications a red ferrosol soil was used. The soil used in each preemergence experiment was collected from experimental field site A (chapter 13), and the soil characteristics are detailed in Table 13.1. In the preemergence trials a known number of seeds, (25 to 50) were sown just below (<

5mm) the surface. Following planting, pots were watered to induce germination and herbicides were applied 24 hours after sowing. Foliage applied herbicides were applied at defined growth stages and watering was restricted in the proceeding 24 hours. Unless stated otherwise all trials were arranged as a randomised complete block design on permanent outside benches at the University of Tasmania, Hobart (42^0 90' S, 147^0 32' E). Mean daily maximum and minimum temperatures for Hobart are given in Appendix A.11.

All weed efficacy responses were assessed using the 0 to 100 injury rating system (Appendix A.6). For preemergence applications the number of emerged seedlings at the time of assessment was also recorded. At the completion of each trial all above ground material harvested and weighed. The mean fresh weight reduction (FWR) percentage was then calculated as follows;

Mean FWR percentage = (Mean FW control − Mean FW treatment)/Mean FW control * 100.

Emergence percentages and injury ratings were transformed using arcsine squared root transformation. Transformed data were subjected to analysis of variance with Fishers Protected LSD test (P < 0.05) for mean separation. All treatments were replicated four times.

All herbicide applications were made using a CO_2-pressurised plot sprayer. The sprayer was equipped with 4 single nozzle TeeJet® Standard Flat-Spray Tips (8002VS) on a 2.0m boom set 50cm above the spraying surface. The sprayer was calibrated to deliver 200 l/ha at 220 KPa of pressure. To achieve the desired application rate a walking speed of 1m/s was maintained.

Preemergence control of A. caucalis and T. nodosa

Fifty seeds of *T. nodosa* and *A. caucalis* were sown at a depth of 5mm in 12.5cm diameter pots containing a red ferrosol soil on the 9th November 2001. Applications of dimethenamid (as Frontier® EC, 90%), clomazone (as Command® EC, 48%),

cyanazine (as Bladex[®] FL, 50%), simazine (as Gesatop[®] FL, 50%) and sulfentrazone (as Authority[®] DG, 75%) were applied at rates listed in Table 9.1.

Efficacy of quinclorac

Following the initial preemergence screening trial, quinclorac (as Facet[®] FL, 22%) became available for evaluation. Twenty-five seeds of *T. nodosa* and 40 seeds of *A. caucalis* were sown to a depth of 5 mm in 12.5 cm diameter pots containing a red ferrosol soil. In addition, three seedlings per pot of *A. caucalis* and *T. nodosa* were established in separate pots to determine the foliage applied efficacy of quinclorac. Quinclorac was applied on the 21st July 2002 at rates listed in Table 9.1. Quinclorac was applied preemergence and to established seedlings at the 4-leaf stage of growth.

Efficacy of flumioxazin

Early in 2003 flumioxazin (as Pledge[®] WDG, 50%) became available for evaluation. Twenty-five seeds of *T. nodosa* and 50 seeds of *A. caucalis* were sown to a depth of 5 mm in 12.5 cm diameter pots containing a red ferrosol soil. In addition, three seedlings per pot of *A. caucalis* and *T. nodosa* were established in separate pots to determine the foliage applied efficacy of flumioxazin. Flumioxazin was applied preemergence and to established seedlings at the 4-leaf stage of growth. Flumioxazin was applied at rates shown in Table 9.1 on the 23rd April 2003.

Timing of postemergence applications for the control of T. nodosa and A. caucalis

Seeds of *T. nodosa* and *A. caucalis* were sown at three different planting dates separated by 21 days, to give three differing growth stages at time of herbicide application; 1-2 true leaf, 3-4 true leaf and 7-8 true leaf. Three seedlings per pot were established and herbicides were applied on 11th February 2002.

Carfentrazone-ethyl (as Hammer[®] EC, 24%), carfentrazone ethyl (as Affinity[®] WDG, 40%), imazamox (as Raptor[®] WDG, 70%) and metribuzin (as Lexone[®] DF, 75%) were applied at rates shown is Table 9.2. Analysis of data was completed using a two factor (growth rate by herbicide treatment) with replication ANOVA.

Postemergence control of A. caucalis and T. nodosa

A postemergence pot trial was established in the autumn of 2003 to determine the susceptibility of *A. caucalis* and *T. nodosa* to a range of selected herbicides, including some new previously untested products. As a result of the potential to only observe the applications of these herbicides under field conditions for one-season, selectivity of these herbicides for use in pyrethrum was assessed by establishing pyrethrum seedlings in pots.

Seeds of *T. nodosa* and *A. caucalis* were sown at a depth of 5 mm in 12.5 cm diameter pots containing a standard potting mix (Appendix A.1). Excess seedlings were removed at the 2-3 leaf stage to give three seedlings per pot. Pyrethrum seedlings were established in seedling trays with a standard seedling mix (Appendix A.2). At the 3-4 leaf stage of growth, pyrethrum seedlings were transplanted into pots with one pyrethrum plant per pot established. Plants were allowed to stabilise for 21 days following transplanting. At the time of herbicide application *T. nodosa* and *A. caucalis* seedlings were at the 5-6 leaf stage of growth and pyrethrum seedlings at the 6-8 leaf stage of growth.

Herbicides Flumetsulam (as Broadstrike® WDG, 80%), Rimsulfuron (as Titus® DF, 25%), Picolinafen (as Sniper® WDG, 75%), Imazamox (as Raptor® WDG, 70%) and Bentazone (as Basagran® SC, 48%) were applied at rates listed in Table 9.4 on 21st April 2003. Imazamox was applied with the addition of adjuvant Pulse® a non-ionic organosilicone at a rate of 0.1% (v:v). All rates of herbicide application are stated as an equivalent rate per hectare basis.

9.3 Results

Preemergence control of A. caucalis and T. nodosa

Seedling emergence of *A. caucalis* at 28 days after application (DAA) was significantly reduced ($P < 0.001$) by applications of cyanazine at 1.0 kg/ha, simazine at 2.0 kg/ha, dimethenamid at 3.6 kg/ha, sulfentrazone at 0.38 kg/ha and 0.75 kg/ha, quinclorac at 0.44 kg/ha and 0.88 kg/ha and flumioxazin at 0.075 kg/ha, 0.15 kg/ha

and 0.30 kg/ha (Table 9.1). Although not as effective as the above applications, cyanazine at 0.5 kg/ha and simazine at 1.0kg/ha provided a significant (P < 0.01) reduction in emergence of *A. caucalis*. Dimethenamid at 0.90 kg/ha and 1.80 kg/ha and sulfentrazone at 0.19 kg/ha also resulted in a significant (P < 0.05) reduction in emergence compared with the untreated control. Clomazone applied at 0.06, 0.12 and 0.24 kg/ha resulted in no significant (P > 0.05) difference in emergence of *A. caucalis* compared with the untreated control.

Seedling emergence of *T. nodosa* was significantly (*P* < 0.001) reduced by applications of cyanazine at 1.0 kg/ha, simazine at 1.0 and 2.0 kg/ha, dimethenamid at 3.6 kg/ha, clomazone at 0.06, 0.12 and 0.24 kg/ha, sulfentrazone at 0.38 and 0.75 kg/ha, quinclorac at 0.44 and 0.88 kg/ha and flumioxazin at 0.075, 0.15 and 0.30 kg/ha (Table 9.1). Although not as effective as the above applications, sulfentrazone at 0.19 kg/ha provided a significant (P < 0.01) reduction in emergence. A significant (P < 0.05) reduction in emergence of *T. nodosa* was also achieved by application of cyanazine at 0.50 kg/ha, dimethenamid at 1.80 and 3.60 kg/ha and quinclorac at 0.22 kg/ha. Cyanazine applied at 0.25 kg/ha, simazine at 0.50 kg/ha, dimethenamid at 0.90 kg/ha, and quinclorac at 0.06 and 0.11 kg/ha resulted in no significant (P > 0.05) difference in emergence of *T. nodosa* compared with the untreated control.

Table 9.1 The effect of preemergence herbicides on the emergence of *A. caucalis* and *T. nodosa*.

Herbicide	Rate (kg/ha)	Date of application	Seedling emergence[1] (%) 28 DAA			
			A caucalis		*T. nodosa*	
Cyanazine	0.25	9/11/01	26.0 ± 4.3		52.5 ± 3.4	
Cyanazine	0.50	9/11/01	10.5 ± 3.6	**	48.5 ± 1.5	*
Cyanazine	1.00	9/11/01	2.5 ± 1.3	***	5.0 ± 1.9	***
Simazine	0.50	9/11/01	25.0 ± 1.7		66.5 ± 3.8	
Simazine	1 00	9/11/01	7.5 ± 3.6	**	13 5 ± 8.1	***
Simazine	2.00	9/11/01	3.5 ± 2.1	***	3.5 ± 2.1	***
Dimethenamid	0.90	9/11/01	15.0 ± 4 4	*	52.0 ± 5.9	
Dimethenamid	1.80	9/11/01	13.0 ± 4.0	*	49.0 ± 4.4	*
Dimethenamid	3.60	9/11/01	3.0 ± 1.0	***	39.0 ± 4.4	*
Sulfentrazone	0 19	9/11/01	12.5 ± 5.3	*	28.0 ± 3.6	**
Sulfentrazone	0.38	9/11/01	3.5 ± 2.4	***	6.5 ± 2.6	***
Sulfentrazone	0.75	9/11/01	0.0 ± 0.0	***	0.0 ± 0.0	***
Clomazone	0.06	9/11/01	16.5 ± 1.3		23.5 ± 14.1	***
Clomazone	0.12	9/11/01	21 0 ± 2.4		0.0 ± 0.0	***
Clomazone	0.24	9/11/01	25.0 ± 6.2		0.0 ± 0.0	***
Untreated control		*9/11/01*	*27.0 ± 3.9*		*68.0 ± 4.7*	
Quinclorac	0.06	21/6/02	41.3 ± 8.8		67.0 ± 8.1	
Quinclorac	0.11	21/6/02	33.8 ± 1.3		57.0 ± 5.0	
Quinclorac	0.22	21/6/02	21.9 ± 6 2		48.0 ± 10.6	*
Quinclorac	0.44	21/6/02	4.4 ± 1.6	***	9.0 ± 4.1	***
Quinclorac	0.88	21/6/02	3 1 ± 2.4	***	7.0 ± 7.0	***
Untreated control		*21/6/02*	*32.5 ± 7.8*		*75.0 ± 3.0*	
Flumioxazin	0.075	23/4/03	0.0 ± 0.0	***	0.0 ± 0.0	***
Flumioxazin	0.150	23/4/03	0 0 ± 0.0	***	0.0 ± 0.0	***
Flumioxazin	0.300	23/4/03	0.0 ± 0.0	***	0.0 ± 0.0	***
Untreated control		*23/4/03*	*33.0 ± 5.3*		*59.0 ± 6.8*	

Treatments followed by asterisks are significantly different to the untreated control at * P = 0 05, ** P = 0.01 and ***P = 0 001.
[1]Emergence percentage analysed using transformed data

Greater than 80% FW reduction of both *A. caucalis* and *T. nodosa* was achieved by applications of cyanazine at 1.0 kg/ha, simazine at 1.0 and 2.0 kg/ha, sulfentrazone at 0.38 and 0.75 kg/ha, flumioxazin at 0.075, 0.15 and 0.30 kg/ha and quinclorac at 0.88 kg/ha (Figure 9.1). The results of this experiment are shown pictorially in plates 9.1 to 9.10.
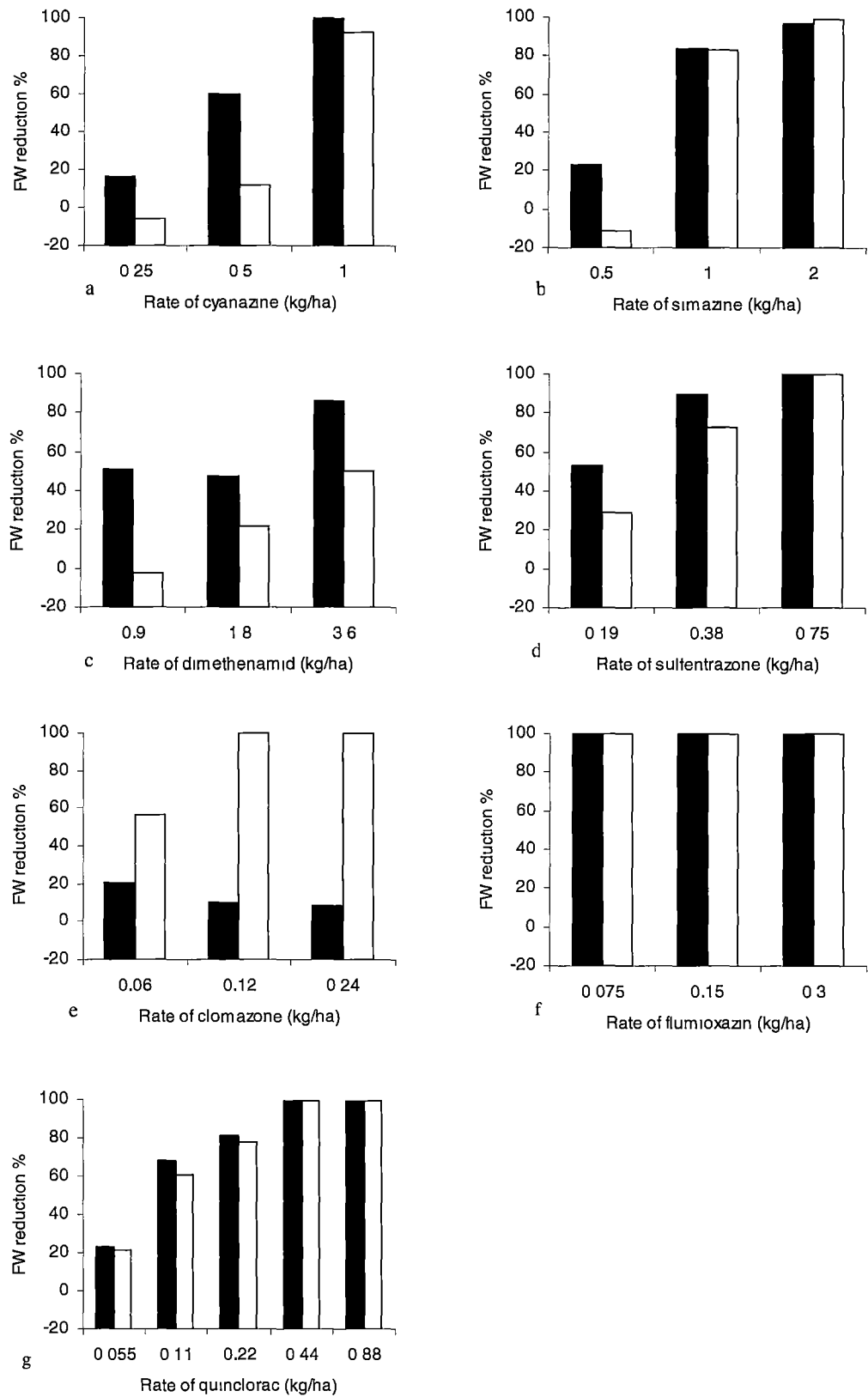
Figure 9.1 Fresh weight reduction (%) of *A. caucalis* (■) and *T. nodosa* (□) as affected by the rates of application of (a) cyanazine, (b) simazine, (c) dimethenamid, (d) sulfentrazone, (e) clomazone, (f) flumioxazin and (g) quinclorac.

Plate 9.1 Preemergence treatment of *T. nodosa* **(Left to Right respectively) with cyanazine at 0.25 kg/ha, 0.5 kg/ha, 1.0 kg/ha and untreated control.**

Plate 9.2 Preemergence treatment of *T. nodosa* **(Left to Right respectively) with simazine at 0.5 kg/ha, 1.0 kg/ha, 2.0 kg/ha and untreated control.**

Plate 9.3 Preemergence treatment of *T. nodosa* **(Left to Right respectively) with dimethenamid at 0.9 kg/ha, 1.8 kg/ha, 3.6 kg/ha and untreated control.**

Plate 9.4 Preemergence treatment of *T. nodosa* **(Left to Right respectively) with sulfentrazone at 0.19 kg/ha, 0.38 kg/ha, 0.75 kg/ha and untreated control.**

Plate 9.5 Preemergence treatment of *T. nodosa* **(Left to Right respectively) with clomazone at 0.06 kg/ha, 0.12 kg/ha, 0.24 kg/ha and untreated control.**

Plate 9.6 Preemergence treatment of *A. caucalis* **(Left to Right respectively) with cyanazine at 0.25 kg/ha, 0.5 kg/ha, 1.0 kg/ha and untreated control.**

Plate 9.7 Preemergence treatment of *A. caucalis* **(Left to Right respectively) with simazine at 0.5 kg/ha, 1.0 kg/ha, 2.0 kg/ha and untreated control.**

Plate 9.8 Preemergence treatment of *A. caucalis* **(Left to Right respectively) with dimethenamid at 0.9 kg/ha, 1.8 kg/ha, 3.6 kg/ha and untreated control.**

Plate 9.9 Preemergence treatment of *A. caucalis* **(Left to Right respectively) with sulfentrazone at 0.19 kg/ha, 0.38 kg/ha, 0.75 kg/ha and untreated control.**

Plate 9.10 Preemergence treatment of *A. caucalis* (Left to Right respectively) with clomazone at 0.06 kg/ha, 0.12 kg/ha, 0.24 kg/ha and untreated control.

Postemergence control of A. caucalis and T. nodosa

Metribuzin applied at 187.5 g/ha resulted in complete kill of *A. caucalis* at all growth stages and complete kill of *T. nodosa* at the 1-2 leaf and 3-4 leaf growth stage (Table 9.2 and 9.3). Carfentrazone ethyl (EC) applied at 24.0 g/ha caused highly significant (P < 0.001) leaf injury at all growth stages to both *A. caucalis* and *T. nodosa* 10 DAA. Carfentrazone ethyl (WDG) applied at 24.0 g/ha also caused highly significant (P < 0.001) leaf injury at all growth stages to both *A. caucalis* and *T. nodosa* 10 DAA. However, injury was significantly (P > 0.05) less than that caused by the EC formulation of carfentrazone ethyl. Significant (P < 0.05) leaf injury was observed 21 DAA when imazamox at 33.8 g/ha was applied to *A. caucalis* at plant growth stages 1-2 leaf and 3-4 leaf and *T. nodosa* at plant growth stage 1-2 leaf. Imazamox resulted in no significant (P > 0.05) leaf injury to *A. caucalis* or *T. nodosa* 21 DAA when applied at the 7-8 leaf stage of growth.

Table 9.2 The effect of postemergence herbicides on the control of *A. caucalis*

Herbicide	Rate (g/ha)	Date of application	Seedling growth stage	Leaf Injury								
				DAA	% Injury		DAA	% Injury		DAA	% Injury	
[1]Carfentrazone –ethyl	24.0	11/2/02	1-2 true leaf	10	96.7 ± 3.3	***	15	100.0 ± 0 0	***	21	100.0 ± 0.0	***
Imazamox	33.8	11/2/02	1-2 true leaf	10	50.0 ± 10.0	***	15	50.0 ± 11.5	**	21	53.3 ± 8.8	**
[2]Carfentrazone –ethyl	24.0	11/2/02	1-2 true leaf	10	76.7 ± 14.5	***	15	66.7 ± 20.3	***	21	60 0 ± 17.3	**
Metribuzin	187.5	11/2/02	1-2 true leaf	10	100.0 ± 0.0	***	15	100.0 ± 0.0	***	21	100.0 ± 0.0	***
[1]Carfentrazone –ethyl	24.0	11/2/02	3-4 true leaf	10	86.7 ± 6.7	***	15	60.0 ± 20.8	***	21	56.7 ± 21.9	**
Imazamox	33.8	11/2/02	3-4 true leaf	10	26.7 ± 3.3	**	15	26.7 ± 14.5	*	21	26.7 ± 14.5	*
[2]Carfentrazone –ethyl	24.0	11/2/02	3-4 true leaf	10	66.7 ± 18.6	***	15	43.3 ± 13.3	**	21	26.7 ± 12.0	*
Metribuzin	187 5	11/2/02	3-4 true leaf	10	100.0 ± 0.0	***	15	100.0 ± 0.0	***	21	100.0 ± 0.0	***
[1]Carfentrazone –ethyl	24.0	11/2/02	7-8 true leaf	10	50.0 ± 10.0	***	15	73.3 ± 12.0	***	21	66.7 ± 18.6	**
Imazamox	33.8	11/2/02	7-8 true leaf	10	10.0 ± 0.0		15	0.0 ± 0.0		21	0.0 ± 0.0	
[2]Carfentrazone –ethyl	24.0	11/2/02	7-8 true leaf	10	36 7 ± 14.5	***	15	20.0 ± 5.8	*	21	10.0 ± 5.8	
Metribuzin	187.5	11/2/02	7-8 true leaf	10	93.3 ± 6.7	***	15	100.0 ± 0.0	***	21	100.0 ± 0.0	***

Treatments followed by asterisks are significantly different to the untreated control at * P = 0 05, ** P = 0.01 and ***P = 0.001
[1] Carfentrazone ethyl formulated as an emulsifiable concentrate
[2] Carfentrazone ethyl formulated as an water dispersible granule

Table 9.3 The effect of postemergence herbicides on the control of *T. nodosa*

Herbicide	Rate (g/ha)	Date of application	Seedling growth stage	Leaf Injury								
				DAA	% Injury		DAA	% Injury		DAA	% Injury	
[1]Carfentrazone –ethyl	24 0	11/2/02	1-2 true leaf	10	63.3 ± 3.3	***	15	50.0 ± 5.8	***	21	36.7 ± 6.7	***
Imazamox	33.8	11/2/02	1-2 true leaf	10	20.0 ± 5.8	***	15	13.3 ± 3.3		21	10.0 ± 0.0	*
[2]Carfentrazone –ethyl	24.0	11/2/02	1-2 true leaf	10	53 3 ± 8.8	***	15	23.3 ± 6.7	**	21	0 0 ± 0.0	
Metribuzin	187.5	11/2/02	1-2 true leaf	10	100.0 ± 0 0	***	15	100.0 ± 0.0	***	21	100.0 ± 0.0	***
[1]Carfentrazone –ethyl	24 0	11/2/02	3-4 true leaf	10	80.0 ± 0.0	***	15	40.0 ± 5.8	**	21	3.3 ± 3.3	
Imazamox	33.8	11/2/02	3-4 true leaf	10	0.0 ± 0.0		15	3.3 ± 3.3		21	3.3 ± 3.3	
[2]Carfentrazone –ethyl	24.0	11/2/02	3-4 true leaf	10	46.7 ± 12 0	***	15	20.0 ± 15.3	*	21	3.3 ± 3 3	
Metribuzin	187.5	11/2/02	3-4 true leaf	10	86 7 ± 6.7	***	15	96.7 ± 3.3	***	21	100.0 ± 0.0	***
[1]Carfentrazone –ethyl	24.0	11/2/02	7-8 true leaf	10	50.0 ± 5.8	***	15	13.3 ± 8.8		21	3.3 ± 3.3	
Imazamox	33.8	11/2/02	7-8 true leaf	10	0.0 ± 0.0		15	3.3 ± 3.3		21	0.0 ± 0.0	
[2]Carfentrazone –ethyl	24.0	11/2/02	7-8 true leaf	10	33.3 ± 3 3	***	15	16 7 ± 8.8		21	13.3 ± 6 7	*
Metribuzin	187.5	11/2/02	7-8 true leaf	10	46.7 ± 6.7	***	15	83.3 ± 8.8	***	21	86.7 ± 6.7	***

Treatments followed by asterisks are significantly different to the untreated control at * P = 0.05, ** P = 0 01 and ***P = 0 001
[1] Carfentrazone ethyl formulated as an emulsifiable concentrate
[2] Carfentrazone ethyl formulated as an water dispersible granule

Carfentrazone ethyl formulated as an EC provided 100% FW reduction of *A. caucalis* when applied at the 1-2 leaf stage of growth but only 77% and 56% when applied at the 3-4 leaf and 7-8 leaf stages of growth, respectively. In comparison carfentrazone ethyl formulated as a WDG provided a lower FW reduction percentage at each corresponding growth stage (Figure 9.2). Metribuzin provided 100% FW reduction of *A. caucalis* when applied at each growth stage. Imazamox provided 71% FW reduction of *A. caucalis* when applied at the 1-2 leaf stage of growth and less than 50% when applied at the 3-4 and 7-8 leaf stage of growth. Metribuzin provided 100% FW reduction of *T. nodosa* when applied at the 1-2 leaf stage and 3-4 leaf stage of growth and 84% when applied at the 7-8 leaf stage. Applications of imazamox and carfentrazone ethyl formulated as either a WDG or an EC provided less than 40% FW reduction of *T. nodosa* when applied at any growth stage.
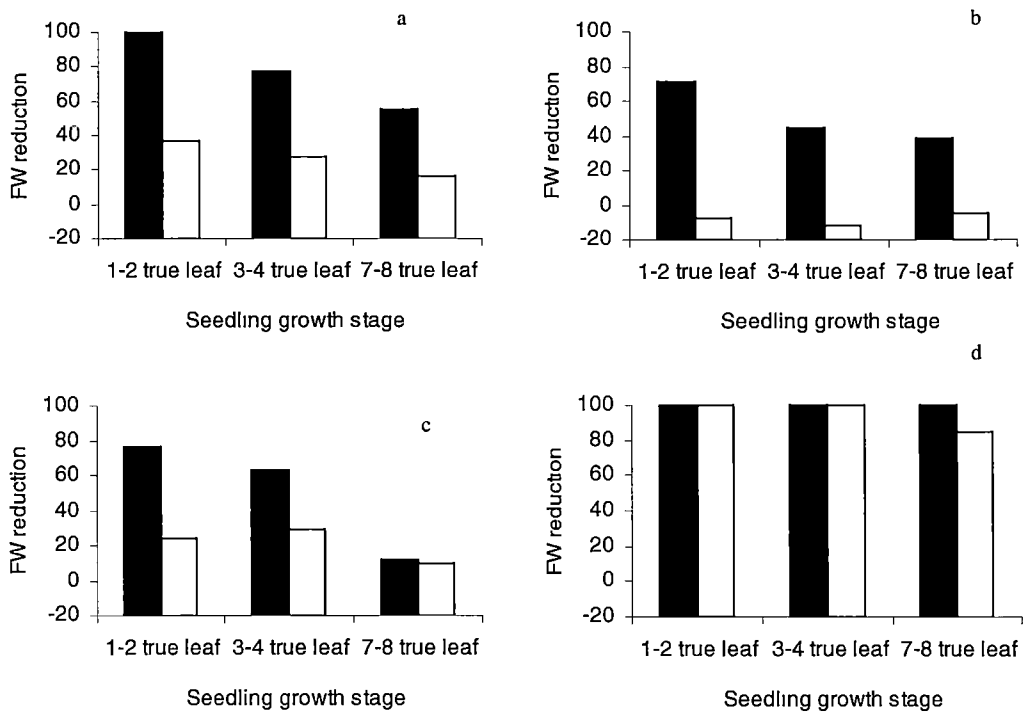
Figure 9.2 Fresh weight reduction (%) of *A. caucalis* (■) and *T. nodosa* (□) as affected timing of application of (a) carfentrazone ethyl EC 24.0g/ha, (b) imazamox 33.8g/ha, (c) carfentrazone ethyl WDG 24.0g/ha and (d) metribuzin 187.5g/ha.

Rate of application of postemergence herbicides for the control A. caucalis and T. nodosa.

Applications of imazamox with a non-ionic organosilicone adjuvant, Pulse® (0.1% v:v), at a rate of 34 and 68 g/ha, rimsulfuron at 30 g/ha, quinclorac at 440 and 880 g/ha and flumioxazin at 300 g/ha all caused more than 70% leaf injury of *A. caucalis* 28 DAA (Table 9.4). Bentazone at 960 g/ha caused 85% leaf injury to *A. caucalis* 7 DAA. This fell to only 57.5 % 28 DAA due to the production of healthy new leaf growth. There was no significant (P > 0.05) leaf injury of *A. caucalis* from applications of flumetsulam at 40 and 80 g/ha, 28 DAA.

Applications of imazamox with adjuvant Pulse® (0.1% v:v) at 34 and 68 g/ha, flumetsulam at 80 g/ha, rimsulfuron at 30 g/ha, bentazone at 480 and 980 g/ha, quinclorac at 880 g/ha and flumioxazin at 300g/ha all caused more than 70% leaf injury of *T. nodosa* 28 DAA (Table 9.5). *Torilis nodosa* was highly susceptible to applications of bentazone at rates of 480 and 960 g/ha, with complete plant death occurring 7 DAA. Less than 20% leaf injury of *T. nodosa* was observed with applications of quinclorac at rates of 55, 110 and 220 g/ha, and picolinafen at 22.5 and 45 g/ha.

Applications of imazamox with adjuvant Pulse® (0.1% v:v) at 34g/ha and 68g/ha, flumetsulam at 40.0 and 80g/ha, rimsulfuron at 15.0 and 30.0 g/ha, picolinafen at 22.5and 45.0 g/ha and bentazone at 480.0 and 960.0 g/ha all resulted in significant (P < 0.001) levels of leaf injury to pyrethrum 28DAA. Less than 45% crop injury was observed with applications of imazamox with adjuvant Pulse® (0.1% v:v) at 34 and 68 g/ha and picolinafen at 22.5 and 45g/ha. All other herbicides resulted in plant injury above 65%, with bentazone resulting in the most noticeable leaf damage to pyrethrum at 28 DAA.

Table 9.4 Efficacy of foliage applied herbicides for the control of *A. caucalis*

Herbicide	Rate (g/ha)	Date of application	Seedling growth stage	% Leaf injury					
				7 DAA		14 DAA		28 DAA	
[1]Imazamox	34.0	21/4/03	6 true leaf	2.5 ± 2.5		62.5 ± 2.5	***	92.5 ± 2.5	***
[1]Imazamox	68.0	21/4/03	6 true leaf	5.0 ± 2.9	*	70.0 ± 4.1	***	90.0 ± 0.0	***
Flumetsulam	40.0	21/4/03	6 true leaf	0.0 ± 0.0		0.0 ± 0.0		0.0 ± 0.0	
Flumetsulam	80.0	21/4/03	6 true leaf	0.0 ± 0 0		0.0 ± 0 0		0.0 ± 0.0	
Rimsulfuron	15.0	21/4/03	6 true leaf	2.5 ± 2.5		40.0 ± 4.1	***	55.0 ± 2 9	***
Rimsulfuron	30.0	21/4/03	6 true leaf	0.0 ± 0.0		55.0 ± 2.9	***	75.0 ± 2.9	***
Picolinafen	22.5	21/4/03	6 true leaf	20.0 ± 0.0	***	25.0 ± 2.9	***	10.0 ± 0 0	**
Picolinafen	45.0	21/4/03	6 true leaf	25.0 ± 2.9	***	30.0 ± 0.0	***	25.0 ± 8.7	***
Bentazone	480.0	21/4/03	6 true leaf	50.0 ± 7.1	***	30.0 ± 0.0	***	20.0 ± 5.8	***
Bentazone	960.0	21/4/03	6 true leaf	85.0 ± 2.9	***	57.5 ± 14.4	***	57.5 ± 14.4	***
Quinclorac	55.0	21/6/02	4-true leaf	10.0 ± 0.0	**	5.0 ± 2.9		3.8 ± 2.4	
Quinclorac	110.0	21/6/02	4-true leaf	26.3 ± 2.4	***	17.5 ± 3.2	**	15.0 ± 2.0	**
Quinclorac	220.0	21/6/02	4-true leaf	40.0 ± 4.1	***	30.0 ± 4.1	***	32.5 ± 3.2	***
Quinclorac	440.0	21/6/02	4-true leaf	80.0 C4.1	***	72.5 ± 11.3	***	70.0 ± 10.8	***
Quinclorac	880.0	21/6/02	4-true leaf	91.3 ± 2.3	***	100.0 ± 0.0	***	100.0 ± 0.0	***
Flumioxazin	75.0	23/4/03	4-true leaf .	15.0 ± 5.0	**	45.0 ± 8.7	***	32.5 ± 2.5	***
Flumioxazin	150 0	23/4/03	4-true leaf	25.0 ± 2.9	***	47.5 ± 11.8	***	60.0 ± 14.1	***
Flumioxazin	300.0	23/4/03	4-true leaf	27.5 ± 4.8	***	60.0 ± 7.1	***	72.5 ± 11 1	***

Treatments followed by asterisks are significantly different to the untreated control at * $P = 0 05$, ** $P = 0 01$ and ***$P = 0.001$

[1] Imazamox applied with the addition of Pulse® adjuvant at 0 1% v:v

Table 9.5 Efficacy of foliage applied herbicides for the control of *T. nodosa*

Herbicide	Rate (g/ha)	Date of application	Seedling growth stage	% leaf Injury					
				7DAA		14 DAA		28 DAA	
[1]Imazamox	34.0	21/4/03	6 true leaf	22.5 ± 6.3	***	72.5 ± 4.8	***	85.0 ± 2.9	***
[1]Imazamox	68.0	21/4/03	6 true leaf	27.5 ± 4.8	***	80.0 ± 5.8	***	87.5 ± 6.3	***
Flumetsulam	40.0	21/4/03	6 true leaf	12.5 ± 2.5	***	45.0 ± 5.0	***	62.5 ± 2.5	***
Flumetsulam	80.0	21/4/03	6 true leaf	12.5 ± 2.5	***	52.5 ± 2.5	***	82.5 ± 4.8	***
Rimsulfuron	15.0	21/4/03	6 true leaf	12.5 ± 2.5	***	50.0 ± 4.1	***	72.5 ± 2.5	***
Rimsulfuron	30.0	21/4/03	6 true leaf	12.5 ± 2.5	***	57.5 ± 2.5	***	75.0 ± 2.9	***
Picolinafen	22.5	21/4/03	6 true leaf	20.0 ± 0.0	***	12.5 ± 2.5	***	5.0 ± 2.9	*
Picolinafen	45.0	21/4/03	6 true leaf	22.5 ± 2.5	***	12.5 ± 2.5	***	12.5 ± 2.5	**
Bentazone	480 0	21/4/03	6 true leaf	100.0 ± 0.0	***	100.0 ± 0.0	***	100.0 ± 0.0	***
Bentazone	960.0	21/4/03	6 true leaf	100.0 ± 0.0	***	100.0 ± 0.0	***	100.0 ± 0 0	***
Quinclorac	55.0	21/6/02	4-true leaf	22.5 ± 2.5	***	0.8 ± 0.8		0.0 ± 0.0	
Quinclorac	110.0	21/6/02	4-true leaf	47.5 ± 2.5	***	4.3 ± 2.2	**	0.0 ± 0.0	
Quinclorac	220.0	21/6/02	4-true leaf	80.0 ± 0.0	***	10.5 ± 2.1	***	6.3 ± 2.4	**
Quinclorac	440 0	21/6/02	4-true leaf	87.5 ± 2.5	***	58 8 ± 3.1	***	41.3 ± 3.8	***
Quinclorac	880.0	21/6/02	4-true leaf	90 0 ± 0.0	***	92.5 ± 2.8	***	98.3 ± 1.2	***
Flumioxazin	75.0	23/4/03	4-true leaf	17.5 ± 2.5	**	30 0 ± 4.1	***	20.0 ± 0.0	**
Flumioxazin	150 0	23/4/03	4-true leaf	25.0 ± 2.9	***	40.0 ± 7.1	***	47.5 ± 11.8	***
Flumioxazin	300 0	23/4/03	4-true leaf	35.0 ± 5.0	***	75.0 ± 9.6	***	85.0 ± 6.5	***

Treatments followed by asterisks are significantly different to the untreated control at * P = 0 05, ** P = 0 01 and ***P = 0.001

[1] Imazamox applied with the addition of Pulse® adjuvant at 0.1% v·v

Table 9.6 Phytotoxicity of foliage applied herbicides on pyrethrum

Treatment	Rate (g/ha)	Date of application	Growth stage of pyrethrum	% Leaf Injury					
				7 DAA		14 DAA		28 DAA	
[1]Imazamox	34.0	21/4/03	8 true leaf	0.0 ± 0.0		20.0 ± 0.0	***	37.5 ± 2.5	***
[1]Imazamox	68.0	21/4/03	8 true leaf	2.5 ± 2.5		25.0 ± 5.0	***	45.0 ± 2 9	***
Flumetsulam	40.0	21/4/03	8 true leaf	0.0 ± 0.0		47.5 ± 6 3	***	77.5 ± 2.5	***
Flumetsulam	80.0	21/4/03	8 true leaf	5.0 ± 2.9		52.5 ± 11.1	***	72.5 ± 4.8	***
Rimsulfuron	15.0	21/4/03	8 true leaf	0.0 ± 0.0		42.5 ± 2.5	***	65.0 ± 6.5	***
Rimsulfuron	30.0	21/4/03	8 true leaf	7.5 ± 4.8	*	50.0 ± 7.1	***	72.5 ± 7.5	***
Picolinafen	22.5	21/4/03	8 true leaf	15.0 ± 2.9	***	25.0 ± 2.9	***	35.0 ± 2.9	***
Picolinafen	45.0	21/4/03	8 true leaf	20.0 ± 4.1	***	40.0 ± 0.0	***	40.0 ± 0.0	***
Bentazone	480.0	21/4/03	8 true leaf	30.0 ± 4.1	***	65.0 ± 9.6	***	82.5 ± 11 1	***
Bentazone	960.0	21/4/03	8 true leaf	70.0 ± 7.1	***	92.5 ± 7.5	***	97.5 ± 2.5	***

Treatments followed by asterisks are significantly different to the untreated control at * P = 0.05, ** P = 0 01 and ***P = 0.001
[1] Imazamox applied with the addition of Pulse® adjuvant at 0 1% v·v

9.4 Discussion

Dimethenamid applied at a rate of 1.8 and 3.6 kg/ha resulted in substantial preemergence control of both *A. caucalis* and *T. nodosa*. The effect on emergence was not as discernible as that on FW reduction as dimethenamid did not prevent emergence or kill a high percentage of emerged seedlings, however emerging seedling leaves were tightly rolled and severely stunted. These symptoms were more prevalent for *A. caucalis* (Plate 9.3) than *T. nodosa* (Plate 9.8) resulting in a higher FW reduction percentage of *A. caucalis*. Both species were highly susceptible to the photosynthetic inhibiting herbicides simazine and cyanazine. Emergence and seedling growth of both *A. caucalis* and *T. nodosa* were also restricted by the applications of flumioxazin at a rate of 0.075 kg/ha and above, sulfentrazone at 0.38 and 0.75 kg/ha and quinclorac at 0.44 and 0.88 kg/ha. There was some contrast in efficacy of the preemergence applications between the two species. *Torilis nodosa* was found to be highly susceptible to applications of clomazone at 0.12 and 0.24 kg/ha while *A. caucalis* was extremely tolerant to clomazone applications. The selectivity and activity of those herbicides that provided preemergence control of *A. caucalis* and/or *T. nodosa* are further investigated under field conditions in the following chapters.

Both *A. caucalis* and *T. nodosa* were highly susceptible to postemergence applications of the photosynthetic inhibiting herbicide metribuzin. The contact herbicide carfentrazone ethyl had a variable efficacy response. Substantially more leaf injury to both species, but in particular to *A. caucalis*, was found with the EC formulation of carfentrazone ethyl compared with the WDG formulation. Plant recovery was observed for both formulations of carfentrazone ethyl when applied at later growth stages to *A. caucalis* and *T. nodosa*. This was believed to be due to the contact activity of carfentrazone ethyl. When carfentrazone ethyl was applied to later growth stages complete spray coverage was made more difficult due to the higher amount of leaf material present and this resulted in incomplete kill of the target species.

The efficacy of postemergence applications on *A. caucalis* and *T. nodosa* appeared to be influenced strongly by their growth stage at the time of application. This was to be

expected for carfentrazone-ethyl applications which have contact activity and therefore complete coverage is needed to obtain plant death. Metribuzin, which has systemic activity, also provided better activity on younger seedlings of *T. nodosa*. Consistent with this result is the commercial recommendation that for effective broadleaf weed control in peas and faba beans metribuzin be applied before the 3 leaf stage of weed growth (Anon. 2000c).

In examining the FW reduction percentages of *A. caucalis*, *T. nodosa* and pyrethrum, from the rate of application of postemergence herbicides study, it appeared that the applications of imazamox at 34 g/ha with Pulse® (0.1% v:v) has the most potential to be applied as a commercial treatment. It provided greater than a 95% reduction in FW of both *A. caucalis* and *T. nodosa* and less than a 60% reduction in seedling pyrethrum FW (Figure 9.3). This level of leaf damage to pyrethrum may possibly be acceptable under field conditions due to the crops ability to produce compensatory regrowth throughout the winter and spring period. At present imazamox is being applied at 34g/ha as a commercial recommendation in pyrethrum to provide control of *Raphanus raphanistrum* and *Solanum nigrum* with no discernible affects on crop productivity (Grooms, pers comm. 2003). However, its efficacy with the absence of an adjuvant has been observed to be unacceptable in the control of *A. caucalis* and *T. nodosa*. The efficacy and crop safety of imazamox with addition of an adjuvant requires further investigation under field conditions. The timing of application is also viewed as an important factor with the likely climatic conditions affecting imazamox activity. The activity of imidazolinone herbicides has been shown to be increased under cooler conditions and reduced under warmer conditions (Malefyt and Quakenbush, 1991). The activity of imazamox applied alone in the growth stage pot experiment was low and it is believed that the prevailing warm conditions and the absence of an adjuvant may have limited its activity. Symptoms following imazamox applications were slow to develop on both *A. caucalis* and *T. nodosa*. However, at 28 DAA significant losses of green pigment and development of necrosis and stunting became clearly visible (Plate 9.11 and 9.12). Slight chlorosis of emerged pyrethrum leaves and stunting were observed with imazamox applications however no obvious leaf death was observed for the duration of the experiment (Plate 9.13).

Postemergence applications of flumetsulam, rimsulfuron and bentazone caused an unacceptable level of injury (> 65%) to pyrethrum. Although pyrethrum appeared to be highly susceptible to applications of flumetsulam, rimsulfuron and bentazone these herbicides still require further investigation under field conditions as the response of established pyrethrum plants has been shown to be noticeably different to that of seedling pyrethrum (Groom, pers comm. 2002). Under commercial production the application of these products would not occur until late autumn to early winter. Even if these herbicide products were applied to newly established crops, pyrethrum plants would have had at least an eight month period to establish and would be of a considerably larger size in comparison to those used in the pot experiment.

Flumetsulam resulted in considerable necrosis to *T. nodosa* and pyrethrum but no symptoms were observed on *A. caucalis*. Rimsulfuron resulted in obvious restrictions to the growth of *A. caucalis* and *T. nodosa* causing greater than 75% reduction in FW of both species (Figure 9.3). Both species displayed stunting, leaf rolling and a slight loss of color at 28 DAA of rimsulfuron although there was no obvious leaf necrosis (Plates 9.17 and 9.18). In pyrethrum similar symptoms were observed with any new growth of pyrethrum being restricted and towards the end of the experiment, plants developed chlorotic regions and occasional necrotic lesions (Plate 9.19).

Picolinafen at rates of 22.5 and 45 g/ha resulted in less than 60% FW reduction of *A. caucalis*, *T. nodosa* and pyrethrum (Figure 9.3). Picolinafen applications resulted in discernible bleaching of leaves of all three species 7 DAA, however further development of the bleaching was not observed and all three species showed visible signs of recovery at 28 DAA. Bentazone applied at 960 g/ha resulted in 90% FW reduction of *A. caucalis* and *T. nodosa* but only a 70% FW reduction for *A. caucalis* when applied at 480 g/ha (Figure 9.3). Symptoms of bentazone applications were complete necrosis of *T. nodosa*. In comparison, *A. caucalis* although displaying high levels of leaf necrosis (85% damage) 7 DAA was able to recover and produce healthy new growth.

Significant rate responses were found with applications of quinclorac and flumioxazin. Only when flumioxazin was applied at a rate of 300 g/ha was the FW

reduction of *A. caucalis* and *T. nodosa* greater than 80% (Figure 9.3). The FW reduction of both species was below 70% when flumioxazin was applied at a rate of 150 g/ha and 75 g/ha. Applications of quinclorac at 440 g/ha and 880 g/ha resulted in greater than 80% FW reduction of *A. caucalis* (Figure 9.3), which appeared more susceptible to quinclorac than *T. nodosa*. Only at the highest rate of application of quinclorac was there a greater than 80% FW reduction of *T. nodosa*. Postemergence symptoms of quinclorac applications on both *A. caucalis* and *T. nodosa* became obvious within 7 DAA. Symptoms observed included twisting and thinning of the leaf petiole and curling of the leaf lamina. Although those symptoms appeared early and were clearly evident at the low and middle rates of application, both *A. caucalis* and *T. nodosa* showed significant signs of recovery 28 DAA.
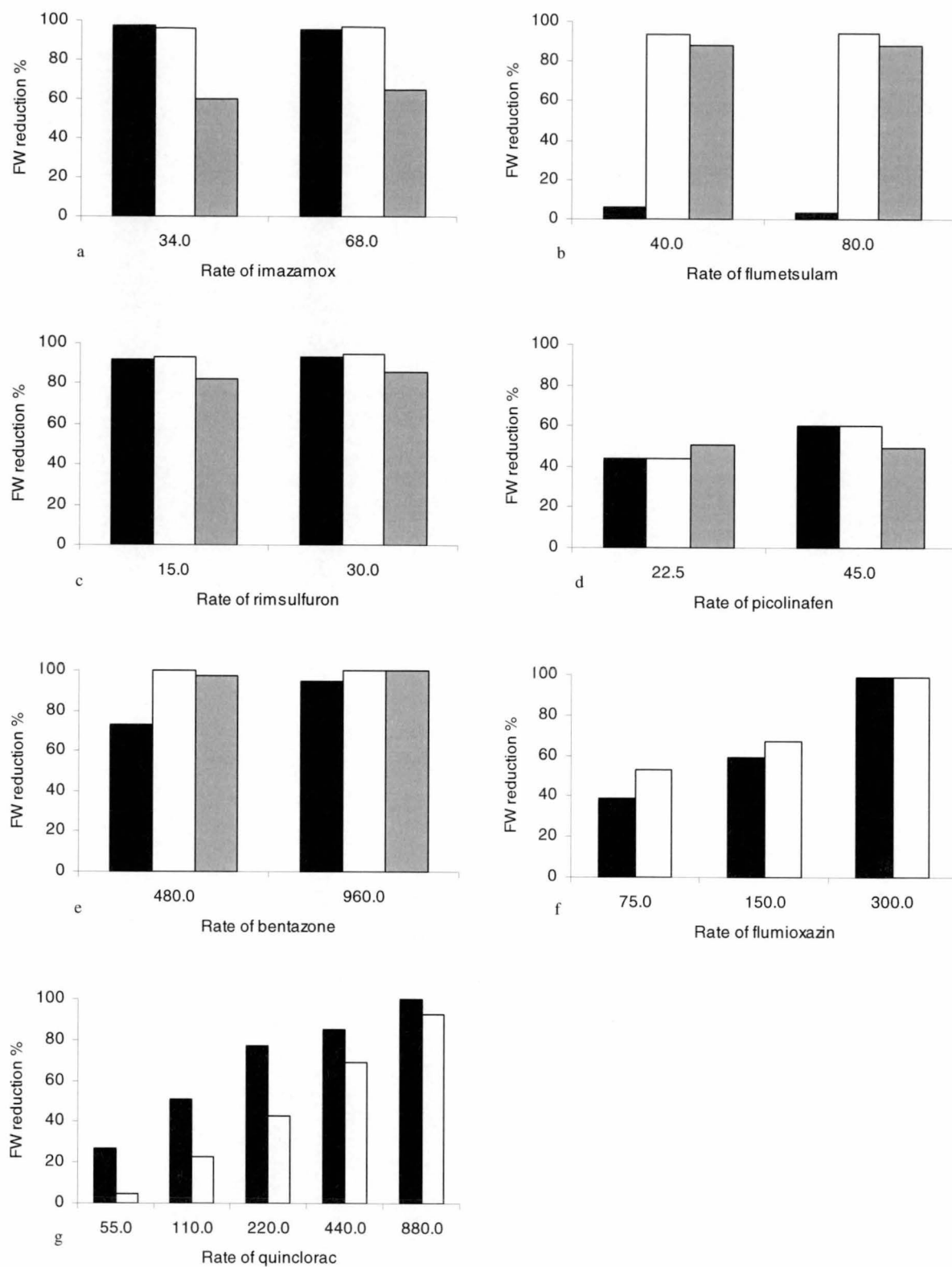
Figure 9.3 Fresh weight reduction (%) of *A. caucalis* (■), *T. nodosa* (□) and pyrethrum (▨) as affected by the rates (g/ha) of application of (a) imazamox with the addition of Pulse® adjuvant (0.1% v:v), (b) flumetsulam, (c) rimsulfuron, (d) picolinafen, (e) bentazone, (f) flumioxazin and (g) quinclorac.

Plate 9.11 Imazamox applied at 34 g/ha (left), 68 g/ha (centre) to *T. nodosa* and the untreated control, 28 DAA

Plate 9.12 Imazamox applied at 34 g/ha (left), 68 g/ha (centre) to *A. caucalis* and the untreated control, 28 DAA.

Plate 9.13 Imazamox applied at 34 g/ha (left), 68 g/ha (centre) to pyrethrum and the untreated control, 28 DAA.

Plate 9.14 Picolinafen applied at 22.5 g/ha (left), 45 g/ha (centre) to *A. caucalis* and the untreated control, 28 DAA.

Plate 9.15 Picolinafen applied at 22.5 g/ha (left), 45 g/ha (centre) to *T. nodosa* and the untreated control, 28 DAA.

Plate 9.16 Picolinafen applied at 22.5 g/ha (left), 45 g/ha (centre) to pyrethrum and the untreated control, 28 DAA.

Plate 9.17 Rimsulfuron applied at 15 g/ha (left), 30 g/ha (centre) to *A. caucalis* and the untreated control, 28 DAA.

Plate 9.18 Rimsulfuron applied at 15 g/ha (left), 30 g/ha (centre) to *T. nodosa* and the untreated control, 28 DAA.

Plate 9.19 Rimsulfuron applied at 15 g/ha (left), 30 g/ha (centre) to pyrethrum and the untreated control, 28 DAA.

Plate 9.20 Flumetsulam applied at 40 g/ha (left), 80 g/ha (centre) to *A. caucalis* and the untreated control, 28 DAA.

Plate 9.21 Flumetsulam applied at 40 g/ha (left), 80 g/ha (centre) to *T. nodosa* and the untreated control, 28 DAA.

Plate 9.22 Flumetsulam applied at 40g/ha (left), 80g/ha (centre) to *pyrethrum* and the untreated control, 28 DAA.

Plate 9.23 Bentazone applied at 480 g/ha (left), 960 g/ha (centre) to *A. caucalis* and the untreated control, 28 DAA.

Plate 9.24 Bentazone applied at 480 g/ha (left), 960 g/ha (centre) to *T. nodosa* and the untreated control, 28 DAA.

Plate 9.25 Bentazone applied at 480 g/ha (left), 960 g/ha (centre) to pyrethrum and the untreated control, 28 DAA.

Plate 9.26 Effect of postemergence applications of quinclorac on *A. caucalis*. 3 DAA displaying distinct epinasty response L -R. Quinclorac applied at 0, 0.055, 0.11, 0.22, 0.44, 0.88 kg/ha.

Plate 9.27 Effect of postemergence applications of quinclorac on *T. nodosa*. 3 DAA displaying distinct epinasty response L-R. Quinclorac applied at 0, 0.055, 0.11, 0.22, 0.44, 0.88 kg/ha.

9.5 Conclusion

A number of herbicides for the control of *A. caucalis* and *T. nodosa* were identified in series of pot experiments. Further investigation into their selectivity and weed efficacy under field conditions was warranted. This included the preemergence herbicides: dimethenamid, sulfentrazone, simazine, quinclorac, cyanine, flumioxazin and clomazone and the postemergence herbicides: carfentrazone ethyl, imazamox, metribuzin, bentazone, quinclorac and rimsulfuron. The potential use of these products was investigated under field conditions over two years and the results are presented in the following chapters.

Chapter 10 Preemergence control of *A. caucalis* and *T. nodosa* in Pyrethrum

10.1 Introduction

Anthriscus caucalis and *T. nodosa* behave predominantly as winter annuals with germination mainly occurring in mid to late autumn. During the autumn period the growth of pyrethrum is slow and crop canopy coverage is poor, allowing the establishment of winter annual species. The preemergence control of most common weeds is achieved by the application of pendimethalin. However pendimethalin has been shown to have no activity against *A. caucalis* and *T. nodosa* (Groom pers. comm. 2001). Successful application of preemergence herbicides to control the emergence of these problematic weeds will reduce crop yield losses and may reduce the overall cost of weed control.

Field studies were initiated to determine:

➢ The effectiveness of dimethenamid, cyanazine, simazine, sulfentrazone, chloridazon, quinclorac, clomazone, and flumioxazin for the preemergence control of *A. caucalis* and *T. nodosa*.

➢ Effect of herbicide application on pyrethrum flower yield.

10.2 Materials and Methods

Two herbicide experiments were established in February and March 2002 to assess the preemergence control of *A. caucalis* and a third trial was established in 2003 to assess the preemergence control of *T. nodosa* and *A. caucalis*. Experimental site A was a newly established pyrethrum crop where the presence of *A. caucalis* had been reported in a previous crop of pyrethrum. Experimental site B was an established pyrethrum field where a number of *A. caucalis* plants had escaped cultural control and set seed in the previous season. Herbicides were applied on the 20th February 2002 and 24th March 2002 at sites A and B, respectively. Experimental site C was a newly established pyrethrum crop, where the presence of *T. nodosa* and *A. caucalis* had been reported in a previous crop of pyrethrum. Herbicides were applied on 2nd April 2003. Details of trial sites and relevant climatic data are given in Tables 10.1-

10.2. Daily maximum and minium temperature and daily rainfall for all field trials are given in Appendices A.7- A13.

Table 10.1 Details of experimental sites used for preemergence herbicide experiments.

Site	Location	Soil classification	Soil Texture	pH (1:5 H₂O)	Date of pyrethrum sowing	Date of herbicide application
A	420252E 5448918N	Red Ferrosol	Clay loam	6.3	August 2001	20 February 2002
B	441103E 5439008N	Red Ferrosol	Clay loam	6.6	July 1999	24 March 2002
C	391557E 5465710N	Red Ferrosol	Clay loam	6.0	September 2002	2 April 2003

Table 10.2 Crop and soil conditions at time of herbicide application and subsequent rainfall data.

Site	Crop health status	Soil moisture	Time to first precipitation (hrs)	Precipitation first 14 Days (mm)	Precipitation first 30 Days (mm)	Total Precipitation (mm)
A	Poor-Average	Dry	4	9.2	14.2	745.0
B	Good	Dry	18	1.4	6.6	598.8
C	Good	Dry	6	103.2	110.6	800.4

Each experiment was arranged as a randomised complete block design with a plot size of 7m by 2m and three replications.

The preemergence herbicides dimethenamid (as Frontier® EC, 90%), cyanazine (as Bladex® FL, 50%), simazine (as Gesatop® FL,50%), sulfentrazone (as Authority® DG, 75%), quinclorac (as Facet® DF, 75%), clomazone (as Command® EC, 48%), flumioxazin (as Pledge® WDG, 50%) and pendimethalin (as Stomp® EC, 33%) were applied at the rates listed in Tables 10.4 and 10.5.

Spraying procedure

Herbicide applications were made using a CO_2-pressurised plot sprayer (Bellspray, 2001). The sprayer was equipped with 4 single nozzle TeeJet® Standard Flat-Spray Tips (8002VS) on a 2.0 metre boom set 50cm above the soil. The sprayer was

calibrated to deliver 200 L ha^{-1} at 220 KPa of pressure. To achieve the desired application rate a walking speed of 1m s^{-1} was maintained.

Assessment procedures

Visual crop injuries were recorded. Ratings were based on a scale of 0 = no injury to 100 = crop death, relative to untreated control plots (Appendix A.6). Crop responses to treatments were quantitatively assessed by determining flower fresh weight (FW) and flower dry weight (DW) yield. This procedure involved hand removal of flowers from two 0.5m^2 quadrats placed at random within the middle section of each plot. This procedure ensured that edge effects were removed. Flower maturity and mean flower DW% were also assessed using a combined sub sample of > 100g of the samples per treatment. Flower maturity was determined using a pyrethrum field maturity index (FMI). The flowers from the sub sample were divided into eight (1-8) flower stages (Plate 10.1 and Table 10.3). The number of flowers was recorded and the FMI determined using the formula below.

FMI No. =   100 * {(Sum of (Flower number * Stage Number)}/ Total No. of flowers.
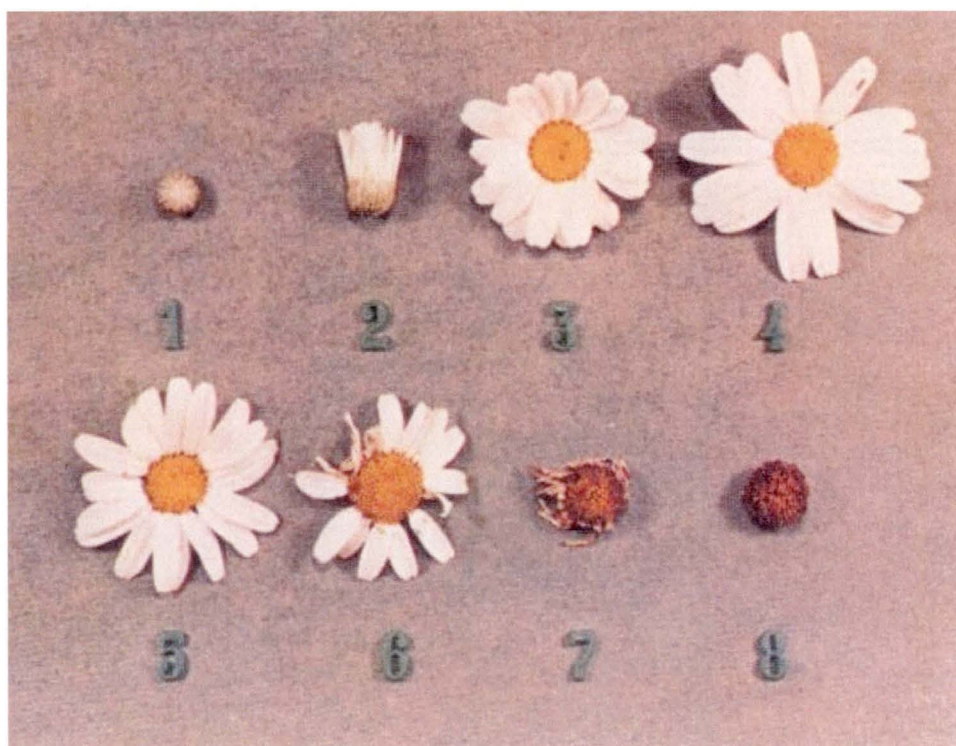
Plate 10.1 Pyrethrum flower maturity indices taken from Casida (1973)

Table 10.3 Weights of flower heads before and after drying at different stages of development

Stage of flower development		Approximate time for development (days)	Average fresh weight (mg)	Average dry weight (mg)	Total Pyrethrins (mg)	Pyrethrins dry wt (%)
Stage No.	Description					
1	Well-developed closed buds	0	178	52	0 40	0.76
2	Ray florets vertical	12	418	119	1.78	1.49
3	Ray florets horizontal; first row of disc florets open	16	480	126	2 48	1.97
4	Approximately three rows of disc florets open	19	615	164	3.45	2.10
5	All disc florets open; fully mature	21	689	195	3 89	2 00
6	Early overblown condition, color of disc diminishing but ray florets still intact	31	716	253	3 92	1 55
7	Late overblown condition little color remaining in disc, florets dried out	43	666	347	4 02	1.16
8	Disc florets fallen, stems dry ½ in below head – suitable for collection for seed	60	321	280		

Taken from (Casida, 1973)

Visual estimates of herbicide efficacy were determined using the EWRC scoring system (Appendix A.5) for experimental sites A and B. The EWRC scoring system was selected in preference to the 0 to 100 rating scale for these experiments, due to the low weed population density at these sites.

Visual estimates of herbicide efficacy were determined on a scale of 0 = no weed control to 100 = complete weed control for experimental site C. Quantitative estimates of weed control were determined by FW destructive harvest measurements in which the shoots of the weed species were removed and weighed.

Statistical analysis

Data collected were subjected to analysis of variance as a randomised complete block design. Crop injury and weed control percentages were analysed as arcsine transformations of raw data. Data are shown as mean recorded values with statistical significance indicated for transformed data, where appropriate. Fresh weights and

transformed data were subjected to analysis of variance with Fishers Protected LSD test (P < 0.05) for mean separation.

10.3 Results

At experimental sites A and B, applications of pendimethalin at 0.99 kg/ha and simazine at 1.0 kg/ha failed to provide any preemergence control of *A. caucalis*. Applications that provided excellent levels of control up to 15 weeks after application at both trial sites were simazine at 2.0 kg/ha, dimethenamid at 1.8 kg/ha and 3.6 kg/ha, quinclorac at 0.38 kg/ha and cyanazine at 0.5 kg/ha (Table 10.4). The results were consistent with those of the glasshouse study although lower levels of control with sulfentrazone were observed at experimental site A. Applications of sulfentrazone provided control at experimental site A, although the longevity of residual control was generally not commercially acceptable. At experimental site B results were inconclusive due to *A. caucalis* occurring in only one replicate plot (Table 10.4). In the weed infested plots, excellent levels of control were recorded for most herbicide treatments. The results between the two sites were generally consistent.

Table 10.4 Mean EWRC score for the control of *A. caucalis* at experimental site A and B, year 2002; 1 = total kill, 9 = no effect.

Treatment	Trial site A DAA 92 [1]	Trial site A DAA 105 [1]	Trial site A DAA 159[1]	Trial site B DAA 85 [2]	Trial site B DAA 127 [2]	Trial site B DAA 155 [2]
Dimethenamid 1.8kg/ha	1.00	1.00	8.67	1.00	1.00	1.00
Dimethenamid 3.6kg/ha	1.00	1.00	4.33	1.00	1.00	1.00
Sulfentrazone 0.19kg/ha	5.00	5.00	6.33	1.00	1.00	1.00
Sulfentrazone 0.38kg/ha	5.00	5.00	8.67	1.00	1.00	1.00
Simazine 1.0kg/ha/ha	9.00	9.00	8.00	9.00	9.00	9.00
Simazine 2.0kg/ha	1.00	1.00	4.33	1.00	1.00	1.00
Quinclorac 0.19g/ha	1.00	1.00	4.67	9.00	9.00	9.00
Quinclorac 0.38g/ha	1.00	1.00	1.00	1.00	1.00	1.00
Cyanazine 0.5kg/ha	1.00	1.00	8.33	1.00	1.00	1.00
Cyanazine 1.0kg/ha	1.00	5.00	6.00	1.00	1.00	1.00
Pendimethalin 0.99kg/ha	9.00	9.00	9.00	9.00	9.00	9.00
Untreated	9.00	9.00	9.00	9.00	9.00	9.00

[1]Mean of only two replications due the absence of *A. caucalis* in the control plot.
[2]Result of only one replication due the absence of *A. caucalis* in the control plot.

Experimental site C had a much higher population of *T. nodosa* than *A. caucalis*, although at 208 DAA quantitative assessment of the shoot material of both *T. nodosa* and *A. caucalis* was possible. At 33 DAA 100% control of *T. nodosa* was achieved by applications of sulfentrazone at 0.38 kg/ha, dimethenamid at 1.8 kg/ha and 3.6 kg/ha, simazine at 2.0 kg/ha, flumioxazin at 0.150 kg/ha and clomazone at 0.12 kg/ha and 0.24 kg/ha (Table 10.5). Applications of clomazone resulted in significant bleaching of the cotyledons of *T. nodosa* (Plate 10.2). At 160 DAA 100% control of *T. nodosa* was achieved by applications of simazine at 2.0 kg/ha, flumioxazin at 0.15 kg/ha and clomazone at 0.12 and 0.24 kg/ha.

Plate 10.2 Effect of clomazone applied at 0.12 kg/ha on the emergence of *T. nodosa* 33 DAA. Note the bleaching of emerged seedlings.

In addition to those applications that provided 100% control of *T. nodosa*, greater than 80% FW reduction was also achieved with applications of dimethenamid at 1.8 kg/ha and 3.6 kg/ha, simazine at 1.0 kg/ha and cyanazine at 1.0 kg/ha. Less than 70% FW reduction was achieved with applications of sulfentrazone at 0.19 kg/ha and 0.38 kg/ha and cyanazine at 0.5 kg/ha.

Table 10.5 Mean Control (%) and biomass reduction of *T. nodosa* at experimental site C, year 2003.

Treatment	% Control					Mean FW (g)	Mean FW reduction %
	12 DAA	33 DAA	47 DAA	56 DAA	160 DAA		
Dimethenamid 1.8kg/ha	100.0***	100.0***	100.0***	83.3***	83.3***	34.5***	89.3
Dimethenamid 3.6kg/ha	100.0***	100.0***	100.0***	93.3***	93.3***	3.9***	98.8
Sulfentrazone 0.19kg/ha	83.3***	70.0***	43.3***	33.3**	40.0**	159.5*	50.5
Sulfentrazone 0.38kg/ha	100.0***	100.0***	50.0***	50.0***	63.3***	101.1**	68.6
Simazine 1.0kg/ha/ha	96.7***	96.7***	73.3***	70.0***	73.3***	35.4***	89.0
Simazine 2.0kg/ha	100.0***	100.0***	100.0***	100.0***	100.0***	0.0***	100.0
Cyanazine 0.5kg/ha	80.0***	43.3***	56.7***	50.0***	46.7**	157.0*	51.2
Cyanazine 1.0kg/ha	93.3***	63.3***	73.3***	66.7***	73.3***	15.8***	95.1
Flumioxazin 0.075kg/ha	93.3***	93.3***	86.7***	90.0***	66.7***	67.0**	79.2
Flumioxazin 0.150 kg/ha	100.0***	100.0***	100.0***	100.0***	100.0***	0.0***	100.0
Clomazone 0.12kg/ha	100.0***	100.0***	100.0***	100.0***	100.0***	0.0***	100.0
Clomazone 0.24kg/ha	100.0***	100.0***	100.0***	100.0***	100.0***	0.0***	100.0
Untreated (Weedy)	0.0	0.0	0.0	0.0	0.0	322.0	0.0
LSD (P = 0.05)						145.8	

Treatments followed by asterisks are significantly different to the untreated control at * P = 0.05, ** P = 0 01 and ***P = 0 001.

Consistent with the glasshouse studies clomazone failed to provide any residual control of *A. caucalis*, as did sulfentrazone at 0.19 kg/ha (Figure 10.1). Detailed assessment of the control of *A. caucalis* was not undertaken due to a low population density of *A. caucalis* throughout the trial site. Applications of dimethenamid at 3.6 kg/ha, simazine at 2.0 kg/ha, cyanazine at 1.0 kg/ha and flumioxazin at 0.075 and 0.150 kg/ha provided 100% control of *A. caucalis*.
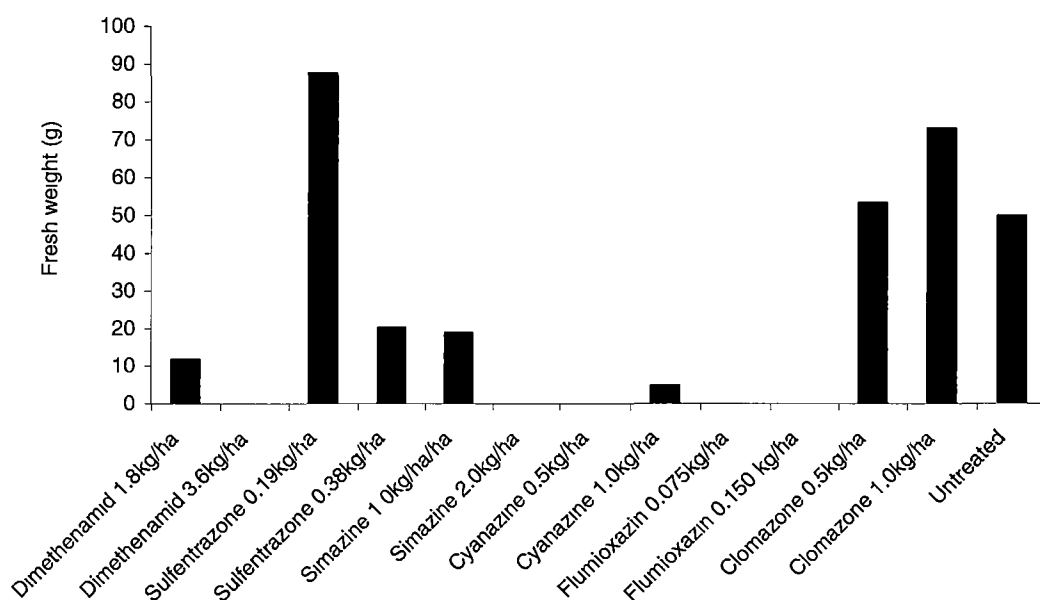
Figure 10.1 Fresh weight of *A. caucalis* as effected by preemergence herbicide applications.

Applications of cyanazine and sulfentrazone resulted in the most significant (P < 0.05) immediate crop injury at experimental site A. Cyanazine applied at a rate of 0.5 and 1.0 kg/ha resulted in mean crop injury of 40.0% and 46.7% respectively, 19 DAA (Table 10.7). Observed symptoms included chlorosis of the leaves and stunting. Sulfentrazone applied at a rate of 0.19 and 0.38 kg/ha resulted in mean crop injury of 25.0% and 38.3% respectively, 19 DAA. Observed symptoms included distinct leaf necrosis and stunting. At 105 DAA, however, no crop injury was noticeable between the treated and untreated plots (Table 10.6). There was no significant (P > 0.05) difference in pyrethrum flower DW yield between treatments or the mean flower DW per 100 flowers. Preemergence herbicide treatments had no significant effect (P > 0.05) on FMI. All other herbicide applications resulted in low

levels of phytotoxicity although simazine applications resulted in slight crop injury with low levels of leaf chlorosis observed.

Consistent with experimental site A, at site B applications of cyanazine and sulfentrazone resulted in the most significant (P < 0.05) crop injury although injury was slower to develop and was less pronounced with sulfentrazone (Table 10.7). At 60 DAA the mean crop injury from cyanazine applied at 0.5 and 1.0 kg/ha was 31.7% and 48.3%, respectively. All other applications resulted in zero crop injury or very low levels except for applications of quinclorac. No visible injury symptoms of quinclorac were recorded for the first 21 DAA, however, stunting and reduced growth became more obvious with time and at 197 DAA significant (P < 0.05) crop injury was visible. Applications of cyanazine at 0.5 kg/ha caused a significant (P < 0.05) decrease in the flower FW and DW compared with the untreated control. The mean FMI of pyrethrum treated with cyanazine at 1.0 kg/ha was 355 in comparison to all other applications where the mean FMI was above 390. This indicated that the development of the pyrethrum plants had been restricted by the application of cyanazine.

At experimental site C applications of cyanazine and clomazone resulted in the highest level of crop injury immediately following application (Table 10.8). Cyanazine applications at 0.5 and 1.0 kg/ha resulted in a mean crop injury of 16.7% and 20.0% respectively, 12 DAA. Clomazone application at 0.12 kg/ha and 0.24 kg/ha resulted in a mean crop injury of 20.0% and 23.3% respectively, 12 DAA and 23.3% and 40.0%, 33 DAA. Observed symptoms to clomazone included a distinct bleaching and yellowing of the pyrethrum foliage. The mean crop injury from applications of flumioxazin at 0.075 kg/ha and 0.150 kg/ha was 26.7% and 30.0%, 33 DAA with noticeable stunting of the pyrethrum plants observed. In contrast to site A and B sulfentrazone resulted in no crop injury. Consistent with site A and B, dimethenamid applications resulted in no crop injury. At 121 DAA no crop injury was recorded for any of the applications. There was no significant (P > 0.05) difference in flower FW and DW yield and FMI among treatments.

Table 10.6 Pyrethrum crop response to preemergence herbicide application at experimental site A.

Herbicide application	% Crop injury				Flower FW (kg/ha)	Flower DW (Kg/ah)	FMI	DW per 100 flowers
	19 DAA	33 DAA	54 DAA	105 DAA				
Dimethenamid 1.8kg/ha	0.0	0.0	0.0	0.0	9371 ± 449	2360 ± 69	323.0 ± 9.1	15.2 ± 0.8
Dimethenamid 3.6kg/ha	0.0	0.0	0.0	0.0	8625 ± 908	2097 ± 237	315.2 ± 4.2	14.3 ± 0.4
Sulfentrazone 0.19kg/ha	25.0***	16.7***	3.3*	0.0	10347 ± 804	2451 ± 176	295.5 ± 16.3	14.0 ± 0.5
Sulfentrazone 0.38kg/ha	38.3***	18.3***	9.0***	0.0	9967 ± 1686	2294 ± 359	296.2 ± 10.3	13.8 ± 0.4
Simazine 1.0kg/ha/ha	0.0	5.0	9.3***	0.0	9593 ± 373	2336 ± 59.1	324.0 ± 15.8	14.1 ± 0.3
Simazine 2.0kg/ha	1.7	16.7***	9.3***	0.0	11431 ± 979	2599 ± 167	315.1 ± 6.6	14.0 ± 1.1
Quinclorac 0.19g/ha	6.0***	1.7	1.7	0.0	9600 ± 840	2328 ± 197	317.7 ± 10.7	13.7 ± 1.0
Quinclorac 0.38g/ha	6.0***	5.0	5.0***	0.0	11569 ± 868	2666 ± 180	318.5 ± 13.6	14.5 ± 1.0
Cyanazine 0.5kg/ha	40.0***	25.0***	8.3***	0.0	11230 ± 1350	2614 ± 264	324.2 ± 14.1	14.5 ± 0.7
Cyanazine 1.0kg/ha	46.7***	28.3***	8.3***	0.0	9850 ± 1055	2270 ± 225	308.2 ± 8.5	13.7 ± 0.9
Pendimethalin 0.99kg/ha	0.0	0.0	0.0	0.0	9923 ± 511	2424 ± 85	330.5 ± 18.8	14.5 ± 0.8
Untreated	0.0	0.0	0.0	0.0	10468 ± 897	2450 ± 198	343.5 ± 21.0	13.8 ± 0.7
LSD (P = 0.05)					n.s.	n.s.	n.s.	n.s.

Treatments followed by asterisks are significantly different to the untreated control at * P = 0.05, ** P = 0.01 and ***P = 0.001.

Table 10.7 Pyrethrum crop response to preemergence herbicide application at experimental site B

Treatment	% Crop injury				Flower FW Yield (kg/ha)	Flower DW Yield (kg/ha)	Mean 100 Flower DW	FMI
	22 DAA	43 DAA	60 DAA	127 DAA				
Dimethenamid 1.8kg/ha	0.0	0.0	0.0	0.0	10852 ± 700	3208 ± 221	15.2 ± 1.1	426.3 ± 46.0
Dimethenamid 3.6kg/ha	0.0	0.0	0.0	0.0	11261 ± 519	3293 ± 157	14.8 ± 0.1	408.7 ± 31.9
Sulfentrazone 0.19kg/ha	8.3***	6.7*	5.0*	5.0**	11917 ± 1121	3342 ± 251	15.2 ± 1.3	407.3 ± 30.7
Sulfentrazone 0.38kg/ha	10.0***	10.0***	15.0***	8.3***	13358 ± 827	3862 ± 206	16.3 ± 1.7	404.3 ± 12.2
Simazine 1.0kg/ha/ha	0.0	0.0	1.7	3.3	10119 ± 382	2981 ± 133	14.7 ± 0.3	409.7 ± 27.5
Simazine 2.0kg/ha	0.0	0.0	1.7	5.0**	12007 ± 244	3431 ± 156	15.4 ± 0.6	415.6 ± 17.8
Quinclorac 0.19g/ha	0.0	0.0	1.7	13 3***	11545 ± 437	3315 ± 195	15.1 ± 0.8	412.9 ± 5.0
Quinclorac 0.38g/ha	0.0	3.3	3.3	18.3***	10055 ± 478	2876 ± 156	15.5 ± 0.2	399.5 ± 8.5
Cyanazine 0.5kg/ha	3.3	26.7***	31.7***	16.7***	9366 ± 887*	2786 ± 251*	16.4 ± 0.8	403.0 ± 39.5
Cyanazine 1.0kg/ha	3.3	30.0***	48.3***	18.3***	10291 ± 656	2936 ± 237	15.9 ± 2.4	355.5 ± 41.7
Pendimethalin 0.99kg/ha	0.0	0.0	0.0	0.0	11145 ± 792	3261 ± 265	15.4 ± 2.1	392.0 ± 50.3
Untreated	0.0	0.0	0.0	0.0	11659 ± 725	3376 ± 145	16.0 ± 1.3	414.7 ± 11.9
LSD (P = 0.05)					1949	539	n.s.	n.s.

Treatments followed by asterisks are significantly different to the untreated control at * P = 0.05, ** P = 0.01 and ***P = 0.001.

Table 10.8 Pyrethrum crop response to preemergence herbicide application at experimental site C

Treatment	% Crop injury				Flower FW Yield (kg/ha)	Flower DW Yield (kg/ha)	Mean 100 Flower DW	FMI
	12DAA	33DAA	47DAA	121DAA				
Dimethenamid 1.8kg/ha	0.0	0.0	0.0	0.0	12855 ± 690	3547 ± 303	13.3 ± 0.59	372.5 ± 21.5
Dimethenamid 3.6kg/ha	0.0	0.0	0.0	0.0	13449 ± 772	3833 ± 47	13.2 ± 0.90	381.3 ± 9.1
Sulfentrazone 0.19kg/ha	0.0	0.0	0.0	0.0	12588 ± 1126	3578 ± 244	13.0 ± 0.18	380.0 ± 14.7
Sulfentrazone 0.38kg/ha	0.0	0.0	0.0	0.0	12044 ± 282	3506 ± 117	12.8 ± 0.36	406.5 ± 13.9
Simazine 1.0kg/ha/ha	0.0	0.0	0.0	0.0	14475 ± 695	3906 ± 83	12.8 ± 0.42	393.2 ± 13.2
Simazine 2.0kg/ha	0.0	0.0	0.0	0.0	12884 ± 1601	3608 ± 411	11.8 ± 0.62	348.0 ± 4.3
Cyanazine 0.5kg/ha	16.7***	3.3	0.0	0.0	11719 ± 976	3356 ± 161	11.0 ± 0.31	398.8 ± 5.6
Cyanazine 1.0kg/ha	20.0***	6.7**	0.0	0.0	11770 ± 1049	3402 ± 140	12.1 ± 0.63	383.5 ± 28.8
Flumioxazin 0.075kg/ha	3.3	26.7***	16.7***	0.0	12197 ± 937	3562 ± 164	11.8 ± 0.27	378.8 ± 25.9
Flumioxazin 0.150 kg/ha	6.7**	30.0***	30.0***	0.0	11842 ± 1288	3407 ± 218	12.9 ± 0.83	365.6 ± 1.3
Clomazone 0.12kg/ha	20.0***	23.3***	13.3***	0.0	13205 ± 423	3838 ± 156	12.7 ± 0.56	390.1 ± 32.4
Clomazone 0.24kg/ha	23.3***	40.0***	36.7***	0.0	11623 ± 1368	3309 ± 186	12.2 ± 0.12	381.1 ± 22.6
Untreated (Hand weeded)	0.0	0.0	0.0	0.0	14330 ± 1306	4154 ± 194	12.8 ± 0.31	408.8 ± 6.6
Untreated (weedy)	0.0	0.0	0.0	0.0	12747 ± 1030	3736 ± 239	12.2 ± 0.16	392.3 ± 13.1
LSD (P = 0.05)					n.s.	n.s.	n.s.	n.s.

Treatments followed by asterisks are significantly different to the untreated control at * P = 0.05, ** P = 0.01 and ***P = 0.001.

10.4 Discussion

Preemergence applications of the assessed herbicides resulted in no significant pyrethrum flower yield reductions although applications of cyanazine, quinclorac, clomazone and flumioxazin and to a lesser degree sulfentrazone and simazine caused noticeable crop injury. The timing of herbicide applications in early autumn may have allowed a sufficient lag period between application and flowering such that the pyrethrum crop was able to recover from any sustained crop injury. The concern however is that these applications, in conjunction with the present herbicide program, may be detrimental to yield as current applications for the control of *Galium aparine* and *Trifolium repens* also result in some crop injury (Groom, pers comm. 2003). The addition of those herbicides that resulted in crop injury may therefore have a cumulative effect on crop injury if included in the current program, potentially resulting in yield reductions.

Applications of dimethenamid resulted in no injury and appeared to be the most viable option for the preemergence control of *A. caucalis* and *T. nodosa*. Low application rates of clomazone at 0.12 kg/ha resulted in low amounts of pyrethrum injury, and at 121 DAA no crop injury was recorded, as well as providing 100% control of *T. nodosa*. At higher rates of application of clomazone (0.24 kg/ha) there was more noticeable leaf injury to the pyrethrum crop, but no statistically significant evidence that this had affected yield. The lowest pyrethrum flower FW and DW yield was recorded with applications of clomazone at 0.24 kg/ha. This was 20% below the untreated treatment. A combination of dimethenamid at 3.6 kg/ha and clomazone at 0.12 kg/ha would be an approach which may be suitable as a commercial recommendation to provide acceptable level of control of both weed species and to give a broader spectrum of weed control. Dimethenamid is registered as providing preemergence control of some grass species. The potential preemergence control of grasses is beneficial to the current program as the over reliance on aryloxyphenoxypropionate and cyclohexanedione herbicides has led to development of resistance in some grass species in pyrethrum (Groom pers comm. 2003, Frost pers comm. 2003). Clomazone would be included due to excellent residual control of problematic weeds in pyrethrum namely *Galium aparine* and *Senecio vulgaris*. Complete control of *A. caucalis* may not be obtained in all situations with this

treatment however the inclusion of an appropriate postemergence application following weed emergence in late autumn or early winter would need to be included in the program to provide complete control.

Alternative approaches would include the use of simazine at 2.0 kg/ha. Simazine at 1.0 kg/ha provided significant control of *A. caucalis* in the preliminary pot trials however under field conditions no control was evident. It was concluded that the efficacy of simazine had diminished with time due to the long period (approx 11 weeks) between application and emergence time. Simazine applied at 0.5 kg/ha in pots failed to control of *A. caucalis*. Under field conditions the highest rate of application of simazine (2.0 kg/ha) provided excellent control of *A. caucalis*. Sulfentrazone or flumioxazin would also be viewed as alternatives, although the crop response to flumioxazin needs to be studied in more detail as only one year's experimental data is reported and results showed a greater than 10% reduction in flower yield compared with the untreated control. Residual control of *A. caucalis* and *T. nodosa* treated with flumioxazin has been determined as being greater than that of sulfentrazone and if only minimal phytotoxicity occurs with its application with no detrimental effect on yield, then it would be used in preference to sulfentrazone. Cyanazine is dismissed due to its low level of selectivity for use in pyrethrum. Cyanazine applications at all three experimental sites resulted in high levels of phytotoxicity to pyrethrum and this would restrict its use commercially. The delay in crop injury at experimental site B was attributed to the small amount of rainfall received immediately following application (Table 10.2) resulting in a slow activation of cyanazine. Although pyrethrum flower FW and DW yield following applications of cyanazine at 1.0 kg/ha were not significantly different to the untreated control treatment at P = 0.05, they were at P =0.1 and resulted in a 13% reduction in flower DW yield compared with the untreated. Quinclorac was applied at experimental site A and B with only a low level (< 20% crop injury) of phytotoxicity recorded, however symptoms were slow to develop and became most obvious during flowering. Quinclorac use as a potentially commercial herbicide for use in pyrethrum requires further investigation before a commercial recommendation can be made.

The low activity of pendimethalin against *A. caucalis* is consistent with literature of pendimethalin activity against Apiaceae species. As such the over reliance on

pendimethalin to control broadleaf weeds in pyrethrum has undoubtedly contributed to the success of these species.

10.5 Conclusion

Autumn applications of dimethenamid at 3.6 kg/ha provide acceptable levels of preemergence control of *A. caucalis* and *T. nodosa* and has a very low level of phytotoxicity to pyrethrum. Clomazone applied at 0.12 kg/ha provides excellent preemergence control of *T. nodosa*, however clomazone had a low level of activity on *A. caucalis*. Pyrethrum displayed acceptable tolerance to applications of clomazone at 0.12 kg/ha, although high rates of application resulted in discernable levels of cop injury and possible reductions in crop yields. Dimethenamid and clomazone have the greatest potential for use commercially. Applications of cyanazine provided high levels of control of *A. caucalis* and *T. nodosa*, however its use commercially was dismissed based on high levels of phytotoxicity. There is potential for the use of simazine, sulfentrazone, quinclorac and flumioxazin to provide control of *A. caucalis* and *T. nodosa* although the tolerance of pyrethrum to these herbicides requires further investigation.

Chapter 11 Postemergence control of *A. caucalis* in pyrethrum.

11.1 Introduction

Anthriscus caucalis is the most commonly observed Apiaceae weed occurring in pyrethrum and is considered one of the major weeds of pyrethrum due to its competitive ability and cost of control. The present herbicide program for pyrethrum has failed to provide any postemergence control of *A. caucalis* and as a result removal is achieved predominantly by manual means. Carfentrazone ethyl, metribuzin, sulfentrazone, quinclorac, imazamox and rimsulfuron have been identified through preliminary pot trials as having activity against *A. caucalis*.

Field studies were undertaken to determine the postemergence and residual control of *A. caucalis* by applications of metribuzin, carfentrazone-ethyl, simazine, sulfentrazone, quinclorac, imazamox, rimsulfuron and bentazone. In addition crop responses to herbicide applications were also assessed.

11.2 Materials and Methods

Postemergence control of *A. caucalis* was assessed during the winters of 2002 and 2003 at sites A and B respectively. Details of each site and relevant climatic data are given in Table 11.1 and 11.2. Unfortunately no postemergence trials for the control of *T. nodosa* could be established due the unavailability of appropriate field sites where the level of occurrence was sufficient to establish a trial.

Each trial site was selected based on an even distribution of *A. caucalis* seedlings between the cotyledon and 6 true leaf stage of growth prior to application. Prior to spraying, at trial site A, the seedling density of *A. caucalis* for each plot was determined by quadrat ($0.5m^2$) estimates replicated three times per plot. This was repeated at each assessment following application.

Table 11.1 Details of experimental sites used for postemergence herbicide experiments.

Site	Location	Soil classification	Soil Texture	pH (1:5 H₂O)	Date of pyrethrum sowing	Date of herbicide application
A	420293E 5448518N	Red Ferrosol	Clay loam	6.3	August 2001	5 June 2002
B	461943E 5433681N	Red Ferrosol	Clay loam	6.6	August 2002	11 June 2003

Table 11.2 Crop and soil conditions at time of herbicide application and subsequent rainfall data.

Site	Crop health status	Soil moisture	Time to first precipitation (hrs)	Precipitation first 14 Days (mm)	Precipitation first 30 Days (mm)	Total Precipitation (mm)
A	Fair	Dry	24	60	93.4	745.0
B	Good	Dry	48	36.8	57.6	534.3

Each experiment was arranged as a randomised complete block design with three replications. Plot size was 10 by 2m and 7 by 2m for site A and B respectively.

Only one herbicide rate was investigated with selection determined from the weed control efficacy results of the preliminary pot trials. Herbicides metribuzin (as Lexone® DF, 75%), carfentrazone-ethyl (as Hammer® EC, 24%), carfentrazone-ethyl (as Affinity® WDG, 40%), simazine (as Gesatop® FL,50%), sulfentrazone (as Authority® DG, 75%) and quinclorac (as Facet® FL, 22%) were applied at rates given in Table 11.3. Simazine, although recommended only as a preemergence herbicide, was included to examine its residual activity in more detail and if any early postemergence activity was evident, and what effect its application in late autumn had on the pyrethrum crop.

The most promising treatments were repeated in season 2003 with the addition of the herbicides imazamox (as Raptor® WDG, 75%), rimsulfuron (as Titus® DF, 25%) and bentazone (as Basagran® SC, 48%) at rates given in Table 11.5. Spraying procedure,

assessment and statistical analysis were performed as described in Chapter 10. Pyrethrum assays were also undertaken from experimental site A.

Pyrethrum assay procedure

Harvested pyrethrum flowers were dried at 60°C for 24hrs, ground through a 1mm sieve and stored at -18°C until extracted. Extractions were conducted by adding 0.2 g of grounded pyrethrum flowers to 9.8 ml hexane (Riedel-de-Hahn, Chromasolv grade), placed on a vortex to enable mixing for 15 seconds and left to stand for 24hrs in the dark. 2ml of sample was then removed and placed in labelled vials ready for analysis. Samples were stored at –18°C until High-performance liquid chromatography (HPLC) was undertaken. HPLC analyses and quantitation were performed largely as described by McEldowney and Menary, (1988), with the exception that pyrethrins were chromatographically separated using a 150 mm × 4.6 mm Alltech 'Prevail' silica column with a 0.275% (v/v) isopropanol and 99.725% (v/v) hexanes solvent, at a flow rate of 0.9 ml/min for 8.3 min, which was then ramped straight to 1.1 ml/min until all pyrethrins had eluted. The HPLC system (Waters Alliance 2690) was connected to a Waters 996 diode array detector. Pyrethrin content is expressed as percentage of total pyrethrins per dry weight of extracted sample.

Assay percentage was calculated as follows:

Area of sample/Area of standard * (Concentration of standard (g/ml)*Concentration of pyrethroids in standard)/Concentration of sample (g/ml).

11.3 Results

Experimental site A

At 12 DAA, 100% weed control of *A. caucalis* was achieved by the applications of sulfentrazone and metribuzin (Table 11.4). This was significantly ($P < 0.05$) better than all other treatments. At 33 DAA greater than 70% control was achieved with applications of sulfentrazone, quinclorac, carfentrazone ethyl EC and metribuzin. At 124 DAA metribuzin was found to provide significant ($P < 0.05$) control of *A. caucalis* while there was no significant ($P < 0.05$) difference in the control provided

by sulfentrazone, carfentrazone ethyl (EC) and quinclorac, which were significantly ($P < 0.05$) better than applications of carfentrazone ethyl formulated as a water dispersible granule (WDG) and simazine.

Applications of metribuzin, quinclorac, sulfentrazone and carfentrazone ethyl (EC) resulted in significant ($P < 0.05$) reductions in *A. caucalis* shoot biomass. Metribuzin, sulfentrazone, quinclorac and carfentrazone ethyl (EC) were not significantly ($P > 0.05$) different from each other, although applications of metribuzin provided the most significant ($P < 0.001$) reduction in FW compared with the untreated control. Carfentrazone ethyl (WDG) and simazine provided no significant ($P > 0.05$) reduction in FW from the untreated control. Metribuzin provided a 97.5% FW reduction of *A. caucalis*, sulfentrazone an 85.9% reduction, quinclorac an 87.3% reduction and carfentrazone ethyl (EC) a 79.2% reduction (Table 11.3). Applications of simazine and carfentrazone ethyl WDG resulted in 37.7% and 15.6 % FW reductions, respectively. The DW results were consistent with the FW data.

Table 11.3 Mean percentage control and biomass reduction of *A. caucalis* as affected by postemergence herbicide applications.

Treatment	% Control					FW (g m^{-2})	DW (g m^{-2})	Mean FW reduction %
	12DAA	33DAA	54DAA	82DAA	124DAA			
Sulfentrazone 0.38kg/ha	100.0^a	97 3^b	97.3^a	97.3^{ab}	81 7^h	253.9 ± 21.6**	28.0 ± 0.3**	85.9
Quinclorac 0.44kg/ha	56.7^c	76.7^c	81.3^b	80.0^b	73 3^b	227.7 ± 99.5**	26.9 ± 12.7**	87.3
Carfentrazone ethyl EC 0.024kg/ha	73 3^b	81.7^c	78.3^b	75.0^b	73.3^b	374.6 ± 99.0**	37.6 ± 10.9**	79.2
Carfentrazone ethyl WDG 0.024kg/ha	23.3^d	8.3^d	13.7^c	16.7^{cd}	8.3^d	1519.2 ± 68.3	164.7 ± 13.7	15.6
Metribuzin 0.19kg/ha	100.0^a	100.0^a	98.3^a	99.0^a	97.7^d	44.7 ± 23.0***	4 0 ± 2 1***	97.5
Simazine 2.0kg/ha	3 3^e	4.3^d	15.0^c	28.3^c	33.3^c	1120.6 ± 385.6	124.8 ± 45.6	37.7
Untreated	0 0^f	0.0^e	0 0^d	0.0^d	0.0^e	1799.4 ± 460 0	195.6 ± 47 7	0.0
LSD (P = 0.05)						765.3	85.6	

Values of weed control percentages with differing subscripts are significantly (P = 0 05) different for transformed data.
Treatments followed by asterisks are significantly different to the untreated control at * P = 0.05, ** P = 0 01 and ***P = 0.001.

Significant (P < 0.05) decreases in the population density of *A. caucalis* 12 DAA
occurred with all herbicides except for simazine (Figure 11.1). The initial mean
density of *A. caucalis* in the metribuzin treated plots was 8.9 plants/m^2. This fell to
0.0 plant/m^2 12 DAA and remained below 1.0 plant/m^2 for the duration of the trial.
Similar responses were observed for sulfentrazone and quinclorac. The initial mean
density of *A. caucalis* in the simazine plots was 11.9 plants/m^2 and this remained
relatively constant for the duration of the trial. In contrast carfentrazone ethyl in the
EC and WDG formulations resulted in significant (P< 0.05) decreases in population
density 12 DAA, however this was followed by significant (P < 0.05) increases at
subsequent sampling dates. The population of *A. caucalis* fell from 5.7 to 0.5
plants/m^2 when treated with carfentrazone ethyl EC and increased to 3.5 plants/m^2 by
the end of the study. With applications of carfentrazone ethyl WDG the population of
A. caucalis fell from 10.4 to 5.9 plants/m^2 and increased to 16.0 plants/m^2 by the end
of the study. The density of *A. caucalis* in the untreated plots steadily increased from
9.6 to 20.5 plants/m^2.
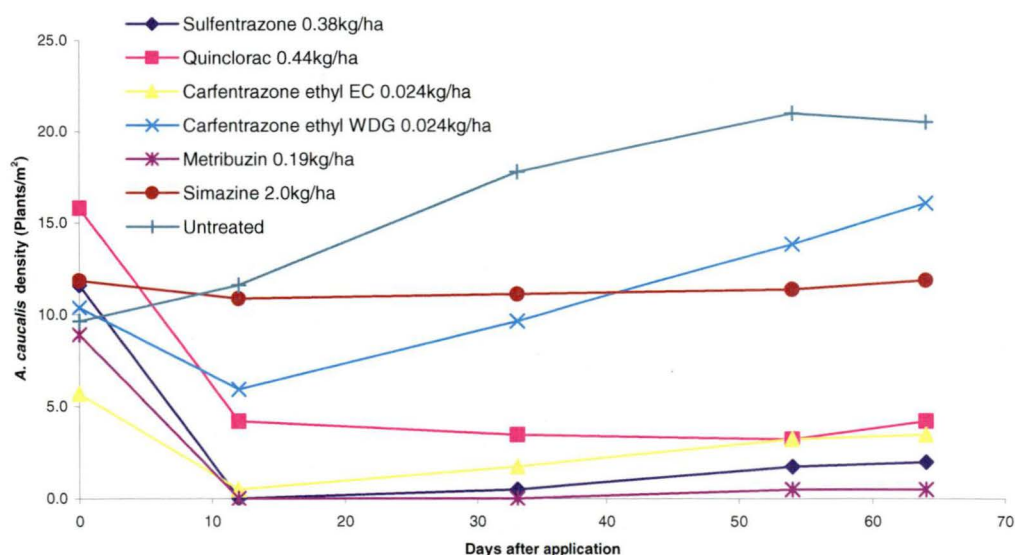
Figure 11.1 Changes in *A. caucalis* density as affected by postemergence herbicide
applications.

The symptoms of herbicides carfentrazone ethyl, metribuzin and quinclorac on *A.
caucalis* are shown pictorially in plates 11.1 to 11.3.

Plate 11.1 Regrowth of *A. caucalis* 12 DAA of carfentrazone ethyl (WDG)

Plate 11.2 Development of necrosis of *A. caucalis* 12 DAA of metribuzin.

Plate 11.3 Epinasty symptoms of *A. caucalis* 12 DAA of quinclorac.

Sulfentrazone caused the most significant ($P < 0.05$) crop injury at 12 DAA with a high level of leaf necrosis (80% leaf injury) recorded (Table 11.4). Although the level of crop injury was high immediately following application (Plate 11.4), the crop was able to recover, with approximately only 30% leaf damage at 124 DAA (plate 11.5). This was due to the production of new healthy leaf growth.
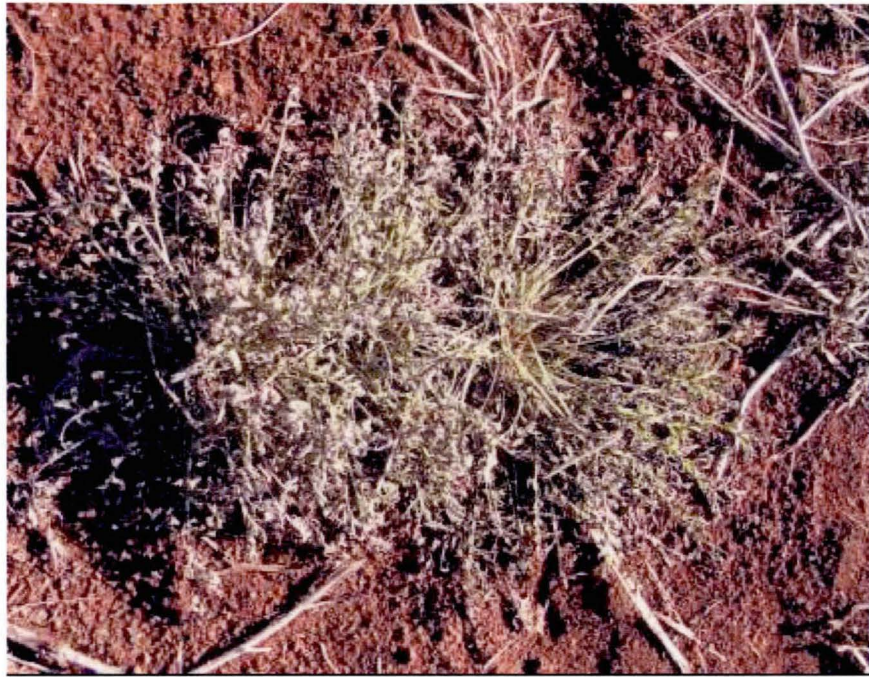
Plate 11.4 Effect of sulfentrazone 12 DAA on pyrethrum showing severe to complete leaf necrosis

Plate 11.5 Recovery of pyrethrum 124 DAA of sulfentrazone.

Crop injury as a result of quinclorac applications became more severe with time and at 124 DAA had caused 52% crop injury, the most significant (P < 0.05) crop injury of all treatments (Table 11.4). The symptoms were severe twisting of the leaves and emerging flower stems and general stunting of the plants. Metribuzin and simazine also resulted in some significant (P < 0.05) crop injury while there was no significant (P < 0.05) crop injury at 124 DAA with applications of carfentrazone ethyl in either formulation.

Simazine was found to be the only herbicide to cause a significant reduction (P < 0.05) in pyrethrum DW yield from the untreated control. There was no significant effect on pyrethrin content or mean 100 flower DW compared with the control treatment. Simazine also resulted in a significantly (P < 0.05) lower flower yield compared to all other herbicide treatments except quinclorac. Quinclorac did not have a significant (P > 0.05) effect on flower DW yield but resulted in a mean pyrethrin assay content of 1.27% which was significantly (P < 0.001) lower than all other herbicide treatments and the control treatment. The mean 100 flower DW was also significantly (P < 005) lower than the untreated control.

Table 11.4 Response of pyrethrum to postemergence herbicide applications at experimental site A.

Treatment	% Crop Injury					Flower FW (kg/ha)	Flower DM (kg/ha)	Pyrethrin content (%)	Mean 100 Flower DW (g)	FMI
	12DAA	33DAA	54DAA	82DAA	124DAA					
Sulfentrazone 0.38kg/ha	80.0^a	73.3^a	66.6^a	35.0^{ab}	31.7^b	9987.1 ± 431 5	2476.1 ± 197.6	2.49 ± 0.04	17.34 ± 0.02	347.9 ± 14.9
Quinclorac 0.44kg/ha	13.3^c	12.3^{cb}	21.7^b	46 7^a	51 7^a	8866.0 ± 765.1	2109.3 ± 185.9	1.27 ± 0.13	15.26 ± 0.79	320 5 ± 15 1
Carfentrazone ethyl EC 0.024kg/ha	23.3^b	6.7^d	3.3^{cd}	0 0^c	0.0^d	11900.2 ± 1058.1	2644.8 ± 222.3	2 43 ± 0.14	16.37 ± 0.54	345.3 ± 13.4
Carfentrazone ethyl WDG 0.024kg/ha	10.0^{cd}	5.0^d	3.3^{cd}	0.0^c	0.0^d	10497.2 ± 505.3	2449.3 ± 172.2	2.50 ± 0.03	18.35 ± 0.26	365.7 ± 20.8
Metribuzin 0 19kg/ha	25.0^b	16.7^b	11.0^{cd}	5.0^c	16 7^c	10032.9 ± 1013.2	2479.5 ± 216.9	2.33 ± 0.11	16.89 ± 0.91	337.9 ± 10.2
Simazine 2 0kg/ha	8.3^d	8.3^{bcd}	18.3^b	20.0^b	28.3^{bc}	8055.6 ± 693.8	1849.2 ± 167.0	2.59 ± 0.06	16.64 ± 0.27	343.2 ± 10.4
Untreated	0.0^e	0.0^e	0.0^d	0.0^c	0.0^d	9378.6 ± 314.7	2279.8 ± 74.5	2.62 ± 0.11	17.17 ± 0.58	350.5 ± 12.3
LSD (P = 0.05)						1779.6	419 1	0.31	1.61	n.s

Values of weed control percentages with differing subscripts are significantly (P = 0 05) different for transformed data

Experiential site B

At 7 DAA greater than 80% control of *A. caucalis* was achieved by applications of sulfentrazone at 0.38 kg/ha and carfentrazone ethyl (WDG) at 24 g/ha with the addition of Pulse® adjuvant (0.1% v:v) (Table 11.5). At 35 DAA greater than 90% control of *A. caucalis* was achieved by applications of sulfentrazone at 0.38 kg/ha, metribuzin at 0.19 kg/ha, carfentrazone ethyl (WDG) at 24 g/ha with the addition of Pulse® adjuvant (0.1% v:v) and imazamox at 33.75 g/ha with the addition of Pulse® adjuvant (0.1% v:v).

Plate 11.6 Stunting and chlorosis symptoms in *A. caucalis* 35 DAA of imazamox at 33.75 g/ha plus Pulse® (0.1% v:v).

Imazamox applied at 33.75 g/ha without an adjuvant and rimsulfuron applied at 15.0 g/ha provided 86.7% and 78.3% control of *A. caucalis*, respectively. Carfentrazone ethyl EC at 24.0 g/ha provided 78.3% control of *A. caucalis* 21 DAA, which was higher than the 60% control achieved by applications of carfentrazone ethyl WDG at 24.0 g/ha, 21 DAA. At 35 DAA lower levels of control of *A. caucalis* (< 60%) for both formulations of carfentrazone ethyl were recorded.

At 118 DAA greater than 90% FW reduction of *A. caucalis* was achieved by applications of sulfentrazone at 0.38 kg/ha, carfentrazone ethyl (WDG) at 24.0 g/ha with the addition of Pulse® adjuvant and imazamox at 33.75 g/ha with the addition of

Pulse® adjuvant. Applications of imazamox at 33.75 g/ha, metribuzin at 0.19 kg/ha and rimsulfuron at 15.0 g/ha resulted in 80-90% FW reductions of *A. caucalis*. Applications of carfentrazone ethyl WDG at 24.0 g/ha and bentazone at 0.48 kg/ha failed to reduce the FW of *A. caucalis* (Table 11.5).

Greater than 25% crop injury was observed with applications of sulfentrazone at 0.38 kg/ha and carfentrazone ethyl (WDG) at 24.0 g/ha with the addition of Pulse® adjuvant (0.1% v:v) 7, 21 and 35 DAA (Table 11.6). At 88 DAA crop injury was significantly (P < 0.05) less pronounced for these applications with less than 10% crop injury. In contrast, symptoms following applications of rimsulfuron at 15.0 g/ha were slow to develop with greater than 40% crop injury occurring at 88 DAA, while in the first 35 DAA injury symptoms to rimsulfuron were inconspicuous.
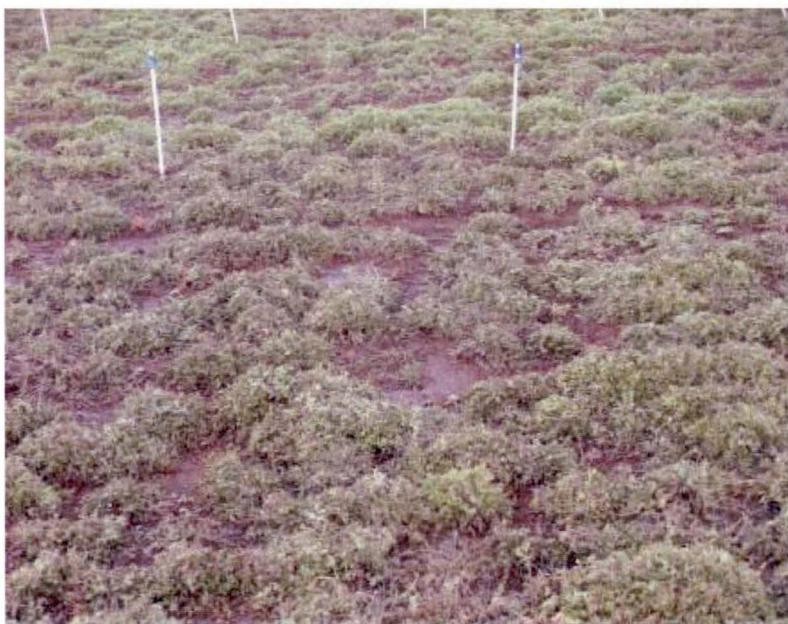
Plate 11.7 Pyrethrum crop response to carfentrazone ethyl (WDG) at 24.0 g/ha with the addition of Pulse® adjuvant (0.1% v:v) taken 21 DAA. Note the obvious leaf burn and crop discoloration.

There was no significant (P > 0.05) treatment effect on flower yield and mean flower weight. There was no significant (P > 0.05) effect on pyrethrum flower yield from the addition of Pulse® adjuvant to carfentrazone ethyl (WDG), although there was a significant (P < 0.05) and clearly visible increase in injury immediately following application.

Table 11.5 Mean percentage control and biomass reduction of *A. caucalis* as affected by postemergence herbicides

Treatment	% Control					FW (g/m²)	Mean FW reduction %
	7 DAA	**21 DAA**	**35 DAA**	**67 DAA**	**88 DAA**		
Imazamox 33.75g/ha	3.3^d	68.3^c	86.7^{ab}	96.7^a	95.0^a	$13.1 \pm 10.6^*$	88.6
Imazamox 33.75g/ha + Pulse (0.1% v:v)	6.7^d	75.0^c	95.3^{an}	98.3^a	98.3^a	$1.9 \pm 0.9^{**}$	98.3
Carfentrazone ethyl EC 24.0 g/ha	60.0^{ab}	78.3^{abc}	56.7^{bc}	53.3^{bc}	50.0^{bc}	60.2 ± 41.3	47.7
Carfentrazone ethyl WDG 24.0 g/ha	41.7^{bc}	60.0^c	35.0^c	36.7^c	33.3^c	151.1 ± 70.1	-31.1
Carfentrazone ethyl WDG 24.0 g/ha + Pulse (0.1% v:v)	85.0^a	96.7^{ab}	97.7^a	93.3^{ab}	83.3^{ab}	$10.9 \pm 7.9^*$	90.6
Metribuzin 0.19kg/ha	3.3^d	97.7^{ab}	94.3^{ab}	93.3^{ab}	78.3^{ab}	$23.1 \pm 13.1^*$	80.0
Rimsulfuron 15.0g/ha	3.3^d	78.3^{bc}	78.3^{ab}	90.0^{ab}	85.0^{ab}	$18.2 \pm 14.3^*$	84.2
Sulfentrazone 0.38kg/ha	83.3^a	99.0^a	98.3^a	98.3^a	96.7^a	$4.7 \pm 4.3^{**}$	95.9
Bentazone 0.48kg/ha	0.0^d	13.3^d	0.0^d	0.0^d	0.0^d	153.1 ± 46.8	-32.9
Untreated Weedy	0.0^d	0.0^d	0.0^d	0.0^d	0.0^d	115.2 ± 50.9	0.0
LSD (P = 0.05)						79.4	

Values of weed control percentage with differing subscripts are significantly different at P = 0 05 for transformed data
Treatments followed by asterisks are significantly different to the untreated control at * P = 0.05, ** P = 0.01 and ***P = 0 001

Table 11.6 Mean percentage crop injury and pyrethrum flower yield as affected by postemergence herbicides

Treatment	% Crop Injury				Flower FW (kg/ha)	Flower DW (kg/ha)	Mean 100 Flower DW
	7 DAA	21 DAA	35 DAA	87 DAA			
Imazamox 33.75g/ha	0.0[d]	0.0[d]	0.0[c]	0.0[c]	5329.9 ± 462.1	2100.7 ± 187.4	17.1 ± 0.73
Imazamox 33 75g/ha + Pulse (0.1% v:v)	0.0[d]	0.0[d]	0.0[c]	0.0[c]	5644.5 ± 439.2	2287.1 ± 197 2	16.5 ± 0.39
Carfentrazone ethyl EC 24.0 g/ha	13.3[b]	13 3[b]	10.0[b]	0.0[c]	4889.7 ± 311.7	1973.3 ± 153.0	17.3 ± 0.52
Carfentrazone ethyl WDG 24.0 g/ha	10.0[b]	13.3[b]	10.0[b]	0.0[c]	4937.0 ± 454.8	1972.8 ± 179.2	16 4 ± 0 76
Carfentrazone ethyl WDG 24.0 g/ha + Pulse (0.1% v:v)	30.0[a]	40.0[a]	26.7[c]	6.7[b]	5213.7± 853.6	2050.3 ± 320.9	15.3 ± 0.60
Metribuzin 0.19kg/ha	13.3[bc]	10.0[bc]	6.7[b]	0.0	5101.3 ± 534.9	2035.7 ± 210.8	17.5 ± 0.45
Rimsulfuron 15.0 g/ha	3.3[cd]	6.7[c]	6.7[b]	43 3[a]	4279.1± 613.6	1646.6 ± 214.8	16.6 ± 0.27
Sulfentrazone 0.38kg/ha	30.0[a]	40.0[a]	30.0[c]	3.3[bc]	5090.8 ± 612.5	2029.8 ± 221.8	16.6 ± 0.51
Bentazone 0.48kg/ha	6.7[bc]	13.3[b]	10 0	0.0[c]	4759.6 ± 429.2	1937 4 ± 109.2	17.6 ± 0.53
Untreated Weedy	0.0[d]	0.0[d]	0.0[c]	0.0[c]	4650.5 ± 675.4	1891.4 ± 260.2	17.3 ± 0.51
Untreated Hand weeded	0.0[d]	0 0[d]	0.0[c]	0.0[c]	5197.6 ± 572.0	2125.0 ± 221.0	17.1 ± 0.57
LSD (P = 0.05)					n.s.	n.s	n.s..

Values of pyrethrum injury percentages with differing subscripts are significantly different at P = 0.05 for transformed data.

11.4 Discussion

The changes in density of *A. caucalis*, at experimental site A, following herbicide applications highlighted the rapid kill of *A. caucalis* achieved with sulfentrazone, metribuzin, quinclorac, carfentrazone ethyl EC and to a lesser degree carfentrazone ethyl WDG. The reduction in population density of *A. caucalis* demonstrated the residual control achieved by simazine, quinclorac, metribuzin and to a lesser degree sulfentrazone. No residual activity was observed with carfentrazone ethyl.

Carfentrazone ethyl in the EC formulation provided higher levels of control of *A. caucalis* than when formulated as a WDG, although the same amount of active ingredient was applied. Although carfentrazone ethyl applied in the WDG formulation provided some reduction in *A. caucalis*, complete kill was not always achieved and the plants were able to produce healthy new leaf growth (Plate 11.1). In comparison following applications of metribuzin, *A. caucalis* plants displayed no visible signs of recovery (Plate 11.2). Epinasty was observed when *A. caucalis* was treated with quinclorac (Plate 11.3).

The severity of crop damage caused by sulfentrazone was high at experimental site A, and similarly at experimental site B although not as severe. This was in contrast with the data obtained from the preemergence trials where sulfentrazone resulted in lower levels of leaf injury. It is suggested that the timing and environmental conditions most likely contributed to this with sulfentrazone appearing to be much more phytotoxic during the cooler winter periods. Consistent with this conclusion is the finding that cool growing conditions increased injury to soybean from sulfentrazone applications (Swantek *et al.*, 1998). The minium air temperature in the day following postemergence applications at site A was 6.9°C. In contrast the minimum air temperature in the day following preemergence applications at sites A and B was 12.1°C and 14.0°C, respectively.

It was important to include the application of simazine as, although no postemergence activity was expected, excellent residual control of *A. caucalis* was obtained. In addition, applications of simazine resulted in a significant (P < 0.05) flower yield reduction which was not observed in the preemergence trials. It was

concluded that the systemic nature and the photosynthetic inhibiting mode of action of simazine had impacted negatively on the number of flowers produced by restricting growth through the winter and early spring period. In comparison early autumn applications have not resulted in any detrimental affect with respect to flower yield and it is suggested that a greater level of recovery from this application is able to occur prior to rapid growth and flowering of pyrethrum in the spring.

The level of leaf injury to pyrethrum from applications of carfentrazone ethyl occurred sufficiently early in the growing season that compensatory leaf growth was able to occur over the winter and spring such that at the time of flowering its impact had diminished and there was no noticeable effect on pyrethrum yield. The efficacy of carfentrazone ethyl was variable over two years, which is believed to be due to the high pyrethrum density and canopy closure at experimental site B (Plate 11.8). As a contact herbicide the efficacy of carfentrazone ethyl is lowered when coverage to the target species is reduced by crop competition.

Plate 11.8 The population of *A. caucalis* at trial site B prior to spraying. Note the presence of *A. caucalis* and the cover supplied by the density of pyrethrum and also by the high weed density of *A. caucalis*

The addition of the non-ionic organosilicone adjuvant Pulse® improved the efficacy of carfentrazone ethyl; however it also significantly increased crop injury. The use of this herbicide to control Apiaceae weeds postemergence was dismissed unless it could be applied prior to the end of April. At such time the canopy of the pyrethrum crop is relatively open and weed seedlings are not protected by the crop canopy. An application of carfentrazone ethyl prior to the end of April would also assist in the control of any weed seedlings that emerged during summer. As an alternative a later application of carfentrazone-ethyl with the addition of the Pulse® adjuvant would provide acceptable levels of control. Although crop injury increases has been observed, no detrimental effects on crop yields has been recorded with this herbicide.

There was no detrimental effect observed with the addition of Pulse® adjuvant to imazamox and the reported poor weed efficacy response to imazamox application in commercial crops previously is viewed as being a two fold effect. The addition of an adjuvant not only improved imazamox efficacy against *A. caucalis* but has been observed to improve the efficacy against other broad leaf weeds (Frosts, pers comm.

2003). Although the preliminary pot trials showed that imazamox displayed a lower efficacy than metribuzin and carfentrazone ethyl the increased activity observed in the field trials appeared to be in response to low temperatures as the pot trials were undertaken during late summer. Researchers studying the effects of other imidazolinone herbicides have also reported that temperature plays an important role in their activity. *Avena fatua* showed less growth inhibition at high temperature (26/16) than at low temperature (11/7) following imazamethabenz-methyl applications (Malefyt and Quakenbush, 1991). This observation was explained by the apparent ability of *A. fatua* to detoxify imazamethabenz-methyl more rapidly at warmer conditions than at cooler conditions. The phytotoxicity of post emergence applications of imazethapyr to soybean and alfalfa has also been shown to be greater in cooler than warmer conditions and similar responses have been reported with imazaquin and imazapyr (Malefyt and Quakenbush, 1991).

FMI assessment was not undertaken at experimental site B due to harvest of this trial being delayed to allow for the harvesting of the other three fields trials in 2003. This and the onset of warm and dry conditions led to the crop being over mature and any differentiation in FMI between treatments was not detectable as greater than 90% of all flowers in each plot were in flower maturity stage 7.

11.5 Conclusion

The results of both field experiments provided substantial evidence to suggest that postemergence control of *A. caucalis* can be satisfactorily achieved by applications of imazamox, metribuzin or sulfentrazone. Imazamox was the most promising due to its higher level of selectivity in pyrethrum. Imazamox provided an 88% FW reduction of *A. caucalis* without the addition of Pulse® adjuvant and this increased to 98% with the addition of Pulse®. Applications of imazamox were concluded to be a potential commercial option. Metribuzin was an alterative option but concerns about pyrethrum tolerance to photosynthetic inhibiting herbicides reduced confidence in its application, although results of these studies indicate that at a rate of 0.19 kg/ha pyrethrum flower yield was unaffected. The postemergence application of sulfentrazone was dismissed based on the observed increased crop injury associated with its application in late autumn/early winter.

The activity of carfentrazone ethyl was influenced by its formulation with the EC formulation providing a better efficacy against *A. caucalis* than the WDG formulation. The addition of a non-ionic organosilicone adjuvant improved the efficacy of carfentrazone ethyl WDG. As a contact herbicide the efficacy of carfentrazone ethyl is lowered when complete coverage to the target species is not achieved and it is hypothesised that the addition of an adjuvant significantly improves contact through lowering the contact angel between droplet and leaf.

The efficacy of both quinclorac and rimsulfuron was high, however selectivity was generally poor and their potential for use commercially was considered low.

Chapter 12 Efficacy of Carfentrazone-ethyl formulation

12.1 Introduction

The postemergence field study and preliminary herbicide pot trials provided substantial evidence that the efficacy of carfentrazone-ethyl was strongly influenced by its formulation. Carfentrazone-ethyl, when formulated as an emulsifiable concentrate (EC), was found to have a much higher efficacy against *A. caucalis* than when formulated as water dispersible granules (WDG) and the addition of a non-ionic organosilicone adjuvant significantly improved the efficacy of carfentrazone ethyl WDG against *A. caucalis*.

An adjuvant refers to any substance included in the formulation of a herbicide or added to the spray tank to enhance herbicide characteristics or application characteristics (Rao, 2000). Foliar retention and droplet contact with the epicuticular surface are very important to herbicide activity, especially for a foliage contact herbicide like carfentrazone ethyl. Spray droplet retention and wetting of the leaf surface varies among plant species, growth stage and environmental conditions (Woznica and Skrzypczak, 1998). The surface tension of water is relatively high, tending to hold water droplets in the form of spheres on waxy surfaces (Plate 12.1) and resulting in limited contact between liquid and leaf surface (Berndt, 1987). The addition of an adjuvant lowers the dynamic surface tension of a spray solution, which results in significant improvement in retention and wetting of the leaf surface (Woznica and Messersmith, 1995).
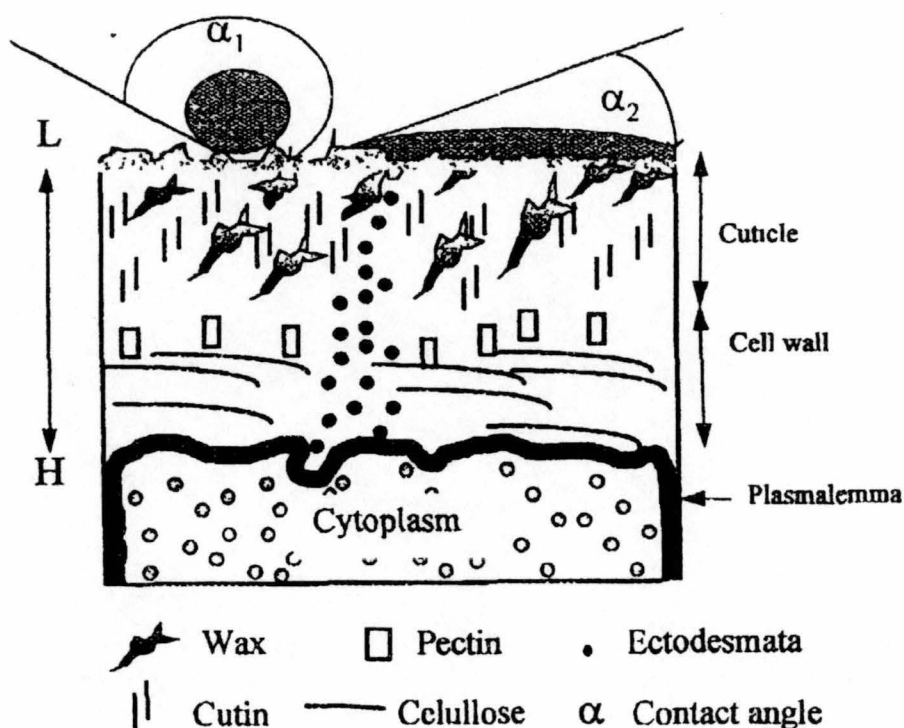
Plate 12.1 Schema of outer wall of an epidermal cell with a droplet of high surface tension (α_1 – high contact angle) and low surface tension (α_2 – low contact angle) and banners of herbicides absorption, L-lipophilic properties, H-hydrophilic properties. Taken from Woznica and Skrzypczak (1998).

Wetting is frequently expressed in terms of the contact angle that a drop of a liquid makes with a solid (Reichard,1988). When an adjuvant is added to a solution, surface tension is reduced and the water droplet becomes flatter; thus there is a lower contact angle. The lower the contact angle, the better the wetting properties of the adjuvant.

The aim of study 1 was to examine the control of *A. caucalis* and *T. nodosa* by the addition of three adjuvants; Pulse® an organosilicone, Synertrol® a vegetable (canola) oil, and Activator® a non ionic surfactant, to carfentrazone ethyl (WDG), and compare these treatments to carfentrazone ethyl (EC) and carfentrazone ethyl (WDG) without the addition of adjuvants.

The aim of study 2 was to investigate the effect of the addition of Pulse®, Synertrol® and Activator® to carfentrazone ethyl (WDG) on droplet spread on leaves of *A. caucalis, T. nodosa* and pyrethrum.

12.2 Materials and Methods:

Study 1 Efficacy of carfentrazone ethyl formulations

Two seeds of *A. caucalis* and *T. nodosa* were sown together in 15 cm diameter pots, with a standard potting mix on the 23rd July 2002. Following establishment of seedlings the weakest seedling was removed to leave one seedling of each species per pot. Seedlings were grown under glasshouse conditions for 3 weeks and moved to benches outside for two weeks prior to spraying to avoid any increases in efficacy associated with warm humid conditions. Carfentrazone ethyl was applied at rates of 12, 24 and 48 g/ha to the plants at the 8-10 leaf stage of growth formulated as either an EC or a WDG. In addition three adjuvants Pulse®, Synertrol® and Activator® were added separately to carfentrazone ethyl (WDG) at a rate of 0.1% v:v. Visual assessment of percentage leaf area injury was undertaken 4 DAA and leaf fresh weights (FW) assessed 30 DAA. An untreated control was included and the six treatments were replicated four times. Assessment procedures and statistical analysis were undertaken as described in Chapter 9.

Study 2 Effect of carfentrazone ethyl formulation on contact angle

Fifteen individual seedlings of *T. nodosa, A. caucalis* and pyrethrum were established in a standard potting mix under glasshouse conditions. After reaching the 3-4 leaf stage of growth the youngest fully expanded leaf of each plant was removed.

Five herbicide treatments were applied to individual leaves of each species
 ➢ Carfentrazone ethyl formulated as an EC
 ➢ Carfentrazone ethyl formulated as an WDG
 ➢ Carfentrazone ethyl formulated as an WDG + Synertrol® (0.1% v:v)
 ➢ Carfentrazone ethyl formulated as an WDG + Activator® (0.1% v:v)
 ➢ Carfentrazone ethyl formulated as an WDG + Pulse® (0.1% v:v)

A concentration of 0.12 ml/L of carfentrazone ethyl was maintained in each treatment.

A Pradavit n24 slide projector was used to project an image of an applied droplet, located on the horizontal leaf onto a A4 sheet of white paper. The projector slide was

adjusted so as a small glass slide (approximately 25mm x 15mm) could be placed on it in a horizontal position (Barnes, 1993). Small sections (approximately 5mm x 10mm) were taken from the leaf and placed with the adaxial surface uppermost onto the slide. Care was taken to avoid damage to the selected leaf area and where possible major veins were excluded. A Hamilton No. 7001 syringe was used to deliver a 1.5 microliter droplet of herbicide solution on the leaf section. The projected image of the droplet was then immediately traced and the contact angles measured from both sides of the drop. This was repeated three times for each treatment to give six contact angle measurements. Analysis of data was completed using a two factor with replication ANOVA.

12.3 Results

Study 1 Efficacy of carfentrazone ethyl formulations

There was a significant (P < 0.001) increase in leaf injury by all treatments compared to the untreated control for both species (Figure 12.1). Complete kill (100% leaf damage) of both *A. caucalis* and *T. nodosa* at 4 DAA was only achieved by the application of carfentrazone ethyl (WDG) at 48 g/ha plus Pulse® (0.1% v:v).

The mean leaf injury for all treatments was significantly higher (P < 0.001) for *T. nodosa* than for *A. caucalis*. At 4 DAA, 90% or more leaf injury of *T. nodosa* was achieved by applications of carfentrazone ethyl (EC) at all three rates, carfentrazone ethyl (WDG) at 24 g/ha and 48 g/ha, carfentrazone ethyl (WDG) at all three rates with the addition of Pulse® or Synertrol®, and carfentrazone ethyl at 24 g/ha and 48g/ha with the addition of Activator®. In comparison greater than 90% leaf injury 4 DAA for *A. caucalis* was only achieved by applications of carfentrazone ethyl (WDG) at 48g/ha with the addition of Pulse® and carfentrazone ethyl (EC) at 48g/ha (Figure 12.1).
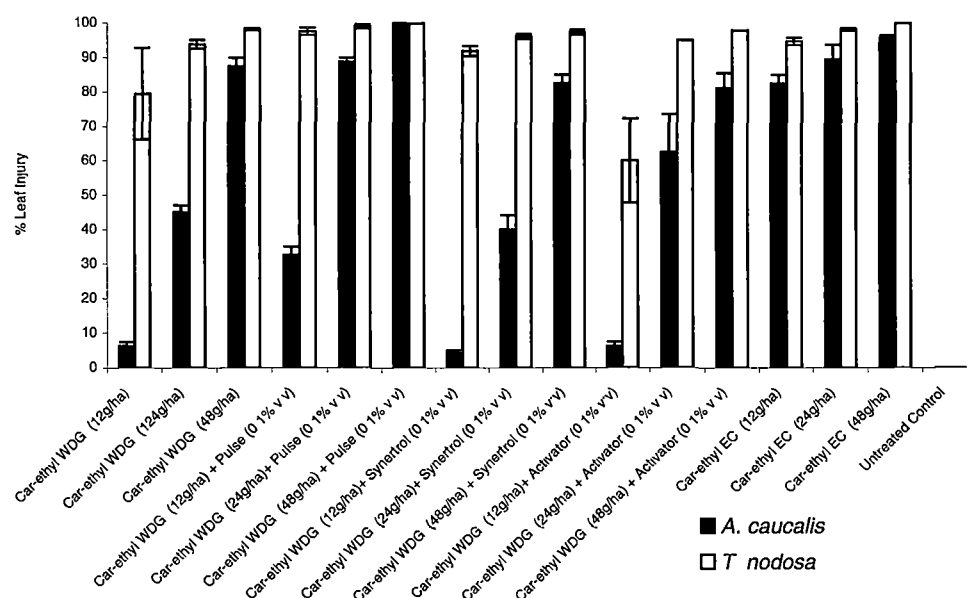
Figure 12.1 Percentage leaf area damage of *A. caucalis* and *T. nodosa* 4 DAA. Standard error of mean shown as error bars.

Complete leaf injury of *T. nodosa* was achieved by the application of carfentrazone ethyl (WDG) at 24 g/ha and 48 g/ha with the addition of Pulse® and carfentrazone ethyl (EC) at 48 g/ha. Complete kill of *T. nodosa* in two or more of the replications was also achieved by applications of carfentrazone ethyl (WDG) at 48 g/ha, carfentrazone ethyl (WDG) at 48 g/ha plus Synertrol® and carfentrazone ethyl (EC) at 24 g/ha.

Complete leaf injury of *A. caucalis* was only achieved by the application of carfentrazone ethyl (WDG) at 48 g/ha with Pulse®. 100% leaf injury in 3 of the 4 replications of *A. caucalis* was also achieved by the application of carfentrazone ethyl (WDG) at 24 g/ha with Pulse®. In comparison, *A. caucalis* plants treated with carfentrazone ethyl (EC) at 48 g/ha were able to recover from more than 90% leaf injury in three of the four replications to produce healthy new growth.

Significant (P < 0.001) reductions in leaf fresh weight compared with the untreated control were achieved by all herbicide treatments for both *A. caucalis* and *T. nodosa* (Table 12.1).

Table 12.1 Effect of the addition of adjuvants on the efficacy of Carfentrazone-ethyl on the control of *A. caucalis* and *T. nodosa*.

Treatment	*T. nodosa* FW (g)	Mean FW Reduction %	*A. caucalis* FW (g)	Mean FW Reduction %
Car-ethyl WDG (12g/ha)	2.83 ± 0.29***	66.6	14.75 ± 1.39***	41.1
Car-ethyl WDG (124g/ha)	1.63 ± 0.20***	80.8	7.83 ± 1.04***	68.7
Car-ethyl WDG (48g/ha)	0.09 ± 0.07***	98.9	4.18 ± 1.55***	83.3
Car-ethyl WDG (12g/ha) + Pulse®	0.49 ± 0.19***	94.2	5.75 ± 1.03***	77.0
Car-ethyl WDG (24g/ha)+ Pulse®	0.00 ± 0.00***	100.0	0.88 ± 0.88***	96.5
Car-ethyl WDG (48g/ha) + Pulse®	0.00 ± 0.00***	100.0	0.00 ± 0.00***	100.0
Car-ethyl WDG (12g/ha)+ Synertrol®	1.94 ± 0.34***	77.1	15.89 ± 2.65***	36.5
Car-ethyl WDG (24g/ha)+ Synertrol®	0.99 ± 0.19***	88.3	11.74 ± 2.50***	53.1
Car-ethyl WDG (48g/ha) + Synertrol®	0.18 ± 0.11***	97.9	4.11 ± 1.15***	83.6
Car-ethyl WDG (12g/ha)+ Activator®	3.13 ± 0.80***	63.0	9.32 ± 0.83***	62.8
Car-ethyl WDG (24g/ha) + Activator®	1.67 ± 0.13***	80.2	6.32 ± 1.84***	74.7
Car-ethyl WDG (48g/ha) + Activator®	0.45 ± 0.04***	94.6	4.25 ± 0.80***	83.0
Car-ethyl EC (12g/ha)	0.78 ± 0.10***	90.8	4.33 ± 0.28***	82.7
Car-ethyl EC (24g/ha)	0.18 ± 0.18***	97.9	1.43 ± 0.82***	94.3
Car-ethyl EC (48g/ha)	0.00 ± 0.00***	100.0	0.74 ± 0.28***	97.1
Untreated Control	8.46 ± 0.91	0.0	25.03 ± 3.08	0.0
LSD (P = 0.05)	0.97		3.65	41.1

Treatments followed by asterisks are significantly different to the untreated control at * P = 0.05, ** P = 0.01 and ***P = 0.001.
Note: Adjuvants added at (0.1% v:v)
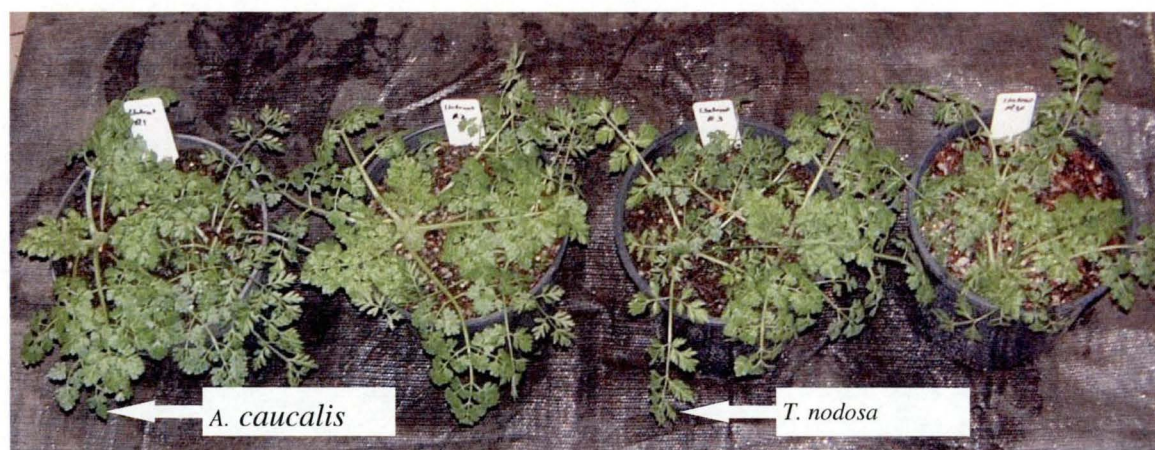
Plate 12.2 The untreated control treatment showing the healthy appearance of *A. caucalis* and *T. nodosa*.

Plate 12.3 Efficacy of carfentrazone ethyl WDG (48 g/ha) plus Pulse® (0.1% v:v) 25 DAA on *A. caucalis* and *T. nodosa*. Note the complete leaf necrosis on all species for each replication.

Plate 12.4 Efficacy of carfentrazone-ethyl WDG (48 g/ha) plus Synertrol® (0.1%) on *A. caucalis* and *T. nodosa* 21 DAA. Note the complete leaf necrosis and plant death of *T. nodosa* in comparison to the observed regrowth and recovery of *A. caucalis*.

Plate 12.5 Efficacy of carfentrazone-ethyl WDG (48 g/ha) plus Activator® (0.1%) on *A. caucalis* and *T. nodosa* 21 DAA. Note the healthy new regrowth and recovery of *A. caucalis* and to a lesser extent *T. nodosa*.

Plate 12.6 Efficacy of carfentrazone-ethyl EC (48 g/ha) on *A. caucalis* and *T. nodosa* 21 DAA. Note the complete leaf necrosis and plant death of *T. nodosa*. Slight regrowth and recovery of *A. caucalis* is visible.

Plate 12.7 Efficacy of carfentrazone-ethyl WDG (12 g/ha) on *A. caucalis* and *T. nodosa* 21 DAA. Note the regrowth and recovery of *A. caucalis* and *T. nodosa*.

Study 2 Effect of carfentrazone ethyl formulation on contact angle

There was a significant (P < 0.001) treatment and species effect on droplet contact angle and a significant (P < 0.05) species by treatment interaction. The contact angle between a droplet of carfentrazone ethyl (WDG) and the leaf surface of *A. caucalis* was significantly (P < 0.05) reduced with the addition of all three adjuvants: Pulse®, Activator® and Synertrol®. The contact angle between a droplet of carfentrazone ethyl (EC) and the leaf surface of *A. caucalis* was significantly (P < 0.05) lower than that between carfentrazone ethyl (WDG) and the leaf surface of *A. caucalis*. Similarly, the addition of all three adjuvants to carfentrazone ethyl (WDG) resulted in a decrease in the contact angle between the applied droplet and leaves of *T. nodosa* and pyrethrum. In contrast to that observed with *A. caucalis* the contact angle

between the leaf surface of *T. nodosa* and also for pyrethrum leaves with carfentrazone ethyl (EC) droplets were not significantly (P > 0.05) different to that of carfentrazone ethyl (WDG) droplets (Figure 12.2).

Pulse® adjuvant resulted in the most significant (P < 0.001) reduction in mean contact angle of the three treatments, while there was no significant (P > 0.05) difference between Synertrol® and Activator®. The mean contact angle for pyrethrum was significantly (P < 0.001) higher than for *A. caucalis*, which in turn was significantly (P < 0.001) higher than for *T. nodosa*.
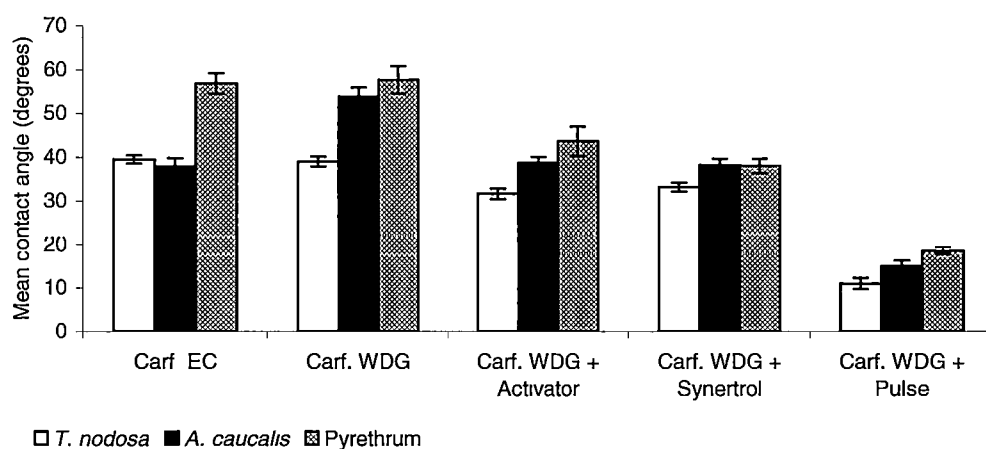
Figure 12.2 Mean contact angle of carfentrazone ethyl on *A. caucalis*, *T. nodosa* and pyrethrum leaves as affected by formulation and addition of adjuvants. Standard errors shown as error bars. LSD (P = 0.05) = 3.63.

12.4 Discussion

The efficacy of active ingredient carfentrazone ethyl on *A. caucalis* and *T. nodosa* was affected by its formulation with the EC formulation resulting in substantially more leaf injury than the WDG formulation. It was concluded that this occurred because herbicides formulated as an EC generally lower the water surface tension reducing the droplet contact angle and allowing for greater entry of the active ingredient into the plant foliage (Rao, 2000).

The addition of the organosilicone adjuvant Pulse® significantly (P < 0.05) improved the efficacy of the WDG formulation of carfentrazone-ethyl. Organosilicone adjuvants are a class of nonionic surfactants. These are a relatively new class of adjuvants and according to Roggenbuck and Penner (2000) they increase pesticide efficacy by lowering the surface tension and increasing droplet spread allowing for a more thorough distribution of the spray solution. The results of this study indicated that the adjuvant Pulse® has increased the efficacy of carfentrazone ethyl WDG by lowering the surface tension and increasing droplet spread. This is especially important for contact herbicides such as carfentrazone-ethyl so that maximum coverage of the applied herbicide is obtained. Addition of adjuvants Activator® and Synertrol® to carfentrazone ethyl WDG reduced the contact angle between the spray droplet and leaves of *A. caucalis*, resulting in better activity against this species. The contact between droplets of carfentrazone ethyl EC and leaves of *A. caucalis* were not significantly (P > 0.05) different to that of carfentrazone ethyl WDG with the addition of Activator® and Synertrol®. This was consistent with the observed activity. Carfentrazone ethyl EC provided greater activity against *A. caucalis* than carfentrazone ethyl WDG with Activator® or Synertrol®. Addition of Activator® and Synertrol® to carfentrazone ethyl WDG reduced the mean contact angle of the droplets on *T. nodosa* leaves although the mean contact angle remained above 30 degrees. As result of this increases the efficacy of these applications against *T. nodosa* were not observed.

The mean contact angle of the droplet of carfentrazone ethyl EC and WDG were not significantly different to each other when applied to pyrethrum which is consistent with the observed phytotoxicity of these formulations under field conditions. Consistent also with the field observations was that the addition of Pulse® to carfentrazone ethyl WDG resulted in a significant (P < 0.001) reduction in mean contact angle of the droplet on pyrethrum leaves resulting in significant phytotoxicity to this herbicide under field conditions.

12.5 Conclusion

The formulation of carfentrazone ethyl strongly influenced the contact angle of the droplet on leaves and this affected the efficacy and phytotoxicity of the herbicide. The EC formulation of carfentrazone ethyl had a greater leaf surface spread than the WDG formulation on leaves of *A. caucalis* resulting in the EC formulation providing a better efficacy against this species. The addition of Pulse® adjuvant increased the spread of carfentrazone ethyl on the leaves of both *A. caucalis* and *T. nodosa*, significantly improving its efficacy. However, the addition of Pulse® adjuvant also increased the spread of carfentrazone ethyl on the leaves of pyrethrum, which increased the level of leaf injury to the crop.

The results of this study provide quantitative evidence to the differences between treatments observed in both the field and pot studies. The addition of Pulse® was beneficial, especially where the target control species was *A. caucalis*, and in situations where complete leaf coverage may be limited through crop canopy protection and or a high weed density. The use of Pulse® however, increases the spread of carfentrazone ethyl on pyrethrum leaves leading to a higher degree of leaf injury. The use of carfentrazone ethyl in the EC formulation is recommended in preference to carfentrazone ethyl in the WDG formulation for the control of *A. caucalis*. The high contact angle between the spray droplets and leaf surface of *A. caucalis* with the latter formulation reduced the amount of leaf coverage achieved and as a result compete kill was not always achieved. There was little difference in the phytotoxicity of these formulations to pyrethrum, which was consistent with the observed contact angle for pyrethrum leaves.

Chapter 13 Field trials examining crop tolerance to herbicides for the control of *A. caucalis* and *T. nodosa*.

13.1 Introduction

Single applications of the preemergence herbicides simazine, sulfentrazone, dimethenamid and flumioxazin applied in early autumn, were found to control *A. caucalis* and/or *T. nodosa*. However, the amount of residual activity of these herbicides was variable and was influenced by rate of application and environmental conditions. As a result a single preemergence application in early autumn may not provide an acceptable level of residual control into the winter period. A postemergence application applied late autumn/early winter may be required to control seedlings that emerge during this period. Alternatively a secondary preemergence application could be applied prior to subsequent seedling emergence. Although either of these herbicide strategies is likely to improve the level of control of *A. caucalis* and *T. nodosa*, there is an increased probability of damage to the pyrethrum crop.

A crop response field study was established in 2002 (experimental site A) and repeated in 2003 (experimental site B) to examine the effects of preemergence herbicides in combination with postemergence herbicides. In addition, a field study was established in 2003 (experimental site C) to examine the effects of repeated applications of preemergence herbicides on the control of *A. caucalis*. The objectives of these studies were to:

> ➤ Assess the level of selectivity of preemergence, postemergence and repeated applications of herbicides showing the most promising weed efficacy against *A. caucalis* and *T. nodosa*
> ➤ Examine the interaction of these herbicides
> ➤ Determine the control of *A. caucalis* using repeated applications of preemergence herbicides.

13.2 Materials and Methods

Experimental site A

Experimental site A was a randomised complete block split plot design with 5 preemergence herbicide treatments as the main plots and 5 postemergence herbicide treatments as the sub plots (Plate 13.1). The main plots were 10m by 10m in size and the sub plots were 10m by 2m and each treatment was replicated three times. The main plot treatments were sulfentrazone at 0.38 kg/ha, simazine at 2.0 kg/ha, dimethenamid at 3.6 kg/ha, pendimethalin at 0.99 kg/ha and an untreated control. The main plot treatments were applied on 19th February 2002. The sub plot treatments were quinclorac at 0.44 kg/ha, carfentrazone ethyl (EC) at 0.024 kg/ha, metribuzin at 0.19 kg/ha, clomazone at 0.12 kg/ha and untreated control. The subplot treatments were applied on the 23rd May 2002. All rates selected were based on results of pot studies except for pendimethalin which was applied at the recommended commercial rate for broad spectrum weed control in pyrethrum. The trial was undertaken on a commercial field site and to avoid seed spread throughout the field all plots were hand weeded 2 to 3 months prior to crop harvest. This allowed enough time for weed assessments to be undertaken and also reduced the weed competition from the crop allowing herbicide effect on crop yield effects to be determined. Site layout and other relevant details are presented in Plate 13.1 and Tables 13.1-13.3, respectively.

Experimental site B

Experimental site B was established in a similar manner to site A except that herbicides flumioxazin and imazamox were substituted for pendimethalin and quinclorac and that the untreated preemergence main plot treatment was removed. The design was a randomised complete block split plot design with 4 preemergence herbicide treatments as the main plots and 5 postemergence herbicide treatments as the sub plots (Plate 13.2). The main plots were 10m by 10m in size and the sub plots were 10m by 2m. Each treatment was replicated three times. The main plot treatments were sulfentrazone at 0.38 kg/ha, simazine at 2.0 kg/ha, dimethenamid at 3.6 kg/ha and flumioxazin at 0.15 kg/ha. The main plot treatments were applied on 17th March 2003. The sub plot treatments were carfentrazone-ethyl EC at 0.024 kg/ha, metribuzin at 0.19 kg/ha, clomazone at 0.12 kg/ha, imazamox at 33.75 g/ha plus Pulse® adjuvant (0.1% v:v) and untreated control. The sub plot treatments were

applied on 28th May 2003. Included in the design for comparative analysis only was a separate untreated control treatment and a hand weeded treatment. Other relevant details are presented in Tables 13.1-13.3. Site layout and other relevant details are presented in Plate 13.2 and Tables 13.1-13.3, respectively

Experimental site C

Experimental site C was established where the presence of *A. caucalis* had been recorded previously. The aim of trial C was to examine the tolerance of pyrethrum to repeated applications of preemergence herbicides and to assess the long-term residual control of *A. caucalis*. The trial was a randomised complete block design with 14 treatments consisting of applications of simazine at 2.0 kg/ha, dimethenamid at 3.6 kg/ha and flumioxazin at 0.15 kg/ha in March 2003 and repeated in May 2003 in combination with each other and metribuzin at 0.19 kg/ha to give 12 herbicide treatments, plus an untreated control and a hand weeded treatment. Plot sizes were 7m by 2m and each treatment was replicated three times. Other relevant details are presented in Tables 13.1-13.3.

10 meters

10 meters

Block 1

Sulfentrazone 0.38kg/ha					Untreated					Simazine 2.0 kg/ha					Dimethenamid 3.6kg/ha					Pendimethalin 0.99kg/ha				
A	E	D	B	C	B	E	C	A	D	D	B	C	A	E	A	B	C	D	E	E	A	B	C	D

Block 2

Untreated					Sulfentrazone 0.38kg/ha					Simazine 2.0 kg/ha					Dimethenamid 3.6kg/ha					Pendimethalin 0.99kg/ha				
E	A	C	B	D	A	C	B	E	D	B	C	D	A	E	E	C	A	B	D	B	D	A	E	C

Block 3

Sulfentrazone 0.38kg/ha					Simazine 2.0 kg/ha					Dimethenamid 3 6kg/ha					Untreated					Pendimethalin 0.99kg/ha				
C	D	E	B	A	A	D	B	C	E	A	C	B	D	E	A	E	D	B	C	A	B	C	E	D

Where   A = Quinclorac 0.44 kg/ha

B = Carfentrazone-ethyl 24.0 g/ha

C = Metribuzin 0.19 kg/ha

D = Clomazone 0.12 kg/ha

E = Untreated

Plate 13.1 Experimental design of site A

10 meters

		Simazine 2.0 kg/ha				Flumioxazin 0.15 kg/ha				Sulfentrazone 0.38 kg/ha				Dimethenamid 3.6 kg/ha			

Block 1: D A E B C | A C B D E | E B C D A | E B C D A

10 meters

	Sulfentrazone 0.38 kg/ha			Dimethenamid 3.6 kg/ha			Simazine 2.0 kg/ha			Flumioxazin 0.15 kg/ha

Block 2: E A D C B | B C A E D | A C E B D | A C E B D

	Dimethenamid 3.6 kg/ha			Sulfentrazone 0.38 kg/ha			Flumioxazin 0.15 kg/ha			Simazine 2.0 kg/ha

Block 3: C B E D A | A E C B D | A D C B E | A D C B E

Hand weeded / Untreated (Block 1)

Hand weeded / Untreated (Block 2)

Untreated / Hand weeded (Block 3)

Where   A = Carfentrazone-ethyl 24.0 g/ha

B = Metribuzin 0.19 kg/ha

C = Clomazone 0.12 kg/ha

D = Imazamox 33.75g/ha plus Pulse® (0.1% v:v)

E = Untreated control

Plate 13.2 Experimental design of site B

Table 13.1 Details of experimental sites used for pyrethrum crop response studies

Site	Location	Soil classification	Soil Texture	pH (1:5 H$_2$O)	Date of pyrethrum sowing	Date of 1st herbicide application	Date of 2nd herbicide application
A	440364E 5439760N	Red Ferrosol	Clay loam	6.6	July 1999	19th February 2002	23 May 2002
B	440064E 5439720N	Red Ferrosol	Clay loam	6.6	July 2001	17 March 2003	28 May 2003
C	420347E 5448518N	Red Ferrosol	Clay loam	6.3	August 2001	18 March 2003	20 May 2003

Table 13.2 Crop and soil conditions at time of 1st herbicide application and subsequent rainfall data

Site	Crop health status	Soil moisture	Time to first precipitation (hrs)	Precipitation first 14 Days (mm)	Precipitation first 30 Days (mm)	Total Precipitation (mm)
A	Good	Dry	14	14	20.0	618.8
B	Good	Dry	4	50.4	147.8	812.0
C	Good	Dry	12	75.6	155.8	765.0

Table 13.3 Crop and soil conditions at time of 2nd herbicide application and subsequent rainfall data

Site	Soil moisture	Time interval to first precipitation (hrs)	Precipitation first 14 Days (mm)	Precipitation first 30 Days (mm)
A	Dry	192	3	53.6
B	Dry	96	98.4	143.0
C	Dry	4	71.2	176.8

Spraying procedure, assessment and statistical analyse were performed as described in chapter 10. Pyrethrum assays were also undertaken as described in chapter 11.

Percentage light interception

An attempt was made to quantify crop injury by measuring the percentage light interception of the crop canopy at experimental site A. A LI-191SA line quantum

sensor was used to determine the percentage light interception of the pyrethrum crop at 97 DAA. The line quantum sensor rod was placed horizontally across the centre of the 2m wide plot and randomly within each third of the plot to give three readings per plot. Two background light readings were recorded per plot, one prior and one following the three plot readings. This allowed for effects due to any changes in photosynthetically active radiation during measurements to be minimised.

The percentage light interception was calculated as,

(Mean background light reading – canopy light reading)/ mean background light reading *100.

Light measurement units were expressed in moles per square meter per second (mol $m^{-2} s^{-1}$).

13.3 Results

Experimental site A – Crop injury and yield response

There was a significant (P < 0.05) interaction between the main plot and sub plot treatments on pyrethrum injury at 67, 97 and 137 DAA (Table 13.4). Preemergence applications of simazine had a negative interaction with postemergence applications of carfentrazone ethyl, metribuzin and clomazone. At 137 DAA preemergence applications of simazine with post applications of carfentrazone ethyl, metribuzin and clomazone resulted in 25%, 28% and 33% crop injury, respectively. In comparison at 137 DAA, preemergence applications of dimethenamid with post applications of carfentrazone ethyl, metribuzin and clomazone resulted in 0%, 13% and 15% crop injury, respectively.

A significant (P < 0.05) main plot treatment effect on pyrethrum crop injury was recorded at all assessment dates except 137 DAA (Table 13.5). Simazine and sulfentrazone resulted in the most significant (P < 0.05) crop injury. At 12 DAA preemergence treatments of simazine and sulfentrazone in combination with all postemergence treatments resulted in a mean crop injury level of 43% and 41% respectively. Significantly (P < 0.05) less injury resulted from preemergence treatments of pendimethalin and dimethenamid. At 97 DAA there was no significant (P > 0.05) difference in the level of crop injury between the untreated control,

pendimethalin and dimethenamid. At 97 DAA simazine resulted in 36% injury, which was significantly (P < 0.05) higher than injury from sulfentrazone, which resulted in 29% crop injury.

A significant (P < 0.05) sub plot treatment effect on pyrethrum crop injury was recorded at all assessment dates (Table 13.6). The mean of all preemergence treatments in combination with carfentrazone ethyl EC resulted in 30% crop injury 12 DAA. However, at 137 DAA injuries had become less pronounced with only 10% crop injury. At 137 DAA quinclorac caused the most significant (P < 0.05) crop injury (70%) of all postemergence treatments. Sub plot treatments of metribuzin and clomazone caused significantly (P < 0.05) higher levels of crop injury compared with the untreated sub plot at all assessment dates.

There was a significant (P < 0.05) pre by postemergence interaction on flower yield (Table 13.4). Preemergence applications of simazine interacted negatively with postemergence applications of metribuzin, clomazone, carfentrazone ethyl and quinclorac resulting in a significant (P < 0.05) reduction in pyrethrum flower DM yield compared with simazine applied in combination with no postemergence herbicide (untreated sub plot). The mean flower DW yield from the preemergence application of simazine alone was 2653 kg/ha. In comparison, preemergence applications of simazine with applications of metribuzin, clomazone, carfentrazone ethyl and quinclorac reduced the flower yield by more than 25%.

There was a significant (P < 0.05) pre by postemergence interaction on flower maturity (Table 13.4). The mean FMI of preemergence applications of dimethenamid with postemergence applications of quinclorac was 249. This was significantly (P < 0.05) lower than the recorded mean FMI of preemergence applications of dimethenamid with any other postemergence (sub plot) treatment, which were all above 297. Preemergence applications of dimethenamid followed by carfentrazone ethyl (EC) resulted in the highest recorded mean FMI of 326, which was significantly (P < 0.05) higher than treatments of sulfentrazone followed by carfentrazone ethyl (EC) (261) and simazine followed by carfentrazone ethyl (EC) (261).

There was no significant (P > 0.05) pre by postemergence interaction on flower assay or mean flower weight.

Consistent with the trials undertaken in chapter 10, preemergence applications had no significant (P > 0.05) effect on flower DW yield, pyrethrum assay content or mean flower weight (Table 13.5). Preemergence applications had a significant (P < 0.05) effect on FMI (Table 13.5). Applications of simazine and sulfentrazone resulted in a mean FMI of 278 and 283 respectively which was significantly (P < 0.05) lower than the mean FMI from preemergence treatments of pendimethalin (300) and dimethenamid (297). There was no significant (P > 0.05) difference in FMI between the untreated control treatment and all other preemergence treatments.

Postemergence treatments had a significant effect (P < 0.05) on pyrethrum flower DW yield, pyrethrum assay content and FMI (Table 13.6). Applications of quinclorac resulted in a mean flower DW yield of 2000 kg/ha and a pyrethrum assay content of 1.65%, which was significantly (P < 0.05) lower than all other postemergence treatments. Consistent with this, applications of quinclorac also resulted in a significantly (P < 0.05) lower mean FMI. The mean flower yield and pyrethrum assay content from applications of carfentrazone ethyl, metribuzin and clomazone were not significantly (P > 0.05) different to each other or the untreated control. The mean FMI of all preemergence herbicides applied without any subsequent postemergence herbicide (untreated sub plot) was 306. This was significantly (P < 0.05) higher than the mean of the postemergence treatments metribuzin (286) and clomazone (290) but not significantly (P > 0.05) different to carfentrazone ethyl (297).

Table 13.4 Pyrethrum injury, flower DW, flower assay, FMI and 100 flower DW following pre and postemergence herbicide applications at experimental site A

Preemergence	Postemergence	% Crop Injury					Flower DW (kg/ha)	Flower Assay (%)	FMI	Mean 100 flowers DW (g)
		12 DAA	45 DAA	67 DAA	97 DAA	137 DAA				
Simazine 2kg/ha	Quinclorac 0 44kg/ha	41 7	46.7	50 0^a	73 3^a	43.3^{ab}	1976.8	1.74	285 9	11 7
Simazine 2kg/ha	Carfentrazone ethyl EC 0 024kg/ha	55 0	56.7	38 3^{ab}	30 0^b	25 0^b	1975 3	2 10	261 1	11.6
Simazine 2kg/ha	Metribuzin 0 19kg/ha	46 7	45.0	35.0^{ab}	28.3^{bc}	28 3^{ab}	1747.7	2.12	268.9	11 3
Simazine 2kg/ha	Clomazone 0 12kg/ha	51 7	53 3	43 3^a	33 3^b	30.0^{ab}	1846 3	1 89	259 7	11 4
Simazine 2kg/ha	Untreated	21 7	20.0	13.3^{cd}	15 0^c	6 7^c	2652.8	2.23	311.7	13 0
Dimethenamid 3 6kg/ha	Quinclorac 0 44kg/ha	13.7	21 7	23 3^{bc}	71.7^a	48.3^a	2012 6	1 56	248 6	13 9
Dimethenamid 3 6kg/ha	Carfentrazone ethyl EC 0 024kg/ha	11 7	10.0	10 0^{cd}	11.7^{cd}	0 0^d	2202.6	2 11	325 8	13 1
Dimethenamid 3 6kg/ha	Metribuzin 0 19kg/ha	15 0	20.0	18.3^c	20.0^{bc}	13 3^{bc}	2098.4	1 99	297 4	12 3
Dimethenamid 3 6kg/ha	Clomazone 0.12kg/ha	11 7	21.7	30.0^d	15.0^c	15 0^{bc}	1773.4	2 03	301.7	12 2
Dimethenamid 3.6kg/ha	Untreated	3 3	1 7	3.3^e	5 0^d	5 0^c	2205 6	1 97	312.3	12 8
Sulfentrazone 0.38kg/ha	Quinclorac 0.44kg/ha	38.3	43.3	30.0^b	73.3^a	41 7^{ab}	2139.0	1 87	265.4	12 1
Sulfentrazone 0 38kg/ha	Carfentrazone ethyl EC 0.024kg/ha	51 7	38 3	16 7^c	15.0^c	6 7^c	2248 6	2 01	285.3	11.6
Sulfentrazone 0 38kg/ha	Metribuzin 0 19kg/ha	45.0	40 0	20.0^{bc}	15 0^c	15 0^{bc}	2197.7	2.13	281.6	11 9
Sulfentrazone 0 38kg/ha	Clomazone 0.12kg/ha	43 3	56 7	46 7^a	28 3^{bc}	28.3^{ab}	2153 6	2 16	286.6	12.1
Sulfentrazone 0 38kg/ha	Untreated	25 0	16 7	10 0^{cd}	11 7^{cd}	3 3^c	2118 7	2.13	297.8	12 8
Pendimethalin 0 99kg/ha	Quinclorac 0.44kg/ha	13 3	26 7	38 3^{ab}	71 7^a	48.3^a	1918 3	1.55	283 6	12.4
Pendimethalin 0 99kg/ha	Carfentrazone ethyl EC 0 024kg/ha	25 0	25.0	11.7^{cd}	11 7^{cd}	3.3^c	2410 8	2 06	307.5	12 3
Pendimethalin 0 99kg/ha	Metribuzin 0 19kg/ha	11 7	15.0	11 7^b	11 7^{cd}	13 3^{bc}	2022.6	2.49	297 8	12 4
Pendimethalin 0 99kg/ha	Clomazone 0.12kg/ha	21 7	20 0	30 0^b	23 3^{bc}	13 3^{bc}	2839 9	2.12	302 6	12.1
Pendimethalin 0 99kg/ha	Untreated	3 3	5 0	0.0^e	0 0^e	0 0^d	2496 9	2.12	307 5	12 4
Untreated	Quinclorac 0 44kg/ha	8 3	13 3	21 7^{bc}	58.3^a	45.0^{ab}	1936 1	1.55	265 1	12 2
Untreated	Carfentrazone ethyl EC 0 024kg/ha	8 3	3.3	4 3^d	6 7^d	3 3^c	2468.1	2.10	305 0	12.1
Untreated	Metribuzin 0 19kg/ha	8.3	16.7	15 0^{cd}	18 3^{bc}	25 0^b	1809 7	1.87	283 0	12 4
Untreated	Clomazone 0 12kg/ha	10.0	20 0	30 0^b	26.7^{bc}	21.7^{bc}	2272.8	2 10	298 6	12 6
Untreated	Untreated	0.0	0 0	0 0^e	0 0^e	0.0^d	2207.2	2 17	300.7	12 7
LSD (P=0.05)		n s					397 4	n.s	29 2	n s

Table 13.5 Response of pyrethrum to preemergence (main plot) treatments at experimental site A

Preemergence	% Crop Injury					Flower DW yield.(kg/ha)	Pyrethrum Assay (%)	Mean 100 Flower DW	FMI
	12DAA	45DAA	67DAA	97DAA	137DAA				
Simazine 2kg/ha	43 3[a]	44 0[a]	36.0[a]	36 0[a]	26.7	2039.8	2.01	11 81	277 5[b]
Dimethenamid 3 6kg/ha	11 1[b]	13 5[c]	17 0[c]	24.7[c]	16 3	2058 5	1.93	12.87	297 2[a]
Sulfentrazone 0 38kg/ha	40 7[a]	40 0[a]	26.7[b]	28.7[b]	19 0	2171.5	2.06	12.12	283.3[b]
Pendimethalin 0.99kg/ha	15 0[b]	18.0[b]	18 7[c]	24 3[c]	18 7	2337.7	2.06	12.33	299 8[a]
Untreated	6.2[c]	8 7[d]	15 2[c]	21.2[c]	18.5	2138 8	1.96	12.39	290 5[ab]
LSD (P=0 05)					n s	n s	n s	n s	13 1

Mean with differing subscripts are significantly different at P = 0.05. For injury percentages differences are for transformed data.

Table 13.6 Response of pyrethrum to postemergence (sub plot) treatments at experimental site A

	% Crop Injury					Flower DW yield (kg/ha)	Pyrethrum Assay (%)	Mean 100 Flower DW (g)	FMI
	12DAA	45DAA	67DAA	97DAA	137DAA				
Quinclorac 0.44kg/ha	23 1[c]	27.2[b]	34.7[a]	69.7[a]	45 3[a]	1996 6[b]	1.65[b]	12 48	269 7[c]
Carfentrazone ethyl EC 0.024kg/ha	30 3[a]	27 9[ab]	16 9[b]	15 7[c]	10.0[c]	2261.1[a]	2.08[a]	12 13	296.9[ab]
Metribuzin 0 19kg/ha	25.3[bc]	26.0[b]	20.0[b]	18.7[c]	19 0[b]	1975.2[b]	2 12[a]	12 06	285 7[b]
Clomazone 0 12kg/ha	27.7[ab]	32 3[a]	36 0[a]	25.3[b]	21.3[b]	2177 2[a]	2 06[a]	12.10	289 9[b]
Untreated	8 8[d]	10.4[c]	4 6[c]	5 8[d]	4.2[d]	2336.2[a]	2 12[a]	12.74	306.0[a]
LSD (P=0.05)						178.9	0.17	n.s	13 1

Mean with differing subscripts are significantly different at P = 0.05 For injury percentages differences are for transformed data

Experimental site A – Light interception

At 97 DAA there was a significant (P < 0.05) pre by postemergence interaction effect on the amount of light intercepted by the crop canopy (Figure 13.1). Those treatments which resulted in 15.0% light interception or less were simazine with carfentrazone ethyl (EC) and all preemergence treatments in combination with quinclorac.

Preemergence (main plot) treatments had a significant (P < 0.05) effect on the amount of light interception by the crop canopy 97 DAA. A significant (P < 0.05) decrease in light interception compared with the untreated was caused by preemergence applications of simazine and sulfentrazone. There was no significant (P > 0.05) difference in light interception among preemergence treatments of dimethenamid, pendimethalin and the untreated. Mean amount of light interception for the preemergence treatments of simazine, sulfentrazone, dimethenamid, pendimethalin and untreated were 17.6%, 18.0%, 23.7%, 28.0% and 25.2%, respectively.

Postemergence (sub plot) treatments had a significant (P < 0.05) effect on the amount of light interception by the crop canopy 97 DAA. Postemergence treatments of quinclorac, clomazone, metribuzin and carfentrazone ethyl (EC) all resulted in a significant (P < 0.05) reduction in light interception compared with the untreated. Postemergence applications of quinclorac resulted in a significantly (P < 0.05) lower level of light interception than clomazone at 97 DAA, which was significantly (P < 0.05) lower than metribuzin and carfentrazone ethyl (EC), which were not significantly (P > 0.05) different from each other. The mean light interception for the postemergence application of quinclorac, carfentrazone ethyl (EC), metribuzin, clomazone and untreated were 11.6%, 25.4%, 23.5%, 18.7% and 33.2% respectively.
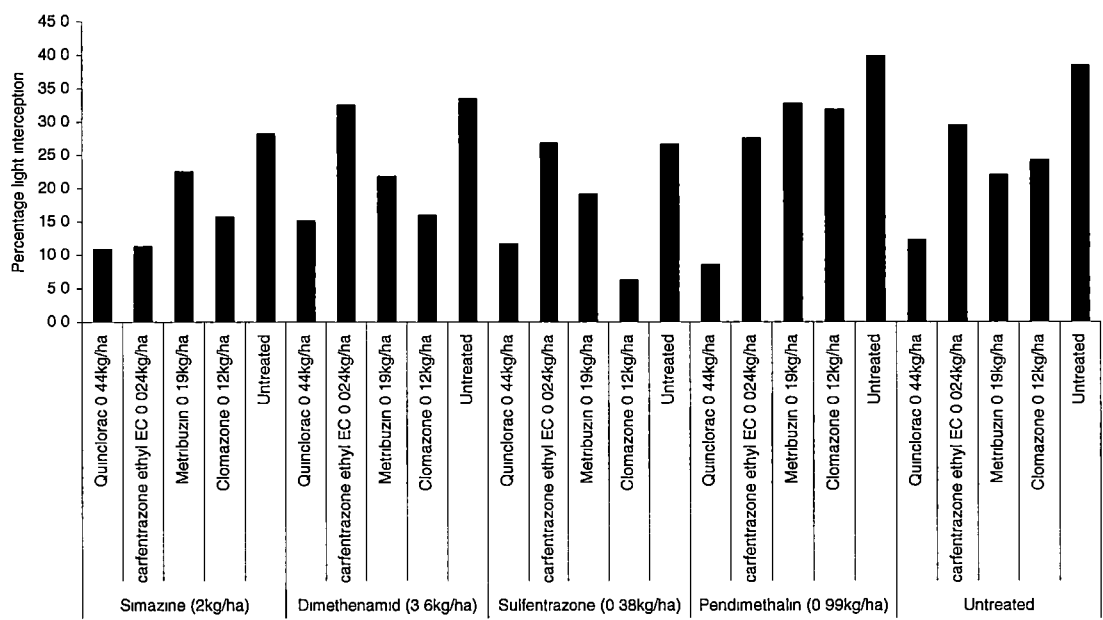
Figure 13.1 Mean percentage light interception of the pyrethrum canopy as affected by herbicide applications 97 DAA. LSD (P = 0.05) = 11.4.

The mean pyrethrum assay yield displayed a significant (P < 0.001) negative correlation with the level of injury determined at 137 DAA (Figure 13.2b). A quadratic equation was found to best describe this relationship, with a proportion of experimental variation (R^2) of 0.72. No significant (P > 0.05) correlation existed at 12 DAA (Figure 13.2a).
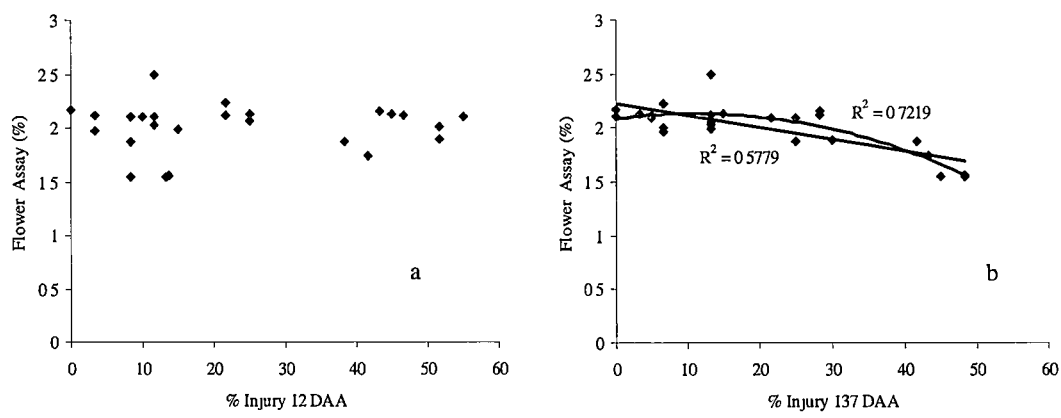
Figure 13.2 The relationship between % crop injury and % flower assay assessed 12 DAA (a) and 137 DAA (b)

There was a significant (P < 0.01) negative correlation found between % leaf injury at 137 DAA and flower DW yield (Figure 13.3b). A linear equation was found to best describe this relationship, although the proportion of experimental variation (R^2) was only 0.26. There was no significant (P > 0.05) correlation between % leaf injury at 12 DAA and flower DW yield.
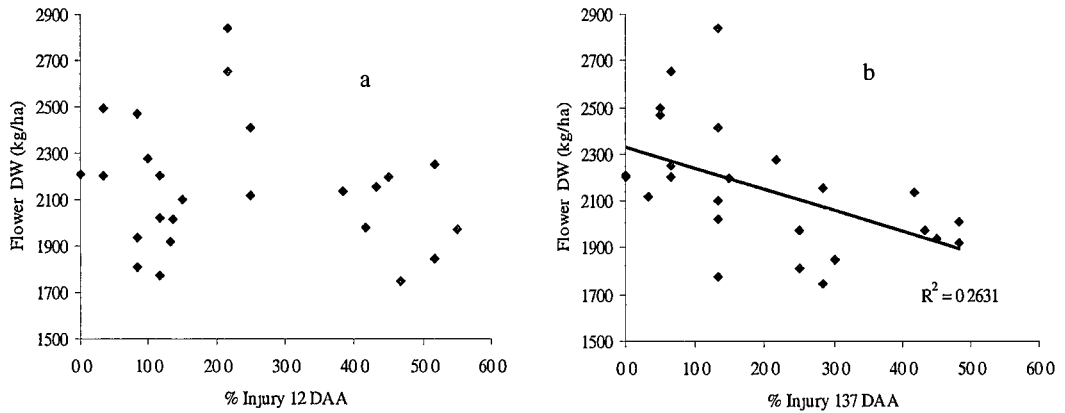
Figure 13.3 The relationship between % crop injury and flower yield (kg/ha) assessed 12 DAA (a) and 137 DAA (b).

Experimental site B – Crop injury and yield response

There was a significant (P < 0.05) preemergence (main plot) and postemergence (sub plot) interaction on pyrethrum injury at 6, 12 and 21 DAA but no significant (P > 0.05) interaction at 63 and 131 DAA (Table 13.7). At 21 DAA preemergence treatments of dimethenamid and sulfentrazone in combination with no postemergence treatment (untreated) resulted in zero crop injury. The most significant (P < 0.05) crop injury occurred with preemergence applications of simazine with postemergence application of carfentrazone ethyl EC (26.7%) or metribuzin (30.0%) and preemergence applications of flumioxazin with postemergence application of carfentrazone ethyl EC (26.7%) and metribuzin (26.7%).

There was a significant (P < 0.05) main plot treatment effect on pyrethrum injury at all assessment dates (Table 13.8). Preemergence applications of flumioxazin and simazine resulted in a similar level of crop injury at all assessment dates which was

significantly (P < 0.05) greater than for sulfentrazone and dimethenamid, which were not significantly (P > 0.05) different to each other (Table 13.8).

There was a significant (P < 0.05) postemergence treatment effect on pyrethrum injury at all assessment dates (Table 13.9). At 6 DAA all postemergence herbicides caused significant (P < 0.05) crop injury compared to the control. At 12, 21, 63 and 131 DAA postemergence applications of imazamox resulted in no significant (P > 0.05) crop injury compared with the untreated control. Applications of metribuzin and carfentrazone ethyl resulted in the most significant (P < 0.05) crop injury 21 DAA, while at 131 DAA crop injuries as a result of postemergence applications of carfentrazone ethyl (EC) were not significantly (P < 0.05) different to applications of clomazone and imazamox.

Plate 13.3 Field day presentation of experimental site B to contracted pyrethrum growers and researchers.

There was no significant (P > 0.05) pre by postemergence herbicide interaction on flower yield, flower assay, individual flower weights or flower maturity. However, treatments that caused low levels of crop injury generally had higher mean flower

yields and those treatments that caused higher levels of crop injury generally had lower mean flower yields (Figure 13.4).
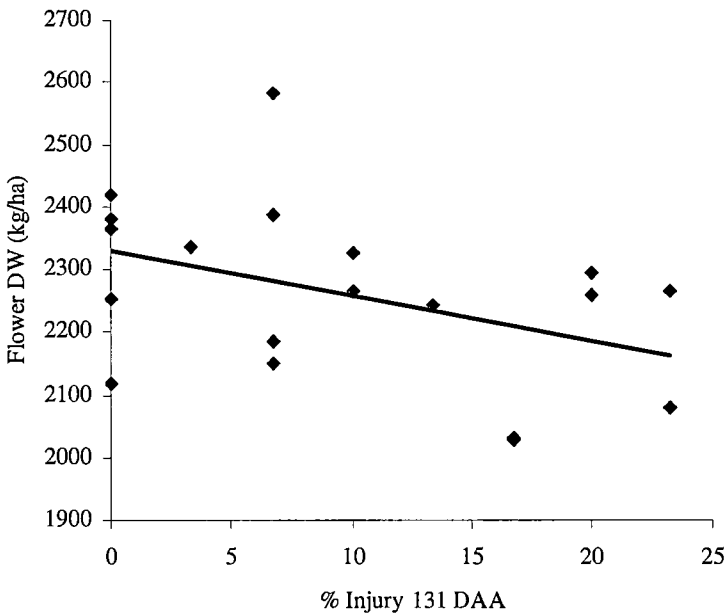
Figure 13.4 The relationship between % crop injury and flower yield (kg/ha) assessed 131 DAA.

Table 13.7 Pyrethrum injury, flower DW, flower assay, FMI and 100 flower DW following pre and postemergence herbicide applications at experimental site B

Preemergence	Postemergence	Crop injury (%)					Flower DW (kg/ha)	Flower Assay (%)	Mean 100 Flower DW (g)	FMI
		6 DAA	12 DAA	21 DAA	63 DAA	131 DAA				
Dimethenamid 3 6kg/ha	Carfentrazone ethyl EC 0 024kg/ha	10 0^d	10 0^d	13 3^{bc}	10 0	0 0	2417	2 01	13 9	331 1
Dimethenamid 3 6kg/ha	Metribuzin 0 19kg/ha	13 3^{cd}	13 3^{cd}	16 7^{bc}	16 7	6 7	2151	1 90	13 9	326 3
Dimethenamid 3 6kg/ha	Clomazone 0 12kg/ha	0 0^f	10 0^d	10 0^e	10 0	0 0	2380	1 95	13 0	324 4
Dimethenamid 3 6kg/ha	Imazamox 33 75g/ha + Pulse (0 1% v v)	6 7^e	6 7^e	3 3^e	6 7	6 7	2583	1 89	13 7	335 7
Dimethenamid 3 6kg/ha	Untreated	0 0^f	0 0^f	0 0^f	0 0	0 0	2119	1 90	13 2	323 9
Simazine 2kg/ha	Carfentrazone ethyl EC 0 024kg/ha	20 0^{abc}	20 0^{abc}	26 7^a	23 3	16 7	2028	1 92	13 1	303 0
Simazine 2kg/ha	Metribuzin 0 19kg/ha	16 7^{bcd}	23 3^{ab}	30 0^a	26 7	23 3	2265	1 93	13 2	310 3
Simazine 2kg/ha	Clomazone 0 12kg/ha	13 3^{cd}	16 7^{bcd}	20 0^{ab}	20 0	20 0	2258	1 91	13 0	318 8
Simazine 2kg/ha	Imazamox 33 75g/ha + Pulse (0 1% v v)	13 3^{cd}	13 3^{cd}	16 7^{bc}	16.7	10 0	2265	1 93	13 3	317 1
Simazine 2kg/ha	Untreated	13 3^{cd}	13 3^{cd}	20 0^{ab}	16.7	6 7	2186	1 87	13 2	319 8
Sulfentrazone 0.38kg/ha	Carfentrazone ethyl EC 0 024kg/ha	13 3^{cd}	13 3^{cd}	13 3^{bc}	13.3	6 7	2388	1 96	12 8	321 8
Sulfentrazone 0 38kg/ha	Metribuzin 0 19kg/ha	0 0^f	3 3^{ef}	16 7^{bc}	16.7	10 0	2325	1 91	12 8	311 5
Sulfentrazone 0 38kg/ha	Clomazone 0 12kg/ha	3 3^e	10 0^d	13.3^{bc}	16.7	3 3	2334	1 86	12.7	302 5
Sulfentrazone 0 38kg/ha	Imazamox 33 75g/ha + Pulse (0 1% v v)	3 3^e	3 3^{ef}	6 7^d	10.0	0 0	2365	1 86	12 4	304 7
Sulfentrazone 0 38kg/ha	Untreated	0 0^f	0 0^f	0 0^f	0 0	0 0	2251	1 90	12 1	301 9
Flumioxazin 0 15kg/ha	Carfentrazone ethyl EC 0 024kg/ha	23 3^{ab}	26 7^a	26 7^a	26.7	20 0	2293	1 87	13 9	318 6
Flumioxazin 0 15kg/ha	Metribuzin 0 19kg/ha	20 0^{abc}	20 0^{abc}	26 7^a	26.7	23 3	2078	1 87	13 4	312 6
Flumioxazin 0 15kg/ha	Clomazone 0 12kg/ha	16 7^{bcd}	20 0^{abc}	16 7^{bc}	23.3	16 7	2032	1 89	13 8	314 9
Flumioxazin 0 15kg/ha	Imazamox 33 75g/ha + Pulse (0 1% v v)	20 0^{abc}	16 7^{bcd}	16 7^{bc}	20.0	13 3	2241	1 98	13 2	305 3
Flumioxazin 0 15kg/ha	Untreated	13 3^{cd}	13 3^{cd}	16 7^{bc}	16 7	10 0	2280	1 98	14 2	341 5
LSD (P=0 05)					n s	n s	n s	n s	n s	n s
Untreated							2154	1 94	13 6	310 3
Hand weeded							2333	1 93	12 4	299 2

Table 13.8 Response of pyrethrum to preemergence (main plot) treatments at experimental site B.

Preemergence	% Crop Injury					Flower DW yield.	Pyrethrum Assay (%)	Mean 100 Flower DW	FMI
	6 DAA	12 DAA	21 DAA	63 DAA	131 DAA				
Simazine 2kg/ha	15 3^a	17.3^a	22 7^a	20.7^a	15.3^a	2200	1.91	13.2	313.8
Dimethenamid 3.6kg/ha	6 0^b	8 0^b	8 7^b	8.7^b	2.7^b	2330	1 93	13 6	328.3
Sulfentrazone 0 38kg/ha	4 0^b	6.0^b	10.0^b	11 3^b	4.0^b	2332	1.90	12.6	308 5
Flumioxazin 0 15kg/ha	20 0^a	19.3^a	20 7^a	22 7^a	16.7^a	2185	1.92	13 7	318 5
LSD (P=0 05)						n s.	n.s	n.s	n.s

Mean with differing subscripts are significantly different at P = 0.05

Table 13.9 Response of pyrethrum to postemergence (sub plot) treatments at experimental site B.

Postemergence	% Crop Injury					Flower DW yield.	Pyrethrum Assay (%)	Mean 100 Flower DW (g)	FMI
	6 DAA	12 DAA	21 DAA	63 DAA	131 DAA				
Imazamox 33.75g/ha + Pulse (0 1% v v)	10 8^{bc}	10.0^b	10.8^c	13.3^{bc}	7.5^{bc}	2364	1.92	13 2	315 7
Carfentrazone ethyl EC 0.024kg/ha	16 7^a	17 5^a	20.0^{ab}	18.3^{ab}	10 8^b	2281	1.94	13 4	318 6
Metribuzin 0.19kg/ha	14 2^b	15 0^a	22.5^a	21 7^a	15 8^a	2204	1.90	13.1	315 2
Clomazone 0 12kg/ha	8.3^{cd}	14 2^a	15 0^b	17.50^{ab}	10 0^b	2251	1.90	13 2	315 1
Untreated	6 7^d	6 7^b	9.2^c	8.3^c	4.2^c	2209	1.91	13 2	321.8
LSD (P=0 05)						n s	n.s	n.s	n.s

Mean with differing subscripts are significantly different at P = 0.05.

Experimental site C– Crop injury and yield response

Applications of flumioxazin in May resulted in significantly ($P < 0.05$) more crop injury than any other treatment (Table 13.10). At 72 DAA dual applications of flumioxazin caused 80% crop injury, as did simazine applied in March followed by flumioxazin applied in May. These applications both resulted in highly significant ($P < 0.001$) decreases in yield compared to the hand weeded treatment. Dimethenamid applied in March followed by either flumioxazin or metribuzin also resulted in a significant ($P < 0.05$) decrease in flower yield compared to the hand weeded treatment. No other herbicide treatment resulted in a significant ($P > 0.05$) difference in flower yield compared with hand weeded treatment. Dimethenamid followed by simazine resulted in a significantly ($P < 0.05$) lower flower yield than applications of simazine followed by dimethenamid. Simazine followed by dimethenamid had a significantly ($P < 0.05$) higher flower yield than repeated applications of simazine. There was no significant ($P > 0.05$) treatment affect on mean individual flower weight or FMI (Table 13.10). All applications provided 100% control of *A. caucalis*.

Plate 13.4 Near complete leaf necrosis of pyrethrum following dual applications of flumioxazin.

Table 13.10 Mean pyrethrum injury and flower DW yield (kg/ha) for each treatment at experimental site C.

1st application 18th Mar 03	2nd application 20th May 03	% Crop Injury					Flower DW (kg/ha)	Mean 100 Flower DW (g)	FMI
		8 DAA	14 DAA	29 DAA	72 DAA	140 DAA			
Simazine 2kg/ha	Dimethenamid 3 6kg/ha	6 7	3 3	3 3	10 0*	10.0*	3563 2 ± 205.7^a	14 3 ± 0.43	404 9 ± 6 1
Dimethenamid 3 6kg/ha	Dimethenamid 3 6kg/ha	0 0	0 0	0 0	3.3	0.0	3215.4 ± 196 0^{abc}	14 0 ± 0.89	416.7 ± 5 4
Flumioxazin 0 15kg/ha	Dimethenamid 3 6kg/ha	20 0***	16 7***	13 3***	16 7**	20 0***	3491 4 ± 189 5^{ab}	14 3 ± 0.61	412 3 ± 8 6
Simazine 2kg/ha	Simazine 2kg/ha	16.7	13 3***	23 3***	30.0***	36 7***	2904 1 ± 44 3^{bc}	14 3 ± 0.93	410.9 ± 8 0
Dimethenamid 3.6kg/ha	Simazine 2kg/ha	3.3	10.0**	13 3***	20 0***	20 0***	2928 3 ± 182 7^{bc}	15 3 ± 0.36	437 0 ± 8 1
Flumioxazin 0.15kg/ha	Simazine 2kg/ha	26 7***	30 0***	26.7***	26 7***	23 3***	3179 8 ± 87.0^{abc}	14.7 ± 0.33	406.3 ± 3.7
Simazine 2kg/ha	Flumioxazin 0 15kg/ha	26 7***	33 3***	46.7***	80 0***	60.0***	2054 5 ± 172 6^d	15.2 ± 0 73	397.3 ± 18 9
Dimethenamid 3 6kg/ha	Flumioxazin 0 15kg/ha	23 3***	30.0***	33.3***	63.3***	46 7***	2647 7± 108 7^{cd}	15.4 ± 0 36	413.3 ± 15 7
Flumioxazin 0 15kg/ha	Flumioxazin 0.15kg/ha	46.7***	53 3***	63.3***	80 0***	66.7***	2072 8 ± 273 5^d	15.9 ± 0.68	409.4 ± 14 1
Simazine 2kg/ha	Metribuzin 0 19kg/ha	10.0*	30 0***	23.3***	36 7***	40 0***	3039 3 ± 50 4^{abc}	16.2 ± 1 26	420 4 ± 15 9
Dimethenamid 3 6kg/ha	Metribuzin 0.19kg/ha	6 7	16 7***	3 3***	10 0*	36 7***	2641 4 ± 348.2^{cd}	15.2 ± 0 54	416.6 ± 2 8
Flumioxazin 0 15kg/ha	Metribuzin 0 19kg/ha	26 7***	30 0***	26 7***	30.0***	43 3***	3066 6 ± 80 7^{abc}	16.1 ± 0.78	407.6 ± 6.9
Untreated (Hand weeded)		0 0	0 0	0.0	0 0	0.0	3343 3 ± 228.7^{ab}	16.1 ± 1.03	438.1 ± 2 6
Untreated (Weedy)		0.0	0 0	0.0	0 0	0.0	3164.3 ± 363 2^{abc}	15.4 ± 0 85	421 6 ± 11 3
LSD (P=0.05)							558.6	n s	n s

Mean with differing subscripts are significantly different at P = 0 05.

Treatments followed by asterisks are significantly different to the untreated control at * P = 0.05, * P = 0.01 and ***P = 0 001.

13.4 Discussion

Applications of dimethenamid provided excellent selectivity for use in pyrethrum and have been shown to provide preemergence control of *A. caucalis* and *T. nodosa*. The longevity of residual control can be improved through repeated applications with no detrimental effect on the crop. The use of dimethenamid in pyrethrum may also be significant in controlling the emergence of grass species. Applications of simazine at a rate of 2.0 kg/ha provide excellent control *A. caucalis* and *T. nodosa*. The use of simazine in pyrethrum to control Apiaceae weeds would be highly dependent on the level of weed control needed. Although excellent control of Apiaceae weeds has been demonstrated the concern is that any applications in May to June would impact negatively on pyrethrum flower yield. Early applications in March/April would provide sufficient longevity for control of Apiaceae weeds however other applications required for the control of subsequent emerged weeds, such as *Galium aparine* and *Trifolium repens*, may impact negatively on the crop. Simazine applications are therefore viewed as a high risk approach. Both sulfentrazone and flumioxazin appeared to provide sufficient control of Apiaceae species although the longevity of residual control with sulfentrazone may not be sufficient to control these species for the entire emergence period which occurs between autumn and winter. Flumioxazin provided longer periods of control however its application has a lower level of selectivity for use in pyrethrum with increasing levels of leaf necrosis in comparison to sulfentrazone. Both applications behave similarly with early autumn application not impacting negatively on pyrethrum yield; however their application beyond April is not recommend based on the higher level of leaf injury observed following applications at these times.

The postemergence application of imazamox with the addition of the organosilicone Pulse® was the most promising postemergence treatment with excellent selectivity for use in pyrethrum. This treatment had excellent activity on *A. caucalis* in the field and also on *T. nodosa* in pot studies. Clomazone applications were also found to have acceptable selectivity in pyrethrum although some crop discoloration was observed. Carfentrazone ethyl has good activity against most weeds and it has acceptable levels of selectivity for use in pyrethrum as no negative impact on pyrethrum yield has been observed with its applications. Its efficacy is dependent on

complete coverage of the weeds and its activity is reduced under lower temperatures. Due to the autumn and winter germinating behaviour of *A. caucalis* and *T. nodosa* its application is not viewed as sufficient to control these weeds in all situations as a result of crop and weed canopy protection which limits the leaf to herbicide contact. The activity of applications at these times is also reduced due to lower temperatures.

Metribuzin has been shown to provide excellent control of Apiaceae weeds and also provide control of many other broadleaf weeds for which its application is registered. Pyrethrum plants displayed susceptibility to photosynthetic inhibiting herbicides metribuzin and simazine although definitive crop yield losses have not clearly been demonstrated. An early application of metribuzin following the emergence of *A. caucalis* or *T. nodosa* in circumstances where the level of weed infestation is high may be adaptable, if no other herbicides were available to provide such control. An application of metribuzin at such time would provide excellent weed control and also provide some residual activity against later germination.

There were some contrasting results between experimental site A and experimental site B. At experimental site A there was a significant interaction between preemergence (main plot) and postemergence (sub plot) treatments on flower yield. At experimental site B, which was a repeat of trial A for those treatments found to be the most promising, there was no significant interaction between preemergence and postemergence treatments. Although no significant yield effects were found at experimental site B, there was a trend with those treatments that caused least crop injury generally having higher yields. Repeated experiments using more replications would be required to demonstrate any differences. Five herbicide treatments resulted in pyrethrum flower yields above the hand weeded treatment; these applications were dimethenamid with carfentrazone ethyl (EC), dimethenamid with clomazone, dimethenamid with imazamox, sulfentrazone with carfentrazone ethyl (EC) and sulfentrazone with imazamox. It is conceivable that they have the greatest potential to be used commercially as crop injury was generally low and weed activity high. No applications with simazine applied preemergence or metribuzin applied postemergence resulted in a higher mean flower yield than the hand weeded treatment. This observation and the results of experimental site A strongly suggest that applications of simazine and metribuzin had a negative impact on the yield of

pyrethrum. A higher level of crop injury following applications of simazine was observed at site A than at site B and it is suggested that this is a result of the differences in the level of rainfall that occurred in the 48 hours following applications. At site A, 14mm was recorded in the 48 hours proceeding application while in comparison only 1mm was recorded at site B. This most likely has resulted in a higher level of activation of simazine at site A than at site B. Similarly there was a higher level of crop injury associated with application of sulfentrazone at site A than site B. Simazine applications result in a photosynthetic stress being applied on the pyrethrum plants (Chapter 14). At site A, at the time of postemergence applications, it is conceivable that this stress was substantially higher than that which occurred at site B due to a higher level of activation of simazine. The pyrethrum plants at site A would have therefore been limited in their photosynthetic capacity at the time of the postemergence (sub plot) treatments and the imposed stresses of these applications have resulted in an increase in crop injury. In contrast at site B the pyrethrum plants appeared to have overcome the effect of the simazine application prior to the postemergence herbicides being applied. As a result applications did not cause an exaggeration of crop injury.

At experimental site C repeated applications of simazine resulted in significantly ($P < 0.05$) more crop injury than flumioxazin applied in March followed by simazine applied in May but significantly ($P < 0.05$) less than simazine followed by flumioxazin. This is due to a high level of sensitivity of pyrethrum to flumioxazin when applied in May. Symptoms to flumioxazin became visible within 7 days of application and when applied in March caused substantially less injury to pyrethrum then when applied in May. Pyrethrum plants are able to recover from early applications of flumioxazin and the effects on yield are insignificant. However, when applied later in the growing season decreases in flower yield are high. Applications of dimethenamid at experimental site C resulted in no visible crop injury and had no detrimental effect on flower yield even with repeated applications.

A quadratic relationship existed between crop injury at 137 DAA and mean flower assay yield at experimental site A and this is consistent with the description of the 0 to 100 rating system (Appendix A.6). According to the 0 to 100 rating system, some yield losses due to injury are expected when the injury is above 40%. At 40% injury,

crop recovery is probable with no detrimental effects on yield expected. Below 40% there are no lasting effects and differentiation in injury levels is based on increasing levels of crop discoloration and stunting. Absence of a relationship between crop injury at 12 DAA and mean pyrethrum assay yield indicates that the level of compensatory growth and recovery that occurred was sufficient enough to negate any effects on pyrethrum assay yield. In contrast, assessment taken later, before flowering, are more representative and indicate those treatments that are likely to result in yield decreases.

Field experiments undertaken in this study have been successful in identifying herbicides with selectivity for use in pyrethrum and activity against Apiaceae weeds. Their use in pyrethrum is only limited by their failure to provide a broad spectrum of weed control against more common agricultural weeds. Were possible, the weed efficacy of herbicide treatments were recorded for all field experiments. Simazine at 2 kg/ha provided an excellent level of preemergence control of *Senecio vulgaris* and *Hypochoeris radicata,* but provided poor levels of control of *Galium aparine* and *Raphanus raphanistrum.* Clomazone at 0.12 kg/ha provided excellent preemergence control of *S. vulgaris* but postemergence control of *S. vulgaris* was substantially lower. Dimethenamid at 3.6 kg/ha provided excellent control of *Fumaria parviflora*, *Sherardia arvensis* and *Hypochoeris radicata*, although it had lower levels of activity against *S. vulgaris*, *G. aparine* and *R. raphanistrum.* Metribuzin is a broad spectrum herbicide and controls many broadleaf weeds, however, *S. vulgaris* regularly escaped postemergence applications of metribuzin at rate of 0.19 kg/ha. Imazamox at 34.0 g/ha provided some level of postemergence control of *S. vulgaris* and excellent control of *S. arvensis* and *H. radicata.* Carfentrazone ethyl at 24.0 g/ha provided excellent activity against a broad spectrum of broadleaf weed seedlings although little activity was observed when applied to species at the cotyledon stage of development. This is believed to be due to carfentrazone-ethyl being most active on newly developing leaves making plant pigments (Cumming, 2002). Sulfentrazone at 0.38 kg/ha and flumioxazin at 0.15 kg/ha provided excellent broad spectrum broadleaf weed control.

13.5 Conclusion

Dimethenamid and imazamox have excellent selectivity for use in pyrethrum with no indication of any detrimental effect on pyrethrum flower yield, assay content or flower maturity. Applications of clomazone and carfentrazone ethyl provided acceptable selectivity although some crop injury was observed immediately following applications. Applications of flumioxazin resulted in high levels of leaf necrosis especially when applied after April and impacted negatively on pyrethrum flower yield. Quinclorac was dismissed as a commercial option due to its low level of selectivity for use in pyrethrum with a highly negative effect on pyrethrum assay content, flower yield and flower maturity. Pyrethrum plants displayed susceptibility to photosynthetic inhibiting herbicides metribuzin and simazine. Their selectivity for use in pyrethrum was unclear and requires further investigation.

Chapter 14 Pyrethrum tolerance to photosynthesis inhibiting herbicides simazine and metribuzin

14.1 Introduction

Simazine and metribuzin are photosynthesis inhibiting herbicides, which have displayed excellent activity against the Apiaceae weeds, *A. caucalis* and *T. nodosa*. Their use in pyrethrum production has been investigated under field conditions but the selectivity of these herbicides has not been clearly demonstrated. Results of 2002 and 2003 field trials suggested that crop selectivity was acceptable with no plant death occurring and no significant yield effect, but some (< 30%) leaf discoloration visible. Although the effects of these herbicides was minimal when applied alone, in combination with other herbicides injury was more pronounced. Simazine and metribuzin are therefore regarded as having a low level of selectivity in the current weed management program. Further investigation was therefore required to determine the level of tolerance of pyrethrum to applications of simazine and metribuzin. Although visual assessment and yield measurements provided an indication that pyrethrum had a moderate to high level of tolerance, a more definitive assessment can be accomplished through the measurement of chlorophyll fluorescence. Chlorophyll fluorescence assessment provides a useful measure of the photosynthetic performance of the treated plants and in turn gives an indication of the level of tolerance displayed by pyrethrum to applications of photosynthetic inhibiting herbicides.

Photosynthesis and triazine herbicides

There are two distinct photosystems involved with the light-requiring reactions of photosynthesis, photosystem I and photosystem II. Photosystem I consists of chlorophyll *a* molecules and generating NADPH, and being linked to PSII by an electron transport chain. This pair of chlorophyll molecules of the photosystem I reaction centre is given the special name P_{700} because they absorb red light of 700 nm most efficiently. Photosystem II consists of chlorophylls *a* and *b* molecules, generating a strong oxidant, and splitting water to produce oxygen. The chlorophyll *a*

molecule in photosystem II is different to the chlorophyll *a* molecule in photosystem I. The reaction centre of photosystem II is named P_{680}.

Light energy enters photosystem II where it is trapped by molecules of P_{680} in the reaction centre, either directly or indirectly via one or more of the pigment molecules. When a P_{680} molecule is excited, its energized electron is transferred to an acceptor molecule, a quinone (Q_A). The electron-deficient P_{680} molecule is able to replace its electron from a dissociated water molecule. This light-dependent oxidative splitting of water molecules in called photolysis (Raven *et al.* 1992). The electrons boosted from P_{680} pass along an electron transport chain to photosystem I. Once photosystem II absorbs light and Q_A has accepted an electron, it is not able to accept another until it has passed the first onto a subsequent electron carrier (Q_B).

Triazine herbicides specific site of action is photolysis (Rao, 2000). Simazine and metribuzin inhibit photosynthesis by binding to the Q_B binding niche on the D1 protein of the PSII complex blocking electron transport from Q_A to Q_B. This stops the fixation and production of ATP and $NADPH_2$. Although these two compounds are essential for plant growth and survival, plant death usually occurs by other processes. The inability of the plant to reoxidize Q_A promotes the formation of triplet state chlorophyll, which interacts with ground state oxygen to form singlet oxygen. Both triplet chlorophyll and singlet oxygen abstracts hydrogen from an unsaturated lipid, producing a lipid radical and initiating a chain reach reaction leading to lipid peroxidation. Lipids and proteins are oxidised, resulting in loss of chlorophyll and carotenoids in "leaky" membranes which allows cells and cell organelles to dry and disintegrate (Anon., 1994). The chlorotic symptoms associated with photosystem II inhibitors occur slowly after root uptake. However foliar applications of photosystem II inhibitors cause more rapid membrane lipid peroxidation, resulting in desiccation and necrosis (Devine *et al.*, 1993).

Using Chlorophyll fluorescence to measure herbicide induced plant stress

Each quantum of light absorbed by a chlorophyll molecule is either used to drive photosynthesis, dissipates excess energy as heat or is re-emitted as light - chlorophyll fluorescence. Fluorescence emission is complementary to the other two alterative pathways and a measurement of the yield of fluorescence gives information about

changes in the efficiency of photochemistry and heat dissipation. Generally, fluorescence yield is highest when photochemistry and heat dissipation are lowest. Measuring fluorescence yield is quite easy, although the total amount of chlorophyll fluorescence is very small, only 1 to 2% of total light absorbed (Maxwell and Johnson 2000). Fluorescence yield is quantified by exposing a leaf to light of defined wavelength and measuring the amount of light re-emitted at longer wavelengths. Upon the application of a saturating flash (8000 μmol m^{-2} s^{-1} for 1 s), fluorescence rises from the ground state value (Fo) to its maximum value, Fm. In this condition, Q_A, the first electron acceptor of photosystem II, is fully reduced. This allows the determination of the maximum quantum efficiency of photosystem II primary photochemistry, given by Fv/Fm = (Fm-Fo)/Fm, where Fv is variable fluorescence. In healthy leaves, this value is always close to 0.8 (Maxwell and Johnson 2000). A lower value indicates that a proportion of photosystem II reaction centers are damaged, a phenomenon called photoinhibition, often observed in plants under stress conditions.

Chlorophyll fluorescence analysis has become one of the most powerful and widely used techniques available to plant physiologists and ecophysiologists (Maxwell and Johnson 2000). When Q_A has accepted an electron and has not passed this electron on the reaction centre it is termed closed. Any treatment that inhibits electron transport beyond the point of Q_A will result in photochemical reduction of Q_B and consequent high yields of fluorescence. According to Ahrens (1989), a plant capable of metabolising PSII inhibiting herbicides would have a lower percentage of inhibited PSII reaction centres and in turn a lower fluorescence yield. Fluorescence should decline relatively rapidly for a plant species having a high rate of herbicide metabolism but decline slowly or not at all for a species having a low rate of metabolism (Ahrens, 1989). For this reason this technique has been used to probe the inhibition of electron transport by photosystem II-inhibiting herbicides.

Many studies using chlorophyll fluorescence have examined tolerance of resistant weed or crop biotypes using seedlings or detached leaves and examined the response over a short duration. The use of PSII inhibiting herbicides in pyrethrum is an option for control of the many problematic weed species in pyrethrum including Apiaceae weeds *A. caucalis* and *T. nodosa*. However, it is hypothesised that pyrethrum is

susceptible to applications of simazine and metribuzin and that their application reduces the maximum photosynthetic capacity of pyrethrum.

The objective of this experiment was to:

➢ Directly assess the effect of photosynthetic inhibiting herbicides simazine and metribuzin on pyrethrum by use of chlorophyll fluorescence

➢ Quantitatively assess the effect of simazine and metribuzin by determining pyrethrum plant biomass and flower production.

14.2 Materials and Methods

Establishment

Pyrethrum seeds were sown into seedling trays during November 2002 with a standard seedling mix (Appendix A.2). In January 2003 a total of 152 pyrethrum seedlings were transplanted into 20 cm pots with a red ferrosol soil to perlite (3:1) mix and placed on outside benches at the University of Tasmania, Hobart (42^0 90'S 147^0 32'E). Plants were watered daily to replace evapotranspiration losses. Daily temperature for the duration of the study is given in Appendix A.11. Three rates of metribuzin equivalent to 187.5 g/ha, 375 g/ha and 562.5 g/ha and three rates of simazine equivalent to 1.0 kg/ha, 2.0 kg/ha and 3.0 kg/ha were applied at three application times:

- Late seedling stage (5-6 true leaf) 10th April 2003.
- Vegetative (10-12 true leaf) 24th June 2003
- Pre-bud - 22nd September 2003

An untreated control was included in the design.

Experimental Design

The experiment was a randomised design with 4 replications. To assess the effect of individual treatments against the untreated, the experiment was analysed using an ANOVA single factor with 19 treatments (6 herbicide treatments by 3 times of application plus untreated) for all assessment variables. In addition, to assess the effect of herbicide treatment and time of application the experiment was analysed using an ANOVA two factor with replication. As no times of application treatment were applicable to the untreated this was removed from the analyses. The trial was

duplicated so that two destructive harvests could be undertaken at early and late flowering. Each harvest was analysed separately.

Chlorophyll fluorescence

Chlorophyll fluorescence measurements were undertaken at 24 and 72 hours following herbicide application, and repeated every 7 to 14 days following. All chlorophyll fluorescence measurements were made using a Mini Pam portable chlorophyll fluorometer and a 2030-B leaf clip holder (Heinz Walz GmbH, Effeltrich, Germany). Single measurements were made on a random selection of six individual leaves, of varying age, from each plant from which the mean readings were calculated. Dark-adapted minimal (Fo) and maximal (Fm) fluorescence were measured following placement into complete darkness for 30 minutes. Maximal fluorescence (Fm) was induced by an 800-ms Pulse of intense saturating white light. The distance from the fibre optics to the leaf was 12mm and the light intensity set such that the Fo value remained below 500. Maximum quantum yield of photosystem II was then calculated as $Fv/Fm = (Fm - Fo)/Fm$.

The first destructive harvest was undertaken on the 21st November 2003 at early flowering. Plant biomass, flower yield, number of primary flowering stalks and FMI was assessed. A second destructive harvest was undertaken on the 23rd December 2003 at mid to late flowering stage of growth.

To maintain healthy plants fungicide applications of difenoconazole (as Score® EC, 25%) at a rate equivalent to 0.125 kg/ha plus chlorothalonil (as Bravo® SC, 72%) at 1.0 kg/ha were applied on the 5th and 28th August 2003.

14.3 Results

Harvest 1 - Early Flowering

At early flowering there was a significant ($P < 0.05$) herbicide treatment effect on total flower number, flower FW yield, number of primary stalks and plant FW (Figure 14.1-14.4.). There was no significant ($P > 0.05$) treatment effect on FMI.

Rate responses were evident, simazine applied at 3.0 kg/ha, metribuzin at 375.0 and 562.5 g/ha resulted in the most significant (P < 0.05) decreases in pyrethrum flower number per plant. Simazine at 1.0 kg/ha resulted in a significantly (P < 0.05) higher number of flowers than all other treatments (Figure 14.1).
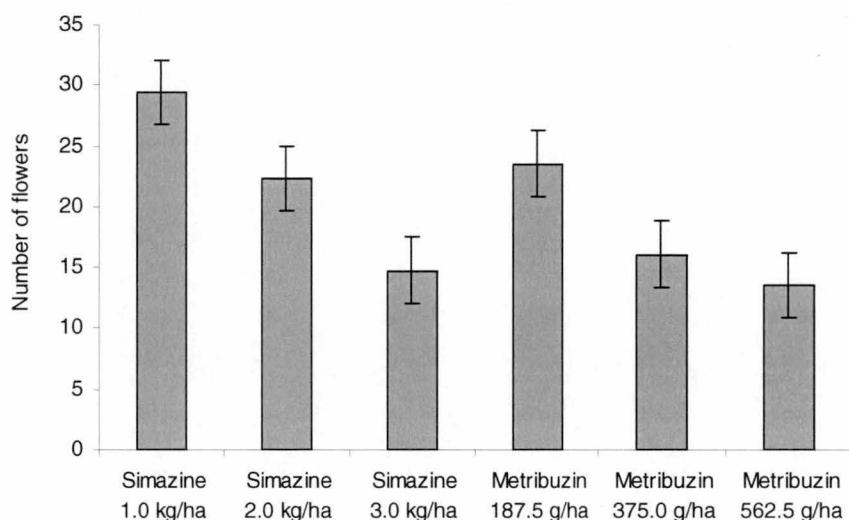
Figure 14.1 The effect of simazine and metribuzin application rate on the number of flowers per plant of pyrethrum. LSD at P= 0.05 shown as error bars.

A similar response was found with flower FW per plant (Figure 14.2). Pyrethrum plants treated with simazine at 1.0 kg/ha produced a significantly (P < 0.05) higher flower FW than all other treatments.
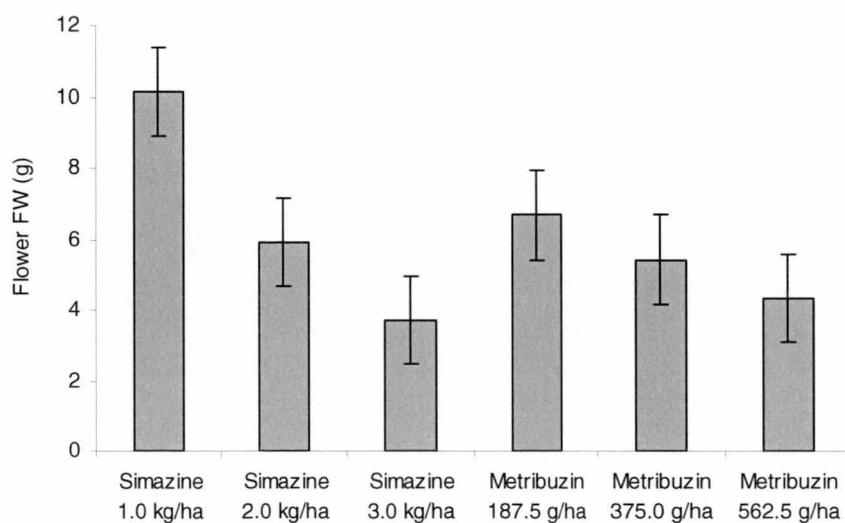
Figure 14.2 The effect of simazine and metribuzin application rate on flower FW per plant of pyrethrum. LSD at P= 0.05 shown as error bars.

Simazine at 1.0 kg/ha also resulted in a significantly ($P < 0.05$) higher number of primary flowering stalks per plant that any other treatment (Figure 14.3) and a significantly ($P < 0.05$) higher plant FW (Figure 14.4).
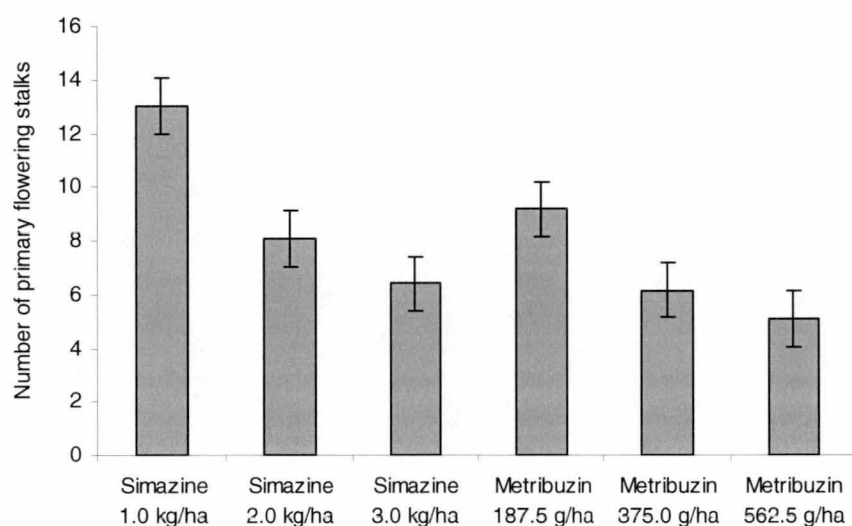
Figure 14.3 The effect of simazine and metribuzin application rate on number of primary flowering stalks per plant of pyrethrum. LSD at P= 0.05 shown as error bars.
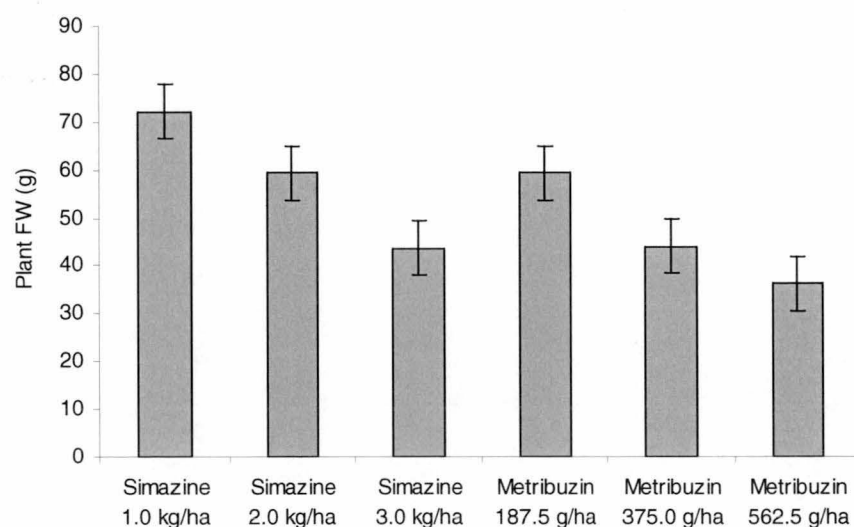
Figure 14.4 The effect simazine and metribuzin application rate on plant FW per plant of pyrethrum. LSD at P= 0.05 shown as error bars.

The growth stage of pyrethrum at the time of herbicide application had a significant (P < 0.05) effect on flower number, flower FW, number of primary flowering stalks and plant FW (Figure 14.5-14.8).

Application of simazine and metribuzin to pyrethrum at late seedling stage of development resulted in a significantly (P < 0.001) lower number of flowers per plant than when applied at the vegetative and pre-bud stage of development. Applications at pre bud resulted in a significantly (P < 0.0) lower number of flowers per plant than when applied at the vegetative stage of development (Figure 14.5).
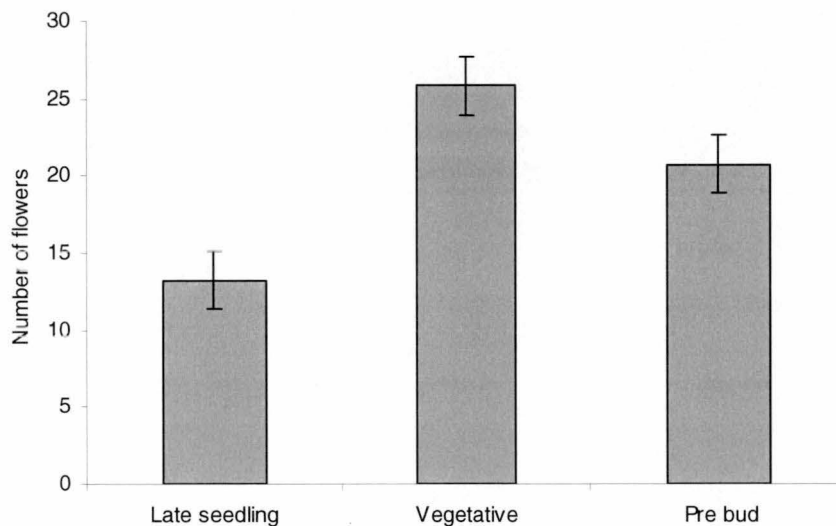
Figure 14.5 The effect of growth stage of pyrethrum at time of herbicide application on the number of flowers per plant. LSD at P= 0.05 shown as error bars.

A similar response was found with flower FW per plant (Figure 14.6), with applications of simazine and metribuzin at late seedling stage resulting in a significantly (P < 0.05) lower flower FW yield than applications at vegetative and pre bud stage which were not significantly (P > 0.05) different to each other.
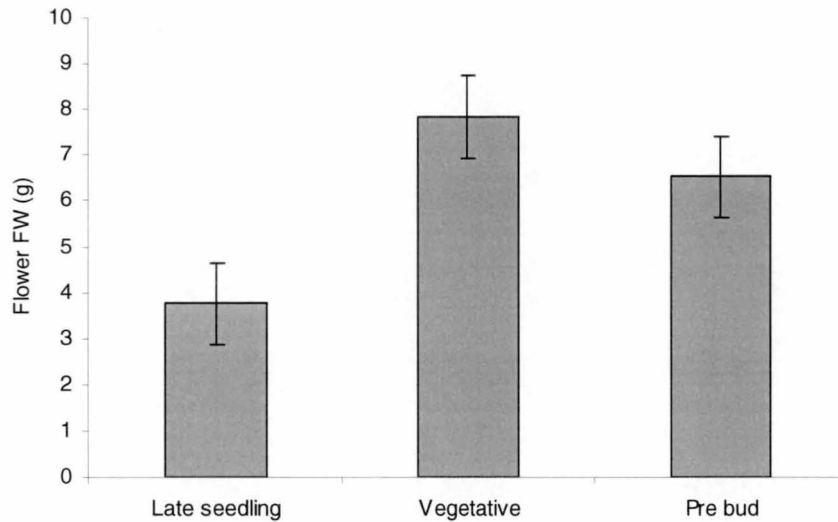
Figure 14.6 The effect of growth stage of pyrethrum at time of herbicide application on the flower FW per plant. LSD at P= 0.05 shown as error bars.

Applications of simazine and metribuzin to pyrethrum at late seedling stage of development also resulted in a significantly (P < 0.05) lower number of flower stalks per plant (Figure 14.7) and a significantly (P < 0.05) lower plant FW (Figure 14.8) than herbicide application at vegetative and pre bud stages of development.
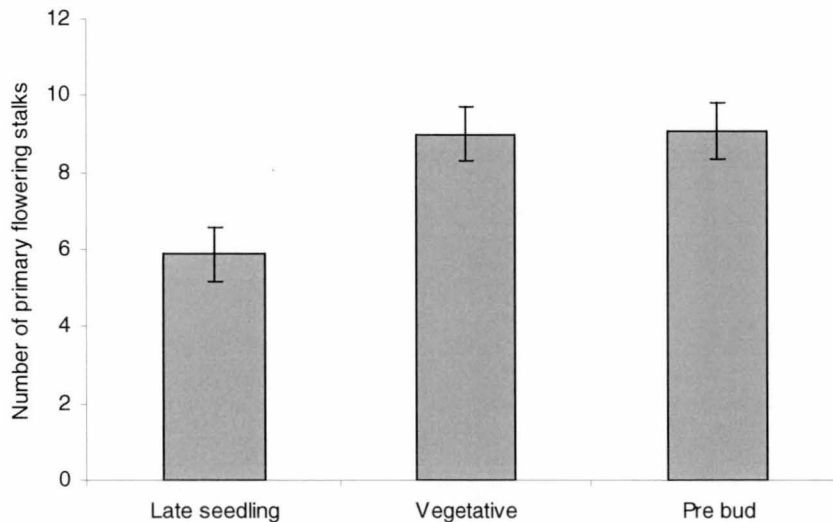
Figure 14.7 The effect of growth stage of pyrethrum at time of herbicide application on the number of primary flowering stalks per plant. LSD at P= 0.05 shown as error bars.
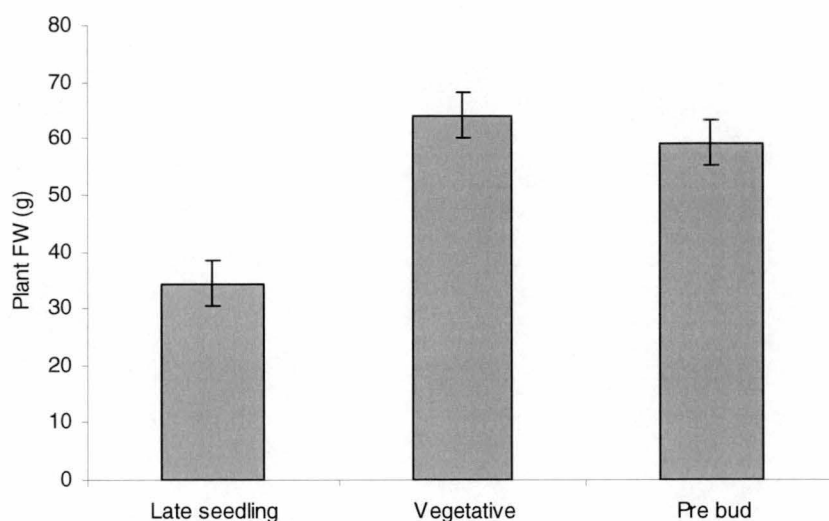
Figure 14.8 The effect of growth stage of pyrethrum at time of herbicide application on the FW per plant. LSD at P= 0.05 shown as error bars.

There was a significant (P < 0.05) herbicide treatment and time of application interaction on the number of primary flowering stalks per plant and FW per plant. All applications of both simazine and metribuzin to pyrethrum at late seedling stage of development resulted in a significant (P < 0.05) reduction in the number of primary flowering stalks per plant compared with the untreated control (Table 14.1). Plant FW and number of primary flowering stalks per plant was significantly (P < 0.05) lower than the untreated for all applications of metribuzin applied at the vegetative stage of development. There was a significant (P < 0.05) reduction in the number of primary flowering stalks per plant for all applications of simazine applied to pyrethrum at the vegetative stage of development. Applications of metribuzin and simazine applied at the pre bud stage of development at all rates resulted in a significant (P < 0.05) reduction in the number of primary flowering stalks compared with the untreated and the total number of flowers.

Metribuzin applied to pyrethrum at the late seedling stage of development at all rates resulted in a significant (P < 0.05) reduction in the number of flowers per plant and plant FW compared with the untreated. Similarly simazine applied at rates of 2.0 kg/ha and 3.0 kg/ha at late seedling stage also resulted in a significant (P < 0.05) reduction in the total number of flowers per plant. There was no significant (P > 0.05) difference in total flower number and plant FW with applications of simazine

at 1.0 kg/ha compared with the untreated. Compared to the untreated the flower FW was significantly (P < 0.05) reduced by applications of metribuzin at 375 g/ha and 562.5 g/ha and simazine at 2.0 kg/ha and 3.0 kg/ha when applied to pyrethrum at late seedling stage of development.

Table 14.1 Effect of simazine and metribuzin applications on total flower number, flower maturity index, flower FW, number of primary flowering stalks and plant FW per plant. Destructive assessment was undertaken on the 21st November 2003.

Herbicide Application	Growth stage of application	Total Flower No.	FMI	Flower FW	No. of Primary Stalks	Plant FW
Control	N/A	41.8 ± 11 6	154 1 ± 24 6	10.3 ± 4.4	20.5 ± 3.0	95.7 ± 12.9
Metribuzin 0.188 kg/ha	Late seedling	25.5 ± 5.5*	168 4 ± 37 0	7.4 ± 2.3	11.3 ± 1.9*	63.7 ± 10.7*
Metribuzin 0.375 kg/ha	Late seedling	4.8 ± 4.8*	121.1 ± 121.1	1.0 ± 1 0*	2.3 ± 2 3*	11.8 ± 11.8*
Metribuzin 0.563 kg/ha	Late seedling	0.0 ± 0.0*	N/A	0.0 ± 0 0*	0 0 ± 0.0*	0 0 ± 0.0*
Simazine 1.0 kg/ha	Late seedling	28 3 ± 2.4	178.3 ± 35 6	9.7 ± 2 1	12.8 ± 2.2*	72.5 ± 8.7
Simazine 2.0 kg/ha	Late seedling	16.0 ± 5 4*	155.9 ± 35.8	3.7 ± 1.5*	6.8 ± 2.1*	40.2 ± 3.8*
Simazine 3.0 kg/ha	Late seedling	5.0 ± 3.0*	104.2 ± 2.9	0.8 ± 0.6*	2.3 ± 1.3*	17.5 ± 10.1*
Metribuzin 0.188 kg/ha	Vegetative	29.0 ± 6.7	157.6 ± 28.0	8.2 ± 1.5	10.3 ± 2.2*	63.4 ± 11.2*
Metribuzin 0.375 kg/ha	Vegetative	18 3 ± 2.8*	230.4 ± 53.8	8.7 ± 2.9	6.8 ± 0.9*	54.7 ± 6.5*
Metribuzin 0.563 kg/ha	Vegetative	21.0 ± 9.0*	165.1 ± 45.5	7.6 ± 3.5	7.5 ± 2.3*	55.8 ± 15 2*
Simazine 1.0 kg/ha	Vegetative	36.3± 3.9	195.4 ± 56.1	10.8 ± 2.2	13.0 ± 2.4*	78.8 ± 10 4
Simazine 2.0 kg/ha	Vegetative	29.0 ± 5.4	152.5 ± 34.4	5.8 ± 2 2	8 5 ± 1.7*	67.6 ± 8.6
Simazine 3.0 kg/ha	Vegetative	21.5 ± 4.2*	169.9 ± 41.3	6.0 ± 2.2	8.0 ± 0.6*	63.7 ± 7 0*
Metribuzin 0.188 kg/ha	Pre-bud	25.3 ± 1.7*	155.7 ± 34.8	6.6 ± 3.2	9.5 ± 0.5*	65.6 ± 6.8*
Metribuzin 0.375 kg/ha	Pre-bud	16.0 ± 8.3*	136.8 ± 24.0	4.6 ± 3.2	6.0 ± 3.0*	50.8 ± 12.6*
Metribuzin 0.563 kg/ha	Pre-bud	19.5 ± 2.9*	177.7 ± 40.5	5.4 ± 1.1	7.8 ± 1.2*	53.3 ± 8.0*
Simazine 1.0 kg/ha	Pre-bud	23.8 ± 2.8*	240.7 ± 48.5	10.0 ± 3.2	13.3 ± 0.9*	65.0 ± 9.5*
Simazine 2.0 kg/ha	Pre-bud	22.0 ± 1.1*	207.0 ± 14.3	8.3 ± 0.8	9.0 ± 0 4*	70.4 ± 14.0
Simazine 3.0 kg/ha	Pre-bud	17.8 ± 1.8*	157.4 ± 20.9	4.3 ± 1.1	9.0 ± 2 1*	49.8 ± 9.2*
LSD (P = 0.05)		14.8	n.s	6.6	5.2	28.2

* = Those treatments that are significantly different to the untreated control at P = 0.05

Harvest 2 Mid to late flowering

Destructive harvests of pyrethrum at mid to late flowering produced similar findings to those recorded at early flowering. At mid to late flowering there was a significant (P < 0.05) herbicide treatment effect on total flower number, flower yield, number of primary flowering stalks and plant FW (Table 14.2). There was no significant (P > 0.05) herbicide treatment effect on FMI.

Simazine at 3.0 kg/ha and metribuzin at 562.5g/ha resulted in a significantly (P < 0.05) lower number of flowers being produced per plant compared with simazine at 1.0 and 2.0 kg/ha and metribuzin at 187.5g/ha, which were not significantly (P > 0.05) different to each other. A similar response was found for flower FW and plant FW (Table 14.2).

Table 14.2 The effect of herbicide treatment on total flower number, flower FW, number of primary flowering stalks and plant FW per plant. Destructive assessment was undertaken on 23rd December 2003.

Herbicide Treatment	Number of flowers	Flower FW (g)	Number of primary flowering stalks	Plant FW (g)
Simazine 1.0 kg/ha	23.58	17.94	9.33	48.13
Simazine 2.0 kg/ha	23.42	17.78	9.08	50.43
Simazine 3.0 kg/ha	17.17	11.68	7.17	37.68
Metribuzin 187.5 g/ha	26.00	19.23	9.50	49.47
Metribuzin 375.0 g/ha	20.58	14.48	7.83	38.96
Metribuzin 562.5 g/ha	13.75	10.46	4.50	25.69
LSD (P = 0.05)	5.68	3.94	2.18	6.79

Growth stage of pyrethrum at time of herbicide application had a significant (P < 0.05) effect on total number of flowers per plant, flower FW, number of primary flowering stalks per plant and plant FW (Table 14.3). Applications of simazine and metribuzin at the late seedling stage significantly (P < 0.05) reduced the total number of flowers per plant, flower FW, number of primary flowering stalks per plant and plant FW compared with the applications at the vegetative stage and at the pre-bud stage of pyrethrum development. Herbicides applied at the vegetative stage and at the

pre-bud stage were not significantly (P > 0.05) different to each other with respect to the number of flowers per plant, flower FW or plant FW. Applications of simazine and metribuzin at vegetative stage of development resulted in a significantly (P < 0.05) lower number of primary flowering stalks per plant compared with applications at the pre-bud stage.

Table 14.3 The effect of growth stage of pyrethrum at time of herbicide treatment on total flower number, flower FW, number of primary flowering stalks and plant FW per plant. Destructive assessment was undertaken on 23rd December 2003.

Growth stage of application	Number of flowers	Flower FW (g)	Number of primary flowering stalks	Plant FW (g)
Late seedling	12.58	8.79	5.00	22.89
Vegetative	23.75	18.55	7.75	50.30
Pre bud	25.92	18.45	10.96	51.99
LSD (P = 0.05)	4.02	2.79	1.54	4.80

There was a significant (P < 0.05) time of application and herbicide treatment interaction on number of flowers, flower FW, number of primary flowering stalks and plant FW (Table 14.4). There was no significant (P > 0.05) difference in FMT between treatments.

All treatments resulted in a significant (P < 0.05) decrease in plant FW and the number of primary flowering stalks compared with the untreated. All applications except simazine at 2.0 kg/ha applied at pre-bud and metribuzin at 187.5 g/ha and 375 g/ha applied at pre-bud resulted in a significantly (P < 0.05) lower flower yield and flower number compared with the untreated control.

The most obvious difference between destructive harvests was in flower yield. At early flowering, flower yield was not significantly (P > 0.05) different from the untreated plants for applications of both simazine and metribuzin at all rates when applied at vegetative or pre-bud stage of development. In contrast, at later flowering differences were evident. At early flowering there was a significant (P < 0.05) difference in the total flower (bud) number, but the yield was found not to be significantly (P > 0.05) different. With flower maturity reduced yields in treatments with lower flower numbers became evident.

Table 14.4 Effect of simazine and metribuzin applications on total flower number, flower maturity index, flower FW, number of primary flowering stalks and plant FW per plant. Destructive assessment was undertaken on the 23rd December 2003.

Herbicide Application	Growth stage of application	Total Flower No.	FMI	Flower FW	No. of Primary Stalks	Plant FW
Control	N/A	40.3 ± 6.8	523.2 ± 29.4	31.9 ± 7.7	18.8 ± 3.9	73.7 ± 9.3
Metribuzin 0.188 kg/ha	Late seedling	25.8 ± 6.4*	580 0 ± 57.4	16.8 ± 4.6=	10.3 ± 2.7*	40.4 ± 9.8*
Metribuzin 0 375 kg/ha	Late seedling	1.3 ± 1.3*	180.0 ± 180.0	0.4 ± 0.4*	0.8 ± 0.8*	3.3 ± 3.3*
Metribuzin 0.563 kg/ha	Late seedling	0.0 ± 0.0*	N/A	0.0 ± 0.0*	0.0 ± 0 0*	0.0 ± 0.0*
Simazine 1.0 kg/ha	Late seedling	29.8 ± 4.8	556.6 ± 55.5	21.3 ± 1.6	12.0 ± 1.1*	48.8 ± 7.4*
Simazine 2 0 kg/ha	Late seedling	18.8 ± 6 0*	491.9 ± 60.1	14.2 ± 5.5=	7.0 ± 2.3*	41.3 ± 6.7*
Simazine 3 0 kg/ha	Late seedling	0.0 ± 0.0*	N/A	0.0 ± 0.0*	0.0 ± 0.0*	3.5 ± 3.5*
Metribuzin 0.188 kg/ha	Vegetative	22.5 ± 1.2*	498.5 ± 25.6	17.6 ± 1.7=	8 8 ± 1.1*	53.1 ± 6.3*
Metribuzin 0.375 kg/ha	Vegetative	24 5 ± 2.0*	562.6 ± 15.8	19.4 ± 1 5=	7.5 ± 1.3*	51.4 ± 4.7*
Metribuzin 0.563 kg/ha	Vegetative	22.3 ± 5.0*	482 9 ± 34.2	17.0 ± 4.0=	5 8 ± 0.9*	39.0 ± 4.8*
Simazine 1.0 kg/ha	Vegetative	21 3 ± 3.9*	492.4 ± 55.5	17.3 ± 3.0=	8.5 ± 1.0*	52.0 ± 8.9*
Simazine 2.0 kg/ha	Vegetative	28.3 ± 7.9	518.6 ± 46.1	21 9 ± 5.8	9.5 ± 2.8*	55.0 ± 3 6*
Simazine 3.0 kg/ha	Vegetative	23.8 ± 8.0*	500.5 ± 41 2	18.1 ± 6.1=	6.5 ± 2.1*	51.3 ± 9.4*
Metribuzin 0.188 kg/ha	Pre-bud	36.0 ± 9.6	458 5 ± 52.3	22 6 ± 4.5	15.3 ± 3 6	52.2 ± 6 9*
Metribuzin 0.375 kg/ha	Pre-bud	29.8 ± 3.1	469.6 ± 25.1	23.3 ± 2 3	9 5 ± 1.0*	54.9 ± 7.0*
Metribuzin 0.563 kg/ha	Pre-bud	19.0 ± 1.1*	472.5 ± 44.1	14.5 ± 1.9=	7.8 ± 0.8*	38.0 ± 2.1*
Simazine 1.0 kg/ha	Pre-bud	19.8 ± 3.2*	459.5 ± 41.8	14.3 ± 3.4=	7.5 ± 1.4*	43.6 ± 2.9*
Simazine 2.0 kg/ha	Pre-bud	23.3 ± 2.7*	491.2 ± 69.7	19.3 ± 1.9=	10.8 ± 1.3*	55.0 ± 3.0*
Simazine 3.0 kg/ha	Pre-bud	23.8 ± 6.3*	430 4 ± 38.3	14 8 ± 3.4=	12.0 ± 3.8*	56.2 ± 4.*
LSD (P = 0.05)		14.3	n.s	10 6	5.8	17.3

* = Those treatments that are significantly different to the untreated control at P = 0.05

Chlorophyll fluorescence

The changes in Fv/Fm of the treated plants indicated that pyrethrum had a low level of tolerance to simazine and metribuzin. All applications resulted in a significant decrease in Fv/Fm from the untreated control (Figure 14.9).

Applications of metribuzin to pyrethrum at late seedling stage of development resulted in a rapid decrease in Fv/Fm in the 24 hours following application while applications of simazine resulted in a slower decrease in Fv/Fm which was not obvious until 3 DAA. Maximum quantum yield (Fv/Fm) of PSII following dark adaptation of the untreated pyrethrum plants remained above 0.8 for the duration of the assessment indicating that the portion of efficiently working PSII units among the total PSII population was high and close to the theoretical maximum for green plants. At 24 hours following applications of metribuzin at 187.5 g/ha, 375.0 g/ha and 562.5 g/ha, to pyrethrum plants at late seedling stage of development, the mean percentage reduction in Fv/Fm compared with the untreated control was 43%, 41% and 50% respectively. In contrast at 24 hours following application of simazine at 1.0 kg/ha, 2.0 kg/ha and 3.0 kg/ha the mean percentage reduction in Fv/Fm compared with the untreated control was 0%, 1% and 3% respectively.

The difference in the response between herbicides at 24 hours appeared to be in response to the slower uptake of simazine through the root system in comparison to the immediate foliar uptake of metribuzin. The reductions in Fv/Fm at 8 DAA compared with the untreated control for simazine applications at 1.0 kg/ha, 2.0 kg/ha and 3.0 kg/ha were 21%, 32% and 40%, respectively, supporting the conclusion that reduced rate of uptake of simazine delayed the response. Rate responses were also evident with the highest rates of application resulting in prolonged decreases in Fv/Fm. Rate response became more evident with time indicating that the lasting effect of PSII inhibition is prolonged at higher rates of application. Pyrethrum plants at late seedling stage of development treated with simazine at 1.0 kg/ha and metribuzin at 187.5 g/ha displayed high levels of recovery, producing Fv/Fm values similar to the untreated at 65 DAA. Similarly seedlings of pyrethrum treated with

simazine at a rate of 2.0 kg/ha were also able to recover but this was not observed until after 100 DAA (Figure 14.9).

Similar changes in Fv/Fm were observed when simazine and metribuzin where applied to pyrethrum at the vegetative and pre-bud stage of development, although levels of crop injury were significantly (P < 0.05) higher when applied at late seedling stage. Following the application of metribuzin at all rates to vegetative pyrethrum plants there was a rapid decrease in the Fv/Fm in the first 24 hours while in comparison a significant (P < 0.05) decrease in Fv/Fm was not observed until 3 DAA of simazine. At 30 DAA the mean Fv/Fm for metribuzin applied at 187.5 g/ha, 375.0 g/ha and 562.5 g/ha to vegetative pyrethrum was 0.348, 0.230 and 0.219, respectively. In comparison, the mean Fv/Fm for simazine applied at 1.0 kg/ha, 2.0 kg/ha and 3.0 kg/ha was 0.597, 0.593 and 0.534, respectively. At 143 DAA the pyrethrum plants displayed recovery to all rates of application of both simazine and metribuzin (Figure 14.9).

Metribuzin applied at a rate of 187.5 g/ha, 375.0g/ha and 562.5 g/ha to pyrethrum at the pre bud stage of development resulted in 21%, 24% and 37% reduction in Fv/Fm compared with the untreated plants 24 hours after application. In comparison pyrethrum plants that received applications of simazine at the pre-bud stage of development displayed no significant (P > 0.05) change in Fv/Fm compared with the untreated plants 24 hours after application. Differences in rates response were clearly evident for metribuzin applications; however, at 59 DAA all metribuzin treatments resulted in less than 20% reduction in Fv/Fm compared with the untreated control. Differences in Fv/Fm rates response were not as evident for applications of simazine. At 8 DAA the mean Fv/Fm for simazine applied at 1.0 kg/ha, 2.0 kg/ha and 3.0 kg/ha was 0.309, 0.355 and 0.329, which were not significantly (P > 0.05) different to each other. All pyrethrum plants showed a high level of recovery 59 DAA, which was much more rapid than recovery following applications at the late seedling and vegetative stages of development. Consistent with the assessments for applications at late seedling and vegetative stage of development was the rapid fall in photochemical efficiency immediately following applications of metribuzin, which was considerably greater in comparison to simazine.
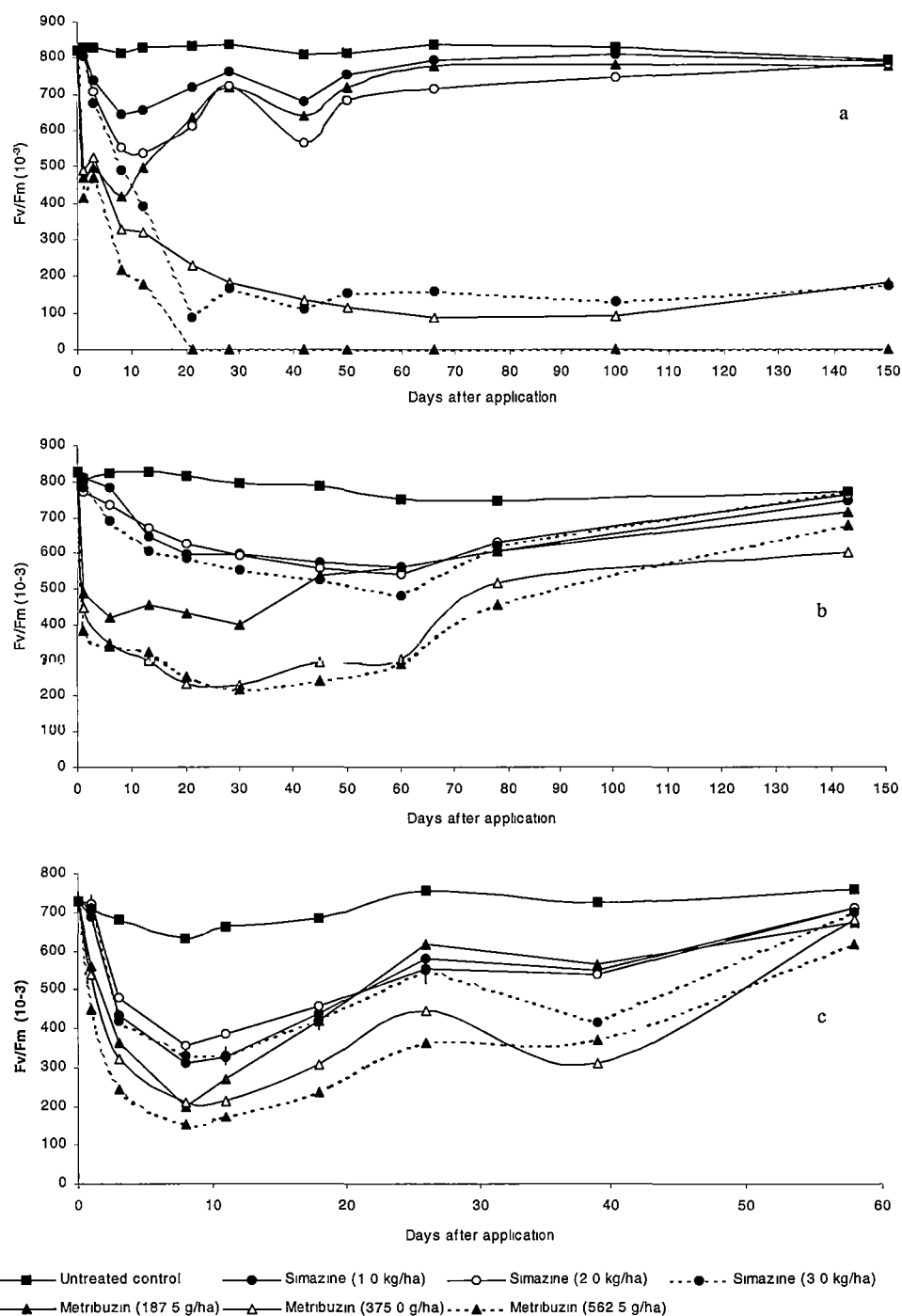
Figure 14.9 Changes in the mean photochemical efficiency of dark-adapted pyrethrum with time as affected by the rate of metribuzin and simazine applied at (a) late seedling stage, (b) vegetative stage and (c) pre-bud stage of development.

14.4 Discussion

Both metribuzin and simazine induced a high level of phytotoxicity to pyrethrum as measured by significant decreases in the Fv/Fm. Under field conditions this phytotoxicity was not detected due to only low levels of crop discoloration being observed and no significant yield effects. The ability of the pyrethrum plant to recover from these applications, as shown by the increases in Fv/Fm, results in negligible yield difference under trial conditions however the concern was that the photochemical efficiency of the plants was severely affected following applications of simazine and metribuzin. This could lead to exacerbation of injury with dual applications or subsequent herbicide applications.

The more severe response observed with applications of simazine and metribuzin to pyrethrum in the late seedling stage of development suggests that there maybe some tolerance of the more established plants through their ability to survive on energy reserves in the roots while photosynthesis is being inhibited (Lingenfelter and Hartwig, 2003). Applications of simazine or metribuzin should therefore be avoided on pyrethrum seedlings due to their increased susceptibility.

Applications of metribuzin and simazine to pyrethrum at vegetative and pre-bud stages of development were also found to impact negatively on flower yield and plant development when compared with the untreated plants. The results of the application at pre-bud stage indicated that flower production was restricted which would limit the application of metribuzin and simazine at such time. When simazine or metribuzin were applied at the pre-bud stage of development, there was a reduction in the number of pyrethrum flowers. This study provided conclusive evidence that pyrethrum is only mildly tolerant to simazine or metribuzin applications and due to the negative impact on plant development, flower yield and photochemical efficiency their adoption commercially is limited.

14.5 Conclusion

The pyrethrum crop was shown to be tolerant to a single application of metribuzin at a rate of 187.5 g/ha and also single applications of simazine at 1.0 kg/ha and 2.0 kg/ha under field conditions. However, these applications restricted the pyrethrum plants ability to maximise its photochemical efficiency. Applications of either simazine or metribuzin, therefore, placed the crop under stress, reducing flower yield and potentially causing a negative interaction with other herbicide applications. The observed tolerance by pyrethrum to applications of simazine or metribuzin under field conditions was achieved through a recovery response which occurs approximately 10 weeks after application and compensatory growth prior to flowering. It was concluded that as pyrethrum was only slightly tolerant to applications of simazine or metribuzin their use in pyrethrum should be limited.

Chapter 15 Conclusion and recommendations

The aim of this project was to provide the pyrethrum industry in Tasmania with sufficient knowledge of the biology of *A. caucalis* and *T. nodosa* to develop an effective management program for these weeds. Recommendations for chemical and cultural control strategies have been developed based on studies of weed seed dormancy, phenology and both crop and weed responses to herbicide applications. The management strategies have been designed to integrate with existing weed and crop management programs.

Pyrethrum production is a relatively new industry to Tasmania and although the industry has been successful, supplying 30% of the world market, there is a strong demand on research to support the production of higher and more reliable yields. A major area of this research is weed management. Prior to this project being undertaken the pyrethrum industry had become increasingly concerned about the increased occurrence of Apiaceae weed species, *A. caucalis* and *T. nodosa*. Although it was suggested that these species were becoming problematic weeds to the industry there was no known documentation or quantitative assessment of their level of occurrence or severity in pyrethrum. In addition, there was confusion within the industry about the correct identification of these unfamiliar species. There was also a paucity of information on the biology of these species which was restricting the development of management practices for their control.

Both *A. caucalis* and *T. nodosa* were found to be significant weed problems in pyrethrum crops. Approximately one in three pyrethrum crops contained either or both these species. *Anthriscus caucalis* was the more prevalent of the two species. Although the severity of infestation was generally low, older established pyrethrum crops had a higher level of infestation, and were more likely to contain the weed species. This indicated that the species were accumulating in the paddock due to poor levels of control. The conclusions drawn from the survey were that *A. caucalis* and *T. nodosa* posed a serious threat to the pyrethrum industry, that existing weed control strategies were not adequately controlling the spread of the weeds, and that management of the weeds in crops following pyrethrum in rotation was likely to be an issue given the increase in incidence and severity of the weeds with crop age. The

survey also increased awareness of both the presence and severity of these species amongst contract growers of pyrethrum and highlighted the need for further research into these species.

Anthriscus caucalis and *T. nodosa* were distinguished at maturity by their differing growth habit with *A. caucalis* having upright vertical stems with striate longitudinal veins and *T. nodosa* having procumbent stems with a climbing growth habit. The fruit of *A. caucalis* and *T. nodosa* was similar in size (2.5 to 3.5mm) and ovoid in shape, although the seeds of *T. nodosa*, which were light green in colour, were heteromorphic with the inner seed (mericarp) tuberculate and the outer having barbellate spines. In contrast the seeds of *A. caucalis* were distinguished by being dark green in colour, with hooked spines and a short beak. The pedicels of *A. caucalis* also had a distinguishing ring of hairs at the top. Seedlings could be distinguished by their differing leaf shape. Both species have compound pinnate leaves, with *A. caucalis* being tripinnate and *T. nodosa* bipinnate. The observed plant characteristics of *A. caucalis* were consistent with those described by Davis (1972) and those for *T. nodosa* were consistent with those described by Curtis (1963). Production of a technical note, detailing these characteristics, aided the correct identification of these previously obscure species by industry field staff and contract growers of pyrethrum. This improved the efficiency of spot spraying and mechanical removal of *A. caucalis* and or *T. nodosa*, lowered the risk of seed planting material contamination, improved the documentation of paddock history, allowed strategic harvesting decisions to be clearly designed lowering the likelihood of weed seed transportation and generally increased the awareness of *A. caucalis* and *T. nodosa* within the agricultural sector.

Understanding the biology of any weed species is of critical importance in developing weed management approaches to their control (Aldrich and Kremer, 1997). Investigation of floral biology revealed that both species have a similar breeding system, bearing hermaphrodite flowers which were weakly protandrous with protandry more evident in *A. caucalis* than *T. nodosa*. *Anthriscus caucalis* produced more umbels per plant and to higher order that *T. nodosa*, while *T. nodosa* produced more flowers per umbellet than *A. caucalis*. Both species have the potential to produce more than 5000 propagules per plant, giving an indication of the ability of

these species to establish themselves as major problematic weeds of crops. In comparison to other species, the level of seed production of *A. caucalis* and *T. nodosa* was significantly higher than *Galium aparine* which typically produces between 100 and 1000 seeds per plant (Malik *et al.*, 1988), and less than *Senecio vulgaris* which typically produces greater than 10000 seeds per plant (Salisbury, 1976). Both *G. aparine* and *S. vulgaris* are considered weeds of significance in pyrethrum. The potential large seed propagule production of *A. caucalis* and *T. nodosa* highlighted the importance of preventing seed maturation, especially in a non-tillage production system like pyrethrum which favours the accumulation of small seeded annuals at or near the surface (Ball and Miller, 1990). An examination of the seedbank of pyrethrum was consistent with this, with approximately 70% of weed seeds occurring in the upper 5cm of soil.

Anthriscus caucalis was found to set seed and mature approximately 6 to 8 weeks earlier than *T. nodosa*. Seed maturation of *A. caucalis* occurred in early summer and the seeds were easily dispersed from the open umbel structure. In comparison, seed maturation of *T. nodosa* occurred in mid to late summer and the seeds ripened on the senescing adult plant and were not dispersed from the compact umbles of the parent plant until complete senescence had occurred. Maturation of both species coincided with the harvesting of pyrethrum which begins in the last week of December and continues through into late summer. Knowledge on the timing of seed maturation of *A. caucalis* and *T. nodosa* was used to develop approaches with the aim of limiting seed propagule production and seed transportation. It was recommended that transportation of weed seeds onto farm machinery be avoided by removal of *A. caucalis* and *T. nodosa* prior to flowering and/or development of a strategic harvesting procedure where first year crops free of Apiaceae weeds are harvested prior to older pyrethrum crops or alternatively that a single harvester be devoted only for use in newly established pyrethrum crops free of *A. caucalis* and *T. nodosa*. The open umbel structure and upright growth habit of *A. caucalis* allows for a high level of seed attachment to harvesting equipment in comparison to *T. nodosa* which has compact umbel structures and a more prostrate growth habit. It was concluded that this would have contributed to the higher level of occurrence of *A. caucalis*.

The establishment of pyrethrum as a commercial crop had contributed to the development of *A. caucalis* and *T. nodosa* becoming significant agricultural weeds in northern Tasmania. Changes in management production practice as a result of the commercialisation of pyrethrum in northern Tasmania included a shift to a non-tillage production system, an over reliance on a small number of chemicals to control many common broadleaf weeds and the introduction of new planting material.

Because the weed management program developed for pyrethrum in northern Tasmania is heavily reliant on the preemergence herbicide pendimethalin which, although providing a broad spectrum of weed control, has little or no activity on species from the family Apiaceae (Chaudhary, 2000; Rapparini and Campagna, 1996; Read, 1990; Singh *et al.* 2002), it was decided that a review of the present weed management program be undertaken with the aim of developing effective and selective options for the control of *A. caucalis* and *T. nodosa*.

Pot and field experiments identified a range of herbicides with potential for controlling *A. caucalis* and *T. nodosa*. Dimethenamid applied at a rate of 3.6 kg/ha appeared to be the most selective and effective option for preemergence control. Due to the high level of selectivity of dimethenamid, dual applications may be the most effective approach but would increase the cost of production. Clomazone is an alternative herbicide for the preemergence control of *T. nodosa* as low rates of applications, 0.12 kg/ha, provided high levels of control. The most effective and selective postemergence control options were imazamox applied at 0.034 kg/ha and carfentrazone ethyl applied at 0.024 kg/ha with both displaying excellent crop safety. Sulfentrazone applied at 0.38 kg/ha and flumioxazin at 0.15 kg/ha were found to provide acceptable levels of preemergence control of both *A. caucalis* and *T. nodosa* with flumioxazin providing longer levels of control. Applications in February and March provided acceptable weed control and had low levels of phytotoxicity with no detrimental effects on crop yield. However, unacceptable levels of crop injury occurred when these herbicides where applied in May. A number of photosynthetic inhibiting herbicides were examined for the use in pyrethrum and herbicides with this mode of action were found to be highly effective against *A. caucalis* and *T. nodosa*. Herbicides simazine and cyanazine provided acceptable residual control of both *A. caucalis* and *T. nodosa* when applied at rates of 2.0 kg/ha and 1.0 kg/ha

respectively. Metribuzin applied at a rate of 0.19 kg/ha provided acceptable postemergence control of *A. caucalis* and *T. nodosa* with some residual control also found. Noticeable phytotoxicity was displayed with applications of cyanazine indicating that tolerance of pyrethrum to photosynthetic inhibiting herbicides was low, although both simazine and metribuzin were observed to have acceptable levels of crop safety. Further investigation revealed that the level of tolerance displayed in individual pyrethrum plants to simazine and metribuzin was generally low with photochemical efficiency reduced following herbicide application. It was concluded that both simazine and metribuzin significantly inhibit photosynthesis in pyrethrum. Selectivity of herbaceous and woody perennials like pyrethrum to photosynthetic inhibiting herbicides is often a result of the plants ability to survive on energy reserves in the roots while photosynthesis is being inhibited (Lingenfelter and Hartwig, 2003). It was concluded that pyrethrum can survive application of simazine or metribuzin when the plants are fully established but are quite susceptible at the seedling stage of development. It was concluded at 60 to 70 days after application that the plants have recovered to a state where photochemical efficiency is no longer being affected, although the length of this recovery period was rate dependent. This reduction in photochemical efficiency can impact flower initiation and development, plant biomass production and result in a negative interaction with other herbicide applications that may be applied during this period. It was recommended that simazine and metribuzin be considered high risk and that their usage in pyrethrum should generally be avoided. In instances where these herbicides are required to provide substantial weed control, then the herbicides should be applied to established plants and other herbicides applications should be avoided for a period of at least two months.

The application of dimethenamid at a rate of 3.6 kg/ha from early autumn to early winter was recommended. This application would provide acceptable levels of control of *A. caucalis* and *T. nodosa*. Any resulting mid winter escape of *A. caucalis* and/or *T. nodosa* following this application could be controlled by the application of imazamox at rates of 0.034 kg/ha. Clomazone application at 0.12 kg/ha was recommended as an alternative preemergence control option to that of dimethenamid for the control *T. nodosa* only, and its addition could also be used effectively to provide control of *S. vulgaris*. It was further recommended that alternative weed

management programs be developed which could be alternated between seasons. Rotation of herbicide groups could be used based on the number of products identified as selective in pyrethrum in this project. This approach would reduce the risk of herbicide resistance, and also reduce the likelihood of escaped species establishing themselves as problematic weeds of pyrethrum, similar to what has occurred with the establishment of *A. caucalis* and *T. nodosa*.

The timing of herbicide application is critical not only with respect to crop selectivity but to also provide the highest level of efficacy against the weeds and reduce the number of chemical applications. There was therefore a requirement to understand the seed biology and determine the periodicity of emergence of *A. caucalis* and *T. nodosa* in order to develop recommendations for timing of herbicide applications. Both *A. caucalis* and *T. nodosa* behaved as winter annuals with emergence predominantly occurring in autumn. There was a seedcoat dormancy and dry after-ripening requirement associated with *A. caucalis*. This prevented emergence of *A. caucalis* during times of unfavourable conditions following seed dispersal in summer. Following dispersal, the level of seed coat dormancy and the requirements for dry after-ripening, may be satisfied during the summer period, but the timing was found to vary between seed lots and seed position on the parent plant. With the onset of cooler and moister conditions in autumn, germination of *A. caucalis* commenced and continued into the winter period until such time that environmental factors became unfavourable. *Torilis nodosa* displayed no innate dormancy and emergence under favourable environmental conditions occurred immediately following seed dispersal. The compact umbel of *T. nodosa* which hold seeds tightly within its structure and the later maturity of this species restricted dispersal to late summer/early autumn and reduced the likelihood of exposure to false breaks during the summer. With the onset of winter the emergence of *T. nodosa* was restricted by lower temperatures and was therefore likely to have a smaller window of emergence to *A. caucalis*, although germination in spring of *T. nodosa* was not restricted as no inducement of dormancy during cooler periods was found. The predicted emergence patterns based on the germination studies were consistent with that recorded under field conditions in northern Tasmania. This provided valuable information to aid in improving the timing of herbicide applications. Identifying the timing of seedling establishment would improve the efficacy of a contact herbicide like carfentrazone

ethyl and potentially remove the need for the addition of an adjuvant. Correctly identifying the periodicity of emergence will reduce the requirement of preemergence herbicide to one single application and potentially lower the required rate to achieve effective residual control

The germination and emergence information may also be used to identify appropriate rotational crops so that the impact of the weeds can be reduced through cultivation practices. The majority of crops grown in rotation with pyrethrum are spring sown and cultivation occurring after the emergence of *A. caucalis* and *T. nodosa* would be expected to substantially reduce the occurrence and severity of these weeds in following crops. It was therefore recommend that spring sown crops be grown in rotation with pyrethrum and that following the pyrethrum crop cultivation be restricted until the spring period so that the seeds of *A. caucalis* and *T. nodosa* are allowed to emerge. Conventional tillage prior to the emergence of *A. caucalis* and *T. nodosa* in autumn and winter will increase the percentage of seed buried below 50 mm restricting their emergence. Due to the dormancy associated with *A. caucalis* and also the light stimulus requirement for germination of both species, the seedbank longevity under conventional tillage systems may be extended. As a result cultivation immediately following harvesting of pyrethrum in mid to late summer should be avoided. It was recommended that sowing of new pyrethrum crops in old pyrethrum fields where severe infestations of *A. caucalis* or *T. nodosa* have been recorded previously should also be avoided until such time that an effective chemical control program is adopted.

This project has been successful in developing an understanding of the biology of both *A. caucalis* and *T. nodosa* and identified a number of chemical and cultural control options for use in pyrethrum. The scientific information generated in the project has provided a basis for developing recommendations to the pyrethrum industry, recommendations that have now been adopted and used to improve the weed management of *A. caucalis* and *T. nodosa*.

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Appendix

A.1 Standard Potting Mix

Ingredients	Composition (%)
Composted Pine Bark	70%
Coarse Sand	20%
Sphagnum Peat	10%
Limil	90g/50litres (l)
Dolomite	90g/50l
Osmocaote Plus, 5-6 month	300g/50l
Ferrrous sulphate	25g/50l
pH	6.0

A.2 Standard Seedling Mix

Ingredients	Composition (%)
Composted Pine Bark	70%
Coarse Sand	20%
Sphagnum Peat	10%
Limil	90g/50litres (l)
Dolomite	90g/50l
Osmocaote Plus, 5-6 month	300g/50l
Ferrrous sulphate	25g/50l
pH	6.0

A.3 Hoaglands Solution

Chemical	Stock solution concentration	Volume of stock solution added to 100 litres (ml)
Magnesium sulphate	9.860 kg/40l	200ml
Calcium nitrate	9.448kg/40l	500ml
Potassium nitrate	4.040kg/40l	500ml
Potassium di-hydrogen phosphate	2.722kg/20l	100ml
Iron chelate	6.56g/20l	100ml
Micro nutrients;		100ml
Boric Acid	57.2g/20l	
Manganese Chloride	36.2g/20l	
Zinc sulphate	4.4g/20l	
Copper sulphate	1.6g/20l	
Sodium molybdate	0.5g/20l	

A.4 Geographic locations of plant growth assessment

Location	Species Assessed	Co-ordinates
Cressy	*Anthriscus caucalis*	516240E 5376084N
North Motton	*Anthriscus caucalis*	422171E 5440112N
Table Cape	*Anthriscus caucalis*	390546E 5466277N
Sassafras	*Anthriscus caucalis*	462043E 5433661N
Hagley	*Torilis nodosa*	492814E 5405957N
North Motton	*Torilis nodosa*	422179E 5440187N
Kindred	*Torilis nodosa*	433328E 5433765N
Table Cape	*Torilis nodosa*	388146E 5466285N

A.5 EWRC Scoring System

Rating	Weed Control Efficacy (% weed Kill)	Crop Tolerance
1	Complete kill (100%)	No effect
2	Excellent (98 to 99%)	Very slight effects
3	Very Good (95 to 97%)	Slight effects, stunting and yellowing obvious; effects reversible
4	Good to acceptable (90 to 94%)	Substantial chlorosis and/or stunting; probably no effect on yield; most effects reversible
5	Moderate but generally not acceptable (83 to 89%)	Strong chlorosis/stunting; thinning of crop; some yield loss expected
6	Fair (70 to 82%)	
7	Poor (56 to 69%)	Increasing severity of damage
8	Very Poor (30 to 55%)	
9	None (0 to 30%)	Total loss of crop

A.6 The 0 to 100 rating system

Rating	Description	Weed Control Response	Crop Injury Response
0	No effect	Zero	Zero
10		Very poor	Slight crop discoloration or stunting
20	Slight Effect	Poor	Some crop discoloration or stunting
30		Poor to deficient	Injury more pronounced, but not lasting
40		Deficient	Moderate, crop usually recovers
50	Moderate Effect	Deficient to moderate	Injury more lasting, recovery doubtful
60		Moderate	Lasting, no recovery
70		Somewhat less than satisfactory	Heavy injury and stand loss
80	Severe Effect	Satisfactory to good	Crop nearly destroyed
90		Very good to excellent	Only occasional live crops remain
100	Complete Effect	Weed destruction	Crop destruction

A.7 Soil behaviour of herbicides examined

Herbicides	Soil behaviour
Bentazone	Weakly adsorbed to soil particles. Average half life in soil is typically 12 days. Bentazone has little to no soil activity. Average K_{oc} is 34 mL/g
Carfentrazone-ethyl	Carfentrazone-ethyl is rapidly degraded in soils under aerobic and anaerobic conditions. The half life in soil is 1-2 days. It is rapidly hydrolysed at pH 9 but stable at pH 5. Field studies show that carfentrazone-ethyl has low mobility in soil.
Clomazone	Clomazone is degraded in soils under aerobic and anaerobic conditions with half lives ranging between 1 to 4.5 months depending upon soil conditions. Average K_{oc} is 300mL/g.
Cyanazine	Reversibly adsorbed to soil particles. Average K_{oc} is 190 mL/g. Has somewhat short soil residual activity with an average field half-life of 14 days.
Flumetsulam	Adsorbed much more tightly to OM than clay. Greater adsorption and lower activity at low vs high pH. Half-life is 1-3 months. Shorter persistence
Imazamox	Imazamox is only moderately persistent, and it degrades aerobically in the soil to a non-herbicidal metabolite which is immobile or moderately mobile. Imazamox also degrades by aqueous photolysis. The range of dissipation half-lives is 15 to 130 days with the more representative half-lives appearing to be 35 and 50 days.
Metribuzin	Moderately adsorbed on most soils. Metribuzin has high affinity for soil OM, but is less tightly adsorbed to clay. Average K_{oc} is 60 mL/g. Half-life typically is 30 to 60 days during the growing season, but varies greatly with soil type and climatic conditions.
Quinclorac	Residue may injure certain crops planted 1 year after application
Simazine	More readily adsorbed on muck or clay soil than to soils low in OM and clay. Average K_{oc} is 130 mg/L and an average field half-life of 60 days.
Sulfentrazone	Sulfentrazone has the following characteristics: 1) moderately soluble, 2) not susceptible to hydrolysis, 3) extremely susceptible to direct photolysis in water, 4) very stable to photolysis on soil, 5) aerobic half-life of 1.5 years, 6) anaerobic halflife of 9 years, 7) very high mobility in soil (average K_{oc} = 43, Kd < 1), and 8) low volatility from soils and water.

Adapted from Anonymous (1994) and http://www.msds.com.au.

Where K_{oc} = Soil organic carbon sorption coefficient.

      OM = Organic matter

A.8 Precipitation to 9 am (mm) for Forth side Research Station

Days

Year	Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
2002	1		12.2	2 4	0	0		8	0 6	0	0	0	14	0	0	0	16 6	0	0	0	0	0	4.2	0	0	0	0	0		34	0	0	
2002	2	0	0	0.6	0	0	0	0	8 2	3.2	0	0	0	0	0	0	0	0	0	0	0 4	13 6	0	0	0	0	0	0	0				14
2002	3	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0 2	0.4	0	0	0	0	0	6.6
2002	4	0	0	0	0 8	0	0	0	0	0 4	0	0	0	2.8	0	0	0	0	0	0 8	1.2	0	0	0	0	17.6	0	0	0	0			23.6
2002	5	0	0	0	0	0	0	0	0	0	0	5.2	0	1 2	0	0	13.8	8 ε	0		6 2	0	0	0	0	0	0	0	0	0	0	1	36 2
2002	6	0	0	0	0	0	0	2				5 8	4 8	5 2	0		29 2	0	0	0	3 2	2.4	0	0	0 4	7 4	6	1 2	10.2	0	0		77.8
2002	7	0	4			11	0	0	1 2	25.6	5 2	0	4 8	0		3.6	6 2	7	0	0 2	7 2	0	0	5 4	0 8	0	6.4	0	0	35	0	0.4	124
2002	8	1.4	1.6		10 6	0	13	5.2	0	0		13 4	0	0	0	0	0	0	0	0	3.6	3.4	0 8	0	0	0	0	0	0 4	54.4	0		107.8
2002	9		2 6	13.2	10 4	1 4	2		21 8	3.2	0 6	0	0	0	0	15 4	4	6.8	11 4	0 6	8	0	0	0	2	66	1		18	0			112 8
2002	10	0	0	0 8	0	0		9 2	76	18	0	0	0		33 8	0	0	0	0	8.2	0	0	20.8	0	28	0	0	0	0	0	0.2		85 2
2002	11	0	0	7	0	0	0 4	0	0	0 4	0	0	0	26	0 2	0	0	0	0	0	0	0	0	0	0	1.2	2	0	0	0	0		13.8
2002	12	3 2	0	0	0 2	12 8	0 8	0	0	0	0	0	0	0	0	0	0	0	0 ε	0	0	0	0	0	0	0	0	0	0	0	2 4	6	17
2003	1		31 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0 2	0.6	0	0	0	0	0	0	0	0	26 2	7.2	
2003	2	0	0	0	0	0	3 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0 6	0	0	0				
2003	3	0	0	0	0	0	0	0	0	0	0	3 4	0	0	0	0	0	2.8	0.4	0.2	27.6	9 4	0	0	0	0 4	0	0	0	0	0	9 6	50.4
2003	4	0	0.6	0	0	0	0	0.2	3	0	0	0	0	0	86.2	7 4	0	0	0	0	0	0	0	0 4	0	0	0	0	0 4	0.8	2 2		101 2
2003	5	0	0	0	0	0	0	0	0	12 4	0	0	0 6	0.2	1.2	1 4	2.2	0	0	35	6 4	0	0	2.6	0	0	11.4	0 2	0	0	0	0	73 6
2003	6	0	18.8	4 4	10 4	9.2	38 6	0	0	0	17	0 4	0	15 2	0	0	16.2	0	0	0	0	0	0	12.4	0	0	0 2	0 2	0	0	15		158
2003	7	0	0	0	0			13 4	2 4	0 4	0	0		9 6	3 8	2.4	0 2	0			0 2	13	1 2	28 6	11 4			1.2	11 4	0			99 2
2003	8	0	0	0	8 2	0	6 8	6	11.8	0	0	4.4	12.8	8 4	0.6	0.4	0	0	7.2	0	0	0	13 6	0	0	59 2	0	1 2	0	8	0	0	148 6
2003	9	10 8	0	2	0	2.6	0	0	0 8	0	3 6	6	88	0	0	16 8	2.4	0 ε	2	13 6	0	0	7.4	13.2	13.8	11	5	0	0	8	0		128.6
2003	10								0 4								2				11 8	16	0.4						2				18.2
2003	11	0	0	0	2 8	0	0 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0.8	0	0	14 4	0 8	1.2	0 6	0	0	0		21 6
2003	12	0	0	1	0 2	0	0	0	0	0 2	0	3 8	4	0	0	3 4	0	0	0 6	9	0	0	51.4	0	0	0	0	0	0	0	0		12 6
2004	1							3.4	4		3 4		14.2		0.2															107 6	16.4	15 4	812

A.9 Precipitation to 9 am (mm) for Penguin

		Days																													
Year	Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2002	1	12.8	5 2	7.2	0.2	0 8	0	4.6	0.4	0	0	0	2	0.4	0	0 4	14.8	0 2	0	0	0	0	1.8	0 2	0	0	1.4	0	32	1 8	0.2	0
2002	2	0	0 8	1.6	0	0	0	0	16	46	0	0	0	0	0	0	0.8	0	0	0	0.2	8.8	0 2	0	0	0	0	0	0			
2002	3	0	0	0	0	0	0	0	0	0.2	0	0	38	0	0	0	0	0	0	0	1	1 4	0	0	0	0	0.4	0	0	0	0	0
2002	4	0	0	0	1 2	0	0	0	3 2	0.8	0	0	0	2	0	0	0	0	0	0.4	1	0	0	0	0.4	13 8	0	0	0	0	0	
2002	5	0	0 2	0	0	0 2	0	0	0	0	5 2	0	0.4	1 4	0	0	17	10.4	0 2	25.4	0	0	0	0	0	0	0	0 2	0	0	0	1 8
2002	6	0	0	0	0	0	0 2	2 2	4.6	3.4	3.8	1	6.8	8 2	0	21.8	0	0	0	0	5.6	2	0.4	0	1.4	10 6	6.2	1	14.2	0	0	
2002	7	0 2	3 4	12 2	2.8	12	3 6	0 6	0 6	24	8 6	0 2	68	0.2	3 8	4 8	5 2	64	0 2	0	11.2	0.4	0 4	4.6	4.2	0	9	11	6 2	6.8	0 2	0.6
2002	8	3.4	0	3 2	46	0	22 8	6	0 2	0	0	4 2	98	0	0	0	0	0	0	0	0	0	4 6	2.6	0.4	0	0	0	0	0	51 2	0 2
2002	9	1.4	0	18 2	12 6	2	3 2	18.6	3.8	14 4	2.2	1 2	0	0	0	0	13.8	3 8	8	11 4	0.8	9 2	0.2	0	0	3 4	8 8	4	0.2	0.4	0 4	
2002	10	0	0 2	1 4	0 2	0	3.4	8	7 2	1 6	0.6	0	0	12	12 4	2 8	0 2	0 4	0	8 6	5.2	0	0	26.8	0.4	2 6	0.4	0	0	0	0	1
2002	11	0 4	0		8 2	0 4	2.4	0	0	1 2	0	0	0	36	0 6	0	0	0	0	0	0	0	0	0	0	1 2	3	0	0	0	2 8	
2002	12	3 8	0	0	2 2	17	2 6	0	0.2	0	0	0	0	0	0	0	0	0 8	0	0	0	0	0	0	0	0	0	0	0	0	2	7.8
2003	1	32 4	2 6	0	0	0	0	0	0	0 4	0	0	0	0	0 2	0 4	0.4	0	0	0	0.2	0.4	0	0	0	0	0	0.2	0	0	24 8	5 8
2003	2	0 2	0	0	0	0	3 8	0	0	0	0	0	0	0 2	0	0	0	0	0	0	0	0	0	0	0 4	0.4	0	0.2	0			
2003	3	0.2	0	0	0	0	0	0	0	0.8	0	0 8	0	0	0	0	0	0 8	0	1.6	40 4	8.2	0	0	0	0	0	0	0	24 2	0.2	0
2003	4	0	1	0	0	0	0	0 6	3 6	0	0	0	28 4	9.8	29 4	8	0.4	0	0	0	0	0	0	0	0	0	0	0 2	0 2	1 2	2 4	
2003	5	0 2	0	0	0	0	0	0	0	6 8	0	0	0	1	4 8	1 6	0 8	5	2 2	33	4 4	0	0	11 8	13 8	0 2	0	0	0.4	0 4	0	0
2003	6	7 8	10 4	5.8	16 2	11	35	19.2	0 4	0	0 8	2 2	0	19 4	17 6	0	0	0	0	0	0	1 8	27.8	0	0	4 2	0	0	20	0.4	0.3	
2003	7	0	0	0	0	2 8	5 8	1	6.6	0 6	0	0	8 4	4.6	2 6	6	3 6	0	0	0	0	1.2	10.2	3	21.6	10	0	1 8	0	10 8	0	0
2003	8																															
2003	9	0	0	4 6	0 2	4 2	0	0	0	0	3 6	4 4	10.8	1.2	16 6	7 4	6 4	1.8	4	19	0	4.4	0 2	12.8	17	18.6	6 2	0.8	0	8.8	0	
2003	10	0	0	0	0	0	0	0	0.8	1.2	10 2	0	0	0	0	0	2 2	0	0	8 4	6	10	1 8	0	0	0	0	0	0	0	0	0
2003	11	3 8	0	0	0	0	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	1 2	1 4	0	1.2	8	2	1 8	0.8	0	0	0	
2003	12	0	0	4	0	0	0	0	0	0	0	64	18	9 8	0	0	0	0	0.8	9	0 4	0	53	0	0	0	0	0	0	0	0	0
2004	1	0	0	0	0	0	0	0	8 4	2	0.6	0 8	0	0	0 6	0	0	0	0	0	0	0	0 6	0	0	0	0	0	50	12.1	10 6	0

A.10 Precipitation to 9 am (mm) for Wynyard

		Days																														
Year	Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2003	1	12.4	04	0.2	0	0	0	0	0	0.4	0	0	0	0	0	0.4	02	0	0	0	02	1	0	0	0	0	0	0	0	0	22	6
2003	2	06	0	0	0	0	1.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1.6			
2003	3	04	0	0	0	0	0	0	0	08	0	02	0.8	0	0	0	0	0	0	2	19	82	02	0	0	0	0	0	0	8	0	0
2003	4	0	1	0	0	0	1	02	3.2	0	0	0	64	68	168	10.2	0	0	02	0	0	0	0	0	0	0	0	0	0	14	54	
2003	5	0	04	02	02	0	02	0	0	32	0	0	0.2	0	06	08	0.4	04	56	208	6.8	04	02	144	06	0	0	0	0	02	02	0
2003	6	92	20	44	74	4	23	20	1	02	2	06	0	17	10	0.4	0	0.6	02	0	0.2	1	136	0	02	0	06	0	25	0	0	
2003	7	0	0.2	0.2	0.2	18	10.2	0.6	4.4	12	0.2	0	7.2	4.8	4	7.6	4	04	02	02	0	04	126	06	178	16	02	6.4	1	106	02	0
2003	8	0	1	7.8	0	0	9	7.8	6.8	72	0.6	03	5.2	7.2	1	0.2	0.8	02	4	0	0	0	44	0	184	182	42	1.6	04	11.8	62	52
2003	9	02	0	5	0	5.2	06	08	0	0	6.6	3.8	144	14	146	12.8	4.4	3	9.2	14	3.6	4.2	0	14	136	112	7	0.6	1	66	0	
2003	10	0	0	0	0	0	0	02	0	1.4	12.6	0	0	0	02	0	2	0	0	8.4	7.6	112	1.2	0.6	06	0	0	0	0	0	0.4	08
2003	11	64	0	0	0	0	06	0	0	0	0	0	0	0	0	0	0	0	0	0	1.4	2.6	0	0	0	3.4	0.3	0	0	0	0	
2003	12	0	0	12	0	0	0	0	0	0	0	4	06	5.6	0	0	0	0	0.6	7.6	0	0	49	0	0	0	0	0	0	0	0	0
2004	1	0	0	0	0	0	0	7.2	5	08	3.8	1.6	0	0	06	0	0	0	0	0	0	0	0	0	0	0	0	0	288	12.4	6	0

A.11 Precipitation to 9 am (mm) for Sassafras

Year	Month																Days															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2003	1	30	28	0	0	0	0	0	0	0	0	0	0	0	02	0	0	0	0	0	0	12	0	0	0	0	04	0	0	0	33.6	6.8
2003	2	0	0	0	0	0	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0	0	0	0	0	0			
2003	3	0	0	0	0	0	0	0	04	06	0	0	0	0	0	0	0	0	0	0	142	16.2	0	0	0	0	0	0	92	9.8	1.2	0
2003	4	0	0	0	0	0	0	0	3.2	0	0	0	146	274	40	146	0	0	0	0	0	0	0	0	0	0	0	0	0	12	1	
2003	5	0	0	0	0	0	0	0	0	66	0	0	0	0	1	0	6.2	5	24	74	10.4	0	0	0	20	0	0	0	0	0	0	0
2003	6	21.8	108	36	74	27	50.6	162	0	0	0	0	0	23.6	92	0	0	0	0	0	0	4	0	0	0	1	0	0	12	0		
2003	7	0	0	0	0	42	0	0	3.6	0	0	0	0	0	114	0	0	0	0	0	0	0	10	24	354	10	0	0	1	10.4	0	0
2003	8	0	0	9	0	0	7	36	46	24	0	0	128	8	0	0	0	0	58	0	0	0	232	0	342	7.6	0	0	0	11.6	98	7
2003	9	0	0	0	0	2.2	58	98	0	0	2	58	0	106	152	38	3	0	06	14	46	24	12.2	128	0	184	3	13	0	4.4	0	
2003	10	0	0	0	0	0	0	0	06	0	2.6	0	0	0	0	0	2	0	0	5.2	7	56	0	0	0	0	2	0	0	0	0	0
2003	11	32	0	0	0	0	04	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0.6	0	14	34	0	1.4	0	0	0	0		
2003	12	0	0	34	0	0	0	0	0	0	0	8.4	14	136	0	0	0	0	0.4	98	04	0	44	0	0	0	0	0	0	0	0	0
2004	1	0	0	0	0	0	0	7.6	3.8	0	1	0.2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	878	60.6	19.4	0

A.12 Minium and Maximum Daily Air Temperature for Hobart

			Days																														
Year	Month	N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2002	1	Min Temp (°C)	119	86	97	116	94	115	15	121	116	9	108	103	121	133	106	89	115	12	126	15.4	138	137	125	131	142	16	185	183	155	148	11
2002	1	Max Temp (°C)	202	165	186	191	173	206	165	169	183	194	211	168	186	179	167	182	202	201	269	256	156	201	219	176	221	27	247	262	222	273	179
2002	2	Min Temp (°C)	11	162	86	94	107	96	133	146	154	79	107	116	125	129	169	155	141	132	139	155	122	99	129	103	144	154	10	81			
2002	2	Max Temp (°C)	255	255	179	161	175	19	21	217	205	145	171	179	237	262	325	249	235	196	221	278	179	20	234	219	234	204	174	193			
2002	3	Min Temp (°C)	109	131	128	10	114	147	118	89	92	127	122	124	114	108	129	139	137	118	128	116	10	66	109	108	145	149	115	111	113	94	81
2002	3	Max Temp (°C)	204	189	227	199	236	264	185	156	186	235	276	191	213	21	21.4	196	206	301	213	149	176	225	263	241	28	208	256	242	159	159	199
2002	4	Min Temp (°C)	108	128	158	75	9	92	136	112	141	114	119	121	129	6	6.7	88	75	66	11	133	104	119	93	128	144	99	81	61	5	61	
2002	4	Max Temp (°C)	22	27	244	152	19	209	165	21	261	214	20	167	182	155	186	176	168	153	187	175	139	156	187	216	20	139	122	13.7	167	19	
2002	5	Min Temp (°C)	74	67	61	9	97	106	85	136	151	113	86	10	119	58	4.2	45	96	55	38	4	53	104	81	23	31	61	46	68	75	4.2	53
2002	5	Max Temp (°C)	171	17	191	217	231	173	184	225	203	183	201	191	166	159	148	159	14	135	128	125	125	127	108	116	122	135	134	122	124	142	141
2002	6	Min Temp (°C)	35	54	114	104	129	92	98	62	62	82	61	118	67	69	7.8	56	63	59	11	24	84	87	98	113	98	59	87	63	52	36	
2002	6	Max Temp (°C)	151	164	167	159	179	157	192	112	145	125	154	118	13	126	108	109	94	104	134	116	13	134	149	16	13	121	127	91	115	108	
2002	7	Min Temp (°C)	46	5	63	44	55	56	6.2	83	96	7	5	74	45	57	5.9	71	43	71	106	89	63	53	73	55	21	3	56	77	73	48	32
2002	7	Max Temp (°C)	144	132	128	103	109	106	148	165	137	135	141	145	159	13	145	142	116	157	183	13	13	138	143	89	89	148	179	157	123	15	131
2002	8	Min Temp (°C)	51	27	45	58	26	36	86	78	95	109	12	68	7	55	3	52	57	47	7	81	88	8	43	3	26	34	26	57	51	57	77
2002	8	Max Temp (°C)	127	123	152	127	126	142	131	136	169	198	162	112	89	106	137	146	135	157	139	156	167	129	96	128	138	141	169	18	164	143	146
2002	9	Min Temp (°C)	66	47	97	89	56	96	62	55	54	21	65	67	57	124	9.1	142	5	69	19	31	88	85	67	78	64	67	71	68	64	71	
2002	9	Max Temp (°C)	168	175	162	13	182	158	11	149	115	116	151	161	181	214	253	18	138	115	101	138	153	171	137	131	166	146	175	117	155	174	
2002	10	Min Temp (°C)	10	91	45	85	10	123	129	106	62	69	58	69	106	48	7.4	11	82	10	93	94	76	109	93	7	88	45	63	88	48	82	108
2002	10	Max Temp (°C)	191	101	134	126	165	184	228	142	138	165	147	19	139	144	166	165	166	216	145	175	172	187	133	158	131	139	136	139	165	252	165
2002	11	Min Temp (°C)	85	84	111	95	99	102	112	121	113	111	47	116	107	11	89	6	113	133	82	115	89	95	6	133	14	123	77	113	121	116	
2002	11	Max Temp (°C)	172	229	222	149	171	209	30	179	206	17	198	312	172	202	172	195	259	156	187	166	169	173	207	278	199	166	219	194	212	155	
2002	12	Min Temp (°C)	119	99	152	116	107	86	97	118	92	65	136	128	129	76	127	111	124	131	133	151	143	141	86	121	106	65	121	129	169	212	17
2002	12	Max Temp (°C)	198	236	227	19	166	143	203	21	175	196	223	203	197	188	131	219	222	203	251	24	288	185	208	197	173	177	187	26	27	248	271

A.11 Minium and Maximum Daily Air Temperature for Hobart

Year	Month	N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2003	1	Min Temp (°C)	155	146	147	136	94	125	179	129	10	102	114	134	159	166	107	147	144	179	126	125	157	134	116	119	165	172	95	115	147	18	106
2003	1	Max Temp (°C)	257	236	226	186	22	278	351	198	226	222	224	264	308	258	21	233	264	255	235	35.9	23	229	21	253	374	196	246	279	311	222	19
2003	2	Min Temp (°C)	13	10	139	147	19	147	161	104	115	126	89	11	13	101	101	127	94	118	104	75	118	167	151	166	17	143	153	125			
2003	2	Max Temp (°C)	223	216	217	323	229	222	247	211	276	203	215	23	196	234	184	172	166	188	17	205	267	269	296	335	227	226	217	138			
2003	3	Min Temp (°C)	59	94	85	108	104	89	129	116	103	111	111	13	175	95	132	137	134	168	178	97	108	111	10	99	68	88	119	133	107	123	114
2003	3	Max Temp (°C)	16	144	177	165	216	229	215	144	138	174	225	278	212	198	205	184	301	307	188	132	144	143	132	146	184	203	189	16	194	199	169
2003	4	Min Temp (°C)	106	126	78	79	81	76	92	127	104	79	111	132	135	99	125	72	82	98	61	86	116	94	116	92	54	55	74	107	111	98	
2003	4	Max Temp (°C)	176	148	125	121	138	175	201	152	131	155	165	177	211	205	152	142	149	139	157	169	163	18	209	149	176	174	197	214	204	124	
2003	5	Min Temp (°C)	41	88	118	37	61	96	10.8	111	121	6	45	51	42	56	82	10	112	122	114	115	117	94	58	73	54	57	77	72	94	135	128
2003	5	Max Temp (°C)	154	173	119	128	202	163	187	166	141	132	109	128	144	159	169	177	16	175	172	15.6	129	116	135	154	13	172	146	151	152	158	202
2003	6	Min Temp (°C)	79	69	74	10	92	8	56	7	108	9	89	73	86	36	39	105	86	87	59	27	44	68	26	47	09	16	44	63	77	52	
2003	6	Max Temp (°C)	127	17	154	147	14	126	117	16	145	154	15	175	131	115	144	171	153	146	128	11.9	139	96	104	105	106	144	125	134	10	83	
2003	7	Min Temp (°C)	37	15	27	42	22	43	68	89	52	63	37	44	45	52	69	31	44	93	31	35	22	33	45	56	66	38	53	78	47	53	65
2003	7	Max Temp (°C)	9	86	83	105	139	169	163	144	114	121	148	126	121	148	116	107	149	121	103	11.5	119	143	135	12	115	102	149	149	111	96	12
2003	8	Min Temp (°C)	2	36	10	122	88	67	69	89	32	48	52	63	75	39	41	6	78	5	17	14	23	44	43	69	82	5	39	77	7	84	33
2003	8	Max Temp (°C)	146	156	197	17	164	114	151	133	98	148	133	153	182	84	12	131	15	98	126	119	137	122	161	134	131	124	12	159	174	91	97
2003	9	Min Temp (°C)	28	71	47	68	78	61	65	2	48	75	68	43	66	6	23	6	56	41	64	63	67	36	82	83	69	43	23	3	4	4	
2003	9	Max Temp (°C)	131	156	129	206	11	143	119	102	12	11	134	145	16	13	113	143	143	122	152	163	162	171	188	142	13	125	104	146	107	15	
2003	10	Min Temp (°C)	36	62	62	3	56	71	107	68	41	41	44	46	65	66	12	105	101	89	133	84	85	41	37	46	85	24	81	49	61	77	82
2003	10	Max Temp (°C)	13	11	115	14.2	136	17	17	111	117	105	139	147	138	221	231	189	211	25	17	18.3	17	13	135	167	108	149	15	146	146	156	138
2003	11	Min Temp (°C)	77	63	88	104	106	91	61	98	115	84	137	94	61	11	129	8	87	88	138	155	87	87	88	93	97	98	96	107	118	192	
2003	11	Max Temp (°C)	143	142	176	203	21	187	166	168	201	214	192	159	195	281	326	141	176	232	285	19.5	14	165	136	15	165	157	153	215	268	319	
2003	12	Min Temp (°C)	113	113	14	124	96	61	119	118	148	16	16	115	92	121	101	141	135	126	137	9	119	137	118	95	135	113	105	122	104	188	141
2003	12	Max Temp (°C)	191	214	24	239	172	186	192	201	237	253	247	241	176	229	215	334	174	183	169	173	206	189	213	209	23	193	199	191	307	358	261
2004	1	Min Temp (°C)	158	124	141	134	106	125	139	89	112	144	108	91	106	83	11.9	101	128	69	6	128	127	117	11	111	98	107	116	148	138	128	13
2004	1	Max Temp (°C)	232	275	215	226	228	253	202	162	228	229	195	203	254	196	252	212	162	167	24	339	253	197	213	181	164	201	206	159	148	158	201

A.13 Minium and Maximum Daily Air Temperature for Devonport

			Days																														
Year	Month	N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2002	1	Min Temp (°C)	89	89	89	109	7	10	155	142	69	122	118	87	85	116	123	106	105	11	106	159	173	136	87	136	136	173	178	186	106	136	102
2002	1	Max Temp (°C)	165	169	207	194	174	205	194	225	193	189	174	188	216	20	19	174	209	191	231	227	206	205	25	209	217	249	231	196	219	215	211
2002	2	Min Temp (°C)	114	152	51	73	74	106	119	148	124	74	85	124	139	143	164	155	104	94	13	171	121	11	11	12	115	146	104	81			
2002	2	Max Temp (°C)	21	218	212	209	198	203	21	243	23	202	196	194	213	227	257	22	215	212	227	208	186	209	23	199	235	245	204	188			
2002	3	Min Temp (°C)	102	13	91	104	139	148	88	64	112	127	154	83	5	12	106	138	91	102	10	11.5	58	63	78	99	14	15	10	103	104	46	68
2002	3	Max Temp (°C)	204	225	23	206	215	227	21	20	19	21	231	207	237	206	217	213	223	214	195	189	182	177	183	221	216	211	207	266	197	188	184
2002	4	Min Temp (°C)	99	118	129	35	64	68	57	122	135	119	89	126	122	78	75	96	88	105	141	126	113	102	11	124	139	105	43	56	69	81	
2002	4	Max Temp (°C)	191	201	201	171	227	228	202	20	204	192	193	189	199	196	196	195	199	204	222	214	211	202	182	183	177	174	151	16	166	18	
2002	5	Min Temp (°C)	82	88	89	43	89	91	85	92	104	11	61	97	88	53	64	96	65	36	8	25	28	106	34	26	41	31	18	19	52	07	45
2002	5	Max Temp (°C)	181	168	157	17	167	187	175	181	169	188	166	181	172	172	165	164	15	134	156	147	18	171	133	136	136	132	132	147	138	129	16
2002	6	Min Temp (°C)	17	28	61	87	10	69	84	7	8	11	89	122	65	2	74	41	43	0	19	61	77	102	92	108	99	38	8	23	12	1	
2002	6	Max Temp (°C)	134	178	15	155	156	159	168	122	149	137	158	144	142	136	129	153	12	117	138	127	137	152	151	149	13	126	119	119	141	12	
2002	7	Min Temp (°C)	3	34	45	65	61	31	59	109	92	69	4	74	73	66	55	95	08	53	117	103	31	4	73	19	04	32	56	7	29	29	43
2002	7	Max Temp (°C)	148	134	122	127	13	12	147	143	121	147	127	132	151	129	133	137	12	141	14	131	127	121	131	122	118	13	142	125	134	129	136
2002	8	Min Temp (°C)	75	19	05	29	49	76	107	49	51	83	102	73	66	04	04	14	2	06	46	2	9	62	18	02	-05	21	45	54	105	81	5
2002	8	Max Temp (°C)	138	126	148	145	124	14	148	136	141	147	141	133	148	118	12	157	151	124	144	138	134	131	127	114	113	125	134	153	13	153	137
2002	9	Min Temp (°C)	37	62	107	94	75	97	86	53	72	18	4	44	68	73	88	12	34	85	31	34	95	69	24	66	44	82	89	8	4	37	
2002	9	Max Temp (°C)	139	143	141	131	136	137	123	133	11	123	158	136	149	153	195	129	128	13	118	131	169	17	145	134	144	143	144	154	163	172	
2002	10	Min Temp (°C)	77	58	106	104	11	127	113	76	48	51	58	72	121	57	6	104	56	8	11	101	72	69	86	57	92	45	27	58	68	95	101
2002	10	Max Temp (°C)	145	156	154	198	189	16	17	142	135	144	146	161	14	135	189	157	175	155	15	175	179	144	147	158	157	16	17	151	145	171	165
2002	11	Min Temp (°C)	71	96	122	75	9	82	68	101	128	98	67	116	97	101	54	81	89	12	131	104	93	74	76	123	114	12	127	77	126	117	
2002	11	Max Temp (°C)	178	169	18	148	169	162	173	16	179	198	167	205	168	188	20	164	194	21	166	175	168	206	175	192	177	192	227	175	19	214	
2002	12	Min Temp (°C)	128	126	143	104	114	58	89	115	62	4	117	122	113	98	134	113	146	116	133	125	149	145	64	109	122	11	144	127	179	175	179
2002	12	Max Temp (°C)	178	185	196	155	147	168	172	173	182	20	231	192	222	183	181	191	198	199	208	221	229	21	185	224	229	188	193	225	228	233	198

A.12 Minium and Maximum Daily Air Temperature for Devonport

Year	Month	N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2003	1	Min Temp (°C)	16 6	13 9	12 1	12	7 2	11 1	11 9	12 3	8 5	9 6	12 2	12 2	15 9	18 4	8 8	13 8	14	18 2	9 2	12 4	14 6	11	10 2	12 9	15 1	17 2	13	9 1	12 6	16 5	9 3
2003	1	Max Temp (°C)	18 8	21	21 9	22 2	19 2	20 1	21 4	20 3	21 6	21 1	21 1	21 8	22 4	23 9	20 4	21 4	25 9	26 5	21	19 8	23 7	22 8	20 7	23 6	25 3	23 9	23 2	21 3	24 2	22	19
2003	2	Min Temp (°C)	13 2	11 5	11 6	15 9	16 9	16 7	16 7	12 2	12	7 7	9 8	10 5	9 4	9 7	10 6	14 9	6 8	5 3	7	12 1	16 6	17 5	14 9	16 9	16 5	14 2	12 3	9 8			
2003	2	Max Temp (°C)	21 6	20	22 9	24 5	21 8	22 9	27 6	21 1	22 8	24	19 9	20 9	21 8	20 5	20 8	23	21	24 1	18 9	21 1	25 6	24	24 1	24 3	23 1	21 4	23 2	21 3			
2003	3	Min Temp (°C)	4 7	8 5	3 8	5 5	6 4	7 9	9 1	12 7	9 8	13 9	13 7	13	12 5	11 4	14 7	13 8	14 9	15 5	16	12 1	11 1	7 6	9 9	7 8	10	9 1	11 8	13 5	13 3	11 6	9 5
2003	3	Max Temp (°C)	19 4	20 1	20 6	22	20 2	19 5	19 6	19 7	23	24 8	21 6	21 5	24 8	20 4	20 8	21 4	21 5	23 9	20 5	19 5	20	20	19	18 4	18 6	19 7	20 2	20 3	19 8	21 1	20 4
2003	4	Min Temp (°C)	9 3	14 2	6 4	5 1	6 1	9 4	10 4	10 4	4 3	8 8	12	14 9	16 1	12 5	11 9	3 9	5 7	5 7	6	9 8	10 7	9 7	7 5	10 3	6 9	10 1	11 2	10 8	11 7	11 3	
2003	4	Max Temp (°C)	19 9	23 2	16 8	17 2	17 2	17 8	19 1	19 8	16 2	18 7	18 6	19 8	18 3	18.7	15 3	15 8	17	16 8	16 4	17.6	18 3	18 3	20 8	17 8	17 5	18 7	19 3	19 6	18 6	18 7	
2003	5	Min Temp (°C)	1 7	7 8	12 5	1 5	4 3	2 6	4 6	6 7	9	4 8	3 5	4 8	7 1	9 3	13 4	12 4	13	15	13 8	10 2	10 8	7 8	9 2	8 8	8 4	6 1	6	4 4	7 9	12 5	6 9
2003	5	Max Temp (°C)	15	17	16	13	16 1	17 4	18	16 8	17 5	13	14 3	17 1	15 9	17 8	18 5	19 2	17 2	16 6	17 1	15.8	18 5	16	12 1	15 1	15 8	15 3	15 1	15 4	16 5	15 7	16 4
2003	6	Min Temp (°C)	11 5	9 2	11 3	10 9	10 3	9 7	6 5	7 5	5 7	5	8 8	12 9	8 4	4 9	5 4	9	7 4	3 8	4 3	-0 6	3 1	5 9	2 9	2 1	3 6	4 2	6 4	8 5	7 5	5 8	
2003	6	Max Temp (°C)	15 3	16 8	14 7	16 4	14 3	11 7	13 7	15 7	15 1	15 1	15	16 1	13	10 9	14 7	13 7	18 8	16 3	13 8	12 1	11	13	12 7	12 8	12 9	14 6	14 6	14 3	14 9	10 5	
2003	7	Min Temp (°C)	0 5	2	2 6	1 7	3 8	10	7 1	5 9	1 5	6	7	10 1	4 2	3 4	6	1 5	3 1	6 6	3	4 3	6 6	8 3	10 3	8 6	6 7	1 2	3 4	8 4	4 2	2	1 3
2003	7	Max Temp (°C)	10 9	12 6	10 9	12 6	13 7	14 4	14 1	12 8	14 3	12 4	13 9	11 4	13 4	13 4	10 8	11 7	14	14 6	11 2	11 1	13 5	13 9	13	10 7	11 9	12 1	13	12 9	12 2	13	14 4
2003	8	Min Temp (°C)	3	4 9	11	8 7	7 9	8	8 7	8 7	2 2	1 5	6	9	11 5	5 6	3 5	2 1	5 3	1 1	0	1 9	1 7	7	5	8 5	9 2	3 8	3 3	7 2	10 7	9 4	1 4
2003	8	Max Temp (°C)	12 3	13 7	14 2	14 2	15 3	12 2	13 4	11 9	10 7	12 4	12 6	13 5	14 2	10 7	12 7	11 9	12 7	11 4	10 5	11 3	13 3	13 7	15 3	12 6	12 5	12 6	12 3	13 4	14 3	11 6	12 2
2003	9	Min Temp (°C)	0	6 5	6 9	4 4	8 9	2 9	6 3	2 7	4	7 1	3 3	3 3	3 3	4 2	3 9	7 3	8 1	4 4	8 6	4 2	9 3	2 6	6 3	9 3	9 2	5 6	2 3	1	3 3	1 5	
2003	9	Max Temp (°C)	13 2	14 5	13 7	12 9	12 6	13 8	14 7	12	12 6	9 2	14 1	13	13 7	9 7	14 2	13 7	13 7	12 7	14	13 5	16 7	12 8	14 1	13 6	13	12	13 3	12 3	13	13 9	
2003	10	Min Temp (°C)	1 4	8 3	3 9	5 3	9 7	4 1	8 4	6 1	3	0 5	2 7	4 5	6 5	8 3	9 4	8 4	8 4	6 3	10 9	7 9	10 3	3 2	3 9	6	9 5	4 7	5 4	3 2	4 2	7 3	6 3
2003	10	Max Temp (°C)	11	16 1	13 8	14	12 5	16 8	14 6	12 9	11 6	13 4	13 4	14 6	14 6	14 8	16 5	15 6	15 5	16 7	14 2	14 5	14 4	13 2	12 2	14	16 3	16 8	17 2	13 5	16 1	15 8	13 1
2003	11	Min Temp (°C)	7 6	4 8	8 6	9 3	5 4	11 2	4 6	6 3	7 2	7 4	12 1	8 5	4 5	5 5	10 8	9 8	8 3	10 9	12 8	14.9	11 6	11 8	11 2	9 9	11 8	12 3	13	11 2	11 2	12 7	
2003	11	Max Temp (°C)	15 3	15 6	19 2	15 1	14 6	19 2	15 2	15	16 4	20 5	22	18 9	15 3	18 3	23 9	17 4	16 3	18 1	18 1	19.2	16	16 9	14 1	15 7	17 2	16 9	18	18 7	22 1	21 4	
2003	12	Min Temp (°C)	10 8	10 5	12 4	13 8	7 9	11 4	9 8	13 3	14 2	13 6	14 6	7 9	8 3	9	9 4	12 1	14 3	16 3	12 9	12 3	14 9	13 8	11	10 1	15	11 4	7 5	8 5	11 1	13 7	13 1
2003	12	Max Temp (°C)	19 2	17	20 4	19 9	21 9	17 8	19 3	19 6	20 6	21 5	19 3	18 2	19	21 8	19 2	22 6	23 4	19 6	23 1	19.4	20 4	23 5	22 3	19 4	23 3	20 6	20 6	20	21 6	25	19 7
2004	1	Min Temp (°C)	13 2	8 9	12 8	12	6 3	9 2	13 5	7 2	11 5	13 5	10 2	7 3	10	8 6	10 5	8 9	7 9	5 1	7 5	11.8	8 7	10 8	6	10 4	14 4	12 7	11		14 2	14 7	13 4
2004	1	Max Temp (°C)	19 6	20	20 3	23 7	21 1	18 7	17 6	17 2	18 2	18 2	19 9	18 3	17 7	20	18 4	17 4	20 2	19 7	20 2	22 4	18 9	20 6	18	23 9	19 8	19 9		20 1	18 1	24 5	21 6

A.14 Minium and Maximum Daily Air Temperature for Wynyard

			Days																														
Year	Month	N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2002	1	Min Temp (°C)	65	76	87	10	63	53	14	133	71	76	135	62	114	112	122	116	8	116	89	171	176	14	101	132	159	166	182	154	9	131	92
2002	1	Max Temp (°C)	166	159	19	188	185	194	188	199	195	18	171	169	231	206	18	18	231	196	219	226	21	215	248	203	208	224	207	205	237	229	20
2002	2	Min Temp (°C)	141	159	24	96	71	98	128	148	116	5	41	10	152	165	182	127	89	52	142	167	95	99	122	114	132	143	53	65			
2002	2	Max Temp (°C)	197	211	194	196	192	20	18	234	216	207	185	19	201	217	23	226	238	228	189	204	168	191	254	206	227	235	199	177			
2002	3	Min Temp (°C)	91	116	83	79	134	164	7.5	51	79	134	156	36	8	133	81	128	116	91	53	95	43	2	43	64	119	134	78	89	103	63	62
2002	3	Max Temp (°C)	204	21	244	208	21	213	199	193	194	20	202	208	224	231	224	20.3	219	225	203	189	20	192	184	211	226	222	259	248	168	176	187
2002	4	Min Temp (°C)	61	104	114	29	21	57	31	7	152	65	54	124	124	85	86	128	83	46	73	94	67	46	132	117	132	64	16	18	29	62	
2002	4	Max Temp (°C)	197	20	197	167	198	207	197	192	207	212	198	191	192	184	183	192	187	196	213	22	204	194	175	179	179	162	153	156	165	195	
2002	5	Min Temp (°C)	55	38	31	16	61	43	98	89	78	82	33	76	8	12	36	113	64	11	73	09	23	9	04	-16	-12	-09	-02	2	12	-05	26
2002	5	Max Temp (°C)	179	173	207	192	189	182	187	185	154	176	168	18	17	154	154	163	143	138	161	156	163	154	132	131	132	133	143	138	137	134	155
2002	6	Min Temp (°C)	-06	13	55	48	57	5	66	53	53	103	74	116	49	19	45	19	0	-33	-15	36	29	73	56	102	98	27	56	24	-06	-15	
2002	6	Max Temp (°C)	158	166	156	162	168	158	173	121	146	13	156	142	129	142	133	162	129	115	133	125	135	144	152	152	131	124	99	12	132	116	
2002	7	Min Temp (°C)	17	17	4	27	6	37	6	94	95	27	17	56	7	48	52	87	-05	36	114	75	09	58	74	03	-36	15	47	38	23	03	32
2002	7	Max Temp (°C)	143	138	115	125	129	108	139	148	117	145	127	148	145	134	138	134	124	146	142	126	131	118	146	121	116	142	155	126	14	124	14
2002	8	Min Temp (°C)	72	02	52	27	08	69	95	2	35	3	71	47	64	-13	-01	07	02	-06	08	18	48	34	-1	-27	-08	-08	22	38	115	84	2
2002	8	Max Temp (°C)	133	117	127	143	127	131	136	149	165	152	153	126	126	129	147	152	158	16	151	14.3	146	135	124	122	138	118	131	139	122	147	143
2002	9	Min Temp (°C)	08	32	106	84	62	54	72	37	67	03	14	17	29	58	6	121	-01	82	32	0	78	66	-03	87	28	7	83	73	43	51	
2002	9	Max Temp (°C)	148	14	149	134	147	139	12	129	109	123	158	152	156	185	206	126	13	119	105	13.4	159	171	133	137	145	153	163	137	152	174	
2002	10	Min Temp (°C)	46	36	102	93	117	117	119	73	16	13	32	69	117	44	72	107	27	35	99	97	47	63	71	62	83	12	48	49	46	58	91
2002	10	Max Temp (°C)	151	191	148	174	183	172	196	135	148	143	144	149	162	134	178	161	171	158	15	17.1	176	15	141	149	153	157	176	188	157	175	155
2002	11	Min Temp (°C)	76	7	125	7	7	57	53	96	122	95	33	128	81	68	44	87	123	92	135	93	91	45	32	147	91	118	6.9	71	118	124	
2002	11	Max Temp (°C)	186	154	165	154	156	201	19	191	19	185	158	183	168	175	192	159	187	284	173	198	166	196	175	186	199	195	213	184	182	215	
2002	12	Min Temp (°C)	148	125	15	63	94	52	74	10	32	42	104	106	109	61	98	83	124	93	157	12.1	161	128	87	78	107	108	97	105	174	169	178
2002	12	Max Temp (°C)	181	181	192	147	14	154	184	181	171	184	205	171	194	184	24	192	196	198	21	233	231	198	226	208	209	192	195	207	223	219	199

A.13 Minium and Maximum Daily Air Temperature for Wynyard

			Days																													
Year	Month	N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2003	1	Min Temp (°C)	12 9	11 9	11 7	10 1	9	12 6	12 2	9 8	4 8	8 7	9 5	16 6	16 5	17 3	10 6	14 5	13 6	17	5 2	15 1	14	11 4	9	13 3	17 5	15 3	10 4	6	14 3	16 8	7 9
2003	1	Max Temp (°C)	19	21 3	20 8	20 2	21 6	19 4	21 8	19 2	20 2	22 7	20 9	20 5	20 8	23 2	21 6	21 8	25	25 2	25 3	19 6	22 1	24 8	23 3	23 4	25 7	21 3	25 3	23	23 8	20 9	18 2
2003	2	Min Temp (°C)	11 7	8 9	9 3	17 3	18 7	14 1	18 5	12 2	11 6	9 6	10 6	5 2	10	6 1	9 5	16	8 2	4 8	8 3	11 2	16 9	18 8	17 9	19	14	8 5	11 3	9 1			
2003	2	Max Temp (°C)	22 7	20 6	22 3	23 3	22 9	22 3	27 3	22 2	23 2	23 3	20 9	21 4	21 3	21 7	23 3	22 7	19 4	21 1	19 3	20.9	22 7	24 5	23 4	23 7	29 1	23 5	26	19 9			
2003	3	Min Temp (°C)	24	79	2	29	21	26	41	10	68	84	11	91	118	121	51	83	132	139	174	109	96	114	75	57	86	74	10	9	12	9	87
2003	3	Max Temp (°C)	179	19.2	186	218	229	215	208	221	222	236	20	211	224	213	209	221	215	239	201	17.7	172	215	186	185	197	20	204	197	20	228	23
2003	4	Min Temp (°C)	78	134	51	51	49	53	105	87	09	47	143	151	161	114	103	12	21	32	41	5	63	69	64	121	67	128	149	85	107	106	
2003	4	Max Temp (°C)	234	216	164	168	162	171	188	177	158	177	173	197	189	177	146	156	16	156	175	182	197	181	215	179	168	178	189	189	185	16	
2003	5	Min Temp (°C)	12	67	116	-03	19	07	26	51	58	07	-13	17	74	116	143	125	111	153	139	88	106	95	54	58	84	47	42	2	49	83	33
2003	5	Max Temp (°C)	142	173	148	152	166	197	195	176	162	132	14	15	153	171	174	188	166	165	171	167	171	159	132	131	142	163	172	159	169	162	169
2003	6	Min Temp (°C)	92	68	8	78	98	76	45	28	24	3	5	73	45	24	5	92	71	5.5	4	-16	16	39	24	08	-02	05	43	81	44	32	
2003	6	Max Temp (°C)	154	171	15	168	14	101	135	149	157	143	146	156	12	97	138	13	172	149	124	125	139	133	124	125	14	149	136	15	148	114	
2003	7	Min Temp (°C)	-3	-18	-17	-1	22	7	57	44	11	11	74	78	15	13	82	-09	24	18	-05	33	74	96	76	75	29	12	15	101	35	09	04
2003	7	Max Temp (°C)	109	115	105	126	142	166	145	136	141	134	145	115	13.9	136	99	125	139	139	121	11	132	139	132	99	121	116	127	131	105	119	147
2003	8	Min Temp (°C)	12	48	105	84	91	63	83	83	32	-06	4.6	92	111	44	05	09	45	05	-24	-0.8	05	85	74	105	85	-01	-1	39	86	87	16
2003	8	Max Temp (°C)	137	139	149	151	146	129	147	118	11	144	123	134	154	103	123	125	121	112	13	117	128	143	134	111	122	122	134	15	144	115	108
2003	9	Min Temp (°C)	-19	52	66	05	54	2	58	-16	48	72	35	15	15	28	25	62	74	41	61	07	36	07	29	63	84	42	26	-1	27	0	
2003	9	Max Temp (°C)	131	14	13	14	135	147	135	116	113	102	143	138	136	92	141	135	138	127	137	14	159	13	145	143	128	131	119	12	123	157	
2003	10	Min Temp (°C)	02	55	35	36	68	32	54	54	-14	22	22	33	31	47	87	69	68	37	117	56	84	16	29	39	85	55	65	17	37	54	34
2003	10	Max Temp (°C)	117	141	131	131	134	176	172	129	107	138	157	169	143	144	159	186	19	157	141	14.5	164	142	118	139	176	155	161	142	15	151	145
2003	11	Min Temp (°C)	59	52	65	69	38	66	26	54	35	59	106	86	38	32	88	95	111	111	134	13.6	115	83	11	112	88	12	89	59	78	9	
2003	11	Max Temp (°C)	145	152	154	176	182	18	153	155	221	235	20	182	147	269	271	196	152	171	184	22.7	157	177	16	157	174	184	193	183	204	205	
2003	12	Min Temp (°C)	106	129	127	85	68	9	68	137	15	153	138	76	66	53	62	141	112	163	122	10.1	154	131	94	73	13	8	65	72	98	103	78
2003	12	Max Temp (°C)	212	162	196	22	188	18	193	194	191	198	20	191	181	223	192	218	233	188	229	19.3	177	206	216	216	22	198	196	223	207	284	235
2004	1	Min Temp (°C)	85	73	131	76	37	65	132	6	106	136	87	74	63	57	91	59	83	34	17	135	43	86	48	86	133	113	99	126	144	126	102
2004	1	Max Temp (°C)	227	228	253	225	204	191	179	16	197	197	194	227	192	189	234	216	187	189	188	254	194	197	217	23	202	195	209	193	177	233	223