Review

The Biology of Australian Weeds
24. *Raphanus raphanistrum* L.

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Name

Raphanus was derived from the Greek *ra* (quickly) and *phanomai* (to appear), referring to rapid germination and growth of seedlings. The genus *Raphanus* contains eight species which are native to western and central Europe, through the Mediterranean to central Asia. In Australia, three species have been recorded: *R. raphanistrum*, *R. maritimus* and *R. sativus* (Anon. 1982). *R. raphanistrum* is sometimes treated as an aggregate which includes *R. maritimus* and other taxa as subspecies (Rich 1991).

R. raphanistrum is a member of the Brassicaceae, a family of world-wide distribution comprising about 3500 species, nearly all of them herbaceous and mainly annuals (Rich 1991). Included in the family are important economic plants as well as numerous common weeds. The plants of this family can be readily recognized by the four sepals, four petals and, typically, six stamens of their flowers. The fruit varies considerably in structure, but there is little departure from the typical form of the flower.

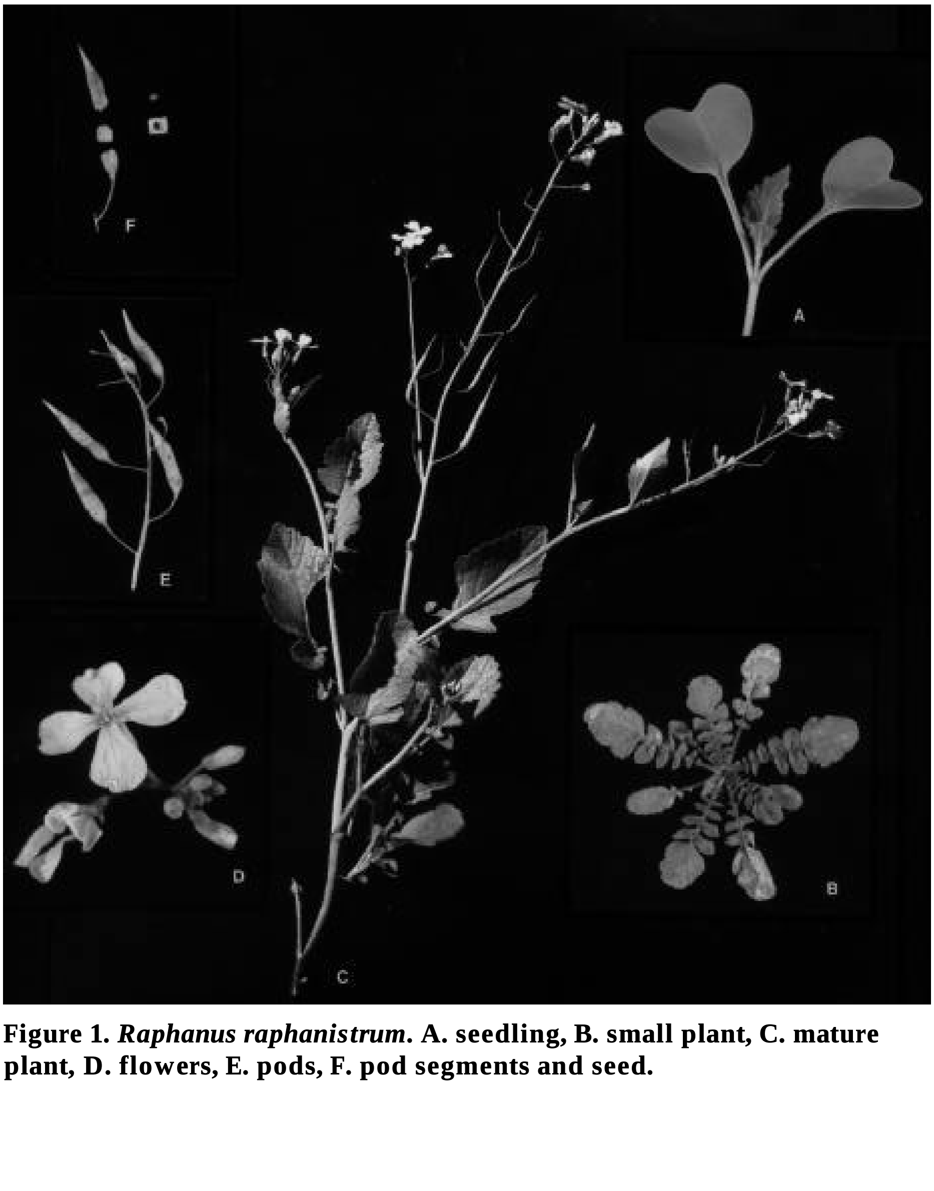

Figure 1. *Raphanus raphanistrum*. A. seedling, B. small plant, C. mature plant, D. flowers, E. pods, F. pod segments and seed.

The common name in Australia is wild radish but it is also sometimes called white weed. Alternative names are jointed charlock (USA), runch (UK), ramnas (South Africa), white charlock, wild charlock, wild kale, wild turnip, jointed radish and cadlock.

Description and account of variation

Description

The following description of wild radish (Figure 1) was compiled from Hyde-Wyatt and Morris (1975), Auld and Medd (1987), Rich (1991), Cunningham *et al.* (1992), and Parsons and Cuthbertson (1992).

An erect annual herb, sometimes behaving as a biennial in cooler regions. Plants may reach up to 1 m high, reproducing only by seed. The basal leaves have a strong turnip-like odour when crushed.

At the seedling stage, the cotyledon leaves are 8–15 × 10–20 mm with a petiole 10–25 mm long, and are hairless. There is a short hypocotyl; an epicotyl may be present or absent.

The first leaf normally has a few distinct lobes at the base, though these may be absent. The young plant develops as a flat rosette. As the plant matures, it usually branches from near the base, with erect branches covered with prickly hairs. Lower stem leaves are also covered with prickly hairs, deeply lobed with a rounded terminal lobe, as wide as the rest of the leaf. Upper stem leaves become narrower, shorter and often undivided.

The flowers are arranged in racemes on the ends of stem branches (Figure 1). Flowers are regular with four petals alternating with four sepals. The petals are 12–20 mm long, and the sepals 5–10 mm. Petals range in colour from white to purple to pink or pale yellow, often with light or dark distinct veins.

Fruit and seed set is often variable due to self-incompatibility and unpredictable pollination. The fruit is a pod, constricted between seeds, and with a slender, seedless beak (Figure 2). When mature, the yellowish brown pod breaks into distinct segments, each containing one seed. The pod segments are 3–7 mm long by 2–5 mm wide. The seeds are 2–3 mm in diameter, ovoid to almost globular, yellowish to reddish brown, net-veined on the surface.

The chromosome number is $2n=18$.

Distinguishing characters

In Australia, the plant may sometimes be confused with charlock (*Sinapis arvensis*), wild turnip (*Brassica tournefortii*), and garden radish (*Raphanus sativus*).

The yellow form of wild radish, in the absence of fruit, is sometimes confused with charlock. However, wild radish has sepals pressed against the back of the petal, while in charlock the sepals are widely spreading. The petals of wild radish are longer and narrower, do not overlap or touch and are of a paler yellow. In the seedling stage it is extremely difficult to separate the two species, except that the leaves of wild radish are rough while those of charlock tend to be smoother and rather shiny, with less deeply impressed veins.

Wild radish can be distinguished from wild turnip in the seedling stage. The leaves of wild turnip carry 'warts' on the upper surface and are broader in relation to their length. As the plants mature, the flat basal rosette of leaves remains until late in the growing season in wild turnip, but not in wild radish. Wild turnip has very few stem leaves. The flowers of wild turnip are similar to charlock rather than wild radish in colour, shape and size. The seed pods of wild turnip split lengthwise when ripe to release the seeds.

Wild radish is similar to garden radish in its above-ground parts, but garden radish flowers are purplish, pink or white, never yellow, and the seed pods are spongy, lack distinct joints, and split in various ways at maturity but not into segments containing single seeds.

The distinctive, constricted seed pods of wild radish split into segments, but never lengthwise. The variation in fresh fruits of the three *Raphanus* species in Australia is shown in Figure 2.

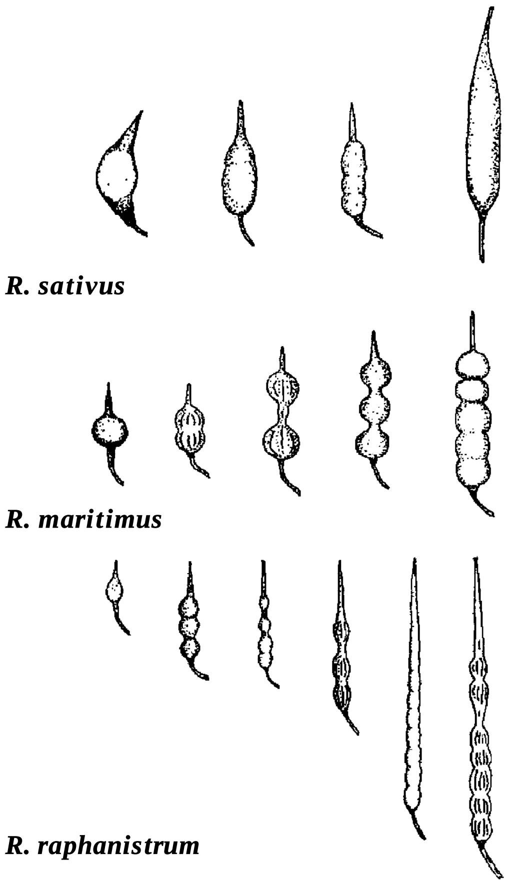

Figure 2. Variation in fresh fruit of *Raphanus* species. (Modified from Rich 1991).

Intraspecific variation

Plants often display a petal colour polymorphism. In Australia, various colours including yellow, white, cream, pink, purple, and yellowish brown have been recorded. Those with yellow or white petals are the most common; pink petals are rare. Purple-flowered plants are very common in the northern wheatbelt of Western Australia. In Britain, the yellow flowered plants are widely distributed. White flowers are most common in the south and east, but are rare in the far north and west (Perring 1968). Purple flowered plants occur mainly in England. However, all types can occur within a population.

History

Wild radish was probably introduced accidentally into Australia in about the middle of the 19th century, and spread as a contaminant in agricultural produce (Donaldson 1986). It was reported as naturalized around Melbourne, Victoria as early as 1860 and around Sydney, New South Wales, by 1867. It was found around Adelaide, South Australia by 1875 and in parts of Queensland by 1913 (Parsons and Cuthbertson 1992). Its occurrence and distribution in Western Australia closely followed agricultural development. It occurs in most parts of Tasmania, but is not yet reported in the Northern Territory. Its introduction to Australia as a contaminant in agricultural produce has been documented several times. Stapledon (1916) lists wild radish as an impurity in oats from Russia, Germany, Argentina, Chile, Canada and Great Britain; Broad (1952) lists it as an impurity in wheat, barley, oats and rye. Breakwell (1918) mentions it as an impurity in canary seed from Morocco. By 1908, it had spread far and wide with imported lucerne seed in Victoria (Audas and Morris 1925). On 10 July, 1909 wild radish was proclaimed under the Quarantine Act in the Commonwealth of Australia Gazette (Maiden 1920). The Act was passed to prevent the entry of undesirable plants into the Commonwealth even though some plants already had a firm hold in the country. In such cases the object was to restrict the importation of known weeds into clean areas.

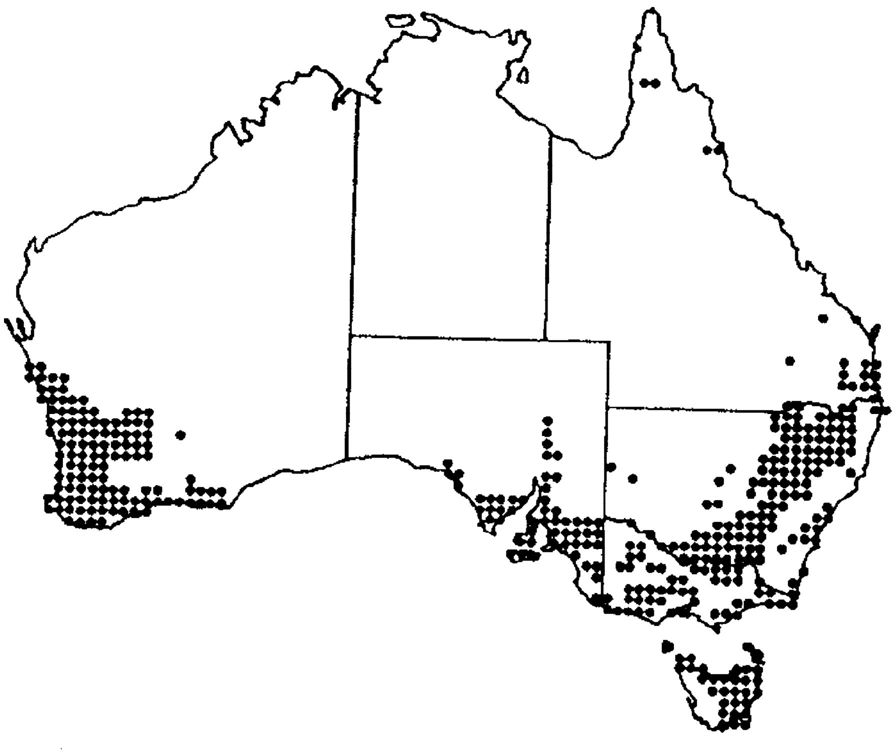

Figure 3. Distribution of wild radish in Australia (Parsons and Cuthbertson 1992).

Figure 4. Wild radish in wheat. The large reserve of wild radish seeds within the soil allowed many seeds to germinate with the crop.

Geographical distribution

Australia

Wild radish occurs in all States but is not found in the Northern Territory. It is distributed in a broad band from south-eastern Queensland, through New South Wales, Victoria, Tasmania and South Australia (Figure 3). Its distribution is interrupted by the Nullarbor Plain, but it is widespread in the cereal cropping areas of Western Australia. It is one of the most troublesome weeds in lupin crops in the northern wheatbelt of Western Australia. In New South Wales the heaviest infestations occur in the higher rainfall areas of the southern wheatbelt and it is increasing in importance along the western slopes of the Great Dividing Range in New South Wales, and throughout Victoria. In Victoria it is regarded as a significant weed of crops in the north east, parts of the Western District and in the cropping areas of east Gippsland (Donaldson 1986). The higher rainfall, high fertility regions of south-eastern South Australia and Kangaroo Island are also under threat (Parsons and Cuthbertson 1992).

Outside Australia

The native home of wild radish may be in the Mediterranean region (Frankton 1955), but it is now distributed nearly all over the world. It was introduced to the British Isles during the Roman occupation (Parsons and Cuthbertson 1992). It is now a common weed of cultivation throughout Europe, except the arctic regions. It is a widespread weed in North Africa and Asia Minor, but is rare in Siberia and the Far East. From Europe it has been introduced into South Africa, Japan, Australia, New Zealand, North and South America.

Habitat

Wild radish is a common weed of cultivation, particularly in winter crops, along roadsides, in wastelands and in other disturbed habitats. It occurs in moderately exposed and cool to warm sites up to subalpine level (Anon. 1971). It grows best in fertile nitrogenous soils (Hanf 1983). In the British Isles, it is most abundant on clay or sandy soils, avoiding most calcareous habitats (Streeter 1983). It is one of the most widespread and troublesome weeds of cereal and grain legume crops over a range of soil types in southern Australia. It is less common in pastures and undisturbed areas because of competition from other species, grazing by stock and the absence of soil disturbance which is required to stimulate seed germination (Cheam 1986, Cheam and Martin 1993).

In Australia, where wild radish occurs in field crops, it is frequently the dominant species in patches or large portions of paddocks, largely to the exclusion of other species (Figure 4). This is probably due to its strong competitive ability and allelopathic effects. It occurs at lower densities in communities that include other common weeds of field crops, such as annual ryegrass (*Lolium rigidum*), wild oats (*Avena* spp.), capeweed (*Arctotheca calendula*), wireweed (*Polygonum aviculare*) and spiny emex (*Emex australis*).

Growth and development

Morphology

Mature plants produce a large number of branches which push outwards soon after the emergence of the inflorescence from the rosette. This results in intense competition for light, often at the expense of the crop plant which finds itself as the understorey. Modern crop cultivars, being shorter, can be rapidly dominated by wild radish. For example, wild radish did not appear to be as competitive with early cultivars of lupins such as Uniharvest and Uniwhite which were relatively tall. Its long tap root enables it to withstand moisture stress and also provides adequate reserves for regrowth in the event of leaf loss through slashing, grazing or the activity of some herbicides.

Phenology

Most seeds germinate in autumn and winter, but seedlings can emerge at any time providing soil moisture is sufficient (e.g. after summer thunderstorms). After emergence, phenological development is dependent upon both temperature and day length (Figure 5). Plants that emerge in autumn through to early winter usually die in early summer and produce many seeds. Plants that emerge in spring are usually short lived, but always produce some seeds. As shown by Reeves

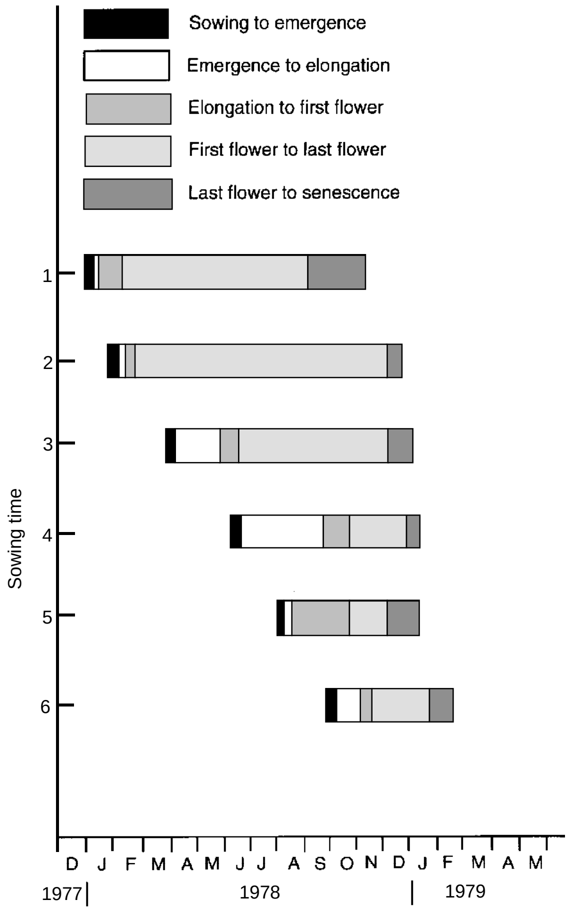

Figure 5. Phenology of wild radish sown at various intervals at Rutherglen 1977–1979. (Modified from Reeves *et al.* 1981).

Table 1. Days from sowing to flowering and seed production by wild radish plants sown at 3-weekly intervals at South Perth, Western Australia in 1982 (Cheam 1986).

Sowing date	Days from sowing to flowering	Seeds/plant
11 May	90.0	789
1 June	76.0	224
22 June	71.5	189
13 July	65.5	120
3 August	59.5	45.2
24 August	56.0	30.4
14 September	48.7	6.8

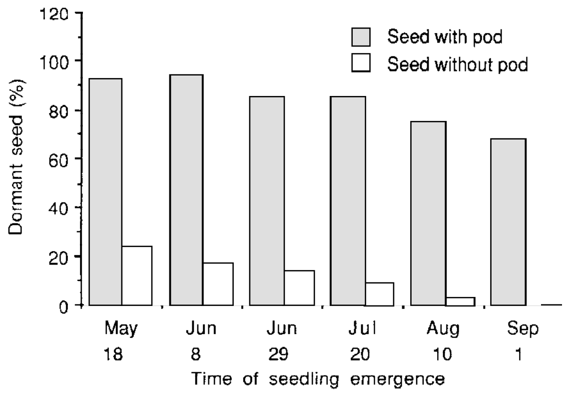

Figure 6. Percentages of dormant seeds produced by wild radish plants emerging at different times during the growing season (Cheam1986).

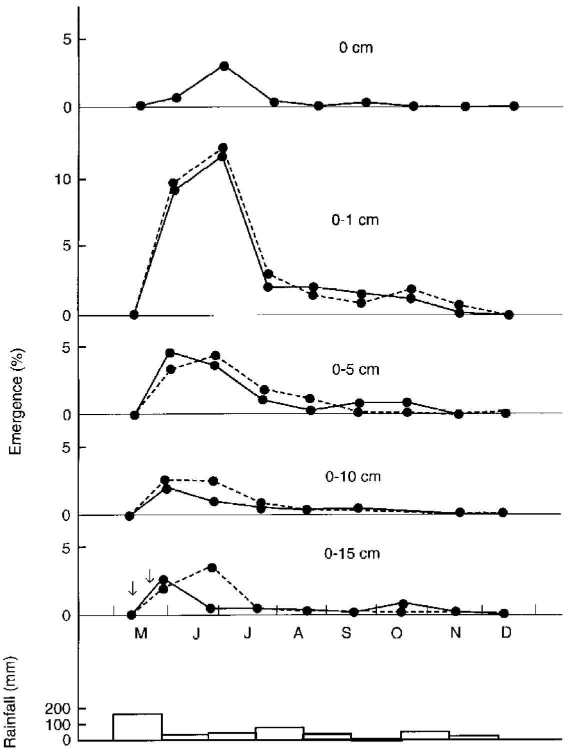

Figure 7. Emergence of wild radish seedlings from seeds lying undisturbed on the soil surface and from seeds mixed with different depths of cultivated soil at Chapman (— one cultivation, --- two cultivations, ↓ time of cultivation) (Cheam 1986).

et al. (1981), spring-germinated plants flower for a short period only and die during summer, (their life cycle being completed in about five months). Summer and early autumn germinated plants may take 10 months to complete their life cycles if soil moisture is adequate. Winter germinated plants complete their life cycle in 5–7 months (Figure 5). Temperature is the major factor controlling development up to flowering, while day length, as well as temperature, influence the duration of flowering. Its flexible flowering patterns, requiring less than 600 degree-days to flower, indicate that wild radish has the capacity to grow and set seeds in most areas of southern Australia (Reeves *et al.* 1981). In arable land, however, most of the wild radish seedlings are killed during seed bed preparation at the start of the growing season, which usually occurs in May.

Mycorrhiza

Most members of the Brassicaceae are not generally colonized by vesicular-arbus-cular or arbuscular mycorrhizal fungi (Tommerup 1992). This may be due to their production of isothiocyanates which are derived from glucosinolates found in cruciferous plants (Dick 1994). Wild radish is a poor mycorrhizal host and contributes nothing or little to new mycorrhizal propagules (I.C. Tommerup personal communication).

Reproduction

Floral biology

In Australia, the bulk of wild radish seeds germinate after autumn rains, and the first flowers usually appear in late July. Sequential sowings of wild radish between May and September at South Perth, Western Australia showed that plants that emerged in May grew larger than those that emerged later, produced more seeds and took longer to flower (Cheam 1986) (Table 1). There was a distinct trend, with shorter duration to flowering with later emergence. A significant linear relationship between date of emergence and time to flowering was recorded. Similar results were obtained in a later study which included wild radish and nine other cruciferous weeds (Cousens *et al.* 1993). The shorter duration between germination and flowering with later emergence means that the time available to apply control measures before the formation of viable seeds is reduced.

Wild radish is self-incompatible (Sampson 1964) and the flowers are visited by a wide range of insects, including bumble bees, honey bees, solitary bees, syrphid flies, and butterflies (Stanton 1984b). Kay (1976) found that *Pieris* spp., especially *P. rapae* (Lepidoptera, Pieridae) and *Eristalis* spp. (Diptera, Syrphidae) showed a strong or very strong preference for the yellow-flowered morph of wild radish in Britain. She suggested that pollinator discrimination of this type may have a role in determining the balance of the flower-colour morphs in wild radish, which shows both geographical clinal variation and local mosaic differentiation in flower-colour morph frequency. The white morph predominates in polymorphic populations in southern and eastern England, but the yellow morph predominates or forms monomorphic populations in western and northern Britain.

Seed production and dispersal

Wild radish is a prolific seeder. Reeves *et al.* (1981) showed that seed production ranged from 292 seeds m^{-2} from 1 plant m^{-2} to 17 275 seeds m^{-2} from 52 plants m^{-2} in a wheat crop. As the density of wild radish increased, seed production per plant decreased. Seed production also varied considerably between seasons. Ten plants m^{-2} produced approximately 1000 seeds m^{-2} in 1977 and 6000 seeds m^{-2} in 1978. Fifty plants m^{-2} produced approximately 3000 seeds m^{-2} in 1977 and 17 000 m^{-2} in 1978. Up to 45 000 seeds m^{-2} were produced in some plots (Reeves *et al.* 1981).

The effect of interspecific competition on seed production per plant was demonstrated by Code and Walsh (1987), who found that seed production per plant in simazine-treated lupins ranged from 39.9–190 compared with 4.5–21.8 in unsprayed lupins. The control of other weeds in the sprayed crops resulted in lower interspecific competition, thus allowing wild radish survivors to produce more seeds. Panetta *et al.* (1988) found that in simazine-treated lupins, low numbers of surviving plants from the first cohort of emergence produced up to 237 seeds per plant. In contrast, 73 seeds per plant were recorded in the first cohort of seedlings in lupins not treated with herbicide.

Panetta *et al.* (1988) also showed that probabilities of reproduction of wild

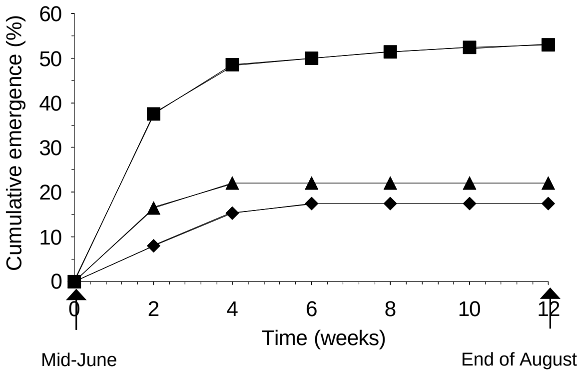

Figure 8. Cumulative emergence of seedlings of different forms of wild radish (◆ white, ▲ purple, ■ yellow) from seeds sown in the field at South Perth (Cheam 1984).

radish seedlings decreased markedly with later dates of emergence within lupin crops. Plants which emerged later than 21 days after crop emergence failed to reproduce altogether. When in monoculture however, wild radish plants emerging at any time of the year can go on to flower and set viable seed. Early emerging plants produced more seeds (Table 1) and also more dormant seeds than the later emerging ones (Cheam 1986) (Figure 6).

The fruits contain from 1–10 seeds of varying size, ranging from 1.5–12 mg in mass (Stanton 1984a). The numbers of seeds within a fruit is limited by pollen in some years (Stanton 1984b). Stanton (1984a) showed that seed weight has a marked impact on emergence and post-emergence productivity. Plants from large seeds grew more rapidly and had greater reproductive output than those from smaller seeds.

Spread of wild radish is entirely due to movement of seeds, brought about by humans, other animals, wind and water. They may be soil-borne on footwear, hooves, machinery and vehicles. However, its occurrence as a contaminant of agricultural produce, is the main source of spread.

Physiology of seeds and germination

Dormancy and longevity are the two important characteristics of wild radish seed that enable the species to survive and persist as a common weed of agriculture (Mekenian and Willemsen 1975, Piggin *et al.* 1978, Reeves *et al.* 1981, Roberts and Boddrell 1983, Cheam 1984, Amor 1985, Cheam 1986).

The initial flush of germination following cultivation at the start of the season is the most prominent (Figure 7). The remaining dormant seeds allow germination to occur sporadically, after rain, at any time over a period of years. Dormancy is largely due to the pod surrounding the seed and although the exact mechanism is not known, Mekenian and Willemsen (1975) have suggested that the presence of a non-leachable chemical inhibitor in the pod, which is gradually broken down during after-ripening, is responsible. Mechanical restriction by the pod was also suggested as a possible mechanism.

One complication in wild radish seed dormancy is that the three major flower colour forms produce seeds of different levels of dormancy: seeds of white- and purple-flowered forms are significantly more dormant than those of the yellow form (Cheam 1984) (Figure 8). This is likely to be a genetically based variation because consistent results were obtained from plants grown and tested under identical conditions. This means that the white- and purple-flowered wild radish have a greater likelihood of avoiding chemical sprays because they have greater ability to germinate after early herbicide applications. This has been observed in the field.

Dormancy may also vary with the geographical location in which the seeds were produced. Seeds from the warmer northern agricultural districts of Western Australia were found to have a lower dormancy level than seeds from the cooler southern districts (Cheam 1986). This differential dormancy was shown to be under genetic control.

Time of emergence also influences the dormancy factor because early emerging plants produce more seeds with greater innate dormancy (Figure 6). It is particularly important to control these plants so as to minimize the production of large quantities of highly dormant seed.

The dormancy of freshly-shed seeds is lost to some extent over the summer months, but induction of dormancy occurs at the start of the growing season, probably caused by a drop in temperature (Cheam 1986). Evidence is accumulating that some weed seeds in the field pass through similar cycles of decreasing and increasing dormancy. As high as 70% of wild radish seeds are in a state of dormancy at the start of the season. The proportion of germinable seeds could be increased through shallow burial (1–2 cm depth) of the freshly dispersed seeds in early summer (Cheam 1986). Wild radish germinates well over a wide range of alternating and constant temperatures, germinating best under wide diurnally fluctuating temperatures (Piggin *et al.* 1978). This explains why wild radish germinates well in the field after rainfalls in autumn, when temperatures fluctuate widely. This peak autumn germination continues through to approximately mid-winter. After that, smaller flushes of germination occur through to late winter / early spring, and during late spring and summer, in response to rainfall events (Piggin *et al.* 1978, Reeves *et al.* 1981, Cheam 1986, Code, Walsh and Reeves 1987, Panetta *et al.* 1988). Generally, it takes only 4–5 days from imbibition to emergence. The minimum temperature for germination is below 5°C, the maximum above 35°C, and the optimum 20°C. The optimum diurnal fluctuation is 25 / 10°C (Lauer 1953, Cheam unpublished).

Cultivations promote germination and emergence of seedlings. This is because germination is stimulated by darkness and the availability of soil moisture surrounding the seed. Shallow burial of the seed, up to 1 cm depth results in greatest emergence (Table 2), consequently resulting in a more rapid loss of viable seed (Table 3). Since deep burial extends seed viability, subsequent cultivation would need to be shallow to avoid bringing seed back to the surface, where it can germinate. Under long-term pasture, the rate of

Table 2. Emergence of wild radish from various depths (% of total seed planted in May 1977). (Modified from Code, Walsh and Reeves 1987).

Depth of burial	Percentage emergence						Total
(cm)	1977	1978	1979	1980	1981	1982	1977–1982
0	32.53	4.03	1.30	0.60	0.10	0.13	38.69
1	72.47	0.53	1.08	0.30	0.00	0.10	74.38
5	15.47	0.10	1.30	0.02	0.10	0.02	17.01
10	0.58	0.00	0.02	0.00	0.00	0.00	0.60

Table 3. Percentages of wild radish seed remaining viable after burial at various depths (Code, Walsh and Reeves 1987).

Depth of burial	Duration of burial (years)					
(cm)	0.5	1	2	3	4	6
0	43	19	5	4	5[A]	0
1	10	12	16[A]	5	3	1
5	55	47	52[A]	27	21	7
10	75	57	53	44	43	0

[A] Apparent increases in viability with time due to variation between samples.

loss of viability has been determined as more than 30% per year, with an average half-life of two years (Chancellor 1986).

Vegetative reproduction
Wild radish does not reproduce vegetatively.

Hybrids

Populations intermediate between *R. raphanistrum* and *R. maritimus*, of hybrid origin, occur frequently on the coasts of north-west Europe (Tutin *et al.* 1993). The hybrid populations are 50–60% pollen- and seed-sterile (Harberd and Kay 1975).

Where *R. raphanistrum* has occurred as a weed near *R. sativus*, hybrids have been observed which are partially fertile, usually with white and variously intermediate flower colours and with partly dehiscent fruits and thin roots (Stace 1991). No hybrids have been recorded in Australia.

Population dynamics

Wild radish, being a weed of disturbed habitats, has several inherent biological characteristics that have contributed to its success as a weed over a wide range of conditions. Flexibility in the plant's life cycle, lack of stringent requirements for germination, high levels of seed production and seed dormancy contribute to this success. The influences of these characteristics with respect to population changes have been dealt with under previous sections. In this section we will focus on the effects of crop management practices on wild radish population dynamics.

In studies by Amor (1985) on weed seedling emergence patterns in the Victorian Wimmera region, 6% of the total seasonal emergence of wild radish occurred in early autumn, 73% in late autumn/early winter, and 21% in late winter/early spring. Patterns of seasonal emergence were similar in studies in north-east Victoria (Piggin *et al.* 1978, Reeves *et al.* 1981) and in the Western Australian wheatbelt (Panetta *et al.* 1988).

Seedling density in the largest cohorts in late autumn and winter has been measured at 300–800 m^{-2} in cultivated situations in the field, with later cohorts reducing to 1–10 m^{-2} or less (Reeves *et al.* 1981, Panetta *et al.* 1988).

Of the first two seedling cohorts to emerge in lupin crops, Panetta *et al.* (1988) found that approximately 30–40% died during the season. Some of the remaining plants produced seeds, but no plants in third and subsequent cohorts produced seeds, either in a simazine-treated or untreated crop.

In experiments from 1981–1985 near Rutherglen (north-east Victoria), seed production and population changes were examined in continuous wheat and wheat/lupin rotations, treated with herbicides for wild radish control, or unsprayed. In unsprayed continuous wheat, a wild radish population increased from 383 plants m^{-2} in 1981 to 1408 m^{-2} in 1985. Seed production was 4280, 1440, 1540 and 8700 seeds m^{-2} for the years 1981–1984, respectively.

In an unsprayed lupin-wheat-wheat-lupin-wheat rotation the population increased from 479–1851 m^{-2} over the same period. Wild radish seed production was generally higher each year in the wheat/lupin rotation than in the continuous wheat, with 4920, 2343, 2100 and 16 550 seeds m^{-2} for 1981–1984, respectively.

In continuous wheat sprayed at early tillering stage with bromoxynil plus MCPA ester, and between the end of tillering and the boot stage with 2,4-D amine, wild radish seed production was virtually eliminated, with 0, 1, 0 and 0 seeds m^{-2} for 1981–1984, respectively. The wild radish plant populations in each wheat crop, before spraying were 383, 379, 88, 163 and 99 m^{-2} for 1981–1985, respectively. In contrast, much more seed was produced in the lupin-wheat-wheat-lupin-wheat rotation, with wheat crops sprayed twice per year (as in continuous wheat), and lupins sprayed with simazine. Seed production was 7405, 0, 0 and 11 600 seeds m^{-2} for 1981–1984, respectively. Wild radish plant populations in lupins after spraying with simazine in 1981 and 1984 were 212 and 61 plants m^{-2} respectively, and in wheat before spraying in 1982, 1983 and 1985 were 830, 179, and 1335 plants m^{-2} respectively (Code and Walsh 1987, Code, Reeves and Gales 1987).

These results show the persistence of wild radish populations, even under an intensive herbicide program. In the fifth year of the experiment described above, after four years of continuous wheat, sprayed twice per year, 99 wild radish plants m^{-2} occurred. Obviously, control programs over a longer period are required to reduce wild radish to very low levels. The results also show the difficulty of maintaining wheat/lupin rotations on wild radish infested paddocks where simazine is the only herbicide used in the lupins. However, the use of diflufenican in conjunction with simazine, significantly improves wild radish control in lupins (Walsh and Code 1987).

Importance

Detrimental
Wild radish is very competitive, especially in cereal and other winter crops. Its competition with wheat has been well researched (Code *et al.* 1978). At Rutherglen, Victoria, nearly 50% yield loss with a wild radish density of 200 plants m^{-2} has been documented (Figure 9). Even with a wild radish density of only 7 plants m^{-2}, a 10% yield loss has been reported (Code and Reeves 1981). In a similar study in Western Australia, Moore (1979) reported that 25 plants m^{-2} of wild radish emerging with the wheat crop resulted in 7–11 % yield reduction; 50 plants 15–20% reduction, 75 plants 19–26% reduction and 100 plants m^{-2} 25–33% reduction. In the central west of New South Wales, a dense infestation of 160 plants m^{-2} reduced wheat yields by 70–80% (Dellow and Milne 1987). Yield reductions of this magnitude rank wild radish as one of the most damaging weeds of cereal crops (Poole and Gill 1987).

Competition of wild radish with wheat mainly occurs during the early growth stages of the crop, as significant yield increases have resulted when wild radish was controlled by herbicide application during the two- to five-leaf stage of the crop (Dellow and Milne 1987). When control is delayed until the post-tillering stage, yield increases have rarely been obtained (Table 4). Our experience has shown that yield response is often five times higher for wild radish killed at 2.5–3 leaf crop stage, than for control after tillering.

Lupins and canola have also suffered yield losses due to wild radish competition. However, more data on yield reduction in relation to wild radish density for both crops are required. The claim that wild radish competition in canola may lower the oil recovery percentage has not been substantiated.

Table 4. Effect of early and late spraying of wild radish on wheat yields (Dellow and Milne 1987).

Treatment	Wheat yield (t ha^{-1})
Unsprayed	0.14
Sprayed early (3-leaf)	1.66
Sprayed late (tillered)	0.36

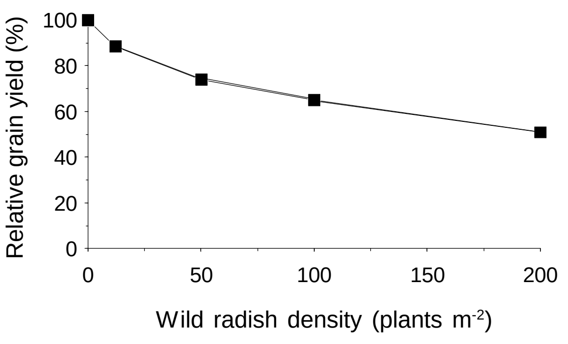

Figure 9. The relationship between the density of wild radish and the relative grain yield of wheat (expressed as a percentage of the weed-free yield). Modified from Code *et al.* 1978).

In addition to yield reductions, wild radish seed and pod material are often contaminants of harvested grains. Wild radish pods shatter during harvest into segments of similar size to wheat grains. Consequently, the seed is difficult to separate from wheat and other winter cereal grains and tends to be spread rapidly. Apart from cereals, the contamination of lupin grains with wild radish and other foreign matter is common. In Western Australia during the 1993 season, grain handling authorities imposed dockages ranging from $A8 per tonne for lupin grain with 2–4% foreign matter to $A15 per tonne with over 4–6% contamination. Grains with more than 6% wild radish contamination were rejected (C. Scally personal communication).

Research in Western Australia has shown that the contamination problem can cause death of lupin and cereal grains when stored with green radish pod segments (Cheam 1985). The wild radish contaminant gives off toxic volatile compounds when stored with the crop seeds at warm to high temperatures, causing the seeds to lose viability or to produce abnormal seedlings.

The presence of the fibrous stems in wild radish can make harvesting difficult because of repeated choking of the comb. Many crops have been left unharvested due to the smothering effect of wild radish and the difficulty of harvesting heavily infested crops. This usually occurs in years with late rains when wild radish continues to grow and remains green after crop maturity (Meadly 1965). At the same time, the moisture squeezed from the wild radish stems during harvest, often raises grain moisture content above acceptable storage levels (Parsons and Cuthbertson 1992). Moisture from wild radish seed as a contaminant of grain can cause the same problem.

Although not readily eaten by livestock, wild radish has proved toxic when animals are confined to areas where it is abundant. Trouche (1936) recorded a mortality amongst lambs grazing the flowering plant, which also caused jaundice, haemoglobinuria and evidence of liver damage in the lambs. Gardner and Bennetts (1956) recorded a similar occurrence of poisoning in cattle that had been crowded on to wild radish to eat down an unusually luxuriant growth of the weed. The affected animals initially lost appetite and most of them showed lassitude, stupor and paralysis; some were excitable. The dung was coated with mucus and as the disease progressed there was watery blood-stained diarrhoea. Abortion was noted in some cows. The seeds of wild radish are regarded as the most dangerous part of the plant (Connor 1977). The poisonous principle is allyl isothiocyanate, derived from the glucosinolate, sinigrin (Cooper and Johnson 1984). Apart from poisoning, wild radish has caused a taint in milk if grazed by dairy cows (McBarron 1977).

Wild radish also acts as an alternate host to a number of plant pests and diseases such as thrips (*Thrips* spp.), flea beetles (*Phyllotreta* spp.), and club root of brassicas (*Plasmodiophora brassicae*). In California, tobacco streak virus (TSV) was isolated from wild radish collected from three tomato fields near Sacramento. All the TSV isolates were infectious to Peto 81 tomato and the virus was seedborne (Cupertino *et al.* 1984). Wild radish also acts as an alternate host to cucumber mosaic virus (CMV) (Dikova 1989).

Beneficial

Although some farmers recognize wild radish as having some forage value, the possibility of stock poisoning outweighs this benefit.

Occasionally the presence of wild radish in a crop may be advantageous. Work in Britain showed that the cabbage aphid, *Brevicoryne brassicae*, is considerably more active in clean crops of brussels sprouts than in weedy ones. Wild radish attracts natural enemies of the aphid which oviposit on the weeds and become more prevalent in weedy crops, helping to keep aphid numbers down (Parsons and Cuthbertson 1992).

Legislation

Wild radish is currently declared as a noxious weed in certain Shires and Municipalities of New South Wales. It is declared as a Class 7 noxious weed in South Australia. Class 7 weeds are agricultural weeds, the control of which is required in a very limited area of the State.

Table 5. Herbicides for early wild radish control in cereals.[A]

Herbicides	Rates (a.i ha^{-1})
Bromoxynil	400 g
Bromoxynil + diflufenican	125–250 g + 12.5–25.0 g
Bromoxynil + MCPA ester	200–400 g + 200–400 g
Bromoxynil + MCPA ester + dicamba	105–200 g + 210–390 g + 30–56 g
Chlorsulfuron	11.25–15.0 g
Dicamba + MCPA amine	80–136 g + 340–578 g
Diflufenican + MCPA ester	12.5–25.0 g + 125–250 g
Diuron + MCPA amine	175–250 g + 175–250 g
Flumetsulam	20 g
MCPA amine	350–1000 g
MCPA ester	550–800 g
MCPA sodium salt	225–550 g
Mecoprop	2500 g
Mecoprop + dicamba	1200 g + 80 g
Metosulam	3.5–5.0 g
Picloram + 2,4-D (triisopropanolamine salts)	23.5 g + 94 g
Picloram + MCPA (potassium salts)	26 g + 420 g
Terbutryn + triasulfuron	222–300 g + 7.4–10.0 g
Thifensulfuron-methyl + metsulfuron-methyl	30 g + 3 g
Triasulfuron	21.4–25.0 g

[A] Sources: Parsons 1992, Dodd *et al.* 1993 and Chemical Registration Information Service, Victorian Department of Agriculture.

Response to herbicides

Herbicides that are registered by the National Agricultural Chemical Registration Authority in Australia for control of wild radish in specific crops are discussed in this section. The effects of some non-registered herbicides are also presented from Australian and overseas references.

Herbicides are available that provide control of wild radish in most situations. However, in some cases control is restricted due to sensitivity of the crop to the available herbicides (e.g. most cultivars of canola). Another problem is its staggered germination. Sequential applications of herbicides within a season, or use of herbicides that provide residual control, can help overcome this problem (Code *et al.* 1978, Code and Reeves 1981, Walsh and Code 1987, Gilbey 1990). Nevertheless, it is difficult to decide on the timing of control in crops to obtain maximum yield responses and minimum contamination of the harvested grain.

Cereals

The herbicides used for early wild radish control in cereals in Australia are listed in Table 5.

Triasulfuron is applied before sowing. All other treatments are applied early post-emergence. Some of the phenoxy herbicides, and mixtures containing them, are recommended for application at the five leaf to early tillering stage of cereals to avoid crop damage. Others can be applied earlier.

All the combinations, except diuron plus MCPA, are available as commercial mixtures.

Choice between these products depends on the variety of cereal being grown, other weeds present, preference for pre- or post-emergence timing and other factors.

In experiments in North America, Schroeder (1989) found 20 g a.i. ha^{-1} of thiameturon provided effective wild radish control in wheat.

Where wild radish occurs at densities of 5–10 m^{-2} or more, early spraying is justified to avoid reduced yields. Where lower densities occur, application of phenoxy herbicides later in the growth of crops may be justified to reduce or prevent wild radish seed set or problems with harvest and grain contamination. These treatments are also used to control late emerging wild radish plants, or escapes from an earlier spraying (Code *et al.* 1978, Code and Reeves 1981).

For late wild radish control in cereals (end of tillering through to jointing), MCPA and 2,4-D can be used. The amine of 2,4-D at 850 g a.i. ha^{-1} or the ester at 560 g ha^{-1} are commonly used in wheat, barley and triticale. In oats, a maximum rate of 500 g a.i. ha^{-1} is recommended on some 2,4-D labels. MCPA is safer and usually preferred for late spraying in oats (Parsons 1992).

Diquat at 200–600 g a.i. ha^{-1}, can be used to desiccate wild radish before harvest. We have observed that wild radish branches can also be turned down below heading level by using 2,4-D amine at 750–1050 g a.i. ha^{-1} or 2,4-D ester at 1120 g ha^{-1}, applied after the wheat dough stage and about 14 days pre-harvest. Caution is needed with the use of this treatment as sample contamination can be increased if the wild radish is not turned down adequately below the heading level. The treatment can reduce the viability of some of the wild radish seed.

Sorghum, millet and maize

In sorghum, millet and maize, atrazine, 2,4-D amine and ester, MCPA, picloram + 2,4-D and linuron (maize only) can be used to control wild radish (Parsons 1992).

Grain legumes

Simazine is widely used in lupins for broad spectrum weed control, including wild radish, at 500–2000 g a.i. ha^{-1} (Parsons 1992). However, it frequently provides inadequate control of wild radish (Code *et al.* 1987, Walsh and Code 1987, Gilbey 1990). Where wild radish is a significant problem, control can be improved by using diflufenican at 50–100 g a.i. ha^{-1} or metosulam at 3.5–5.0 g ha^{-1}, both in conjunction with the standard rate of simazine. Diflufenican can be applied post-sowing, with simazine, or post-emergence after use of simazine at sowing. Metosulam is applied post-emergence (Walsh and Code 1987, Parsons 1992, Chemical Registration Information Service).

Sequential applications of simazine have also improved control of wild radish in lupins (Gilbey 1990, Parsons 1992). This involves an application of simazine just before or after sowing, followed by another application at a lower rate several weeks later.

Diuron at 990 g a.i. ha^{-1}, propazine at 1000–1500 g ha^{-1}, metribuzin at 300 g ha^{-1} and simazine at 250–500 g ha^{-1} + atrazine at 250–500 g ha^{-1} can also be used to obtain control of wild radish in lupins (Parsons 1992).

In experiments, reasonable control of wild radish has been obtained with propazine, metribuzin, linuron, monolinuron, dinoseb and oxyfluorfen (*Lupinus albus* only with oxyfluorfen) (Code unpublished data). Metribuzin, in particular, has shown good results when used either on its own or mixed with diflufenican post-emergence in Gungurru and Merrit lupins (Cooper and Bowran 1993, J. Cooper personal communication).

Small wild radish plants (3–4 leaf) were controlled by 70 g a.i. ha^{-1}, while large plants (up to 1 m in diameter and height) were controlled by a mixture of 105 g ha^{-1} metribuzin plus 50 g ha^{-1} diflufenican (Cooper and Bowran 1993). No other herbicide option is available for the control of wild radish plants of this size in a lupin crop.

In field peas, diflufenican, imazethapyr, metribuzin, cyanazine, flumetsulam and MCPA are registered for use and commonly used where control of wild radish is required (Parsons 1992, Chemical Registration Information Service). Cyanazine, flumetsulam and MCPA are regarded as providing suppression only.

Terbuthylazine has provided control of wild radish in peas in North America (Jensen 1977).

Cyanazine can be used for wild radish control in lentils, faba beans, chick peas and vetch; imazethapyr in faba beans and linuron, metribuzin and bentazone in soybeans (Parsons 1992).

Oil-seeds

Herbicidal control of wild radish can be a problem in safflower or canola, but in linseed and linola control can be obtained with bromoxynil, MCPA, bromoxynil + MCPA and picloram + MCPA (Parsons 1992).

The development of canola cultivars resistant to triazine herbicides has enabled control of wild radish in this crop. One such cultivar is Siren. Growers should apply 2–3 L ha^{-1} of simazine at seeding, and consider a top up at six weeks with atrazine where radish is expected to be a problem (P. Carmody personal communication).

Horticulture

The herbicides registered for wild radish control in vegetables in Australia are listed in Table 6.

Terbuthylazine has controlled wild radish in peas in North America (Jensen 1977), oxadiazon in carrots in Brazil (Leiderman and Grassi 1972), dinoseb in potatoes in North America (Murphy and Morrow 1983) and monolinuron and metobromuron in potatoes in Russia (Kurkova 1980).

In orchard, vineyard and ornamental situations, glufosinate-ammonium, diuron, norflurazon, terbacil, phenmedipham, chlorpropham, dichlobenil, pendimethalin, amitrole + ammonium thiocyanate and oxyfluorfen are among those registered for wild radish control (Parsons 1992, Chemical Registration Information Service).

Table 6. Herbicides for wild radish control in vegetables.[A]

Herbicides	Vegetables
Atrazine	Asparagus
Bentazone	Beans
Chloridazon	Beets
Chlorpropham	Garlic, onions
Cyanazine	Onions, peas, potatoes, sweet corn
Diuron	Asparagus
Ethofumesate	Onions
Ioxynil	Onions
Linuron	Carrots, onions, parsnips, potatoes, sweet corn
MCPA	Peas (suppression only)
Methabenzthiazuron	Onions
Metoxuron	Carrots, parsnips
Metribuzin	Peas, potatoes
Pendimethalin	Beans, broccoli, cabbage, carrots, cauliflower, lettuce, peas
Phenmedipham	Beets
Prometryne	Beans, carrots, celery, peas, potatoes
Propazine	Carrots, parsnips, peas

[A] Sources: Parsons 1992 and Chemical Registration Information Service, Victorian Department of Agriculture.

Pastures and lucerne

In pastures containing subterranean clover (*Trifolium subterraneum* L.) and some other clover species, diflufenican at 50–100 g a.i. ha^{-1} and diflufenican at 6.25–12.5 g ha^{-1} + MCPA ester at 62.5–125.0 g ha^{-1} are registered for wild radish control in Australia. In pastures containing certain clovers or annual medics (*Medicago* spp.) flumetsulam at 20 g ha^{-1} is registered. For certain clovers and seedling lucerne (*Medicago sativa* L.), bromoxynil at 400 g ha^{-1} and bromoxynil at 87.5–250.0 g ha^{-1} + diflufenican at 8.75–25.0 g ha^{-1} are registered. For certain species of clover, medic and seedling lucerne, 2,4-DB at 1120 g ha^{-1} is registered (Parsons 1992, Chemical Registration Information Service). These herbicides are applied post-emergence, when wild radish is in the seedling stage. The mixtures are available commercially.

In lucerne pastures over one year old, diuron at 900–1800 g a.i. ha^{-1}, terbacil at 800–1400 g ha^{-1}, paraquat at 300–400 g ha^{-1}, and paraquat 250–375 g ha^{-1} + diquat 150–225 g ha^{-1} are registered for wild radish control, in addition to those discussed above that are appropriate for seedling lucerne (Parsons 1992).

MCPA and 2,4-D can damage clover at rates that will control wild radish (Nufarm 1992). However, they are registered for use in Australia at lower rates in combination with heavy grazing (Parsons 1992). The herbicide does not kill the weeds, but mobilizes sugars in the plant, thus improving palatability. The following period of heavy grazing with sheep removes the weed by preferential grazing. This technique is commonly called spray-grazing. Sheep are more effective than cattle since they graze closer to the ground. Rates of 175–700 g a.i. ha^{-1} are registered for this use, but 500 g ha^{-1} of MCPA or 250 g ha^{-1} of 2,4-D are typical use rates (Pearce 1972, Mahoney 1984, Parsons 1992). Grazing of wild radish can poison stock as discussed earlier in this review, so caution is needed with the spray-graze technique for control of this weed.

In pastures containing grasses only, herbicides such as MCPA and 2,4-D at higher rates than those used for spray-grazing can be used. Atrazine and diuron are also used in some perennial grass seed crops (Parsons 1992).

Non-crop

In non-crop situations, such as on seed-beds before sowing crop or pasture or in industrial situations, the knock-down herbicides diquat (150–800 g a.i. ha^{-1}), paraquat (150–600 g ha^{-1}), glyphosate (540–720 g ha^{-1}) or glufosinate-ammonium (600–1000 g ha^{-1}) will provide effective non-residual control of wild radish. Atrazine, diuron, bromacil and ethidimuron provide residual control in industrial situations and crop fallows (atrazine only) (Parsons 1992).

Sulfometuron-methyl at 150–300 g a.i. ha^{-1} has effectively controlled wild radish in industrial weed control situations in experiments (P. Mesch personal communication).

Response to other human manipulations

Cultivation

Shallow burial of wild radish seed to a depth of 1–5 cm, is suitable for maximum germination and loss of seed viability, while seed buried deeply, below about 10 cm, will have a reduced level of germination and a slower loss of viability. Seed on the surface loses viability quickly but has a lower level of germination than shallow buried seed (Piggin *et al.* 1978, Reeves *et al.* 1981, Code, Walsh and Reeves 1987).

These responses in wild radish seed allow some population manipulations through cultivation. In work by Piggin *et al.* (1978), deep burial of wild radish seed by mould board ploughing resulted in a population of 90 plants m^{-2} in a following wheat crop. This was significantly lower than after discing to 5 or 10 cm, which resulted in 323 plants m^{-2} and 490 plants m^{-2}, respectively, or after drilling into undisturbed soil which resulted in 207 plants m^{-2}. The lower population after direct drilling can possibly be attributed to seed being only partially covered by soil, thus reducing germination (Piggin *et al.* 1978).

These responses to different cultivation practices can also be used to speed up the depletion of a wild radish seed bank. In work in north-east Victoria by Code and Donaldson (unpublished data), different cultivation and crop establishment practices were compared in their effect on reducing wild radish populations over a four year period. All treatments were sprayed twice each year to ensure no wild radish set seed, so the resultant decline in the population reflected decline of the seed bank that was present at commencement. In the first year of the experiment, 202 wild radish m^{-2} occurred in direct drilled wheat, 116 m^{-2} in wheat sown into a seed bed cultivated to 8 cm and 96 m^{-2} after cultivation to 5 cm. The higher population after direct drilling is in contrast to the results from the work by Piggin *et al.* (1978). In the third year of the experiment, the wild radish infestation had declined to 15 m^{-2} in cultivated and direct drilled treatments, but was only 7 m^{-2} in a treatment cultivated to 8 cm in the first two years and direct drilled in the third and fourth years. In the fourth year, this treatment had only one wild radish per square metre while other treatments ranged between 3 and 6 m^{-2}.

While the differences in this experiment are not large, they indicate that there is possibly some value in one or two years of cultivation to obtain optimum conditions for wild radish germination, followed by minimum disturbance that reduces germination in subsequent years.

Other treatments involving mould board ploughing in year one followed by direct drilling or shallow cultivation in years 2–4 also resulted in significant reductions in wild radish population in crops. Similar results were obtained to the earlier work by Piggin *et al.* (1978). However, mould board ploughing has practical problems over large areas. Also, it would be necessary to ensure that later cultivation did not bring buried seed back to the surface where it could germinate.

Fallowing

Cultivated or chemical fallows, aimed at preventing weed seed set and / or running down seed banks before a crop, would have a limited effect in reducing wild radish populations in crops, due to the presence of dormant seeds, some of which would germinate in the crop after the fallow.

Grazing and slashing

Grazing and slashing have some effect in reducing the vigor, bulk and seed production of wild radish. However, grazing can harm stock (Gardner and Bennetts 1956, Whittet 1968, Everist 1981). Grazing in conjunction with use of a low rate of 2,4-D or MCPA is more effective (see section on herbicide use in pasture). However, grazing and slashing are not likely to greatly reduce seed production unless the stocking rate is heavy, or slashing is frequently repeated, because of the ability of wild radish to rapidly send up a flowering stem and produce seeds (Reeves *et al.* 1981, Cheam 1986).

Hygiene

Cleaning of cultivating and harvesting equipment, sowing of clean seed, quarantine of stock that are likely to have recently consumed wild radish seeds and feeding of clean fodder will reduce the risk of spreading wild radish. If stock have consumed wild radish seeds, a quarantine period, where the stock are kept out of clean paddocks for a short time, would greatly reduce the risk of them passing viable seeds in manure. In work by Heap and Honan (1993), sheep passed the majority of weed seeds over a period of two weeks after consumption ceased.

Grain to be used for sowing should preferably be obtained from wild radish free paddocks, or seed should be cleaned to remove as much of the wild radish seeds as possible. Large grains such as lupins and peas are fairly easily cleaned, but wheat is difficult, since wild radish pod segments are similar in size to wheat grains (Piggin *et al.* 1978, Cheam 1986). However, reasonably effective cleaning can be obtained using a gravity table.

Crop swathing

Wild radish is often still green when grain crops are ready for harvest. This can result in either delays in harvest to wait for the wild radish to dry out, with the risk of grain loss from shattering during the delay, or the contamination of harvested grain with green wild radish pod segments. Harvesting crop with green wild radish can also result in frequent header blockages (Piggin *et al.* 1978, Snowball 1986).

Swathing, or wind rowing of crops, can be a successful way of avoiding at least some of this loss. In experimental work in Western Australia, swathing of lupins successfully desiccated green wild radish and eliminated green material from the grain. In a non-swathed area, where harvesting was delayed until wild radish was dry, yield was reduced by an average of 22% due to shattering, while losses were reduced to 9–12% with swathing (Snowball 1986).

Mulching

Mulching under tree and vine crops and ornamentals can be used very effectively to reduce weed infestations, including wild radish (Walpole *et al.* 1992). Mulches such as straw or other plant material and woven or sheet black plastic can be used.

Solar heating of soil

Reduction of the bank of viable wild radish seed in soil using solar heat (solarization) has been recorded (Cartia 1985).

Other measures

Control measures such as hand weeding, hoeing and burning may be applicable in some situations.

Response to natural enemies

No information could be found in the literature on insect pests that attack wild radish. However, there is anecdotal evidence that redlegged earth mite (*Halotydeus destructor*) severely attacks the plant, particularly in the seedling stage. Plants showing typical redlegged earth mite damage (silvering of leaf surfaces) and heavily infested with mites are commonly seen at all growth stages. Wild radish as an alternate host to thrips and flea beetles has been mentioned in an earlier section. White Italian snail (*Theba pisana*) has also been observed to feed on wild radish.

Morris and Knox-Davies (1980) found that some plant diseases attacked wild radish in glasshouse experiments in South Africa. The plant was a moderate host to *Peronospora parasitica* (downy mildew) and *Albugo candida* (white rust) and could also be infected by *Xanthomonas campestris* (black rot). They found that *A. candida* occurred on wild radish in the field in the west cape of South Africa, although other workers had not recorded its presence (Gorter 1977). They did not find *X. campestris* in the field in South Africa. Wild radish has been listed as a host to *X. campestris* by other authors (Chupp and Sherf 1960, Buchanan and Gibbons 1974). Morris and Knox-Davies (1980) found that *Plasmodiophora brassicae* (club root) did not infect wild radish. However, other authors have listed wild radish as a host (Karling 1968). In Sardinia, Italy, turnip mosaic virus (TuMV) was isolated from wild radish plants showing mosaic, leaf distortion and stunting (Foddai *et al.* 1991). Tobacco streak virus (TSV) and cucumber mosaic virus (CMV) also attack wild radish (see earlier section).

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