Government of South Australia
Department of Water, Land and Biodiversity Conservation

Control of Branched Broomrape

A literature review

by

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with an appendix

A comparison of techniques to reduce the soil seedbank of branched broomrape

by

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1 The origin of branched broomrape

Three lines of evidence support the hypothesis that branched broomrape (*Orobanche ramosa*, in the broad definition of that species) evolved in the northern hemisphere and has subsequently been introduced to a limited area of South Australia.

1. Historical evidence

Orobanche ramosa was first described in 1753 from European material. Specimens collected between that time and the publication of a major revision of *Orobanche* by Beck-Mannagetta (1930) showed that it was distributed in Europe, south-western Asia, northern Africa and introduced into eastern USA and Canada.

Orobanche ramosa occurs in native vegetation and as a weed in crops in the Mediterranean region and SW Asia (Musselman, 1991). Within Europe, it is regarded as native in the southern countries including Italy and Greece, but naturalised further north where it is only known from cultivated crops and gardens (Chater & Webb, 1972).

Beck-Managetta and subsequent authors placed *O. ramosa* and related species in the section *Trionychon* of the genus *Orobanche;* all species of this section are native to the northern hemisphere only. The only specimen of *O. ramosa* (or any closely related species) collected in Australia before 1990 was the specimen from J.M. Black's herbarium collected near Glenelg, SA in 1911 (Barker, 1986).

2. Distribution pattern of the local populations

Within Australia, branched broomrape is only known from an area of SA centred on 35º S 139º 30' E. For several years, Authorised Officers of Animal and Plant Control Boards around the State have assisted in the annual broomrape surveys in this area, and returned to their own areas thoroughly prepared to recognise this plant if it occurred there. The infestations are restricted to a single focus comprising the Quarantine Zone and adjoining areas; no remote infestations have been found in two years' inspections of 484,000 ha on 423 more distant properties linked by ownership or movement of stock/produce to properties in the Quarantine zone.

Branched broomrape is absent from all other Australian States and Territories. It is not recorded from regions with similar climates in Victoria (Barker, 1999), New South Wales (Barker, 1992), or south-western WA (Wheeler, 1987). It has still not been found in Victoria despite recent searches by people familiar with the Murray Bridge infestations (Faithfull & McLaren, 2002).

Its restricted and contiguous local range implies a recent introduction. On the other hand, the only native broomrape species (*Orobanche cernua* var. *australiana*) has become widely dispersed across southern Australia (Barker, 1986) in the long period of time it has taken to evolve significant differences in morphology and host range from the forms of *O. cernua* found overseas.

3. Molecular studies

Two independent sets of molecular data - from the sequencing of three ribosomal genes (Schneeweiss, 2001) and use of RAPD markers in the nuclear genome (Roman et al., 2001) - confirm the conclusion of previous taxonomists that *O. ramosa* with its subspecies or closely related species *nana* and *mutelii* form a distinct clade. *O. aegyptiaca* is placed close to this clade on morphology and molecular evidence (Paran et al., 1997), and can hybridise with *O. ramosa* although it is clearly a distinct species (Katzir et al., 1996).

Orobanche mutelii, or *Orobanche ramosa* subspecies *mutelii,* is a name applied to some populations of the ramosa clade. These plants can grow up to 30 cm tall and often have a longer corolla than typical *O. ramosa*, but they intergrade with other variants. There is no consistent discontinuity with typical *O. ramosa* detectible on morphological criteria (Musselman, 1991; Musselman et al., 1989), but the molecular studies cited above suggest these populations diverged early from the rest of the *ramosa* clade. Populations referred to *O. ramosa* subspecies *mutelii* occur in the Mediterranean basin (Chater & Webb, 1972). Unlike typical *O. ramosa*, they have not moved into northern Europe (Rumsey & Jury, 1991).

Schneeweiss (2001) acknowledges that his *ITS* sequence data is not closely congruent with morphological data for *Orobanche* sect. *Trionychon*. He interprets this to mean that his data is a better measure of phylogeny than the morphological evidence; but the converse interpretation is also possible. South Australian branched broomrape material came out as the sister group to all other members of the *ramosa* clade (labelled as *ramosa* in the narrow sense, *lavandulacea, oxyloba, heldreichii* and *pulchella*) used in his analysis. He tentatively called this plant *O.* cf. *mutelii*, although no confirmed *O. mutelii* was included in the study for comparison.

Roman et al. (2001) similarly found that their sole accession of *O. mutelii* was sister to 5 accessions of *O. ramosa* plus one of *O. nana*. This study is more convincing since all their material came from the same geographic region.

Thus branched broomrape from South Australia is clearly part of the ramosa complex that evolved in the Mediterranean/middle east region.

2 Control strategies

Many management strategies have been tried against *Orobanche ramosa* and other broomrapes, but few of them have proved reliable and these are only economical in high-value agriculture.

The strength of branched broomrape lies in its ability to form a bank of seeds in the soil. A management or eradication program must aim at reducing this seed bank, while minimising the production of new seeds and their dispersal to new sites. Quarantine is therefore an essential element in control or eradication programs.

A simulation model (Kebreab & Murdoch, 2001) predicted that sustainable control of *Orobanche* spp. requires permanently a permanent reduction of the seed bank to below 2000 seeds per square metre. Cultural control techniques, applied individually in their model, needed to be highly effective to achieve this reduction; integrated control using several techniques including those aimed at reducing seed recruitment was therefore recommended.

In-crop control of *Orobanche* also requires an integrated strategy. Linke & Saxena (1991b) recommended a combination of solarisation, herbicides and hand weeding with careful choice of cultivars and sowing times to manage *Orobanche* in legume crops; none of these methods gave complete control when used separately.

Control strategies can only be developed when enough is known of the biology of a weed to recognise its own life strategy, and the vulnerable points in this strategy.

3 Biology of broomrapes

The holoparasitic and hemiparasitic members of Scrophulariaceae form a single clade (dePamphilis et al., 1997; Olmstead et al., 2001) that may also be called the Orobanchaceae. They have evolved from independent green plants, through hemiparasites that need a host for their early growth but later develop green leaves, to holoparasites like *Orobanche* completely dependent on host plants. This shift occurred by the gradual suppression of the more autotrophic later stages of the plant's life history (Raynal-Roques et al., 2001) until even the chloroplast genes necessary for photosynthesis become non-functional (dePamphilis & Palmer, 1990). Since the ability to make parasitic connections via haustoria with host plant roots evolved only once in this clade (dePamphilis et al., 1997) and therefore has a common genetic basis in all genera, studies of the hemiparasite *Striga* can shed light on the mechanism of parasitism in *Orobanche*.

Seed dormancy and germination

O. crenata seeds require conditioning by exposure to moisture at temperatures between 15-20° C for at least 18 days for maximum germination. Prolonged storage in these conditions causes the seeds to enter secondary dormancy (Van Hezewijk et al., 1994a). Increasing storage temperatures increases the percentage of seeds going dormant; there is also some decrease in viability at higher temperatures, with viability reaching zero at 80° C (Mauromicale et al., 2000). The decrease in viability conforms to a sigmoidal curve proportional to moisture and temperature levels (Kebreab & Murdoch, 1999b).

O. crenata shows annual cycles of seed dormancy, with high germination in autumn-winter and very low germination for the rest of the year (Van Hezewijk et al., 1994b). This is described as secondary dormancy, after the seeds have broken their primary dormancy (Kebreab & Murdoch, 1999a). López-Granados & Garcia-Torres (1999) tracked these cycles of dormancy and germinability. Viability falls rapidly in the first three years of burial in field conditions, compared to its longer maintenance in laboratory storage at lower temperature and humidity. *O. ramosa* remains viable for up to 13 years in field conditions overseas (Linke & Saxena, 1991a).

Germination consists of the extension of a 'germ tube', corresponding to the radicle of a normal dicot seedling, from the seed. Soil pH (within the normal range of arable soils) has little influence on germination. Germination of *O. crenata* was not reduced at any pH between 5 and 8.5, although subsequent growth of the radicle was favoured by higher pH within this range (Van Hezewijk et al., 1994c).

Chemical signalling in germination

Orobanche and *Striga* require specific substances (xenognosins) from the host root to germinate. As the xenognosins are unstable, their presence is a reliable "indicator" to the seed of the presence of live roots within a few mm. For parasites dependent on germination factors, host specificity is limited largely by the ability of the host to produce a germination stimulant. However, this is not the complete story, since several nonhost plants also produce xenognosins effective for germination (Yoder, 2001).

Haustorium formation

Induction of haustorium formation by the seedling radicle is a separate process in response to a different xenognosin, termed a haustorium inducing factor (HIF).

There are a range of HIFs that belong to three related groups of phenolic compounds: flavonoids, *p*-hydroxy acids and quinones.

These chemicals are not released in detectable quantities from intact plant roots, but appear after the root surface is damaged. Estabrook & Yoder (1998) hypothesised that parasitic plants actively "mine" them from a potential host plant by producing chemicals that cause their release. Studies on *Striga* (Keyes et al., 2000, 2001) show that hydrogen peroxide released by the parasite diffuses through the soil to oxidize pectins in the cell walls of the host into quinones - these then diffuse back to the parasite seedling where they trigger the formation of a haustorium. Growth of the *Striga* radicle stops immediately, but some hours of exposure to the HIF is needed before it is committed to haustorium formation (O'Malley & Lynn, 2000).

The observation that exogenous cytokinin can also induce haustorium formation in the absence of a host (Keyes et al., 2000) may be a red herring. As Keyes et al. (2001) point out, there are no grounds to assume that the action of this hormone with a broad role in root development in non-parasitic plants overlaps the normal induction pathway of haustoria.

Functional attachment

The haustorium penetrates the host root by means of a peg that forces its way between cells. The parasite produces pectin methyl esterases that degrade host cell walls (Losner-Goshen et al., 1998); the process is similar to what happens in *Cuscuta*. The rate and extent of penetration is dependent on host-specific factors. A haustorium penetrating a non-host shows necrosis and cell-wall degradation, as does the adjacent tissue of the host plant.

The development of a functional attachment can depend on favourable conditions, such as temperature. *Orobanche* spp. that normally parasitise carrots may fail to get past the initial attachment stage if soil temperatures are too high (Eizenberg et al., 2001).

Orobanche draws its nutrition from the host phloem by direct cell contact. By draining carbohydrates, it can force the host to increase its rate of photosynthesis (Hibberd & Jeschke, 2001).

The following table relates the control techniques considered for use in South Australia to the processes of the broomrape life cycle. For further detail see Kebreab & Murdoch (2001) Fig. 1, where control methods are related to stages of the life cycle.

Processes in broomrape life cycle	**Corresponding control methods**
seed dispersal	quarantine
seed survival in soil	fumigation solarisation
seed conditioning	
seed germination	trap crops (false hosts) germination stimulants germination inhibitors
growth of radicle to host root	nitrogen fertilisers
penetration of host	crop resistance
functional attachment to host	crop resistance
underground growth tubercle growth	glyphosate sulfonylureas catch crops (sacrificial hosts)
emergence of flowering shoot	
seed production	spot spraying hand weeding burning biological control grazing

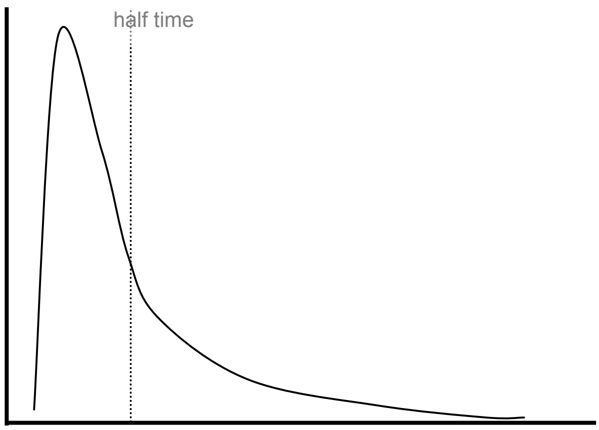
4 Quarantine of stock

There is direct evidence that *Orobanche* seed can be dispersed in the gut of grazing livestock and excreted in a viable condition. However, there is little quantitative evidence for the retention time of viable *Orobanche* seed in the gut. The best direct evidence comes from Jacobsohn et al. (1987) who placed seed of *O. aegyptiaca* (closely related to *O. ramosa* in the section *Trionychon*) and two other *Orobanche* species in the rumen of rams and recovered viable seeds from the faeces. Most of the seeds were excreted in the second day after ingestion, and no viable seeds were recovered after the fourth day although faeces were collected and tested up to the seventh day.

Some inferences can be drawn from general studies of retention and viability using other types of seed.

Retention time

Brandt & Thacker (1958) established a mathematical model for the movement of material through the gut of a mammal, based on a theory of constant flow through a volume in which complete mixing occurs. After an initial lag phase representing the minimum time in which material can pass through the gut, the rate of excretion of a marker substance is exponentially related to the time elapsed since ingestion of a single measured dose. This is because the concentration of the marker remaining in the gut is also decreasing exponentially. It is therefore possible to speak of a **half-time** by which 50% of the marker dose has been excreted.



However, this model is only an approximation, especially if applied to the whole gut contents (**digesta**). Digesta consists of a mixture of liquid and solid particles of various sizes that move at different rates. A key review of the subject by Warner (1981) concluded that **mean retention time,** defined as the average time of retention in the gut of all the elements of the digesta, is the best measure of digesta flow and compared various methodologies for determining it.

So half-time is the appropriate measure for a specific seed type in the gut, and mean retention time applies to the whole digesta.

Among herbivores in general, mean retention time is greater in larger animals and also greater in ruminants than in non-ruminants of similar size. Within a species, it varies with the age and condition of animals, type of feed, amount of feed and water content (Warner, 1981).

The following table lists some experimentally determined mean retention times, in hours, as summarised by Warner (1981). The wide ranges of results for sheep and cattle reflect the number and diversity of studies on these species:

rabbit	15
horse	26-37
grey kangaroo	38-45
goat	43
sheep	31-103
cattle	54-127

Mean retention times tend to be longer in cattle than in sheep, as noted by Atkeson et al. (1934).

The half-time of one component of the digesta, such as a seed, can be higher or lower than the mean retention time. Smaller particles generally move faster through the gut than larger ones (Warner, 1981). An estimate of the retention time based on movement of a soluble chemical marker is therefore likely to be lower than the half-time for a seed in the same animal. For example, Hartnell & Satter (1979) reported a retention time of 50 hours in cattle, with all traces of the marker gone within 120 hours.

Digesta does not move at the same rate in all sections of the gut. Some material gets delayed by being temporarily held in various *culs de sac,* ie:

- the rumen of sheep, goats and cattle
- the caecum
- folds of the ilium and colon

The caecum selectively removes large solid objects from the digesta flow, returning them at intervals. Storage in the caecum can account for the anomalous retention by sheep of an occasional seed of *Reseda lutea* for up to 12 days, or of *Solanum elaeagnifolium* up to 31 days reported by Heap & Honan (1993). In an extreme case, the large hard-coated seeds of the tree *Enterolobium* were retained by horses for up to 60 days (Janzen, 1981); but these seeds are each about 12,000 times the volume of an *Orobanche ramosa* seed.

In two other case studies of seeds ingested by sheep, *Echium plantagineum* seed was mostly passed within 3 days (Piggin, 1978) and recovery of *Nassella trichotoma* peaked on days 3 and 4 and had fallen to a low level by day 7 (Cook, 1998).

In cattle, Gardener et al. (1993a) found half-times of 34-50 hours for retention of a range of 10 legume and 8 grass species, although occasional seeds were still being voided when the experiment was terminated at 160 hours.

All these results support the model: the great majority of seeds are passed by the fourth day, but occasional seeds may lag for an indefinite time.

Viability

Ingested seeds can be damaged by

- mastication, during ingestion and/or subsequent rumination (Piggin, 1978; Özer, 1979),
- microbial activity in the rumen (Simao Neto & Jones, 1987; Gardener et al., 1993b).
- digestive enzymes and acid in the stomach (Simao Neto & Jones, 1987; Gardener et al., 1993b).

If the seeds imbibe sufficient water to begin germination or rupture the testa, they are rapidly destroyed by chemical and mechanical stresses (Janzen, 1981; Gardener et al., 1993a). This can occur anywhere along the gut.

Some of the studies cited above in relation to retention times also demonstrate a decrease in seed viability. Although Piggin (1978) found some *Echium* seeds passed by sheep after the third day, none of these were viable. Atkeson et al. (1934) and Harmon & Keim (1934) reported that the percentage germination of over 20 weed species decreased with time in the gut. Gardener et al. (1993) also found high decreases in viability in all of their 18 pasture species except for hard-seeded legumes. However, Cook (1998) recovered a few viable seeds of *Nassella* after 7 days in sheep; and the solitary seeds of *Reseda* and *Solanum* voided by sheep after 12 and 31 days respectively were viable (Heap & Honan, 1993).

Seeds of *Orobanche aegyptiaca* remained viable for up to 4 days in the gut of sheep (Jacobsohn et al., 1987). *Solanum elaeagnifolium* and *Reseda lutea* both have resistant, sclerified testas and *Nassella* seeds are similarly protected by a sclerified lemma. Since *Orobanche* seeds are very small with a thin testa, they may be less well adapted to survive in the stomach than these larger seeds. This should be tested by further experiments. One approach would be to agitate some *O. ramosa* seeds in a warm solution of hydrochloric acid plus pepsin and test samples at intervals for viability, as done for grass seeds by Ocumpaugh & Swakon (1993).

The use of fresh manure containing seeds excreted in a viable condition on fields is believed to spread *Orobanche*. However, if the manure is processed into granules or pellets, the high temperatures of this process kills a high percentage of seeds (Joel et al., 1988). Some seeds may survive because they are more resistant to heat shock when dry than if they are in an imbibed condition. Even the storage of manure containing weed seeds is known to reduce their percentage viability, down to virtually 0% after 3 months for most weeds (Atkeson et al., 1934; Harmon & Keim, 1934) although hard-seeded legumes survived longer (Özer, 1979).

The indirect evidence suggests that viable seeds of *Orobanche ramosa* will not be excreted more than 6 days after ingestion by sheep, or more than 7 days by cattle. This may be confirmed by experiments using *O. ramosa* seed.

5 Fumigation

Fumigation aims at eliminating the seed bank in 1-2 years. It is assisted by burning with straw in the first year only to destroy seed at the soil surface.

Fumigation to destroy buried seed, using one of the following chemicals. Soil must be wet at the time of application as seeds are only vulnerable when they are in the imbibed state.

Methyl Bromide

Methyl bromide has high effectiveness when correctly applied. A rate of 350 kg/ha is generally adequate to control *Orobanche* (Foy et al., 1989). Before the chemical is applied, soil must be cultivated by rotary hoe prior and be kept moist for 10-14 days to ensure all seeds are imbibed. Fumigation can only be done by a licensed contractor and the soil is covered with a plastic mulch, which is kept in place for at least 48 hours after application of the chemical.

One application can kill virtually 100% of the seed bank, as demonstrated by local experience since 1992 and also overseas experience (Parker & Riches, 1993). It is used pre-planting control of *O. ramosa* in tomato production in Egypt, where 350-500 kg/ha gives effective control (Zahran, 1970)

However, it is expensive and cost of the chemical will increase as it is phased out. The cost of treatment - rotary hoeing, chemical application and mulching - was estimated at $10,400/ha/year in 2000. Some paddocks in the area are too stony to be cultivated, and could be fumigated by hand at a cost of $2.5/sq. m

The development of alternative mulches (eg. foam) to a stage where they could be approved by the National Registration Authority would require research effort over several years as they are not used overseas (Peter Williamson, Fumigation Services of SA , pers. comm.)

Metham sodium

Metham sodium (sodium methyl dithiocarbamate, releasing the active ingredient methyl isothiocyanate) applied as a liquid product such as Vapam® is the preferred soil fumigation method in the USA. It gives 50% kill of *Orobanche* seed, but is rapidly lost from soil by volatilisation (Goldwasser et al., 1994). Control is greatly improved if would be higher if a plastic mulch is used to reduce this loss.

500 L/ha Vapam has given excellent control of *O. minor* in tobacco and *O. crenata* in broad bean (Zahran, 1970); it has also been applied in irrigation water, where it reduced broomrape density by 50%, or higher with polyethylene mulching. Applications of 800 L/ha in two successive years would be expected to give a similar reduction of the broomrape seedbank to one of methyl bromide.

Cost of chemical was $1,660/ha/year in 2000. Application by machine without plastic mulch costs $480/ha for small areas, reducing to $170/ha or less for areas over 50 ha.

Plastic mulching has never before been combined with metham application in Australia; it would require trials by the contractors to adapt their machinery. The estimated total cost of rotary hoeing, chemical application and mulching is

$5,300/ha/year. As this needs to be done in at least two successive years, it is as expensive as a single application of methyl bromide.

Dazomet

Dazomet (tetrahydro-3,5-dimethyl-2H-1,3,5-thiadiazine-2-thione) is a solid compound that releases methyl isothiocyanate when wetted; it is used less frequently than liquid metham overseas due to its higher cost. It is highly effective against *Orobanche* seeds (Khalaf et al., 1994). Dazomet is available as Basamid® (940 g/kg dazomet), costing $270 per 20kg drum. At a rate of 500kg/ha, this is $6,750/ha

The granules must be incorporated 15cm deep in the soil and watered (at least 5 L/sq m, or 50,000 L/ha) immediately after application; this would limit its use to properties with irrigation systems or to small areas that can be watered with a trailer tanker (400L) or a fire tanker (up to 5,000L).

Costs of rotary hoeing and plastic mulching would be similar to those for liquid metham although application would be cheaper. Effectiveness may be less than with liquid metham (Zahran, 1970), ie treatment in at least two successive years needed. The total cost of $10,000/ha/year makes it a less attractive option.

Ethylene dibromide

Ethylene dibromide has been used in the USA to control *O. crenata*. However, it is not effective against *O. ramosa* (Foy et al., 1989).

Recent substitutes for methyl bromide

Methyl iodide and Telone (1,3-dichloropropene) have been trialled overseas as substitutes for methyl bromide. They not available in Australia, and the industry has not yet considered adopting them. The application methods and costs would be similar to methyl bromide.

1,3-dichloropropene has achieved successful control of *O. ramosa* (Jacobson et al., 1991). However, it has not been routinely used and more research is needed.

None of the fumigants replacing methyl bromide for general soil sterilisation against pathogens and invertebrates are as effective in killing weed seeds (McDonald, 2002), implying that they will also be inferior in broomrape control.

6 Inhibition by soil nitrogen

It is a general observation that root parasitic plants are most abundant in infertile soils. Parasitic attachment occurs most readily in potting media low in nutrients, and the addition of nitrates or other nitrogenous fertilisers inhibits parasitism to varying degrees (Jain & Foy, 1992). The same effect was found in the field after application of ammonium compounds (Van Hezewijk et al., 1991). Several mechanisms may have been involved: direct inhibition of the *Orobanche* seed or seedling, or indirect via the host metabolism.

Abu-Irmaileh (1994) found that in *O. ramosa* the reduction in germination and the reduction in length of the radicle were proportional to ammonium concentration. The observation that ammonium is more effective than nitrate in reducing germination suggests that the mechanism is direct inhibition of radicle elongation by ammonium ions (Westwood & Foy, 1999), either liberated directly from ammonium compounds or produced from other nitrogen compounds.

The report by Ghosheh et al. (1999) that amendment of soil with olive jift greatly reduces either germination or attachment by *Orobanche* to known host plants may have a similar cause. Alternatively, it may be due to specific inhibitory chemicals in the jift or to indirect effects via changes to the soil microflora, as has been observed in cases of pathogen control by soil amendment.

The application of nitrogen fertilisers limited practical importance as a control measure for *O. crenata* (Dhanapal et al., 1996). However, the cost of this technique in pasture could be offset by increased yield.

7 Solarisation

Solarisation is the heating of soil by sunlight trapped under a mulch of black, or more usually clear, polyethylene film. The temperatures of 48-57°C reached (Jacobsohn et al., 1980; Sauerborn et al., 1989a) kill *Orobanche* seeds that are in the imbibed state; therefore soil must be wet at the time of treatment. Seeds of *O. ramosa* can survive 35 days at 50°C in dry air, but are quickly killed by temperatures of 40°C when wet (Drennan & Mohamed-Ahmed, 1992).

This technique has been used successfully on cropping land in the Middle East with an endemic *Orobanche* problem, as a pre-planting treatment for tomato, carrot, eggplant, faba beans and lentils (Abu-Irmaileh, 1991; Jacobsohn et al., 1980; Sauerborn et al., 1989a).

36 to 50 days of solarisation gave 90-100% reduction in emergence of *O. ramosa* and *O. aegyptiaca* in crops planted immediately after treatment (Abu-Irmaileh, 1991; Jacobsohn et al., 1980; Sauerborn et al., 1989a). The figures of less than 100% control occurred when solarisation was carried out during a period of cool weather.

In another study, 40 days solarisation decreased the *Orobanche* seedbank by 88-96% in the top 5 cm of soil (Sprich et al., 1990). The heat does not reach lower soil layers, and broomrape reappears if the soil is tilled after solarisation (Abu-Irmaileh, 1991). However, there is some residual control if the soil is not disturbed, with significantly higher crop yields for two years after treatment (Sauerborn et al., 1989a).

Solarisation is a technique of control, not eradication. The cost of cost of plastic mulching is high, and the technique can only be use in the hot months of the year. Solarisation may be more effective if combined with added nitrogen fertilisers; this can dramatically improve the kill of *Orobanche* seed at greater depths (Haidar & Sidhamed, 2000).

8 Germination stimulants

Orobanche requires substances (xenognosins) from the host root to germinate. This suggests the use of suitable chemicals to reduce the seed bank by stimulating seeds to germinate in the absence of a host.

The first germination-inducing xenognosin to be isolated, strigol, is a quinone. An isomer of strigol, orobanchol, has been identified as the corresponding chemical in *Orobanche minor* (Yokota et al., 1998). Analogues of strigol have been synthesised and shown to have similar effects, and a mechanism for their action involving their ethylene-like C=C bond was proposed by Mangnus & Zwanenburg (1992).

The need for a chemical signal for germination can be bypassed experimentally. Germination of *O. ramosa* can be induced by soaking seeds in gibberellic acid (Abu-Shakra et al., 1970). Exposure to ethylene gas for over 2 hours may produce a similar effect, but the evidence for this is inconclusive (Foy et al., 1989), and it seems too unreliable to have any practical use.

The following chemicals are possible germination stimulants. Soil must be wet at the time of application as seeds are only able to germinate when they are in the imbibed state.

Methyl isothiocyanate

The fumigant methyl isothiocyanate also acts as a germination stimulant when present in low concentrations in wet soil. This has been demonstrated for *O. ramosa* by Zhelev (1987)

In Bulgaria, very low application rates of Vapam® (1.5-2 kg /ha) or dazomet (30-40 kg/ha) are used to induce branched broomrape germination prior to planting tobacco. (Bozukov,1998, Chalakov,1998). However, these encouraging results have not been repeated in recent trials in other countries (Klaus Wegmann, pers. comm.)

There is a need for formal research to identify the critical concentration under field conditions in South Australia. This would be a cheaper option than using high rates of metham sodium or dazomet as a fumigant.

Nijmegen-1

Synthetic molecules analogous to strigol such as GR_{24} have been designed (Mangnus & Zwanenburg, 1991) and tested for activity on *Orobanche* seed. One of these, Nijmegen-1, is being developed for possible commercial release.

Some initial results are promising, eg. 92% reduction in emergence of Orobanche in a tobacco crop, but this was not repeated in two other trials (Klaus Wegmann 2001 pers. comm.)

When supplies of Nijmegen-1 become available, formal research should be undertaken to determine the critical rate for *O. ramosa* control under field conditions in South Australia.

9 Trap crops

Seed can also be stimulated to germinate by a catch crop (a host crop that is then sacrificed before the broomrape can emerge), or by a trap crop (a false host that stimulates the broomrape to germinate but does not allow it to attach).

Two or three successive catch crops grown in the same year are more effective than a single trap crop (Sauerborn, 1991).

Sacrificial host crops

A broadleaf host crop such as canola (*Brassica napus*) is sown at sown at a high density. It is killed prior to broomrape emergence by cultivating it into the soil as green manure or spraying out with a high rate of glyphosate.

A local cultivar of *Brassica campestris* has been used as a catch crop in Nepal, reducing the *O. aegyptiaca* seed bank by around 30% (Acharya et al., 2002).

Use of berseem clover (*Trifolium alexandrinum*) as a catch crop reduced *O. crenata* emergence in faba beans by 92% over 3 years and by 98% over 4 years; fenugreek (*Trigonella foenum-graecum*) was also effective (Al-Menoufi, 1991).

This method requires appropriate choice of host plants, and complete control of these hosts by appropriate timing of kill. The main cost is the loss of production from the land in the year the sacrificial crop is grown.

Laboratory and field research to identify suitable *Brassica* cultivars for this purpose in SA has been initiated by John Virtue and John Matthews, CRC for Australian Weed Management.

Sacrificial volunteer pasture

The weedy volunteer pastures found in the Murray Bridge area could be used like a catch crop by allowing weedy hosts such as *Arctotheca calendula* to grow through the winter and spraying out with non-selective rates of glyphosate just prior to broomrape emergence. This has been successful in Texas, reducing roadside infestations to a few isolated plants (Langston et al., 1985). Due to the lower host density in these patchy pastures, broomrape germination rates would be lower than in a host crop.

False host crops

False hosts are crops that stimulate germination of seeds of parasitic plants but do not function as hosts for the parasite to develop further. This has the advantage over sacrificial crops that the land is not taken out of production.

Germination and early haustorium formation are induced by a wide range of plants that produce any of the requisite chemicals, but the actual host range is much narrower. Also, once stimulated by a HIF, haustoria may attach to other roots or to inert material in the soil.

Various broadleaf crops including three species of *Phaseolus*, *Vigna catjang* and *Hibiscus cannabinus* stimulated germination of *O. crenata* seed; so did the grasses *Sorghum* and to a lesser extent *Setaria* and maize. Some broomrape seedlings attached to the roots of these plants; however, they then shrivelled without developing into a broomrape tubercle (Krishnamurthy & Chandwani, 1975). The control in their trials was tobacco, on which the *Orobanche* develops to maturity.

Exudates of flax (*Linum usitatissimum*) seed induced 75% germination of *O. crenata* and 16.6% germination of *O. ramosa*. This effect only continues for eight days after sowing the flax. Neither *Orobanche* species can form functional attachments to the flax (Khalaf, 1992). Flax crops achieved 50% reduction in one year (Zahran, 1982).

An annual reduction of 15-20% in the seed bank can be expected from an effective trap crop (Linke et al. 1991b), although as much as 30% of the broomrape seed may be germinated in a year (Sauerborn 1991).

On the other hand, even resistant crops like falx and certain vetches may allow a small number of broomrapes to attach and emerge (Kleifeld et al., 1998). To control these, and to remove host weeds from the crop, selective herbicide treatments are still needed.

Broomrape-resistant Popany vetch is currently being studied in SA as a potential trap crop.

10 Selective herbicides in-crop

In some situations, low rates of herbicide can control broomrapes when applied to the host crop. This has the attraction of allowing cropping on infested land, but rates and timing must be precise to prevent broomrape emergence. There is also the risk of developing resistance when low rates of the same herbicide are applied to a weed population is successive years.

Glyphosate

Any substance that is translocated in the phloem but not metabolised will become concentrated in the parasite, which accumulates them in its own tissues. Herbicides applied to the host at low rates can therefore reach lethal concentrations in the parasite. This is the basis of selective, broadacre chemical control using low rates of glyphosate (Nandula et al., 1999).

The late post-emergence application of glyphosate was effective (Lolas 1986) on *O. ramosa* in tobacco. Two treatments of 50 g/ha glyphosate reduced the number of *O. ramosa* and increased celery yield (Americanos, 1991).

A single application of 200 g/ha glyphosate gave complete control of *Orobanche* with no crop damage in faba bean (Kasasian, 1973). Two applications of 80 g/ha glyphosate, gave almost complete control of broomrapes in faba bean but with no yield increase (Sauerborn et al., 1989b). Lower rates were effective in vetch (Nandula et al., 1999) or medic (Matthews, 2002).

This technique is useful for reducing crop damage from broomrape, but cannot guarantee complete control. The safety margin in non-herbicide resistant crops is low and increasing the glyphosate rates has a heavy penalty in reduced yields. Yield loss due to the herbicide may balance the gain from broomrape control (Sauerborn et al., 1989b).

The recent development of glyphosate-resistant GM canola raises the possibility of using a glyphosate/Roundup Ready Canola® combination in infested paddocks. However, current research in Israel noted by Jupp (2001) is showing that high rates of glyphosate may be necessary to prevent broomrape emerging; the parasite responds to the herbicide by drawing more amino acids from its resistant host.

Sulfonylureas

Sulfonylureas are a class of soil-active herbicides that can also be selectively accumulated by developing *Orobanche* tubercles.

Chlorsulfuron has been applied by soil incorporation prior to transplanting tomato seedlings in glasshouses; trials showed that a rate equivalent to 2.44 g/ha prevented emergence of *O. ramosa* with moderate reduction to crop growth (Qasem, 1998).

In field trials, sulfonylureas were effective when applied to tomatoes as split applications through sprinkler irrigation systems (chemigation). Three applications of 2.5 g/ha chlorsulfuron or 7.5 g/ha triasulfuron gave 80-90% control with yield increase of 25-47% (Hershenhorn et al., 1998). Chlorsulfuron gave 88% control when used as a 10 g/ha foliar spray; a second treatment of 5 g/ha was needed for complete control, but delayed crop maturity (Kotoula-Syka & Eleftherohorinos, 1991).

7.5 g/ha triasulfuron applied as a single foliar spray caused unacceptable damage to potatoes (Goldwasser et al., 2001). However, 3 applications of 12.5 or 25 g/ha rimsulfuron (registered in Australia as Titus® for use on tomatoes) selectively controlled *O. ramosa* with no crop damage. Rimsulfuron does not reduce broomrape attachment but interferes with tubercle development; split applications are needed as its effect is temporary (Kleifeld et al., 1994).

The sulfonylureas also have the advantage of selectivity for preventing emergence of broomrape growing on broadleaf weeds in a non-host cereal crop. 3 g/ha metsulfuron-methyl, 15 g/ha chlorsulfuron or 22.5 g/ha triasulfuron gave 100% control of *O. ramosa* without damage to wheat or barley crops (Matthews, 2002). This may be due both to their direct effect on *Orobanche* and to their reduction of broadleaf weed hosts.

Imidazolinones

10 g/ha imazaquin also controlled broomrape in faba bean, but caused more crop damage than glyphosate (Sauerborn et al., 1989b). On the other hand, Saber et al. (1994) found that two applications of 20 g/ha imazaquin gave better control than 23 g/ha glyphosate with no crop damage.

Other imidazolinones have given selective control of broomrapes in sunflower (Garcia-Torres & Lopez-Granados, 1991), faba beans and peas (Linke, 1992) and cabbage (Americanos & Vouzounis, 1995).

OnDuty® is a mixture of imazapyr and imazapic that could be used on crops of imidazolinone-resistant Clearfield Canola. In trials, 20 g/ha prevented all emergence of *O. ramosa* (Matthews, 2002).

Other herbicides

Glufosinate ammonium has been used for in-crop control on tobacco in Bulgaria (Jupp, 2001), and could be trialled in Australia as it is readily available. The phenoxy-acids (MCPA and 2,4-D) are not suitable, as rates low enough to avoid crop damage will not prevent all broomrape emergence.

11 Post broomrape emergence spot treatments

These are non-selective spot-spraying treatments to prevent emerged broomrape plants from setting seed. They are too labour-intensive to be more than first aid for newly located infestations.

Options include non-selective rates of glyphosate, burning with dry straw or diesel oil, and hand weeding

The effectiveness of these methods is being investigated by John Matthews, CRC for Australian Weed Management.

12 Other management options

Grazing

Intensive grazing by sheep of pasture containing broadleaf hosts could have a similar effect on *O. ramosa* seed bank to sacrificial pasture. But if stocking rate or timing were wrong, the broomrape could still set seed.

Cereal crops

O. ramosa has not been found in cereal crops that are free of broadleaf weeds. It would therefore be possible to maintain cereal crops or grass pasture on infested land if all broadleaf weeds were controlled by herbicides. However, annual decrease in the seed bank is slow under grass fallow (Linke et al. 1991b).

Soil inversion

Trench ploughing 45-50 cm deep with a mouldboard plough reduced *O. ramosa* by 80-90% in tobacco fields of Eastern Europe (Parker & Riches, 1993) by burying seed to depths where it is unlikely to germinate. This method would have limited usefulness here due to the risk of drift on light soils and the need to follow up with minimum tillage for several years.

13 Longer term approaches to broomrape control

These are directions for future research into the management of broomrapes – including *O. ramosa*, *O. minor* and other species that may reach Australia.

Biological control

The fungus *Ulocladium atrum* has been used experimentally to control *Orobanche crenata* in faba beans in Syria (Linke et al., 1992), destroying emerged shoots and underground tubercles. This raises the possibility of using this or a related fungus as a mycoherbicide to control *O. ramosa.*

Fusarium lateritum gave up to 68% control of the underground stages of *Orobanche* when applied to soil in irrigation water (Bozukov & Kouzmanova, 1994). A species of *Fusarium* has now been commercialised for control of *Orobanche cumana* in Egypt and Jordan (Jupp, 2001).

Phytomyza orobanchia is a fly whose larvae mine in stems and capsules of *O. ramosa* and other *Orobanche* spp., reducing seed production. Its short life cycle allows it to complete up to three generations in one broomrape season (Norambuena et al., 2001). Inundative control with *P. orobanchia* has been used to reduce local infestation levels of *Orobanche* spp. in crops (Klein & Kroschel, 2002).

However, its introduction to Australia is unlikely to be approved due to its potential impact on the native *Orobanche cernua* var. *australiana*. It would be of little value in the current branched broomrape eradication program as it attacks flowering stems after emergence and can only reduce, not totally prevent, seed production. Any biocontrol agent would will have difficulty persisting and increasing in South Australia, where branched broomrape populations are small, widely-scattered and ephemeral. Biological control is also an expensive option due to the high capital cost of host specificity testing, and the possible need for continued captive rearing for inundative releases.

Development of resistant crop cultivars

Resistance is the ability of a potential host plant to prevent the *Orobanche* making a functional attachment. Degrees of resistance or susceptibility vary within a host species and may be influenced by several factors, both heritable and non-heritable. Resistance in vetch is determined by anatomical characters that provide mechanical resistance to penetration by haustoria, and possibly also chemical characters (Goldwasser et al., 2000). Host plants react to the penetration of their tissues by an *Orobanche* haustorium via the same systems that detect invasion by pathogens (Joel & Portnoy, 1998); one such response is the formation of phytoalexins that stop haustorium growth (Wegmann et al., 1991). This is distinct from tolerance, the ability of a host to grow with minimum loss of nutrients to the *Orobanche.*

The production by potential host plants of the chemical stimuli that induce *Orobanche* seed germination is determined by genes in these plants. This implies a potential for breeding cultivars of susceptible crops that do not stimulate *Orobanche* germination. Strains of *Arabidopsis thaliana* with reduced ability to cause germination of *O. ramosa* seeds can be produced by artificial mutagenesis (Goldwasser & Yoder, 2001). However, no wild strains of *Arabidopsis* carrying such mutations were found.

Cultivars resistant to broomrape attachment have been bred overseas in some high-value crops, notably sunflower resistant to *O. cernua*. However, as *Orobanche* is an annual with a high *r,* it can evolve rapidly to overcome crop resistance. New resistant crop strains must be continually developed to keep pace with evolution in the parasite (eg, Fernández-Martínez et al., 2000).

Development of resistant cultivars is an expensive option, useful only as part of a broomrape management strategy in intensive, high-value cropping.

Induced Resistance

Resistance may be turned on in a normally susceptible crop strain by the right stimulus. For example, sunflower seeds exposed to benzothiadiazole subsequently germinate to produce plants with a high level of resistance to *O. cumana* attachment (Sauerborn et al., 2002). This is apparently due to the activation of a pre-existing defence pathway.

Pre-treatment of seed

The feasibility of controlling broomrape (*Orobanche crenata*) in broad bean (*Vicia faba*) and lentil (*Lens culinary*) by soaking seeds with imazethapyr and imazapyr before planting was investigated by Jurado-Exposito et al. (1997). Imazapyr gave 90% control in lentils, and imazethapyr gave 70% control in beans.

Germination inhibitors

As gibberellins and ethylene are synthesised during germination of *O. ramosa* (Zehar & Fer, 2001), compounds that inhibit this synthesis might be used to prevent germination in the field. This would not reduce the seed bank, but would allow cropping on infested land.

The herbicide chlortoluron also inhibits germination of *O. ramosa* seeds (Yordanova et al., 2001), but is not currently registered in Australia.

Mannitol metabolism

Many parasitic angiosperms, including *Orobanche*, store energy as the carbohydrate mannitol. On the other hand, host crops do not form this storage compound. There is an opportunity to develop chemical control techniques that target mannitol production in the parasite, for example by interfering with the action of the enzyme mannose 6-phosphate reductase (Robert et al., 1999).

More complete understanding of the developmental pathway of parasitism – and consequently the potential mechanisms of resistance - in the Orobanchaceae may lead to new approaches to engineering resistance in crops (Joel, 2000).

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APPENDIX

A comparison of techniques to reduce the soil seedbank of branched broomrape.

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Animal and Plant Control Commission
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The following is presented as a list of options for reducing the soil seedbank of branched broomrape, to achieve local eradication. In most cases formal measurements of seedbank reduction have not been done (due to methodological difficulties). Often assessments are based on numbers of emerged spikes only. Research in SA needs to include measurement of seedbank decline.

Note that a combination of techniques will probably be needed each year (e.g. fumigation plus broadleaf control) to minimise risks of broomrape seedset. Also note that seedbank decline is proportional (e.g., a technique which causes a 50% seedbank decline in the 1st year will leave 25% of seed if repeated in the 2nd year, 12.5% if repeated in the 3rd year, etc.). Some techniques still require research under SA conditions to examine their effectiveness and refine their application method.

Technique	**Effectiveness** • **Rate of seedbank decline?**	**Confidence in technique** • **Will it work in SA?** • **Needs refinement?** • **Difficulty for landholder?** • **Risk of broomrape seedset?**	**Relative cost** • **Cost of technique?** • **Any yield for farmer?**
Methyl Bromide fumigation - Legally must be done with plastic mulch in Australia	Very High - *"near-complete control when correctly applied" (in Parker and Riches)* - *350-500 kg/ha effectively controlled* O. ramosa *prior to planting tomato (Zahran 1970)*	High - *no emergence seen in past treated areas in SA*	High - *around $10,000/ha and methyl bromide becoming more expensive as being phased out* - *plastic mulch around $1750/ha* - *No alternative mulches (e.g. foam) being used in the USA, and would require significant $ and several years research to ID a possible alternative and have sufficient efficacy data for the National Registration*

			Authority (Peter Williamson, Fumigation Services of SA , pers. comm.)
Methyl isothiocyanate as high concentration fumigant - *Liquid: Metham sodium, Vapam* - *Granular: Basamid* - *in wet soil (broomrape seeds imbibed)*	Medium to High - *500 L/ha Vapam (metham sodium) provided excellent control of* O. minor *in tobacco and* O. crenata *in broad bean (Zahran 1970)* - *granular (dazomet) less effective than metham sodium (Zahran 1970)* - *metham sodium applied by chemigation reduced broomrape infestation by 50%, higher with polyethylene mulching (Goldwasser et al. 1994)* - *have used metham as a soil drench applied to undisturbed soil in the USA on branched broomrape and clover broomrape with apparent (but unmeasured) success*	Medium - *problems of volatilisation and microbial breakdown* ***Needs formal research comparison to methyl bromide in SA***	Medium to High - *higher with liquid application than granular* - *liquid injected into soil needs to be bladed in (as opposed to points for MeBr or Telone) which has high machinery breakage* - *plastic mulching more effective than trying to surface seal soils (by shallow cultivation, rolling and wetting)* - *Metham may need registration to use plastic, not registered for centre pivot irrigation*
1,3-dichloropropene fumigant - *e.g. Telone*	Medium to High - *successful control of* O. ramosa *been achieved (Jacobson et al. 1991)*	Medium to Low - *not been widely researched* - *not routinely used overseas* ***Needs formal research comparison to methyl bromide in SA***	**Medium to High** - *easier to apply than metham sodium (same machinery as MeBr)*
Methyl isothiocyanate as low concentration germination stimulant - *in wet soil*	Medium - *in Bulgaria, very low application rates of Vapam® = metham sodium (1.5-2 kg ai/ha) or Basamid® (30-40 kg/ha) are used to induce branched broomrape germination prior to planting tobacco. (Bozukov 1998, Chalakov 1998)*	Medium to Low - *methyl isothiocyanate has been shown to stimulate germination of* O. ramosa *(Zhelev 1987)* - *promising Bulgarian results as a low concentration germination stimulant have not been repeated in recent trials in other countries (Klaus Wegmann 2001 pers. comm.)*	**Medium to Low** - *higher with liquid application than granular, but still using lower rates than as a fumigant*

		Needs formal research to identify the critical concentration under field conditions in SA	
Nijmegen-1 Germination stimulant - CURRENTLY UNDER DEVELOPMENT - *in wet soil*	Medium to High - *promising initial results (e.g. 92% reduction in emerged spikes) in Mexico, but not in Bulgaria or Greece (Klaus Wegmann 2001 pers. comm.)*	Medium - *still being tested* ***Needs formal research (when becomes available) to identify the critical concentration under field conditions in SA***	**Medium (?)** - ***but not likely to be available for several years***
Sacrificial host crop - *e.g. Brassica* - *high sowing density* - *kill crop prior to broomrape emergence, by green manure (cultivate into soil) or glyphosate*	Medium - *92% reduction (in emergence?) over 3 years (98% 4 yrs) with berseem clover catch crop for* O. crenata *(Al-Menoufi 1991)* - *50% reduction (in emergence?) in one year for flax with* O. crenata *(Zahran 1982)* - *multiple catch crops in a year more effective than a single trap crop (Sauerborn1991)* - *around 30% of Orobanche seeds are likely to germinate in a trap or catch crop (Dhanapal et al. 1996, citing Linke and Sauerborn)*	High - *but need effective varieties and complete host control* - *need appropriate timing of crop kill* **Lab and Field research initiated (J. Virtue and J. Matthews) to identify Brassica varieties**	Medium - *no yield that year*
Sacrificial volunteer pasture - *allow weed hosts to grow* - *glyphosate spray just prior to broomrape emergence*	Medium to Low - *expect lower rates of branched broomrape germination than sowing a host crop, due to lower host density*	Medium to Low - *depends on weed hosts present and their density* - *need appropriate timing of broadleaves kill to avoid broomrape emergence*	Low to medium - *increased herbicide costs but do get some pasture yield prior to spraying* - *if using very low rate of glyphosate then may still get pasture growth post-spray*
Host crop/pasture with selective herbicide control of broomrape - *spray prior to*	Medium - *promising results from John Matthews trials* - *imi-herbicides has given selective control of broomrapes in sunflower (Garcia-Torres*	Medium to High - *need to ensure appropriate timing and probably need multiple herbicide applications*	Low - *increased herbicide costs but do get a yield*

broomrape emergence - *Group Bs or low rate glyphosate only* - *Clearfield or Roundup Ready canola* - *SU tolerant medic* - *NOT 2,4D or MCPA (still get broomrape emergence)*	*and Lopez-Granados 1991), faba beans and peas (Linke 1992) and cabbage (Americanos and Vouzounis 1995)* - *very low rates of glyphosate used in vetch (Nandula et al. 1999)* - *glyphosate resistant crops show good promise (Nandula et al. 1999)*	- *some crop-herbicide combinations may not give 100% control* - *risks of herbicide resistance with sustained use* **John Matthews GRDC field research now in 2nd year**	
False host crop - i.e. stimulate germination but not allow attachment - flax?, Popany vetch?	Medium - *62.5% reduction (in emergence?) over 3 years with trap crop for O. crenata (Linke et al. 1991a)* - *15-20% reduction per year for most effective trap crops (Linke et al. 1991b)* - *30% germination with trap crop (Sauerborn 1991)*	Medium to Low - *still need selective herbicide for host weeds in crop and any attachments to the false host* - *not absolute/failsafe and can get low levels of parasitism occurring (e.g. on flax and "resistant" vetches – Kleifeld et al. 1998)* **Popany vetch under current study**	Low - *increased herbicide costs but do get a yield (if can ID a suitable economic crop)*
Intensive sheep grazing in host pasture	Medium to Low - *similar to sacrificial pasture?*	Medium to Low - *depends on stocking rate and timing* - *broomrape may recover and/or plants may be missed*	Low - can have a sheep enterprise
Cereal crops/ grass pastures	Low - *limited stimulation of germination, unless allow broadleaf weeds to remain later in crop and sacrifice yield* - *few % decrease per year under fallow*	High - *not found broomrape in clean cereal crops*	Low - *increased herbicide costs but do get a yield*

	(Linke et al. 1991b)		
Post broomrape emergence spot treatments - *pre-flowering glyphosate* - *fire (+ diesel)* - *oils?* - *hand digging of non-seeding stems* - *NiproQuat?* - *<u>Not</u> paraquat/diquat (e.g. Sprayseed, Gramoxone) as can still have viable seed*	Medium to Low - *similar to sacrificial pasture?*	Low - *depends on finding and early action to prevent seed set* - *only for small infestations* - *needs be done at least every fortnight (preferably weekly)* **John Matthews GRDC field research**	Low - *labour in searching and treating*
Residual broadleaf herbicide + perennial grass revegetation	Low - *no stimulation of germination*	Medium - *if herbicide persistent (problem in sandy soils) and follow-up broadleaf herbicide when needed*	Medium - *herbicide cost and light grazing only to retain grass cover*
Soil inversion - moulboard plough	Medium - *80-90% reduction in infestation by trench ploughing 45-50cm deep for* O. ramosa *in tobacco in Eastern Europe (Parker and Riches 1993)*	Medium to Low - *have to be at end of a sequence of other techniques, with subsequent minimum tillage* - *may not work for light soil types* - *risk of soil drift*	Low - *unless rocky and/or shallow soil*
Revegetation with trees/shrubs - *broadleaf weed control in early years until get thick cover*	Low	Low - *what species will grow to sufficient density to exclude annual broadleaves?*	Medium to high - *expect low, long-term returns in the low rainfall environment*
Solarisation - *wet soil underneath*	Medium - *40 days polyethylene film solarisation got*	Medium	Medium to high - *cost of plastic application*

plastic - *added ammonium?*	*88-96% decrease in seedbank for* Orobanche *(Sprich et al. 1990) in top 5 cm soil*	**John Matthews GRDC field research**	
Nitrogen Fertiliser	Low - ammonium appears to inhibit the growth of the seedling radicle, rather than inhibiting the actual germination of *Orobanche* seed (Westwood and Foy 1999) - limited practical importance as a control measure for *O. crenata* (Dhanapal et al. 1996 citing Van Hezewijk)	Low	Medium - *increased yields through increased soil fertility*
Biocontrol	Low - *agents available only attack flowering stems, so will still get some seed production (which can't have if trying to eradicate)*	Low - *Biocontrol agents will have difficulty persisting and increasing as branched broomrape populations in SA are small, widely-scattered and ephemeral* - O. cernua *(our rare native broomrape) is attacked by the seed fly in Europe*	High - *high costs of host-testing* - *possible need for continuous rearing and inundative release*