Short- and long-term economic implications of controlling crenate broomrape (Orobanche crenata Forsk.) in broad bean (Vicia faba L.) under various management strategies

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An economic model is described and used to investigate the short- and long-term implications of controlling crenate broomrape (Orobanche crenata Forsk.) infestations in broad bean (Vicia faba L.) under different management strategies. These include no use of herbicide, applying herbicide once after an infection severity (IS: number of emerged broomrape m⁻²) ≥ 0.1, and applying herbicide every year. Crenate broomrape population evolution was affected by initial IS (IS₀) at the time of implementing the strategy, regardless of the management strategy adopted. Non-application of herbicide was satisfactory when initial infection was very low (IS₀ < 0.1) resulting in average annualized benefits (AB) of about 600 and 800 US $ ha⁻¹ after 3 and 9 years for early sowing dates, respectively. Applying herbicide once did not control parasite populations adequately and could only represent an acceptable low-cost alternative in the long term when IS ≤ 1 giving an AB of about 650 and 630 US $ ha⁻¹ after 3 and 9 years for early sowing dates, respectively. Annual application of herbicide was the best strategy against broomrape at any IS₀ to minimize crenate broomrape populations and obtain maximum net benefits per year regardless of broad bean cropping frequency. A sensitivity analysis was performed to determine the effect of changing the values of the main economic parameters (efficacy of the herbicide, expected yield, fixed and herbicide costs). In general, sensitivity coefficients were between 0.5 and 1, herbicide cost being the parameter which exerted the least effect on AB in all management strategies. Generally, an IS₀ ≤ 1 requires broomrape herbicide treatments in all subsequent broad bean crops in order to ensure economic benefits. © 1998 Elsevier Science Ltd. All rights reserved

Keywords: parasitic weed; planting date; cropping frequency; integrated control

Introduction

In the Mediterranean region, the Middle East and Eastern Europe the root parasitic weed Orobanche crenata causes considerable yield losses in legume crops, particularly in broad bean, peas (Pisum sativum L.) and lentils (Lens culinaris Medik.) (Parker, 1994). An integrated control scheme has to include several control measures that are both effective and economically feasible. Reducing the broad bean cropping frequency increases the number of years required to obtain the maximum crenate broomrape IS but not its absolute value (López-Granados and García-Torres, 1997). Delaying sowing from October to December, although consistently decreasing yield, is a commonly adopted measure for reducing crenate infestation in the Mediterranean area (Raaimakers et al., 1988; Van Hezewijk, 1994). Lowering cropping frequency, delaying sowing and spraying selective herbicide against broomrape, are often included in integrated schemes for broomrape control (Nassib et al., 1984). However, no information is available integrating these all three approaches on a short and long-term basis.

The construction of bio-economic models is a useful technique to assess the economic implications of control strategies. Several authors have made contributions to the evaluation of weed management strategies in order to determine the economic threshold of weed infestation for spraying herbicide or not (Doyle et al., 1986; King et al., 1986; González-Andújar and Fernández-Quintanilla, 1993). Models for the growth of broad bean and its interaction with broomrape and dependence on environmental, and the population dynamics of crenate broomrape in broad bean as affected by planting dates and cropping frequency have been reported (Kropff and Schippers, 1986; López-Granados and García-Torres, 1993a, 1993b, 1997). The objective of this study was...
to construct an economic model of crenate broomrape growing in broad bean in order to assess the short- and long-term implications of controlling broomrape infestations under several management strategies.

**Description of the model**

The presence of crenate broomrape reduces the growth and yield of broad bean crop bean. In selecting the appropriate weed management strategy, the broad bean grower is assumed to be concerned to maximize his annualized benefits ($AB$, US $\text{ha}^{-1}$), i.e. the value of the broad bean crop minus the costs of production.

The economic model was constructed by integrating the demographic and competition sub-models. Demographic cycle under different sowing dates and cropping frequencies has been closely described by the sigmoidal model: $IS_0 = A/(1+e^{-m-c})$, where $A$ is the asymptotic value reached at highest weed density, $B$ is the initial IS (time = 0) and $C$ the point of inflection or IS value corresponding to 50% of the maximum IS (Lopez-Granados and Garcia-Torres, 1993b, 1997). The annualized benefit ($AB$) for any control strategy may therefore be expressed as:

$$AB(t) = B_p Y_{max}(1-Y_t/100(1-f))-D_F-D_H. \quad (1)$$

where $B_p$ is the broad bean price (US $\text{kg}^{-1}$), $Y_{max}$ the expected weed-free broad bean crop yield (kg ha$^{-1}$), $Y_t$ the % of yield losses due to broomrape as previously described ($Y_t = 100$ IS, 0.124, from Mesa-Garcia and Garcia-Torres, 1984), $f$ the efficacy of the herbicide treatment, $D_F$ fixed costs and $D_H$ herbicide cost. If no herbicide treatment is used the previous equation is simplified as follows:

$$AB(t) = B_p Y_{max}(1-0.124IS_0)-D_F. \quad (2)$$

Annualized net return ($AN$) is given by the difference between $AB$ none and $AB$ once or every year. The meaning of all the symbols are given in the following text and in Appendix.

The following values have been ascribed to the described parameters according to current prices and costs for a standard farm in Southern Spain in 1997. Thus, $B_p$ = US $0.27$ kg$^{-1}$, and $Y_{max}$ 2800 and 2500 kg ha$^{-1}$ for early and late planting date, respectively; $D_F$ = US $69$ ha$^{-1}$ (pre-tillage sowing, US $23$ ha$^{-1}$; seed and sowing, US $23$ ha$^{-1}$; and general weed control, US $23$ ha$^{-1}$); $D_H$ = US $38.5$ ha$^{-1}$, equivalent to one application of a preemergence (imazethapyr 75 g ha$^{-1}$ from García-Torres and Lopez-Granados, 1991) and of a postemergence herbicide treatment (glyphosate 40 g ha$^{-1}$ from Mesa García and García-Torres, 1985). The efficacy of the herbicides treatments considered was 90%.

**Crenate broomrape management strategies**

Twelve management strategies were evaluated for the early and late sowing as follows:

**Early sowing date:**

1. Annual broad bean cropping:
   1a. No herbicide application.
   1b. Herbicide applied one year after detecting initial infestation.
   1c. Herbicide applied every year.
2. Triennial cropping:
   2a. No herbicide application.
   2b. Herbicide applied one year after detecting initial infestation.
   2c. Herbicide applied every year.

**Late sowing date:**

3. Annual broad bean cropping:
   3a. No herbicide application.
   3b. Herbicide applied one year after detecting initial infestation.
   3c. Herbicide applied every year.
4. Triennial cropping:
   4a. No herbicide application.
   4b. Herbicide applied one year after detecting initial infestation.
   4c. Herbicide applied every year.

The economic evaluation was made for any of the cropping strategies mentioned above assuming three initial broomrape infestations ($IS_0$, year 0) of 0.1, 1 and 5 emerged broomrape m$^{-2}$. However, insofar as the level of broomrape control in the immediate harvest year will also have implications for the parasitic weed levels in subsequent years, it seems reasonable to consider a rather longer period of time, say 3 (short-) and 9 (long-term) subsequent years for consecutive and triennial cropping, respectively. The relevance of the long-run viewpoint is underlined by the observation that many farmers base their decisions about herbicide application on the need to avoid a future build-up of weed populations. Changes in costs and input prices were considered the same for all years.

**Model sensitivity to parameter variation**

A sensitivity analysis was performed in order to assess the robustness of the $AB$ varying the following parameters: efficacy of the herbicide ($f$); broad bean yield level ($Y$); fixed costs ($D_F$); herbicide cost ($D_H$). Each parameter value varied by $\pm 15\%$, except $f$ which changed by $+6$ and $-15\%$. Sensitivity coefficients ($SC$) were calculated as the ratio between proportional changes in simulation results (output of the model) and in each parameter:

$$(\text{Aoutput/output})/(\text{Aparameter/parameter}).$$

$SC$ were calculated assuming that initial broomrape population was $IS_0 = 0.1, 1$ and 5.

**Results**

Final broomrape populations ($IS$), expected average broad bean yield ($Y$), annualized benefits ($AB$) and
annualized net returns (AN) are shown in Table 1 for the twelve management strategies described. Expected $AB$ were 686 and 604 US $ ha^{-1}$ when $IS = 0$ for early and late sowing date and no herbicide use, respectively (equation 2).

Non-application of herbicide

$IS$ under any of these strategies rapidly reached very high levels. For every sowing date when $IS_0 = 0.1$, the growth rate of the weed population over a 3 and 9-year period was significantly lower, in comparison to higher $IS_0$, and final $IS$ was low (between 10 and 18 emerged broomrape $m^{-2}$). $AB$ were still high (between 600 and 480 US $ ha^{-1}$), and ensured small broad bean losses ($Y > 2$ thousand kg $ha^{-1}$). However, when $IS_0 \geq 1$, broomrape population reached in 3 or 9 years the asymptotic values $IS = 62$ and 31 for early and late sowing dates, respectively, described by López-Granados and Garcia-Torres (1997), and resulting in a nearly total yield losses ($0.3-1.2$ thousand kg $ha^{-1}$). For example, $Y = 0$ for early sowing date, every year cropping frequency and $IS_0 = 5$ emerged broomrape $m^{-2}$.

Under late sowing and triennial cropping, the maximum $IS$ reached remained low (around 16 emerged broomrape $m^{-2}$) and $AB$ were still high (475 and 431 US $ ha^{-1}$). For every year cropping the lowest $AB$ was reached, with only 24 US $ ha^{-1}$ after 3 years.

One herbicide application

Pre or post-emergence herbicides were applied the following year after infections of crenate broomrape were observed. When $IS_0 \leq 1$, these strategies provided an economically acceptable means of keeping the broomrape population at a low level ($IS$ between 3 and 18) for low initial populations. When $IS_0 = 0.1$, differences for $AN$ were very low under all of these strategies (between 50 and 73 US $ ha^{-1}$) because the resulting simulated yield for any cropping frequency (2.7 and 2.3 thousand kg $ ha^{-1}$ for early and late sowing date, respectively) were very close to the broomrape-free expected yield (2.8 and 2.5 thousand kg $ ha^{-1}$ for early and late sowing date, respectively).

Differences between $AN$ were remarkable especially for $IS_0 = 1$ for early sowing date and any cropping frequency, giving an $AN$ of 464 and 296 US $ ha^{-1}$, respectively. Under these strategies the $AB$ was considerably higher (namely 565 and 589 US $ ha^{-1}$, respectively) than that obtained with no herbicide application (153 and 293 US $ ha^{-1}$, respectively) since the broad bean crop achieved its potential yield due to the herbicide use. For $IS_0 = 5$, any sowing date and annual broad bean cropping resulted in a very low yield (0.6 and 1.2 thousand kg $ ha^{-1}$ for early and late sowing date, respectively) and an $IS$ as high as that obtained with no herbicide treatment (62 and 31 emerged broomrape $m^{-2}$ for early and late sowing date, respectively).

Every year herbicide application

Under any of these strategies broomrape populations were kept at an unnoticed level (between 0.02 and 0.0003 emerged broomrape $m^{-2}$), and consequently economic losses were negligible. However, it should be pointed out that for annual broad bean cropping for early sowing date, when initial broomrape infestations were high ($IS_0 \geq 3$), yield was much lower (around 2 thousand kg $ ha^{-1}$) than for lower $IS_0$. Consequently, maximum $AN$ (536 $US \ ha^{-1}$) was reached when $IS_0 = 0.1$ emerged broomrape $m^{-2}$.

Model sensitivity to parameter variation

SC are shown in Table 2 for $IS_0 = 1$ emerged broomrape $m^{-2}$, for higher and lower initial populations $SC$

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Table 1: Estimated broomrape populations (IS: number of emerged broomrape $m^{-2}$), average broad bean yield, annualized benefits and net returns as affected by different initial broomrape infestations and management strategies

<table>
<thead>
<tr>
<th>Sowing date</th>
<th>Cropping frequency</th>
<th>IS0</th>
<th>IS*</th>
<th>AB*</th>
<th>Y</th>
<th>AN</th>
<th>AN</th>
<th>IS0</th>
<th>IS*</th>
<th>AB*</th>
<th>Y</th>
<th>AN</th>
<th>AN</th>
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<th>AB*</th>
<th>Y</th>
<th>AN</th>
<th>AN</th>
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<tbody>
<tr>
<td>Early</td>
<td>Annual</td>
<td>0.1</td>
<td>18</td>
<td>2.5 ± 0.5</td>
<td>600 ± 128</td>
<td>4.6</td>
<td>2.7 ± 0.1</td>
<td>653 ± 30</td>
<td>53</td>
<td>0.0003</td>
<td>2.8 ± 0.07</td>
<td>654 ± 14</td>
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<tr>
<td></td>
<td>1</td>
<td>62</td>
<td>0.6 ± 0.03</td>
<td>153 ± 266</td>
<td>18</td>
<td>2.4 ± 0.5</td>
<td>565 ± 124</td>
<td>464</td>
<td>0.004</td>
<td>2.8 ± 0.01</td>
<td>637 ± 13</td>
<td>536</td>
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<tr>
<td></td>
<td>5</td>
<td>62</td>
<td>0 ± 0</td>
<td>101 ± 266</td>
<td>62</td>
<td>0.6 ± 11</td>
<td>153 ± 266</td>
<td>52</td>
<td>0.06</td>
<td>2 ± 0.06</td>
<td>456 ± 12</td>
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<tr>
<td>Triennial</td>
<td>0.1</td>
<td>16</td>
<td>2.2 ± 0.4</td>
<td>505 ± 100</td>
<td>4</td>
<td>2.7 ± 0.09</td>
<td>630 ± 38</td>
<td>65</td>
<td>0.0003</td>
<td>2.8 ± 0.1</td>
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<tr>
<td></td>
<td>1</td>
<td>62</td>
<td>1.2 ± 1.2</td>
<td>293 ± 295</td>
<td>12</td>
<td>2.5 ± 0.3</td>
<td>589 ± 0.1</td>
<td>296</td>
<td>0.003</td>
<td>2.6 ± 0.03</td>
<td>642 ± 10</td>
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<tr>
<td></td>
<td>5</td>
<td>62</td>
<td>0.3 ± 0.6</td>
<td>293 ± 405</td>
<td>28</td>
<td>1.9 ± 0.1</td>
<td>431 ± 98</td>
<td>138</td>
<td>0.02</td>
<td>2.4 ± 0.02</td>
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<tr>
<td>Late</td>
<td>Annual</td>
<td>0.1</td>
<td>12</td>
<td>2 ± 0.2</td>
<td>480 ± 66</td>
<td>8.3</td>
<td>2.5 ± 0.2</td>
<td>553 ± 44</td>
<td>73</td>
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<td>1</td>
<td>31</td>
<td>1.2 ± 0.6</td>
<td>235 ± 160</td>
<td>12</td>
<td>2.2 ± 0.3</td>
<td>513 ± 64</td>
<td>278</td>
<td>0.006</td>
<td>2.4 ± 0.1</td>
<td>550 ± 21</td>
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<td></td>
<td>5</td>
<td>31</td>
<td>0.8 ± 0.5</td>
<td>24 ± 42</td>
<td>31</td>
<td>1.2 ± 0.6</td>
<td>254 ± 154</td>
<td>230</td>
<td>0.03</td>
<td>2 ± 0.7</td>
<td>452 ± 171</td>
<td>428</td>
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<tr>
<td>Triennial</td>
<td>0.1</td>
<td>10</td>
<td>2.1 ± 0.1</td>
<td>506 ± 36</td>
<td>3</td>
<td>2.3 ± 0.07</td>
<td>556 ± 5</td>
<td>50</td>
<td>0.003</td>
<td>2.5 ± 0.07</td>
<td>564 ± 20</td>
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<tr>
<td></td>
<td>1</td>
<td>16</td>
<td>2 ± 0.3</td>
<td>475 ± 70</td>
<td>6</td>
<td>2.7 ± 0.4</td>
<td>541 ± 66</td>
<td>66</td>
<td>0.03</td>
<td>2.5 ± 0.1</td>
<td>563 ± 8</td>
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<td></td>
<td>5</td>
<td>17</td>
<td>1.9 ± 0.2</td>
<td>431 ± 57</td>
<td>12</td>
<td>2.2 ± 0.2</td>
<td>506 ± 51</td>
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<td>2.4 ± 0.2</td>
<td>546 ± 28</td>
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*Initial crenate broomrape populations
*Final crenate broomrape populations
Average broad bean yield (thousand kg $ ha^{-1}$)
Average net returns (US $ ha^{-1}$)
Annualized net return (US $ ha^{-1}$)
= means the standard deviation of the averaged values
$AB$ applied once after $IS_0 \geq 0.1$ emerged broomrape $m^{-2}$
were similar. In general, the effect of modifying parameter values was low, showing in most cases a $SC<1$. Further, no differences were observed in $SC$ between early or late sowing dates.

Although the efficiency of herbicide control ($f$) was assumed to be 90%, the efficiency reported varied from 75% to 96% depending on cropping systems, environmental conditions and herbicide rates (García-Torres and López-Granados, 1991); values of $SC$ varying this parameter were more pronounced (between 0.25 and 2.34) when herbicide was applied once than for herbicide applied every year ($SC$ ranged 0 and 0.95). The variation of the average broad bean yield (2.8 and 2.5 thousand kg ha$^{-1}$ for early and late sowing date, respectively) considerably affected the annualized benefit for all strategies ($SC$ ranged between 0.6 and 1.6). In general, the model proved to have a very low sensitivity to variations in fixed and herbicide costs ($D_F$ and $D_{H}$, respectively) with an $SC$ ranging between 0.01 and 0.53. Furthermore, changing $D_{H}$ had the least effect on $AB$ in all strategies.

### Table 2. Sensitivity coefficients [$SC = \Delta (V/P)/\Delta (P/P)$ where $V$ and $P$ are model variable and parameters] for one model output variable, $AB$; annualized benefits, to positive and negative changes (%) in herbicide control ($f$: $+6$, $-15$), broad bean yield ($Y$: $+15$, $-15$), fixed costs ($D_F$: $+15$, $-15$) and herbicide cost ($D_{H}$: $+15$, $-15$). Values of $SC$ were calculated using simulated results from economic model for twelve broad bean management strategies

<table>
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<th>Parameter</th>
<th>Herbicide application</th>
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<td>$f$</td>
<td>None</td>
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<td></td>
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<td>$Y$</td>
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<td>$D_{H}$</td>
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</table>

*Herbicide applied once after $IS_0>0.1$ emerged broomrape m$^{-2}$

### Discussion

The economic model described here offers practical guidance for evaluating crenate broomrape management strategies, with the usual limitation of deterministic models. According to our simulated results, when $IS_0 \leq 1$ early sowing date and annual herbicide application were the best weed management strategies because crenate broomrape populations were kept under control ($IS \leq 0.006$), broad bean yield were very acceptable (2.8 thousand kg ha$^{-1}$) and the annualized net returns were the highest (536 US $ ha^{-1}$). However, these strategies would not be followed by broad bean growers in the Mediterranean area because the low productivity of these systems would not justify major input use.

Spraying herbicide once following $IS_0 \geq 1$ did not generally result in a sufficient crenate broomrape control, since final $IS$ varied between 3 and 62 emerged broomrape m$^{-2}$ for the different management strategies although when $IS_0$ was around 1 emerged broomrape m$^{-2}$, the economic penalties were not very heavy.

The repeated use of imidazolinones leads to biotype resistance problems in many weed species, i.e. *Avena fatua*, *A. bulbosa*, *Centaurea cyanus*, *Chenopodium album* and *Xanthium strumarium* (Herker et al., 1995; Konstantinovic and Milosevic, 1995) and this could also be the case for broomrape. This factor plus the reluctance of the farmer to use herbicide every year should be taken into consideration when deciding the parasite management strategy. Late sowing date, triennial cropping and non-application of herbicide, have been traditional practices of broad bean farmers in the Mediterranean area. However, it has been proved an acceptable low-input alternative when $IS_0 \leq 5$ emerged broomrape m$^{-2}$. The same crenate broomrape management for early sowing date, proved insufficient because it failed to control broomrape populations.

According to the results presented here, the economic threshold for herbicide use was around 1 emerged broomrape m$^{-2}$. Simulations from this model have not been validated with experimental results. However, field studies performed for modelling the economics of controlling *O. cernua* Loefl. in sunflowers (*Helianthus annuus* L.), showed that the economic threshold was about 1.5 emerged broomrape m$^{-2}$ for potential yield of 2 thousand kg ha$^{-1}$. This was affected by the crop yield potential and weed control treatment efficiency (García-Torres et al., 1996). The cropping frequency appeared to have little influence on the final weed density, the important factor for deciding the weed management strategy was the $IS_0$. If no herbicide is used for $IS_0 > 1$, early sowing dates produced heavy yield losses and crenate broomrape populations promptly reached the asymptotic value reported by López-Granados and García-Torres (1997). For the same management strategy, annualized net returns were lower for late sowing date than those obtained in earlier planting dates and this indicates that generally early sowing dates should be recommended.
Acknowledgements

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Appendix

Definition of symbols

Independent variables

\( t \) = time (years)

Variables

\( I_{S_0} \) = initial infection severity (emerged broomrapes m\(^{-2}\))
\( Y_{\text{mon}} \) = expected weed-free broad bean yield (thousand kg ha\(^{-1}\))
\( Y \) = broad bean yield (thousand kg ha\(^{-1}\))
\( Y_1 \) = percentage of yield losses due to broomrape
\( AB \) = annualized benefits (US $ ha\(^{-1}\))
\( B_p \) = broad bean price (US $ kg\(^{-1}\))
\( D_t \) = fixed costs (US $ ha\(^{-1}\))
\( D_{11} \) = herbicide costs (US $ ha\(^{-1}\))
\( AN \) = annualized net return (US $ ha\(^{-1}\))

Parameters

\( f \) = efficacy of the herbicide treatment
\( A \) = asymptotic value reached at highest weed density
\( B \) = initial infection severity (time = 0)
\( C \) = point of infection or infection severity value corresponding to 50% of the maximum infection severity
\( SC \) = sensitivity coefficients

References


Van Hezewijk, M. J. Relationship between sowing date and Orobanche (broomrape) development in faba bean (Vicia faba L.) and lentil (Lens culinaris Medikus) in Syria. PhD Thesis Vrije Universiteit Amsterdam pp. 63-79.

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