Competition between *Avena sterilis* ssp. *sterilis* and wheat in South Western Spain

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**Abstract**

*Avena sterilis* ssp. *sterilis* has different growth and demographic characteristics than other weedy taxa of *Avena*. Preliminary studies have shown that wheat yield losses caused by this species were larger than those produced by the ssp. *ludoviciana*. These losses were estimated experimentally in 19 wheat fields distributed throughout western Andalusia. The relationship between *A. sterilis* ssp. *sterilis* density per square meter and the wheat grain weight was estimated using several simple models. The results obtained confirm that this weed species was tremendously competitive even at low densities, obtaining wheat yield losses up to 70 kg ha⁻¹ panicle⁻¹ m⁻². The potential crop yield of the field was considered as an important factor to estimate the yield losses. A relationship between the expected weed-free yield of wheat and the yield loss per panicle of *A. sterilis* ssp. *sterilis* was used to determine the economic threshold. This threshold ranged from 4 to 81 panicles m⁻² depending on the potential yield of each field. Farmers with high potential yields (> 6,000 kg ha⁻¹) should treat their fields if *A. sterilis* density is above 10 panicles m⁻². Farmers with low potential yields (< 3,000 kg ha⁻¹) should not apply any herbicide control to their fields whatever the infestation density. And if the potential yields are between 3,000 and 6,000 kg ha⁻¹ they should estimate the economic threshold value from the exponential equation described in this work.

**Additional key words**: economic threshold; linear model; weed-crop competition; weed density; wild oat; yield loss.

**Resumen**

Competencia entre *Avena sterilis* subsp. *sterilis* y trigo en el suroeste de España.

*Avena sterilis* ssp. *sterilis* tiene diferente crecimiento y características demográficas que otros taxones de malas hierbas del género *Avena*. Estudios preliminares han demostrado que las pérdidas de rendimiento del trigo causadas por esta subespecie fueron mayores que las producidas por la subespecie *ludoviciana*. Estas pérdidas se estimaron de forma experimental en 19 campos de trigo distribuidos por el oeste de Andalucía. La relación entre la densidad de *A. sterilis* ssp. *sterilis* por metro cuadrado y el peso del grano de trigo se estimó mediante modelos de regresión. Los resultados obtenidos confirman que esta especie de mala hierba fue tremendamente competitiva, incluso a bajas densidades, obteniéndose pérdidas de rendimiento del trigo de hasta 70 kg ha⁻¹ panícula⁻¹ m⁻². El rendimiento potencial del campo fue un factor importante para estimar las pérdidas de rendimiento. Con objeto de determinar el umbral económico, se estableció una relación entre el rendimiento esperado de trigo libre de malas hierbas y la pérdida de rendimiento por panícula de *A. sterilis* ssp. *sterilis*. Dicho umbral económico osciló entre 4 y 81 panículas m⁻² en función del potencial de rendimiento de cada campo. Rendimientos potenciales mayores de 6.000 kg ha⁻¹ requerirán tratamiento cuando la densidad de *A. sterilis* supere las 10 panículas m⁻². Rendimientos potenciales menores de 3.000 kg ha⁻¹ no requerirán tratamiento cualquiera que sea la densidad de infestación. Y con rendimientos potenciales comprendidos entre 3.000 and 6.000 kg ha⁻¹, se deberá estimar el umbral de tratamiento de la ecuación exponencial descrita en este trabajo.

**Palabras clave adicionales**: avena loca; competencia mala hierba-cultivo; densidad de malas hierbas; modelo lineal; pérdida de rendimiento; umbral económico.
Introduction

The genus *Avena* L. includes several species which are important crop and pasture weeds throughout the world, causing major crop losses. In Spain, these species include *Avena fatua* L., *Avena sterilis* ssp. *ludoviciana* (Durieu) Nyman and *Avena sterilis* ssp. *sterilis* L. (Syn. *Avena macrocarpa* Moench) in cereal crops and *Avena barbata* Pott ex. Link in pastures and roadsides (Carretero, 2004). Plants of the four taxa are very robust, reaching up to 150 cm tall, and they are highly competitive (Fernández-Quintanilla et al., 1997). *Avena fatua* is mainly found in the North, with cooler weather. Although *A. sterilis* ssp. *ludoviciana* is found all over Spain, it is most abundant in the Central and North. Apparently, it is better adapted to harsh winters (Fernández-Quintanilla et al., 1997), being very rare in the South (Romero-Zarco, 1987). *A. sterilis* ssp. *sterilis* is apparently more thermophilic, infest cereal fields in the south and west of Spain (Garcia-Baudín and Salto, 1978; Fernández-Quintanilla et al., 1997).

In western Andalucia, *A. sterilis* ssp. *sterilis* has been reported as the most important grass weed in cereals, with 58.8% of the cereal fields being infested by this species (Saavedra et al., 1989), although infestations were widespread, densities were very low in most sites. However in this area it is rare to find subspecies *ludoviciana*. In contrast, in eastern Andalusia, where the two *Avena sterilis* subspecies coexisted, *A. ludoviciana* was more frequent and presented higher plant densities (Saavedra et al., 1989). However, both subspecies are clearly distinguishable by the sizes of their vegetative and reproductive traits. Although numerous studies have been conducted on the competition and population dynamics of *A. fatua* and *A. sterilis* ssp. *ludoviciana* (Scursoni and Satorre, 2005; González-Díaz et al., 2007; Dadnia et al., 2009), only a few studies have been published on *A. sterilis* ssp. *sterilis* (Madeira et al., 1984; González-Ponce, 1988; Saavedra et al., 1990; Palma et al., 1990, 1991; González-Ponce and Santin, 2001). According with these studies, the competitive ability and the population growth rates of *A. sterilis* are higher than for *A. ludoviciana*. This fact is perceived by farmers in western Andalucia that generally apply more selective herbicides to control this weed than in the rest of Spain.

Competition between *Avena* spp. and cereal crops is a complex process that involves many different factors. Numerous authors have shown the large effect of *Avena* spp. density on crop yield (Torner et al., 1991; Murphy et al., 2002; Scursoni and Satorre, 2005). Crop density is another important factor: weed competition increases when crop densities are low, increasing yield losses, favoring the production of *Avena* seeds and increasing medium-long term infestations (Wilson et al., 1990; Torner et al., 1991). Weed emergence time also influences the competition process: *Avena* plants emerged earlier are more competitive than late emerging plants (Martin and Field, 1988). The crop species (and variety) is other factor: barley is generally considered more competitive than wheat (Torner et al., 1985; Cousens et al., 1991; Satorre and Snaydon, 1992) and among the wheat varieties, tall varieties are more competitive than semi-dwarf varieties (González-Ponce and Santin, 2001). In relation to soil fertility, Ruiz et al. (2008) found differences in biomass production of *A. sterilis* ssp. *ludoviciana* depending on soil texture, organic matter and nitrogen content. Climatic factors also have an important effect. Torner et al. (1991) estimated different crop losses in barley attributable to differences in the amount and distribution of rainfall. González-Ponce and Santin (2001) studying competition between wheat varieties and *A. sterilis* ssp. *sterilis* found that nitrogen fertilization benefited the growth and seed production in both species, being this response greater in wet years than in dry years.

Previous competition studies conducted with *A. sterilis* ssp. *sterilis* and wheat have yielded inconclusive results (Madeira et al., 1984; Saavedra et al., 1990). Apparently, various factors may be involved in the interference process between these two plants, resulting in variable effects. This study was conducted to obtain a reliable estimation of crop losses attributable to this species in the wheat fields of Western Andalusia through a simple model, trying to identify the possible factors that have most influence on this competition process.

Material and methods

The studies were conducted in three season 1986-87, 1987-88 and 1988-89 in nineteen dry-land winter wheat (*Triticum aestivum*) fields distributed throughout Western Andalusia (Southern Spain), using natural infestations of *A. sterilis* ssp. *sterilis* ("sterile oat") (Fig. 1). The cropping system in all fields consisted of a wheat-sunflower rotation with not too intensive tillage (one or two disk plough passes followed by one or two harrow passes) which have not changed in recent decades. In each field, in an area between 2 and 5 ha,
plots from 200 to 1,000 m² were chosen carefully, with homogeneous soil and slope, avoiding valleys and hills. These plots had A. sterilis ssp. sterilis patches exclusively. Throughout the crop cycle it was checked that there were not changes or inconsistencies neither in the plots nor in the crop due to agronomic factors or diseases. Winter wheat growing practices were standard for that area. Sowing took place between November 15th and December 10th, at doses of 150-180 kg ha⁻¹ in rows 17 cm apart. Main cultivars used were Cañeme, Yecora and Anza, all with similar growth patterns. Soil was fertilized at about 50 to 70 kg N₂ ha⁻¹ and 100 kg P₂O₅ ha⁻¹ at the sowing time and similar amount of N₂ in the tillering growth stage. Phenoxy-type or sulfonylureas postemergence herbicides were applied in middle February-early March for the control of broadleaf weeds. Harvesting time was early June. Rainfall during the growing season (15/Nov-10/June) varied among years and locations, ranging from 300 to 560 mm (Fig. 2). Soils varied between clay to clay loam texture, with pH between 7.5 and 8.2.

**Wheat and weed samplings**

The first year (1987), two fields (Cañete and Carlota) were sampled, with 6 plots on each field. In each plot, 20 samples of 1 m² were taken, with densities...
of *A. sterilis* ssp. *sterilis* varying from 0 plants m\(^{-2}\) (4 samples) to more than 40 plants m\(^{-2}\) (16 samples). Three crop variables (number of stems with ears, aerial dry weight and grain weight) and five weed variables (number of plants, number of panicles, aerial dry weight, number of spikelets per panicle and total number of spikelets) were analyzed. The second year (1988), seven fields (Écija, Osuna, Fuente Palmera, Bujalance, Castro, Alcolea and Sta. Cruz) were sampled. The first field had 5 plots and the rest of them had 2 or 3 plots on each field. In each plot, the samples were taken as in the previous year. In each sample, wheat yield, number of *A. sterilis* ssp. *sterilis* plants and panicles and number of spikelets per panicle were determined. In Écija we also determined the biomass and number of tillers of wheat and the biomass of the weed. The third year (1989), ten fields (Marchena, Santaella, Trebujena, Utrera, El Arahal, Bujalance, Espojo, Fernán Núñez, San Sebastián de los Ballesteros and Arjona) (Fig. 1) were sampled with a single plot per field. In each plot, between 15 and 18 pairs of samples of 1 m\(^2\) were taken. Each pair consisted in one sample taken in an area with 0 density of *A. sterilis* ssp. *sterilis* plants and the other sample took in a near area with low density of the weed species (between 1 and 37 panicles m\(^{-2}\)). In each sample, wheat yield, number of *A. sterilis* ssp. *sterilis* panicles, spikelets and number of spikelets per panicle were determined. The different methodology in the third year of study was based on the previous year results to try to get more information in weed competition in the range of low densities. All samples in the three seasons were obtained a few days before harvest.

**Data analysis**

The relationship between the different variables measured for *A. sterilis* ssp. *sterilis* and wheat the first year (in all fields) and in the second year (only in the Ecija field) was studied through a correlation analysis (Pearson correlation). In the three years of study, regression techniques were used to relate *A. sterilis* ssp. *sterilis* panicle density and wheat yield. Three empirical models where fitted to the data to explain and quantify the competitive relationship.

The equations used were:

\[
Y = Y_o - bX \quad \text{Linear} \quad [1]
\]

\[
Y = Y_o e^{-cX} \quad \text{Exponential} \quad [2]
\]

\[
Y = Y_o \left\{ 1 - \left[ iX/100(1+iX/a) \right] \right\}
\]

**Rectangular hyperbola** [3]

where \(Y\) is the yield obtained in the presence of *A. sterilis* ssp. *sterilis* (kg ha\(^{-1}\)), \(Y_o\) is the weed-free yield (kg ha\(^{-1}\)), \(X\) is *A. sterilis* ssp. *sterilis* density (panicles m\(^{-2}\)), \(b\) is the yield loss per weed density unit, \(c\) estimates the rate of reduction in crop yield as *A. sterilis* ssp. *sterilis* infestation increases, \(i\) is the yield loss per weed density unit as weed density approaches zero, and \(a\) is the yield loss as weed density approaches infinity. The models were fitted to data, which were not transformed, using the statistic program R v. 2.11 (R Core Development Team, 2009, http://www.R-project.org). The AICc (Akaike’s Information Criterion corrected) was used as a measure of the fit of the models. The relationship between the parameters \(Y_o\) and \(b\) of the linear model equation were studied through regression techniques with the same R program mentioned above, adjusting an exponential equation.

The economic threshold (ET), which represents the weed density at which the cost of treatment equals the economic benefit obtained from that treatment, was calculated according to the equation proposed by and Fernández-Quintanilla and García-Torres (1991):

\[
ET = C * 10,000 / \left( b * Y_o * P * K \right) \quad [4]
\]

where \(C\) is the cost of control (€ ha\(^{-1}\)), \(b\) and \(Y_o\) were defined previously, \(P\) is the price of the crop (€ kg\(^{-1}\)) and \(K\) is the efficiency of control (%). To calculate the ET a constant wheat price (€ 0.232 kg\(^{-1}\)) (MARM, 2009), an average herbicide treatment cost of € 45 ha\(^{-1}\), and a percentage of efficiency (98%) was assumed. The \(C\) value estimated came from the average of the two most widely post emergence herbicides used for *Avena* spp. in the area [0.6% iodosulfuron-methyl-sodium and 3% mesosulfuron methyl (Atlantis®WR, Bayer) and 24% clodinafop-proparguil (Topik®, Syngenta)] plus the application cost (€ 6.61 ha\(^{-1}\)) (Barroso et al., 2004). Label rates for these herbicides are: Atlantis, 300-500 g ha\(^{-1}\) and Topik, 200-250 g ha\(^{-1}\), and their prizes in Spain per kg of product are € 135 and € 220 respectively. Finally, the relationship between the ET and the potential yield was established through regression techniques, adjusting an exponential equation.

**Results**

The first two years of the study *A. sterilis* ssp. *sterilis* densities were moderate, with not many patches with densities above 50 panicles m\(^{-2}\) and few samples ex-
ceeding 100 panicles m\(^{-2}\). The average density per field ranged between 15 and 38 panicles m\(^{-2}\) and the average spikelet production per panicle ranged between 8 and 31 (Table 1). Cañete was the field with lowest values in all the \textit{A. sterilis} spp. variables (81.3 g m\(^{-2}\) of biomass, 1.4 panicles per plant and 8 spikelets per panicle), indicating that this weed was less competitive in this site. The third year of study \textit{A. sterilis} spp. densities were relatively low in all sites, the mean values per field ranged between 7.35 and 10.81 panicles m\(^{-2}\). The mean number of spikelets per panicle ranged between 9.36 and 24.42 (Table 2). In 1987 and 1989, the fields with the highest density of panicles per square meter also had the lowest number of spikelets per panicle.

Average weed-free wheat yields ranged from 1,565 kg ha\(^{-1}\) (field I of year 3) to 7,700 kg ha\(^{-1}\) (Field Sta.Cruz, plot 2 of year 1988). The largest yields were obtained in the second year, with the highest rainfall (Fig. 2).

For \textit{A. sterilis} spp. \textit{sterilis}, very high positive correlations were obtained among numbers of plants, numbers of panicles, numbers of spikelets and aerial biomass (Table 3). However, the correlation between number of plants and number of panicles per plant was negative and significant for the three locations (Table 3). In other words, when weed density increased the intra-specific competition resulted in a lower panicle production per plant. However, there was no correlation between the density of infestation and panicle size (measured as the number of spikelets per panicle), indicating that intraspecific competition did not affect significantly this variable in this range of data (Table 3).

For wheat, the three measured variables (number of stems with spikes, aerial dry weight and weight of grain) were positively and strongly correlated (data not shown). The Pearson correlation between crop and weed variables showed that wheat was strongly affected by the presence of \textit{A. sterilis} spp. \textit{sterilis}. All the wheat variables were negatively and significantly correlated with all the measured variables of \textit{A. sterilis} spp. \textit{sterilis} (Table 4). Wheat yield and panicle density of \textit{A. sterilis} spp. \textit{sterilis} were the two variables with the highest correlation values.

In 1987 and 1988, the relationship between wheat yield and \textit{A. sterilis} spp. \textit{sterilis} panicle density was well described by the three models tested. However, in

Table 1. Mean values of the main variables of wheat and \textit{A. sterilis} spp. \textit{sterilis} in the season 1986-87 and 1987-88. Values in parentheses indicate the range.

| Year | Field     | No. of plots | Weed-free yield\(^{a}\) (kg ha\(^{-1}\)) | Weed-infested yield (kg ha\(^{-1}\)) | Stems m\(^{-2}\) | Plants m\(^{-2}\) | Panicles m\(^{-2}\) | Spikelets panicle\(^{-1}\) |
|-----|-----------|-------------|----------------------------------------|-------------------------------------|------------------|------------------|------------------|-----------------|
| 87  | Cañete    | 6           | 3,757 (2,940-4,960)                     | 2,879 (1,280-4,760)                 | 341.1            | 28.25 (0-153)    | 38.54 (0-194)    | 8.37 (1.0-16.9)  |
| 87  | Carlota   | 6           | 4,908 (3,490-7,280)                     | 4,199 (1,450-6,120)                 | 299.1            | 7.12 (0-41)      | 19.24 (0-95)     | 25.75 (11.2-44.8) |
| 88  | Écija     | 5           | 3,355 (2,650-3,950)                     | 2,676 (630-4,230)                   | 326.2            | 5.73 (0-39)      | 38.84 (0-170)    | 31.04 (14.7-45.1) |
| 88  | Osuna     | 3           | 4,087 (3,350-5,370)                     | 3,439 (2,320-4,590)                 |                  |                  | 38.92 (0-138)    | 19.93 (8.1-36.2) |
| 88  | Fuente Palmera | 3       | 3,904 (3,040-5,420)                     | 3,179 (1,690-4,950)                 |                  |                  | 27.58 (0-94)     | 29.81 (14.0-51.8) |
| 88  | Bujalance | 3           | 4,561 (3,410-5,530)                     | 3,995 (1,210-5,300)                 |                  |                  | 27.91 (0-176)    | 22.74 (13.0-32.2) |
| 88  | Castro    | 5           | 5,247 (4,630-6,390)                     | 4,667 (3,620-5,950)                 |                  |                  | 24.82 (0-85)     | 19.10 (12.0-34.6) |
| 88  | Alcolea   | 3           | 5,847 (3,860-8,110)                     | 4,211 (3,090-7,150)                 |                  |                  | 26.15 (0-90)     | 31.64 (16.9-55.2) |
| 88  | Santa Cruz| 3           | 7,385 (5,450-8,890)                     | 6,028 (4,220-7,980)                 |                  |                  | 15.76 (0-48)     | 31.61 (21.4-46.9) |

\(^{a}\) Four samples in each plot.
1989, none of the models fitted well to the data due to the narrow range of densities measured (0 to 37 panicles m\(^{-2}\)) and to the enormous variability found in the data. Generally, the linear and exponential models gave very similar fitting. The hyperbolic model was difficult to converge in some plots due to the yield in weed-free points sometimes was lower than in points with infestation because panicle density was from moderately to low in most of the plots. In addition, this model gave worse fitting or higher AICc than the other two (Table 5). We considered that the linear model explained reasonably well the process of competition and simplified the calculation of ET (Table 6).

When we compared the linear models for each individual plot we found that the parameter \(b\) (yield loss per panicle) ranged between 7.5 and 52.1 kg ha\(^{-1}\) in 1987 and between 6.6 and 70 kg ha\(^{-1}\) in 1988 (Table 6). In 1989, with low infestation levels and taking paired samples, the losses per panicle ranged between 0.96 and 27.6 kg ha\(^{-1}\). This wide variation among plots was related with the expected weed-free yield. In Sta. Cruz, in 1988, the yield losses per panicle were much higher than in all the other fields and this corresponded with much higher expected weed-free yield (Table 6). The same trend was observed with the data from 1989 (data not shown). Using the data from the three years, the relationship between the potential weed-free yield and the yield loss per panicle could be fitted to an exponential equation (Fig. 3).

![Figure 3. Relationship between the potential yield (Yo) in kg ha\(^{-1}\) and the lost per A. sterilis spp. sterilis panicle (b) in kg ha\(^{-1}\) in the two years of study.](image-url)
The ET values, as a function of $Y_o$ and $b$ varied between 3.57 and 80.92 panicles m$^{-2}$ (Table 6). The relationship between this high range of ET values and $Y_o$, showed that when the potential yields were lower than 3,000 kg ha$^{-1}$ a herbicide control of this weed species is not profitable independently of its density. When the potential yields were higher than 6,000 kg ha$^{-1}$ the ET were lower than 10 panicles m$^{-2}$. When the potential yields were between 6,000 and 3,000 kg ha$^{-1}$ the ET values followed an exponential increase (Fig. 4).

**Discussion**

This work highlights the high competitiveness of A. sterilis spp. sterilis growing in wheat fields in

| Aplan   | Aplan   | Atspi   | Asi    | Pan plant$^{-1}$ |
|---------|---------|---------|--------|------------------|
| Cañete  | 0.98*   |         |        |                  |
| Carlota | 0.91*   |         |        |                  |
| Écija   | 0.90*   |         |        |                  |
| Atspi   |         | 0.94*   |        |                  |
| Cañete  | 0.92*   |         |        |                  |
| Carlota | 0.81*   |         |        |                  |
| Écija   | 0.83*   |         |        |                  |
| Aspi    |         |         | 0.41*  |                  |
| Cañete  | 0.18    |         |        |                  |
| Carlota | –0.04   | 0.03    | 0.30*  |                  |
| Écija   | 0.07    | 0.13    | 0.39*  |                  |
| Pan plant$^{-1}$ |         |         |        |                  |
| Cañete  | –0.18*  | –0.02   | –0.02  | 0.15             |
| Carlota | –0.33*  | –0.02   | 0.02   | 0.08             |
| Écija   | –0.38*  | –0.05   | –0.04  | 0.03             |
| Abio    |         |         |        |                  |
| Cañete  | 0.71*   | 0.76*   | 0.75*  | 0.24*            |
| Carlota | 0.73*   | 0.88*   | 0.93*  | 0.31*            |
| Écija   | 0.80*   | 0.94*   | 0.96*  | 0.31*            |

* $p < 0.01$.

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**Table 4.** Pearson correlation coefficients among the wheat and the A. sterilis spp. sterilis variables in Cañete, Carlota and Écija fields in the years 1987 and 1988. For A. sterilis: Aplant: plants m$^{-2}$, Apan: panicles m$^{-2}$, Atspi: number of total spikelets, Aspi: number of spikelets per panicle, Pan plant$^{-1}$: panicles per plant and Abio: Aerial biomass m$^{-2}$. For wheat: Ttill: stems m$^{-2}$, Tbio: aerial biomass m$^{-2}$ and Tyield: grain weight in kg ha$^{-1}$.

|         | Cañete (n = 120) |         | Carlota (n = 120) |         | Écija (n = 100) |
|---------|------------------|---------|------------------|---------|----------------|
| Aplant  | –0.65            | –0.58  | –0.64            | –0.49   | –0.63          |
| Apan    | –0.66            | –0.61  | –0.67            | –0.43   | –0.61          |
| Atspi   | –0.64            | –0.57  | –0.63            | –0.41   | –0.58          |
| Abio    | –0.50            | –0.48  | –0.52            | –0.42   | –0.58          |
| $p$     | $< 0.001$        | $< 0.001$ | $< 0.001$        | $< 0.001$ | $< 0.001$    |

**Figure 4.** Relationship between the potential yield ($Y_o$) in kg ha$^{-1}$ and the economic threshold (ET) in panicles of Avena sterilis spp. sterilis per square meter for the first and second year of study. For ET calculation see Table 6.
Southern Spain, supporting previous results from Saavedra et al. (1990). The only exception was found in one field (Cañete) and it was attributed to the late emergence of the weed. This effect has already been described by Willenborg et al. (2005) for *Avena fatua*. This lower competitiveness (lower yield losses) was accompanied with a lower number of spikelets per panicle and fewer seeds produced. Consequently, a good seedbed preparation and/or a delayed sowing will contribute to destroy early emerging plants (the most competitive ones) and may be particularly useful when infestation levels are under the ET level.

Due to the relatively low population densities of *A. sterilis* spp. *sterilis* present in most fields, intra-specific competition was expected to be low. However, although weed density influenced the number of panicles per plant it did not influence the number of spikelets per panicle. The low correlation coefficient found between the number of plants and the number of panicles per plant was probably due to the enormous variability of the data (among plots and among fields). The experimental design used in this study has the advantage of covering a wide geographic area and a wide range of environmental conditions, being representative of the agricultural reality of the region. However, it has the disadvantage of a high variability in the data (Fernández-Quintanilla and González-Andújar, 1988).

Although there are various regression models available to describe the response of crop yield to increasing weed densities, we decided to use the linear model due to its simplicity. Previously, Streigbig et al. (1989) and Zanin et al. (1993) had used the hyperbola rectangular model whereas Torner et al. (1991) used the exponential model. Other models more complex, involving several environmental factors (such as rainfall) or agronomic factors (such as the use of herbicides and fertilizers, the variety or the seeding rate) (Wagner et al., 2007), were not taken into account because of the lack of information on all these factors. Furthermore, given the complexity of factors that can influence in the competition process, our purpose was to use simple models that can be easily understood and applied by farmers. We found the linear model to describe the data similar to the exponential model and slightly better than the rectangular hyperbola model. However, this similarity of fitting observed could vary if the range of infestation densities had been higher in favor of non-linear models.

Several authors working on *Avena* spp. in cereal crops have estimated ETs in terms of simple variables such as plant density, crop value or herbicide efficiency (Madeira et al., 1984; Zanin et al., 1993; Weaver and Ivany, 1998; Mennan et al., 2003; or Scursoni and Satorre, 2005) but few have highlighted the influence of the expected weed-free yield in the establishment of the ET (O’Donovan et al., 2005) and none had quantified it. Instead of establishing a comparison with the values given by these authors (determined by the wild oat species and highly fluctuating economic factors over the years and countries), we would like to emphasize

| Year | Field   | Plot | Linear  | Exponential | Rectangular hyperbola |
|------|---------|------|---------|-------------|-----------------------|
| 1987 | Carlota | 1    | 311.01  | 311.25      | 313.44                |
|      |         | 2    | 320.32  | 319.57      |                       |
|      |         | 3    | 297.41  | 298.52      | 299.65                |
|      |         | 4    | 283.48  | 283.38      |                       |
|      |         | 5    | 311.07  | 309.12      |                       |
|      |         | 6    | 293.68  | 293.83      | 296.47                |
|      | Cañete  | 1    | 315.31  | 315.74      | 318.14                |
|      |         | 2    | 314.06  | 315.97      |                       |
|      |         | 3    | 316.76  | 319.76      |                       |
|      |         | 4    | 300.45  | 300.02      |                       |
|      |         | 5    | 316.61  | 316.28      |                       |
|      |         | 6    | 307.87  | 308.79      |                       |
| 1988 | Ecija   | 1    | 320.62  | 320.70      | 323.40                |
|      |         | 2    | 308.12  | 306.86      |                       |
|      |         | 3    | 321.39  | 322.61      | 323.51                |
|      |         | 4    | 305.38  | 304.77      |                       |
|      |         | 5    | 323.07  | 322.96      |                       |
|      | Osuna   | 1    | 307.78  | 306.78      | 309.26                |
|      |         | 2    | 306.61  | 306.77      |                       |
|      |         | 3    | 304.44  | 304.28      |                       |
|      | Fuente Palmera | 1 | 320.05  | 318.77      |                       |
|      |         | 2    | 328.89  | 329.24      |                       |
|      |         | 3    | 309.79  | 309.90      | 312.57                |
|      | Bujalance | 1 | 303.91  | 303.90      | 306.39                |
|      |         | 2    | 332.00  | 333.11      |                       |
|      |         | 3    | 306.57  | 305.02      |                       |
|      | Castro  | 1    | 314.28  | 314.42      | 306.06                |
|      |         | 2    | 303.15  | 302.72      |                       |
|      | Alcolea | 1    | 333.29  | 333.52      | 335.99                |
|      |         | 2    | 330.00  | 330.11      |                       |
|      |         | 3    | 291.44  | 291.18      |                       |
|      | Santa Cruz | 1 | 311.92  | 311.31      | 313.55                |
|      |         | 2    | 275.29  | 275.26      |                       |
|      |         | 3    | 327.98  | 328.00      |                       |

1 This model did not converge in some plots.
the tremendous competitiveness of *A. sterilis* ssp. *sterilis*, with a crop yield loss per panicle of up to 70 kg ha\(^{-1}\). Farmers are aware of this risk and they use a wheat-sunflower rotation, fundamentally as a control tool against *A. sterilis*. The ET found for this weed species in the Western of Andalusia region varied from 10 to 80 panicles m\(^{-2}\) depending on the potential yields of each field. Farmers with high potential yields (> 6,000 kg ha\(^{-1}\)) should treat their fields if *A. sterilis* density is above 4 plants m\(^{-2}\) (assuming that an *Avena sterilis* plant has 2 to 3 panicles per plant at those densities). Farmers with low potential yields (< 3,000 kg ha\(^{-1}\)) should not apply any herbicide control to their fields whatever the infestation density. If the potential yields are between 3,000 and 6,000 kg ha\(^{-1}\) they should estimate the ET value from the exponential equation described in this work. So far, it is not possible to determine the long-term ET in a wheat-sunflower rotation. Although demographic variables of *Avena sterilis* ssp. *sterilis* are known for an annual cycle of

### Table 6. Parameter values for the linear model fitted to the data of the different plots and estimated economic threshold (ET) in the first and second year of study for each plot (n = 20)

| Year | Field | Plot | \(Y_o\) (kg ha\(^{-1}\)) | SE (\(Y_o\)) | b (kg ha\(^{-1}\)) | SE (b) | \(R^2\) | p  | ET\(^1\) (panicles m\(^{-2}\)) |
|------|-------|------|-----------------|-------------|----------------|--------|--------|----|------------------|
| 1987 | Carlota | 1 | 4,324 | 191.5 | 28.9 | 7.8 | 0.43 | 0.002 | 15.84 |
|      |       | 2 | 4,411 | 171.1 | 32.1 | 5.4 | 0.66 | < 0.001 | 13.98 |
|      |       | 3 | 4,845 | 201.9 | 52.1 | 8.4 | 0.69 | < 0.001 | 7.84 |
|      |       | 4 | 5,408 | 148.5 | 33.3 | 6.6 | 0.58 | < 0.001 | 10.99 |
|      |       | 5 | 5,805 | 189.3 | 35.7 | 6.5 | 0.62 | < 0.001 | 9.55 |
|      |       | 6 | 5,313 | 140.9 | 23.9 | 4.5 | 0.60 | < 0.001 | 15.59 |
| Cañete | 1 | 3,686 | 171.2 | 9.8 | 3.4 | 0.31 | 0.01 | 54.79 |
|       | 2 | 3,977 | 188.5 | 14.5 | 3.7 | 0.46 | < 0.001 | 30.76 |
|       | 3 | 3,328 | 119.2 | 10.0 | 1.8 | 0.62 | < 0.001 | 59.47 |
|       | 4 | 3,203 | 83.9 | 9.8 | 1.6 | 0.66 | < 0.001 | 63.05 |
|       | 5 | 2,999 | 151.8 | 10.6 | 2.4 | 0.52 | < 0.001 | 62.26 |
|       | 6 | 3,575 | 109.4 | 13.0 | 2.5 | 0.61 | < 0.001 | 42.59 |
| 1988 | Écija | 1 | 3,395 | 225.1 | 10.7 | 4.1 | 0.27 | 0.019 | 45.31 |
|       | 2 | 3,519 | 155.4 | 11.5 | 3.3 | 0.40 | 0.003 | 48.91 |
|       | 3 | 3,019 | 209.5 | 12.9 | 3.2 | 0.48 | 0.001 | 50.82 |
|       | 4 | 3,166 | 225.5 | 12.9 | 5.1 | 0.11 | 0.155 | 48.46 |
|       | 5 | 3,279 | 221.9 | 7.5 | 4.2 | 0.37 | 0.008 | 80.48 |
| Osuna | 1 | 4,258 | 158.2 | 14.2 | 2.6 | 0.62 | < 0.001 | 32.73 |
|       | 2 | 4,092 | 147.1 | 10.8 | 2.8 | 0.45 | 0.001 | 44.79 |
|       | 3 | 3,632 | 144.1 | 6.6 | 3.0 | 0.21 | 0.042 | 82.57 |
| Fuente Palmera | 1 | 4,158 | 233.2 | 18.2 | 5.9 | 0.35 | 0.006 | 26.15 |
|       | 2 | 4,022 | 266.4 | 13.8 | 7.4 | 0.16 | 0.080 | 35.66 |
|       | 3 | 3,218 | 178.2 | 19.4 | 5.5 | 0.41 | 0.002 | 31.70 |
| Bujalance | 1 | 4,225 | 200.9 | 14.1 | 7.1 | 0.19 | 0.063 | 33.22 |
|       | 2 | 4,753 | 252.5 | 12.5 | 4.6 | 0.29 | 0.014 | 33.31 |
|       | 3 | 4,722 | 146.9 | 22.9 | 3.6 | 0.69 | < 0.001 | 18.30 |
| Castro | 1 | 5,077 | 192.3 | 17.2 | 6.1 | 0.31 | 0.012 | 22.67 |
|       | 2 | 5,267 | 223.9 | 14.9 | 6.6 | 0.23 | 0.039 | 25.22 |
| Alcolea | 1 | 6,698 | 295.3 | 30.9 | 8.9 | 0.40 | 0.003 | 9.56 |
|       | 2 | 5,887 | 294.6 | 17.5 | 9.2 | 0.17 | 0.074 | 19.21 |
|       | 3 | 5,015 | 254.5 | 15.7 | 6.5 | 0.27 | 0.028 | 25.14 |
| Santa Cruz | 1 | 7,543 | 282.7 | 60.2 | 12.3 | 0.59 | < 0.001 | 4.36 |
|       | 2 | 7,766 | 283.2 | 70.0 | 11.9 | 0.70 | < 0.001 | 3.64 |
|       | 3 | 6,312 | 460.7 | 41.7 | 34.2 | 0.05 | 0.379 | 7.52 |

\(^1\) ET: \(C \times 10,000 / (b \times Y_o \times P \times K)\), where C is the cost of control (€ ha\(^{-1}\)), b is the yield loss per panicle, \(Y_o\) is the weed-free yield, P is the price of the crop and K is the efficiency of control (%).
wheat (Palma et al., 1990), the population annual growth rates in wheat-sunflower rotation have not yet been investigated. Future research in this direction would improve the knowledge of the population dynamics of Avena sterilis spp. sterilis in this cropping system and would help to find effective measures for management of this species in order to reduce the high competitive ability showed in this study.

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