Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/sjar
Spanish Journal of Agricultural Research 2011 9(3), 862-872
ISSN: 1695-971-X
eISSN: 2171-9292

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

J. Barroso[1], C. Alcantara[2]* and M. Saavedra[2]

[1] *Departamento de Protección de Cultivos. Instituto de Ciencias Agrarias-CSIC. C/ Serrano, 115 bis. 28006 Madrid. Spain*
[2] *Áreas de Producción Agraria y Protección de Cultivos. IFAPA. Centro Alameda del Obispo. Junta de Andalucía. Avda. Menéndez Pidal, s/n. Apdo. 3092. 14080 Córdoba. Spain*

Abstract

Avena sterilis spp. *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 spp. *ludoviciana*. These losses were estimated experimentally in 19 wheat fields distributed throughout western Andalusia. The relationship between *A. sterilis* spp. *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* spp. *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 applied 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 spp. *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* spp. *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* spp. *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.

* Corresponding author: mariac.alcantara@juntadeandalucia.es
Received: 22-10-10. Accepted: 30-06-11.

Abbreviations used: AICc (Akaike's Information Criterion corrected); ET (economic threshold).

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*, 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* spp. *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* spp. *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,

Figure 1. Surveyed geographical fields during the three years of the study.

plots from 200 to 1,000 m^2 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 Cajeme, Yecora and Anza, all with similar growth patterns. Soil was fertilized at about 50 to 70 kg N_2 ha^{-1} and 100 kg P_2O_5 ha^{-1} at the sowing time and similar amount of N_2 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 m^2 were taken, with densities

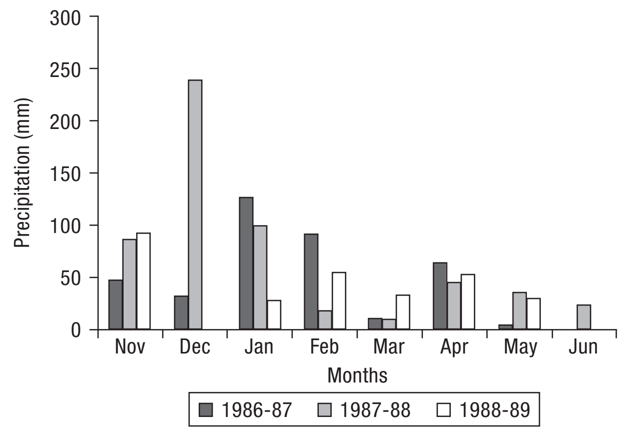

Figure 2. Monthly precipitation during the growing season of the three years of study in the province of Córdoba.

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, Espejo, 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 took in an area with 0 density of *A. sterilis* spp. *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 and numbers of *A. sterilis* spp. *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* spp. *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* spp. *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:

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

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

$$Y = Y_o \{1 - [iX/100(1 + iX/a)]\} \quad \text{Rectangular hyperbola} \quad [3]$$

where Y is the yield obtained in the presence of *A. sterilis* spp. *sterilis* (kg ha^{-1}), Y_o is the weed-free yield (kg ha^{-1}), X is *A. sterilis* spp. *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* spp. *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):

$$ET = C * 10{,}000 / (b * Y_o * P * K) \quad [4]$$

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* spp. *sterilis* densities were moderate, with not many patches with densities above 50 panicles m^{-2} and few samples ex-

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

Year	Field	No. of plots	Wheat			*Avena sterilis* spp. *sterilis*		
			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 (200-469)	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 (116-553)	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 (133-493)	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	2	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.

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 *A. sterilis* spp. *sterilis* 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 *A. sterilis* spp. *sterilis* 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 *A. sterilis* spp. *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 intraspecific 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 *A. sterilis* spp. *sterilis*. All the wheat variables were negatively and significantly correlated with all the measured variables of *A. sterilis* spp. *sterilis* (Table 4). Wheat yield and panicle density of *A. sterilis* spp. *sterilis* were the two variables with the highest correlation values.

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

Table 2. Mean values of the wheat and *A. sterilis* spp. *sterilis* variables for the ten fields in the season 1988-89. Values in parentheses indicate the range

Field	Number of samples	Wheat		*Avena sterilis* spp. *sterilis*	
		Weed-free yield[a] (kg ha^{-1})	Weed-infested yield (kg ha^{-1})	Panicles m^{-2}	Spikelets panicle^{-1}
Marchena	18	3,617 (2,600-4,200)	3,417 (2,470-4,160)	9.22 (3-18)	23.61 (14.2-35.8)
Santaella	18	1,978 (1,080-3,240)	1,892 (1,110-2,650)	8.11 (2-23)	15.02 (9.50-20.5)
Trebujena	16	2,188 (1,480-3,020)	2,151 (1,760-2,790)	10.81 (1-26)	9.36 (5.0 -13.3)
Utrera	18	4,701 (3,680-5,870)	4,506 (3,200-5,480)	7.59 (1-27)	17.90 (10.5-27.7)
El Arahal	17	4,285 (3,500-5,060)	4,215 (3,730-4,570)	7.35 (2-17)	22.58 (14.8-31.7)
Bujalance	17	2,596 (2,030-3,190)	2,425 (2,050-2,740)	8.70 (1-18)	12.50 (6.2-25.8)
Espejo	17	5,169 (3,690-6,680)	4,971 (3,570-7,540)	8.11 (1-37)	22.65 (15.0-38.2)
Fernán Núñez	15	5,559 (2,770-7,130)	5,357 (2,390-6,820)	7.06 (3-19)	24.42 (17.0-35.2)
S. Sebastían	18	1,565 (1,150-2,360)	1,426 (1,020-2,050)	7.44 (1-22)	11.24 (6.5-29.0)
Arjona	15	3,019 (1,980-4,070)	2,899 (1,930-4,150)	10.20 (3-24)	16.60 (8.0-29.0)

[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).

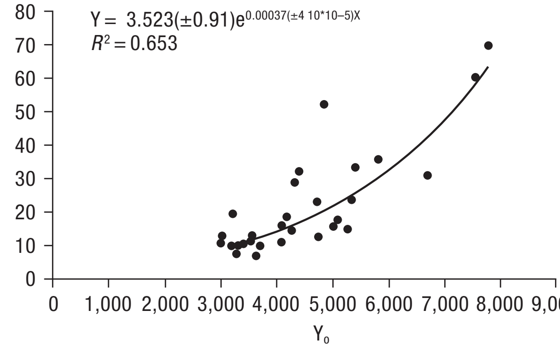

Figure 3. Relationship between the potential yield (Y_o) in kg ha^{-1} and the lost per *A. sterilis* spp. *sterilis* panicle (b) in kg ha^{-1} in the two years of study.

Table 3. Pearson correlation coefficients among *A. sterilis* spp. *sterilis* variables in the Cañete, Carlota and Écija fields in the years 1987 and 1988. Aplan: 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}

		Aplan	Apan	Atspi	Asi	Pan $plant^{-1}$
Apan	Cañete	0.98*				
	Carlota	0.91*				
	Ecija	0.90*				
Atspi	Cañete	0.92*	0.94*			
	Carlota	0.81*	0.95*			
	Ecija	0.83*	0.95*			
Aspi	Cañete	0.18	0.19	0.41*		
	Carlota	–0.04	0.03	0.30*		
	Ecija	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	
	Ecija	–0.38*	–0.05	–0.04	0.03	
Abio	Cañete	0.71*	0.76*	0.75*	0.24*	0.08
	Carlota	0.73*	0.88*	0.93*	0.31*	0.05
	Ecija	0.80*	0.94*	0.96*	0.31*	–0.03

* $p < 0.01$.

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 ka 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 and exponential increase (Fig. 4).

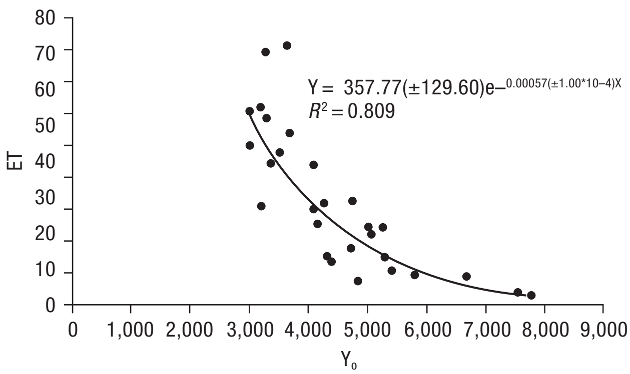

Figure 4. Relationship between the potential yield (Y_o) in kg ha^{-1} and the economic threshold (ET) in panicles of *Avena sterilis* spp. *sterilis* per square meter for the first and second year of study. For ET calculation see Table 6.

Discussion

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

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, 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}. In parenthesis, number of data

	Cañete (n = 120)			Carlota (n = 120)			Ecija (n = 100)		
	Ttill	Tbio	Tyield	Ttill	Tbio	Tyield	Ttill	Tbio	Tyield
Aplant	–0.65	–0.58	–0.64	–0.49	–0.63	–0.67	–0.46	–0.54	–0.55
Apan	–0.66	–0.61	–0.67	–0.43	–0.61	–0.62	–0.52	–0.61	–0.63
Atspi	–0.64	–0.57	–0.63	–0.41	–0.58	–0.61	–0.42	–0.49	–0.56
Abio	–0.50	–0.48	–0.52	–0.42	–0.58	–0.60	–0.45	–0.52	–0.56
p	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Table 5. Akaike's Information Criterion corrected (AICc) values of the linear, exponential and rectangular hyperbola models fitted to each plot (n = 20) in 1987 and 1988

Year	Field	Plot	Linear	Exponential	Rectangular hyperbola[1]
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	
		2	314.06	315.97	318.14
		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	
		2	306.61	306.77	309.26
		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	
		2	303.15	302.72	306.06
	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.

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 being 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, intraespecific competition was expected to be low. However, although weed density influenced the number of panicles per plant it did not influenced 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

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_0)	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 *10,000 / (b * Y_o * P * 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 (%).

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* spp. *sterilis* plant has 2 to 3 panicles per plant at those densities). Famers with low potential yields (< 3,000 kg ha^{-1}) should not applied 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* spp. *sterilis* are known for an annual cycle of 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.

Acknowledgements

This work was supported by the *Consejo Superior de Investigaciones Científicas* with a JAEDoc contract to Judit Barroso and by the European Social Fund with a contract to Cristina Alcántara. The present research was realized under the project INIA 76-36 financed by Ministry of Agriculture and Fisheries. We thank Dr. C. Fernández-Quintanilla for his constructive criticisms that helped improve the work final version.

References

CARRETERO J.L., 2004. Flora arvense española. Ed Phytoma-España, Valencia, Spain. pp.477-480. [In Spanish].

COUSENS R.D., WEAVER S.E., MARTIN T.D., BLAIR A.M., WILSON J., 1991. Dynamics of competition between wild oats (*Avena fatua* L.) and winter cereals. Weed Res 31, 203-210.

DADNIA M.R., PARCHAMI P., LACK S, BEHDARVAND P. 2009. Competition between wheat (*Triticum aestivum* L.) and wild oat (*Avena ludoviciana* L.) for nitrogen. Crop Res (Hisar) 38, 1-4.

FERNÁNDEZ-QUINTANILLA C., GONZÁLEZ-ANDÚJAR J.L., 1988. Utilización del concepto de umbrales de decisión para el control de malas hierbas. ITEA 75, 57-69. [In Spanish].

FERNÁNDEZ-QUINTANILLA C., NAVARRETE L., TORNER C., SÁNCHEZ DEL ARCO M.J., 1997. *Avena sterilis* L. en cultivos de cereales. In: Biología de las malas hierbas de España (Sans F.X., Fernández-Quintanilla C., eds). Phytoma, Valencia, Spain. pp. 77-89. [In Spanish].

GARCÍA-BAUDÍN J.M., SALTO T., 1978. Distribución e importancia del género *Avena* como planta adventicia en España. Symposium Mediterráneo de Herbicidas, Madrid, Spain, March 6-10. Tomo II, pp. 376-390. [In Spanish].

FERNÁNDEZ-QUINTANILLA C., GARCÍA-TORRES L., 1991. Interferencia entre las malas hierbas y los cultivos. In: Fundamentos sobre malas hierbas y herbicidas (García-Torres L., Fernández-Quintanilla C., eds). MAPA, Servicio de Extensión Agraria, Ediciones Mundi-Prensa, Madrid, Spain. pp.73-84. [In Spanish].

GONZÁLEZ-DÍAZ L., LEGUIZAMÓN E., FORCELLA F., GONZÁLEZ-ANDÚJAR J.L., 2007. Short communication. Integration of emergence and population dynamic models for long term weed management using wild oat (*Avena fatua* L.) as an example. Span J Agric Res 5, 199-203.

GONZÁLEZ-PONCE R., 1988. Competition between *Avena sterilis* ssp. *macrocarpa* Mo. and cultivars of wheat. Weed Res 28, 303-307.

GONZÁLEZ-PONCE R., SANTIN I., 2001. Competitive ability of wheat cultivars with wild oats depending on nitrogen fertilization. Agronomie 21(2), 119-125.

MADEIRA J., DORDIO M.F., MIRA R.S., LOPES C., 1984. Population levels and concurrence of wild oats (*Avena sterilis* ssp. *sterilis*) in wheat field in Portugal. Proc EWRS 3rd Symposium on weed problems in the Mediterranean area, Lisbon, Portugal, April 3-5. pp. 461-468.

MARM, 2009. Anuario de estadística 2008. Ministerio de Medio Ambiente y Medio Rural y Marino, Madrid, Spain. p. 523. [In Spanish].

MARTIN M.P.L.D., FIELD R.J., 1987. Competition between vegetative plants of wild oat (*Avena fatua* L.) and wheat (*Triticum aestivum* L.). Weed Res 27, 119-124.

MENNAN H., BOZOGLU M., ISIK D., 2003. Economic threshold of *Avena* spp., and *Alopecurus myosuroides* in winter wheat fields. Pak J Bot 35, 147-154.

MURPHY C., LEMERLE D., JONES R., HARDEN S., 2002. Use of density to predict crop yield loss between variable seasons. Weed Res 42, 377-384.

O'DONOVAN J.T., BLACKSHAW R.E., HARKER K.N., CLAYTON G.W., MAURICE D.C., 2005. Field evaluation of regression equations to estimate crop yield losses due to weeds. Can J Platn Sci 85, 955-962.

PALMA V., SAAVEDRA M.M., GARCÍA-TORRES L., 1990. Dinámica de poblaciones de *Avena sterilis* ssp *sterilis* L. en trigo (*Triticum aestivum* L.). Proceedings of the 1990 Spanish Weed Society Conference, Madrid, Spain, Dec. 11-12. pp. 285-289. [In Spanish].

PALMA V., SAAVEDRA M.M., GARCÍA-TORRES L., 1991. Relación entre épocas de emergencia, parámetros reproductivos y biomasa de *Avena sterilis* ssp. *sterilis* L. Proc Spanish Weed Society Conference, Madrid, Spain, Dec. 11-12. pp. 137-141. [In Spanish].

R DEVELOPMENT CORE TEAM, 2009. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

ROMERO-ZARCO C., 1987. *Avena* L. In: Flora vascular de Andalucía Occidental, vol. 3 (Valdés B., Talavera S., Fernández-Galiano E. eds). Ketres Ed SA, Barcelona. pp. 302-308. [In Spanish].

RUIZ D., BARROSO J., HERNAIZ P., FERNÁNDEZ-QUINTANILLA C., 2008. The competitive interactions between winter barley and *Avena sterilis* are site-specific. Weed Res 48, 38-47.

SAAVEDRA M.M., CUEVAS J., MESA-GARCÍA J., GARCÍA-TORRES L., 1989. Grassy Weeds in winter cereals in southern Spain. Crop Prot 8, 181-187.

SAAVEDRA M.M., JIMÉNEZ-HIDALGO M.J., GARCÍA-TORRES L. 1990. Wild oats (*Avena sterilis* ssp. *sterilis*) and wheat (*Triticum aestivum* L.) competition in southern Spain: a methodological approach. Proceedings EWRS Symposium 1990 Integrated Weed Management in Cereals. Helsinki, Finland, June 4-6. pp. 231-238.

SATORRE E.H., SNAYDON R.W., 1992. A comparison of root and shoot competition between spring cereals and *Avena-fatua* L. Weed Res 32, 45-55.

SCURSONI J.A., SATORRE E.H., 2005. Barley (*Hordeum vulgare*) and wild oat (*Avena fatua*) competition is affected by crop and weed density. Weed Technol 19, 790-795.

STREIGBIG J.C., COMBELLACK J.H., PRITCHARD G.H., RICHARDSON R.G., 1989. Estimation of thresholds for weed control in Australian cereals. Weed Res 29, 117-126.

TORNER C., FERNÁNDEZ-QUINTANILLA C., NAVARRETE L., SÁNCHEZ DEL ARCO M.J., 1985. Tolerancia y capacidad competitive de diferentes variedades de trigo y cebada en presencia de *Avena sterilis* L. ssp. *ludoviciana* (Durie) Nyman. ITEA 59, 65-71. [In Spanish].

TORNER C., GONZÁLEZ-ANDÚJAR J.L., FERNÁNDEZ-QUINTANILLA C., 1991. Wild oat (*Avena sterilis* L.) competition with winter barley: plant density effects. Weed Res 31, 301-307.

WAGNER N.C., MAXWELL B.D., TAPER M.L., REW L.J., 2007. Developing an empirical yield-prediction model based on wheat and wild oat (*Avena fatua*) density, nitrogen and herbicide rate, and growing-season precipitation. Weed Sci 55, 652-664.

WEAVER S.E., IVANY J.A., 1998. Economic thresholds for wild radish, wild oat, hemp-nettle and corn spurry in spring barley. Can J Plant Sci 78, 357-361.

WILLENBORG C.J., MAY W.E., GULDEN R.H., LAFOND G.P., SHIRTLIFFE S.J., 2005. Influence of wild oat (*Avena fatua*) relative time of emergence and density on cultivated oat yield, wild oat seed production, and wild oat contamination. Weed Sci 53, 342-352.

WILSON B.J., COUSENS R., WRIGHT K.J., 1990. The response of spring barley and winter wheat to *Avena fatua* population density. Ann Appl Biol 116, 601-609.

ZANIN G., BERTI A., TONIOLO L., 1993. Estimation of economic thresholds for weed control in winter wheat. Weed Res 33, 459-467.