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# Faba bean adaptation to autumn sowing under European climates

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**Abstract** Faba bean (*Vicia faba* L.) is an important grain legume widely grown as a spring crop to avoid frost damage. However, there is interest in winter types for the expected benefits in grain yield as compared to spring ones. In the current experiments, we compared field performance in autumn sowings of 15 faba bean winter-type cultivars that were sown in two consecutive autumns in 12 climatically contrasting sites in Austria, France, Germany, Spain, and the UK. GGE biplot analyses (genotype plus genotype-by-environment interaction) were conducted to evaluate yield performance of faba bean genotypes and identification of mega-environments. Crossover genotype  $\times$  environment was

large and mainly due to the geoclimatic area. GGE biplot allowed identification of three mega-environments, namely continental, oceanic, and Mediterranean. Due to the climatic diversity of the environments, no cultivar performed well in all environments. Cultivars Clipper, Castel, Target, Wizard, and Gabl-107 performed well in oceanic mega-environment, whereas cultivars Castel, HIX, and Target performed well in continental mega-environment. None of the studied cultivars were suited to Mediterranean environments, and only Irena was able to give some modest yield at Cordoba. The average tester coordinate (defined by the average of first and second principal components of all environments) allowed

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to evaluate cultivars for their yielding ability and stability and to evaluate environments for their discriminating ability and to be more representative of the mega-environment. Thus, Wizard and Gabl-107 were the highest yielding cultivars being relatively stable over oceanic and continental environments. In contrast, the cultivars Irena and Divine yielded poorly at all environments. The results support the specific breeding for each major geoclimatic zone based on distinct genetic bases and selection environments.

**Keywords** Genotype  $\times$  environment interaction · Winter hardiness · Yield stability · *Vicia faba*

## 1 Introduction

Faba bean (*Vicia faba* L.) is an important grain legume crop being used mainly as a source of protein in human diets, as fodder and a forage crop for animals, and for available nitrogen in the biosphere (Duc 1997; Rubiales 2010). Expanding faba bean cultivation is desirable, but it is hindered by unstable yields (Arbaoui et al. 2008; Link et al. 2010). In cool temperate climates, faba bean is widely grown as a spring crop because of the insufficient winter hardiness of the current autumn-sown germplasm. However, there is interest in winter types for the expected benefits in grain yield in winter beans, as compared to spring beans (Link et al. 2010).

Winter faba bean offers several advantages over the spring type. It makes better use of moisture available in winter and partly escapes drought at the end of the season as it matures earlier than spring types. It can also make substantial growth in early spring, before spring-sown cultivars can be sown or become well established. The main disadvantage of winter faba bean is the risk of winter-kill by frost. Genuine winter faba beans survive winter conditions as young plants. Performance of winter cultivars depends not only on frost tolerance but also on its resistance against biotic stresses and its tolerance to adverse abiotic conditions such as levels of saturation of soils with water (Stoddard et al. 2006; Sillero et al. 2010). There are not many winter faba bean cultivars on the market and most of them were not considered suitable for continental winters (Herzog 1989). Nevertheless, winter hardiness exists in faba bean germplasm, and there is potential for expanding the range of winter faba bean through breeding for improved hardiness (Stoddard et al. 2006; Duc et al. 2010; Link et al. 2010). Winter faba beans are currently grown most widely in the UK (>88,000 ha) (Link and Bond 2011) where they represented about half of faba bean grown at the end of the nineteenth century (Bond and Crofton 1999). Winter faba bean types were also widely grown already in the beginning of nineteenth century in the continental climate and at high

altitude in Burgundy, France (Picard et al. 1985). Nevertheless, cultivation of winter faba bean markedly decreased during the twentieth century. Autumn sowing of faba bean is traditional in the Mediterranean basin and in areas of similar climates such as parts of Australia and China having very mild winters or only mild frosts (Link et al. 2010). For this reason, Mediterranean types should not be regarded as genuine winter faba beans.

Multi-environment trials are conducted yearly, and mean performance is often calculated as an average of cultivar performance over years and locations, but comparisons of mean performance are not sufficient for cultivar evaluation unless a due understanding of genotype by environment interactions is added. GGE biplot (genotype plus genotype-by-environment interaction) removes the statistical main effect of the environment and focuses on the genotype and genotype by environment interaction components relevant to cultivar evaluation. The stability comparisons among genotypes can be made with higher precision by removing the noise caused by the environment. A secondary goal of the GGE biplot is to develop understanding of the target region and to determine if the target region can be subdivided into different mega-environments (Yan et al. 2000). The objectives of this research were to evaluate the performance and stability of yield among winter faba bean cultivars and to examine the possible existence of different mega-environments within Europe.

## 2 Materials and methods

### 2.1 Plant material and experimental design

The winter cultivars network was made up of 16 cultivars (Table 1) grown over two crop seasons (2003–2004 and 2004–2005) at 12 contrasting locations covering most of Europe, from UK to Germany and from Austria to Spain (Table 2). An environment was defined as the combination of a year and a location. Since different cultivars were tested from location to location (Table 3), we examined the cultivars that were in common in some year–location environments; thus, four subsets of data were analyzed. Four cultivars were common to 15 environments (first subset of data), other four cultivars were common to 16 environments (second subset of data), 12 cultivars were common to 10 environments (third subset of data) and, 16 cultivars were common to four environments (fourth subset of data).

At each location, a randomized complete block design with two to four replications was used. Sowings took place between October and December, according to local practice, at a sowing density of around 30 seeds  $m^{-2}$ .

**Table 1** Faba bean cultivars included in Winter EUFABA Network with some known characteristics

Accession	Grain yield (kg ha <sup>-1</sup> ) <sup>a</sup>	Characteristics
Castel	5,155	French cv. from SCA Epi Sem—1987. Early, tall plants, frost-tolerant control
Clipper	5,191	British cv. from Wherry & Sons—1996. Late, large-seeded, little winter hardiness
Diva	4,640	French cv. from Agro-Obtention—2002. Similar winter hardiness to Karl. Earlier than Olan
Divine	3,836	French cv. from Agro-Obtention—1995. Spring type used as frost-sensitive control—low vicine content
Gabl-107	5,218	French line from GAE Recherche—not marketed. Good winter hardiness, tall plants
Hiverna	4,688	German cv. from NPZ—1986. Good yield and frost tolerance, tall, large-seeded
HIX	4,817	French line from Agro-Obtention—not marketed. Early, winter hardy, half-determined
Irena	4,399	French cv. from Agro-Obtention—2002. Early, little winter hardiness. Resistant to <i>Ascochyta</i> , short plants
Karl	5,005	French line from Blondeau—1990 not marketed. Old line, best winter hardiness (frost under−15°C), late to flowering
NPZ Wab 01	5,054	German line from NPZ—not marketed. Good frost tolerance
Olan	4,793	French cv. Less winter hardiness than Karl, tall plants, late to harvest
Wizard	5,217	British cv. from Wherry & Sons—2002. Large-seeded
Target	5,183	British cv. from Wherry & Sons—1994. Late, large-seeded, little winter hardiness
HIT	4,409	French line from Agro-Obtention—not marketed. White flowers, winter hardy, early, half-determined
HIP	4,891	French line from Agro-Obtention—not marketed. White flowers
HJC	4,518	French line from Agro-Obtention—not marketed. Winter hardy, early, half-determined

<sup>a</sup> Average yield in subset 4

## 2.2 Statistical analysis

The GGE biplot method (Yan et al. 2000) was employed to study the genotype by location–year environment interaction of faba bean yield. A two-dimensional biplot called GGE biplot (genotype plus genotype-by-environment interaction) was constructed using the first two principal

components derived from subjecting the environment-centered data to singular value decomposition. Singular value partitioning is achieved by providing a scaling factor  $f$  to obtain alternative cultivars and environment scores. We chose the most straightforward variant called symmetric scaling ( $f=0.5$ ) since it bears most of the properties associated to other scaling methods (Yan 2002).

Cultivars and environments were displayed in the same plot. This GGE biplot can identify broadly adapted cultivars that offer stable performance across all sites, as well as cultivars that perform well under specific sites, and also it can identify different mega-environments in the winter faba bean network. A mega-environment is defined as a group of environments that consistently share the same best cultivar or cultivars. The average yield and stability of the cultivars were examined for each subset of data by defining an average tester coordinate (named ATC by Yan (2001)). An average tester coordinate was defined by Yan (2001) as a virtual environment whose first and second principal components scores are equal to the average of the first and second principal component scores, respectively, across all environments. The average tester coordinate  $X$ -axis passes through the biplot origin, and the marker of the average environment and the average tester coordinate  $Y$ -axis passes the plot origin and is perpendicular to the average tester coordinate  $X$ -axis. The average yield of the cultivars is approximated by the projections of their markers to the average tester coordinate  $X$ -axis, and the stability is measured by their projection to the average tester coordinate  $Y$ -axis. The greater the absolute length of the projection of a cultivar, the less stable it is. Similarly, ideal test environments should have a large average tester coordinate  $X$ -axis score (more discriminating of the cultivars in terms of the genotypic main effect) and small (absolute) average tester coordinate  $Y$ -axis score (more representative of the overall environment). Analyses were made by a SAS® 9.3 (SAS Institute Inc.) program for graphing GGE biplots developed by Burgueño et al. (2003).

## 3 Results and discussion

Analysis of variance was constructed for each subset of data to determine the effects of environment, genotype and genotype by environment interaction. The results of combined analysis of grain yield are shown in Table 4. Grain yields of the faba bean genotypes were significantly affected by environment which explained for 53% to 91% of the total variation (genotype+environment+genotype by environment interaction), whereas genotype and genotype by environment interaction accounted for 2% to 11% and 4% to 25%, respectively (Table 4). The large genotype by environment interaction effects compared to genotype suggest

**Table 2** Description of the test locations for Winter EUFABA Network

	Latitude	Longitude	Altitude (m ASL)	Rain fall (mm)		Max. temp (°C)		Min. temp. (°C)		Number frost days	
				2003– 2004	2004– 2005	2003– 2004	2004– 2005	2003– 2004	2004– 2005	2003– 2004	2004– 2005
Egmond, UK	52.59°N	2.15°W	150	763	648	14	13.9	5.9	6.4	52	37
Bersée, France	50.39°N	2.57°E	29	570	617	14.3	13.4	7.1	6.5	30	41
Paris, France	48.43°N	2.07°E	120	390	407	14.2	13.9	6.0	6.2	38	51
Dijon, France	47.25°N	5.09°E	211	438	533	13.0	13.4	3.6	4.6	74	76
La Brosse, France	48.2°N	3.01°E	93	468	419	14.6	13.8	5.8	5.9	41	49
Montbartier, France	44.1°N	1.44°E	107	450	No trial	16.8	No trial	7	No trial	36	No trial
Hohenlieth, Germany	54.25°N	9.53°E	23	647	844	26.1	22.9	-7.4	-4.5	79	64
Gottingen, Germany	51.49°N	9.93°E	150	512	595	28.6	23.8	-7.8	-4.4	82	70
Gleisdorf, Austria	45.10°N	15.71°E	361	392	727	13.7	13.3	2.6	3.4	112	114
Escacena, Spain	37.38°N	6.42°W	171	516	564	21.6	20.3	10.1	9.6	1	0
Córdoba, Spain	37.86°N	4.8°W	117	547	549	21.21	20.2	9.2	8.61	9	6
Logroño, Spain	42.45°N	2.28°W	342	503	408	17.3	15.5	8.64	7.45	10	5

the existence of different mega-environments, in which cultivar rankings are different from other mega-environments (Yan et al. 2000). Also, the partitioning of genotype+genotype by environment interaction through GGE biplot analysis showed that the first two principal components explained for 74% to 96% of total genotype+genotype by environment interaction sum of squares (Table 4). This partitioning showed that the first two principal components were significant factors in all subset of data, except for the second principal component in the first subset.

On the other hand, the much larger genotype by environment interaction relative to the genotype main effect led to strong crossover genotype by environment interactions, as evidenced by the fact that first environment principal component scores took different signs and the environments fell in all quadrants (Fig. 1) (Yan et al. 2000).

Frost damage score was not associated with first genotypic principal component scores in any of the years (data not shown). Also, Annicchiarico (2008) found no association between yield and winter mortality. A negative correlation between first principal component scores and absolute minimum temperatures were significant for subset 1 ( $-0.67^{**}$ ), and a positive correlation between first principal component and minimum temperatures were significant for subset 4 ( $0.77^{*}$ ). However, no associations were observed between first principal component and environmental covariates (total precipitation, absolute maximum temperature; average maximum temperature, absolute minimum temperature; average minimum temperature and total number of frost days) in subsets 2 and 3.

The second genotypic principal component scores were significantly correlated with frost scores in both years

( $0.72^{**}$  and  $0.84^{**}$ , respectively). Frost survival contributed to the performance of the cultivars in the various locations. An increase in the level of expression of this trait would therefore improve the specific adaptation of the genotypes to certain environments, but it is unlikely to lead to improved overall genotype performance.

Second principal component scores were negatively correlated with absolute minimum temperature for subset 2 ( $-0.49^{*}$ ) and with absolute minimum temperature and minimum temperature for subset 4 ( $-0.85^{*}$  and  $-0.95^{*}$ , respectively). Second principal component scores were positively correlated with total number of frost days for subset 4 ( $0.99^{**}$ ). Correlation between second principal component scores and environmental covariates identified minimum temperature and number of frost days as the most important covariates contributing to different genotypic performance.

The polygon view of a GGE biplot explicitly displays the which-won-where pattern of multi-environment trials data, which is important for studying the possible existence of different mega-environments in a region (Gauch and Zobel 1997). Firstly, cultivars that are farther away from the biplot origin need to be identified. Clockwise, these are the genotypes sown in Table 5 that were either the best or the poorest performers at some or all environments, conditional on the particular data set. For example, the cultivar markers of the third faba set (Fig. 1) that were farthest from the biplot origin (cvs. Castel, Clipper, Divine, and Irena) formed the corners of the polygon. By connecting these corner cultivars, the polygon is drawn that encloses all other cultivars in the figure. Starting from the biplot origin, perpendicular lines are drawn to each side of the polygon, which divide the biplot in several sectors, some of them containing one or

**Table 3** Mean grain yield (kilograms per hectare) and standard error (SE) of 16 faba bean cultivars and lines grown at 20 location-year environments from Winter EUFABA Network

Environments	Faba bean accession																Mean
	Castel	Clipper	Diva	Divine	GBL107	HIP	HIT	Hiverna	HIX	HJC	Irena	Karl	NPZ01	Olan	Target	Wizard	
Bersée-03, France	7,036	8,065	6,425	7,060	7,525	M	M	7,583	M	M	6,086	6,685	7,560	7,452	7,590	7,733	7,233
Bersée-04, France	6,803	M	6,147	5,430	7,250	3,890	4,843	M	5,271	5,372	5,555	6,013	M	6,001	M	M	5,689
La Brosse-03, France	3,629	3,581	3,362	3,510	3,467	M	M	3,862	M	M	3,033	3,391	3,591	3,748	3,386	3,352	3,492
La Brosse-04, France	5,092	4,624	4,149	3,530	4,873	4,259	3,831	4,775	4,242	4,254	3,872	4,219	4,803	4,311	4,213	4,543	4,349
Córdoba-03, Spain	693	M	M	292	M	M	M	M	M	M	854	M	M	146	M	M	496
Dijon-03, France	5,662	5,015	5,040	5,292	4,932	M	M	5,193	M	M	5,013	5,032	5,138	5,109	5,344	5,238	5,167
Dijon-04, France	5,086	3,730	4,249	1,709	3,963	4,710	4,531	3,585	5,005	4,141	4,541	3,994	3,857	3,701	3,718	4,136	4,041
Edgmon-03, UK	3,678	4,374	4,291	3,181	4,691	M	M	4,519	M	M	3,856	4,478	4,713	4,367	4,101	4,374	4,218
Edgmon-04, UK	4,557	4,575	4,399	4,648	4,783	4,722	4,406	4,664	4,323	4,761	4,067	4,633	4,617	4,663	4,589	4,672	4,567
Escacena-03, Spain	47	M	M	43	M	M	M	M	M	M	135	M	M	10	M	M	56
Escacena-04, Spain	100	42	M	25	M	M	M	M	M	M	105	M	M	11	97	11	56
Gleisdorf-04, Austria	M	375	2,535	20	3,145	1,075	1,285	2,370	2,000	2,305	970	2,735	3,290	M	1,205	405	1,693
Göttingen-03, Germany	M	5,421	5938	2,401	M	M	M	4,739	M	M	4,935	M	5,980	M	5,111	4,958	4,935
Göttingen-04, Germany	M	5,913	5,953	1,155	6,260	5,443	5,583	5,798	5,653	6,028	4,865	5,843	6,143	M	5,958	5,880	5,462
Hohenlieth-03, Germany	M	6,191	3,254	M	5,330	M	M	5,119	M	M	2,074	4,647	5,737	M	4,977	5,196	4,725
Logroño-03, Spain	3,019	M	M	3,553	M	M	M	M	M	M	2,905	M	M	2,682	M	M	3,040
Logroño-04, Spain	3,908	3,158	M	2,479	M	2,725	2,017	M	1,979	2,694	3,254	M	M	3,113	2,413	2,284	2,765
Montbartier-03, France	4,191	3,429	3,548	3,405	3,262	M	M	2,714	M	M	3,905	3,167	3,214	3,536	3,226	3,774	3,447
Paris-03, France	5,129	4,817	4,088	4,467	4,281	M	M	3,759	M	M	4,202	4,121	4,306	3,837	3,676	4,443	4,260
Paris-04, France	6,237	7,198	6,154	6,094	6,835	5,635	5,091	5,327	5,374	5,321	4,789	7,023	6,639	6,009	7,001	7,070	6,112
Mean	4,087	4,492	4,708	3,123	5,112	4,209	4,246	4,663	4,345	4,531	3,523	4,767	5,028	3,678	4,226	4,331	4,260
SE	287	269	168	259	203	244	248	187	255	230	210	178	186	284	253	260	64

M missing values



**Table 4** Genotype (G), location–year environment (E), and genotype by location–year environment interaction (GE) terms for yield for the winter faba bean performance trials (EUFABA Network), 2003–2004 to 2004–2005

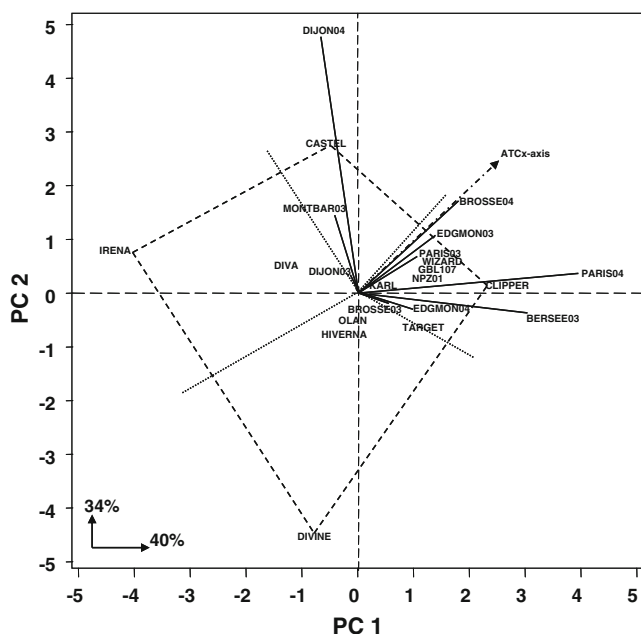
Dataset	Source of variation	df	Mean squares	Explained variation % of G, E, and GE <sup>a</sup>	% of PC1+PC2 <sup>b</sup>
Subset 1	E	14	2,968.71**	78	88+8
	G	3	505.33**	3	
	GE	42	138.78**	11	
Subset 2	E	15	6,096.73**	91	64+25
	G	3	437.66**	2	
	GE	45	99.08**	4	
Subset 3	E	9	6,831.77**	81	40+34
	G	11	185.90**	3	
	GE	99	72.61**	9	
Subset 4	E	3	2,913*	53	56+35
	G	15	123.93**	11	
	GE	45	91.26**	25	

df degrees of freedom

\* $p=0.01$ , significant level of probability; \*\* $p=0.001$ , significant level of probability

<sup>a</sup> Percentage sum of squares with respect from the total sum of squares

<sup>b</sup> Proportions of the first two principal components derived from singular value decomposition of the environment-centered data



**Fig. 1** GGE biplot based on the yield data of 12 faba bean cultivars grown at ten location–year environments from Winter EUFABA Network, in 2003–2004 and 2004–2005 (third subset of data). The cultivar markers located away from origin were connected with straight lines to form a polygon. Lines perpendicular to the side of the polygon are drawn. PC principal component. Proportions of the first two principal components derived from singular value decomposition of the environment-centered data (percentage)

more environments. The GGE biplots based on each subset data separated the mega-environments shown in Table 5. For the third faba set (Fig. 1), the line that starts from the biplot origin and perpendicular to the sides of the polygon divided the biplot into four sectors. Out of the four sectors, only two have environments within them suggesting that two different mega-environments exist in this dataset (Table 5). Clipper was the winning cultivar for the first mega-environment (Bersée-03, Brosse-03, Brosse-04, Paris-03, Paris-04, Edgmond-03, and Edgmond-04). Castel was the winning cultivar for the second mega-environment (Dijon-03, Dijon-04, and Montbartier-03).

In order to evaluate the cultivars in terms of high yielding ability for each subset of data, the “ATC” view of the biplot was examined. In this way, for subset 3, Fig. 1 could be used to evaluate cultivars for their yielding ability and stability and to evaluate environments for their discriminating ability and representativeness. Thus, Wizard and Gabl-107 were the highest yielding cultivars on average (high absolute primary scores, average tester coordinate X-axis) and were relatively stable over the environments (small absolute secondary scores, average tester coordinate Y-axis) (Yan 2001). In contrast, the cultivars Irena and Divine yielded poorly at all environments.

With respect to the test environments, Paris-04, Brosse-04, Dijon-04, Bersée-03, and Edgmond-03 were most discriminating as indicated by the largest distance between their marker projection on the average tester coordinate X-axis and the origin (Fig. 1). However, due to the large secondary score on average tester coordinate Y-axis of the environments Paris-04, Bersee-03, and Dijon-04, cultivar differences observed at these environments may not exactly reflect the cultivar differences in average yield over all environments. Brosse-04 and Edgmond-03 environments were not the most discriminating, but cultivar differences at these environments should be highly consistent with those averaged over environments because of near-zero secondary effect scores (Fig. 1).

The first and second data sets can be analyzed in a similar way as done for the third data set. The first data set suggests two mega-environments, continental and oceanic mega-environments, the second data set defines a Mediterranean mega-environment, and the third (Fig. 1) and fourth data sets distinguish also both continental and oceanic mega-environments (Table 5). In summary, data presented in Table 5 suggest existence of three mega-environments.

The complete set of mega-environments (each characterized by a different winning cultivar) is shown in Table 5. Thus, examination of the environment groupings revealed that Paris, La Brosse, Bersée, Edgmond, and Hohenlieth locations tended to be grouped separately from the other locations, suggesting that these locations represent a mega-environment that we named oceanic mega-environment. Dijon,

**Table 5** Winning cultivars and their mega-environments in the winter EUFABA network

Subset of data	Winning cultivars	Average grain yield (kg ha <sup>-1</sup> )	Environment groupings <sup>a</sup>
Subset 1 <sup>d</sup>	Clipper	4,821	Paris-03, Paris-04 <sup>bc</sup> , Edgmond-03, Edgmond-04, La Brosse-03, La Brosse-04, Bersée-03, Hohenlieth-03 <sup>b</sup>
	Target	4,532	Montbartier-03, Logroño-04, Dijon-03, Dijon-04, Gleisdorf-04, Göttingen-03 <sup>c</sup> , Göttingen-04
	Irena	4,059	
Subset 2	Castel	4,086	Paris-03, Paris-04 <sup>b</sup> , Edgmond-03, Edgmond-04, La Brosse-03, La Brosse-04 <sup>bc</sup> , Bersée-03, Bersée-04 <sup>bc</sup> , Dijon-03 <sup>c</sup> , Dijon-04 <sup>b</sup> , Logroño-03, Logroño-04 <sup>c</sup> , Montbartier-03
	Irena	3,521	Escacena-03, Escacena-04, Córdoba-03
	Divine	3,415	
Subset 3	Castel	5,068	Dijon-03, Dijon-04 <sup>b</sup> , Montbartier-03
	Clipper	4,913	Paris-03, Paris-04 <sup>b</sup> , Edgmond-03 <sup>bc</sup> , Edgmond-04, La Brosse-03, La Brosse-04 <sup>bc</sup> , Bersée-03 <sup>b</sup>
	Divine	4,296	
Subset 4	Irena	4,355	
	HIX	4,817	Dijon-04
	Castel	5,155	
	Target and Clipper	5,183, 5,191	Paris-04 <sup>b</sup> , Edgmond-04, La Brosse-04 <sup>bc</sup>
	Divine	3,836	
	Irena	4,399	

<sup>a</sup>Based on the GGE biplots each subset data separated the mega-environments shown in this Table

<sup>b</sup>Environments with larger projection on average tester coordinate *X*-axis give better discrimination of the cultivars

<sup>c</sup>Environments with smaller projection on average tester coordinate *Y*-axis give better representation of the overall environment

<sup>d</sup>List of all other cultivars tested in each subset, thus, subset 1: Clipper, Irena, Target, Wizard; subset 2: Castel, Divine, Irena, Olan; subset 3: Castel, Clipper, Diva, Divine, GBL107, Hiverna, Irena, Karl, NPZ01, Olan Target, Wizard; subset 4: Castel, Clipper, Diva, Divine, GBL107, HIP, HIT, Hiverna, HIX, HJC, Irena, Karl, NPZ01, Olan, Target, Wizard

Montbartier, Logroño, Göttingen, and Gleisdorf tended to be grouped, suggesting a second mega-environment that we named continental. The proximity of Escacena and Córdoba to the origin of principal component axes makes it uncertain that this area (southern Spain) can be ascribed to either of the other mega-environments. Thus, it should be regarded as a different mega-environment that could be named Mediterranean. These three mega-environments correspond broadly, although not perfectly, to the agro-environmental zones of Europe defined by Metzger et al. (2005). Our oceanic mega-environment corresponds to the Atlantic North and Atlantic Central of Metzger et al. (2005), our continental to their continental, Mediterranean North and the eastern part of Atlantic Central, and our Mediterranean to their Mediterranean South.

The evaluation of the best cultivar or group of cultivars for a particular mega-environment is also represented in Fig. 1 and Table 5. Due to the complexity of the environments, no cultivar performed well in all environments, with the result that the genotype main effects were much smaller than the genotype by environment interaction in all the analyses (Table 4). Genotype by environment interactions mainly due to geoclimatic areas may conveniently be addressed by breeding specific cultivars for each area as

shown by Annicchiarico and Iannucci (2008). The GGE biplots revealed three apparent groups of cultivars in terms of their response to the mega-environments (Table 5). Group 1 consisted of five cultivars, namely Clipper, Castel, Target, Wizard, and Gabl-107 that performed well in the oceanic mega-environment. Group 2 consisted of three cultivars Castel, HIX, and Target that performed well in the continental mega-environment. Group 3 consisted of one cultivar, namely Irena that performed a little bit better than the others in Mediterranean mega-environment, although its yield was still poor. The poor adaptation in Mediterranean areas could be attributed to the little earliness of cycle and drought tolerance of these winter types relative to the Mediterranean germplasm (Kittlitz et al. 1993; Link et al. 1996). Also, little floral adaptation to the predominant pollinator may contribute to the lack of adaptation to southern Spain (Suso 2004), although this is unlikely to play a major role in other Mediterranean regions where different pollinators are present (Marcellos and Perryman 1990).

Thus, two cultivars, namely Castel and Target, performed well in both continental and oceanic mega-environments. The corner cultivar without any environment in its sectors (Divine) was not the highest yielding cultivar at any environment;



moreover, it was the poorest cultivar at all or some environments. Cultivars within the polygon, particularly those located near the plot origin, were less responsive than the corner cultivars.

The better testing locations visually identified based on the GGE biplots have been labeled “bc” in Table 5. Among all locations involved in the 2 years of testing, according to Yan (2001), the location La Brosse was identified as a better location for cultivar evaluation since high and stable-yielding genotypes are most easily identified at locations with large average tester coordinate *X*-axis scores and near-zero average tester coordinate *Y*-axis scores (Table 5).

#### 4 Conclusion

Winter faba bean is an attractive crop for the expected benefits of higher grain yield over that of spring beans. Results presented here show that winter hardiness exists in faba bean cultivars and there is potential for expanding the range of winter faba bean through breeding for improved hardiness (Stoddard et al. 2006; Link et al. 2010).

The GGE biplot allowed identification of three mega-environments, namely continental, oceanic, and Mediterranean. Due to the complexity of the environments, no cultivar performed well in all environments. The results support the specific breeding for each geoclimatic area based on distinct genetic bases and selection environments and that cooperative breeding can be focused within a mega-environment rather than across the whole continent.

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#### References

- Annicchiarico P (2008) Adaptation of cool-season grain legume species across climatically-contrasting environments of southern Europe. *Agron J* 100:1647–1654
- Annicchiarico P, Iannucci A (2008) Breeding strategy for faba bean in southern Europe based on cultivar responses across climatically contrasting environments. *Crop Sci* 48:983–991
- Arbaoui M, Balko C, Link W (2008) Study of faba bean (*Vicia faba* L.) winter-hardiness and development of screening methods. *Field Crop Res* 106:60–67
- Bond DA, Crofton GRA (1999) History of winter beans (*Vicia faba*) in the UK. *J R Agric Soc Engl* 160:200–209
- Burgueño J, Crossa J, Vargas M (2003) SAS programs for graphing GE and GGE biplots. Biometrics and Statistics Unit, CIMMYT, Int, México
- Duc G (1997) Faba bean (*Vicia faba* L.). *Field Crop Res* 53:99–109
- Duc G, Bao S, Baum M, Redden B, Sadiki M, Suso MJ, Vishniakova M, Zong X (2010) Diversity maintenance and use of *Vicia faba* L. genetic resources. *Field Crop Res* 115:270–278
- Gauch HG, Zobel RW (1997) Identifying mega-environments and targeting genotypes. *Crop Sci* 37:311–326
- Herzog H (1989) Freezing resistance and performance of faba bean populations during winter seasons in Northern Germany. *J Agron Crop Sci* 162:225–235
- Kittlitz EV, Ibrahim KIM, Ruckebauer P, Robertson LD (1993) Analysis and use of interpool-crosses (Mediterranean×central European) in faba beans (*Vicia faba* L.): I. Performance of Mediterranean and central European faba beans in Syria and Germany. *Plant Breed* 110:307–314
- Link W, Bond D (2011) Resistance to freezing in winter faba beans. *Grain Legumes* 56:19–20
- Link W, Schill B, von Kittlitz E (1996) Breeding for wide adaptation in faba bean. *Euphytica* 92:185–190
- Link W, Balko C, Stoddard FL (2010) Winter hardiness in faba bean: physiology and breeding. *Field Crop Res* 115:297–307
- Marcellos H, Perryman T (1990) Control over pollination and ovule fertilization in *Vicia faba*. *Euphytica* 49:5–13
- Metzger MJ, Bunce RGH, Jongman RHG, Mucher CA, Watkins JW (2005) A climatic stratification of the environment of Europe. *Glob Ecol Biogeogr* 14:549–563
- Picard J, Duc G, Peletier R (1985) Côte d’Or, a highly frost resistant population of *Vicia faba*. *FABIS Newsl* 13:11–12
- Rubiales D (2010) Faba beans in sustainable agriculture. *Field Crop Res* 115:201–202
- Sillero JC, Villegas-Fernández AM, Thomas J, Rojas-Molina MM, Emeran AA, Fernández-Aparicio M, Rubiales D (2010) Faba bean breeding for disease resistance. *Field Crop Res* 115:297–307
- Stoddard FL, Balko C, Erskine W, Khan HR, Link W, Sarker A (2006) Screening techniques and sources of resistance to abiotic stresses in cool season food legumes. *Euphytica* 147:167–186
- Suso MJ (2004) Pollinators: the neglected side of faba bean improvement. *Grain Legum* 40:8–9
- Yan W (2001) A windows application for graphical analysis of multi-environment trial data and other types of two-way data. *Agron J* 93:1111–1118
- Yan W (2002) Singular value partitioning for biplot analysis of multi-environment trial data. *Agron* 94:990–996
- Yan W, Hunt LA, Sheng Q, Slavnic Z (2000) Cultivar evaluation and mega-environment investigation based on the GGE biplot. *Crop Sci* 40:597–605