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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 United Kingdom. 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 x 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 were able to give some modest yield at Cordoba. The Average Tester Coordinate (ATC, defined by the average of first and second principal components of all environments) allowed 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.

KEY WORDS: genotype x environment interaction; winter hardiness; yield stability;

Vicia faba

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 United Kingdom (>88,000ha) (Link and Bond 2011) where they represented about half of faba bean grown at the end of the 19th century (Bond and Crofton 1999). Winter faba bean types were also widely grown

already in the beginning of 19th 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 20th 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 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 objective of this research was 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 United Kingdom 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), twelve 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.

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 the first and second principal components 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, then 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, suggests 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 2 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 (Figure 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 subset 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 positive 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 shown 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 (Figure 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 more environments. The GGE biplots based on each subset data separated the mega-environments shown in Table 5. For the third faba set (Figure 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 “average tester coordinate (ATC)” view of the biplot was examined. In this way, for subset 3 Figure 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 (Figure 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 had a near-zero secondary effect scores (Figure 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 (Figure 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, 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-environment. 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 Figure 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 analysis (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 (Susó 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 cultivars 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 with “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. *Agronomy 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 Crops 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.
- Crossa J, Cornelius PL (1997) Sites regression and shifted multiplicative model clustering of cultivar trial sites under heterogeneity of error variances. *Crop Sci* 37:405-415
- Duc G (1997) Faba bean (*Vicia faba* L.). *Field Crops 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 Crops Res* 115:270-278
- Fox PN, Rosielle AA (1982) Reducing the influence of environmental main-effects on pattern analysis of plant breeding environments. *Euphytica* 31: 645-656
- Gauch HG, Zobel RW (1996) AMMI analysis of yield trials. In: Kang MS, Gauch HG (eds) Genotype-by-environment interaction. CRC Press, Boca Raton, FL, pp 1–40

- 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, Ruckenbauer P, Robertson LD (1993) Analysis and use of interpool-crosses (Mediterranean $\times$ 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, Balko C, Stoddard FL (2010) Winter hardiness in faba bean: Physiology and breeding. *Field Crops Res* 115:297-307
- 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
- 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. *Global 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 Crops Res* 115:201-202
- SAS Institute (1996) SAS/STAT Software: changes and enhancements through release 6.11. SAS Inst., Cary, N.C, USA.

- 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 Crops 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 Legumes* 40:8-9
- 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
- Yan W (2001) A windows application for graphical analysis of multi-environment trial data and other types of two-way data. *Agronomy J* 93:1111-1118
- Yan W (2002) Singular value partitioning for biplot analysis of multi-environment trial data. *Agronomy* 94:990-996

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

accession	grain yield (kg ha⁻¹)^a	Characteristics
Castel	5155	French cv. from SCA Epi Sem - 1987. Early, tall plants, frost tolerant control.
Clipper	5191	Brithish cv. from Wherry & sons - 1996. Late, large-seeded, little winter hardiness
Diva	4640	French cv. from Agro-Obtention - 2002. Similar winter hardiness to Karl. Earlier than Olan
Divine	3836	French cv. from Agro-Obtention - 1995. Spring type used as frost sensitive control – low vicine content
Gabl-107	5218	French line from GAE Recherche - not marketed. Good winter hardiness, tall plants
Hiverna	4688	German cv. from NPZ - 1986. Good yield and frost tolerance, tall, large-seeded
HIX	4817	French line from Agro-Obtention - not marketed. Early, winter hardy, half-determined
Irena	4399	French cv. from Agro-Obtention - 2002. Early, little winter hardiness. Resistant to ascochyta, short plants
Karl	5005	French line from Blondeau - 1990 -not marketed. Old line, best winter hardiness (frost under-15°C), late to flowering
NPZ Wab 01	5054	German line from NPZ - not marketed. Good frost tolerante
Olan	4793	French cv. Less winter hardiness than Karl, tall plants, late to harvest
Wizard	5217	British cv. from Wherry & sons - 2002. Large-seeded
Target	5183	British cv. from Wherry & sons - 1994. Late, large-seeded, little winter hardiness
HIT	4409	French line from Agro-Obtention- not marketed. White flowers, winter hardy, early, half-determined
HIP	4891	French line from Agro-Obtention- not marketed. White flowers
HJC	4518	French line from Agro-Obtention- not marketed. Winter hardy, early, half-determined

^a Average yield in subset 4.

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, United Kingdom	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

Table 3. Mean grain yield (kg ha⁻¹) 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	7036	8065	6425	7060	7525	M	M	7583	M	M	6086	6685	7560	7452	7590	7733	7233
Bersée-04, France	6803	M	6147	5430	7250	3890	4843	M	5271	5372	5555	6013	M	6001	M	M	5689
La Brosse-03, France	3629	3581	3362	3510	3467	M	M	3862	M	M	3033	3391	3591	3748	3386	3352	3492
La Brosse-04, France	5092	4624	4149	3530	4873	4259	3831	4775	4242	4254	3872	4219	4803	4311	4213	4543	4349
Córdoba-03, Spain	693	M	M	292	M	M	M	M	M	M	854	M	M	146	M	M	496
Dijon-03, France	5662	5015	5040	5292	4932	M	M	5193	M	M	5013	5032	5138	5109	5344	5238	5167
Dijon-04, France	5086	3730	4249	1709	3963	4710	4531	3585	5005	4141	4541	3994	3857	3701	3718	4136	4041
Edgmon-03, United Kingdom	3678	4374	4291	3181	4691	M	M	4519	M	M	3856	4478	4713	4367	4101	4374	4218
Edgmon-04, United Kingdom	4557	4575	4399	4648	4783	4722	4406	4664	4323	4761	4067	4633	4617	4663	4589	4672	4567
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	2535	20	3145	1075	1285	2370	2000	2305	970	2735	3290	M	1205	405	1693
Göttingen-03, Germany	M	5421	5938	2401	M	M	M	4739	M	M	4935	M	5980	M	5111	4958	4935
Göttingen-04, Germany	M	5913	5953	1155	6260	5443	5583	5798	5653	6028	4865	5843	6143	M	5958	5880	5462
Hohenlieth-03, Germany	M	6191	3254	M	5330	M	M	5119	M	M	2074	4647	5737	M	4977	5196	4725
Logroño-03, Spain	3019	M	M	3553	M	M	M	M	M	M	2905	M	M	2682	M	M	3040
Logroño-04, Spain	3908	3158	M	2479	M	2725	2017	M	1979	2694	3254	M	M	3113	2413	2284	2765
Montbartier-03, France	4191	3429	3548	3405	3262	M	M	2714	M	M	3905	3167	3214	3536	3226	3774	3447
Paris-03, France	5129	4817	4088	4467	4281	M	M	3759	M	M	4202	4121	4306	3837	3676	4443	4260
Paris-04, France	6237	7198	6154	6094	6835	5635	5091	5327	5374	5321	4789	7023	6639	6009	7001	7070	6112
Mean	4087	4492	4708	3123	5112	4209	4246	4663	4345	4531	3523	4767	5028	3678	4226	4331	4260
SE	287	269	168	259	203	244	248	187	255	230	210	178	186	284	253	260	64

^aM = 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 ^a	Mean Squares ^b	Explained variation	
				% of G, E and GE ^c	% of PC1 + PC2 ^d
Subset 1	E	14	2968.71***	78	
	G	3	505.33***	3	88 + 8
	GE	42	138.78***	11	
Subset 2	E	15	6096.73***	91	
	G	3	437.66***	2	64 + 25
	GE	45	99.08***	4	
Subset 3	E	9	6831.77***	81	
	G	11	185.90***	3	40 + 34
	GE	99	72.61***	9	
Subset 4	E	3	2913**	53	
	G	15	123.93***	11	56 + 35
	GE	45	91.26***	25	

^a degrees of freedom

^b **, *** Significant at the 0.01 and 0.001 level of probability.

^c Percentage sums of squares respect from the total sums of squares

^d Proportions of the first two Principal Components derived from singular value decomposition of the environment-centered data.

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

Subset of data	Winning cultivars	Average grain yield (kg ha ⁻¹)	Environment groupings ^a
Subset 1 ^d	Clipper	4821	Paris-03, Paris-04 ^{bc} , Edgmond-03, Edgmond-04, La Brosse-03, La Brosse-04, Bersée-03, Hohenlieth-03 ^b
	Target	4532	Montbartier-03, Logroño-04, Dijon-03, Dijon-04, Gleisdorf-04, Göttingen-03 ^c , Göttingen-04
	Irena	4059	
Subset 2	Castel	4086	Paris-03, Paris-04 ^b , Edgmond-03, Edgmond-04, La Brosse-03, La Brosse-04 ^{bc} , Bersée-03, Bersée-04 ^{bc}
			Dijon-03 ^c , Dijon-04 ^b , Logroño-03, Logroño-04 ^c , Montbartier-03
	Irena	3521	Escacena-03, Escacena-04, Córdoba-03
	Divine	3415	
Subset 3	Castel	5068	Dijon-03, Dijon-04 ^b , Montbartier-03
	Clipper	4913	Paris-03, Paris-04 ^b , Edgmond-03 ^{bc} , Edgmond-04, La Brosse-03, La Brosse-04 ^{bc} , Bersée-03 ^b
	Divine	4296	
	Irena	4355	
Subset 4	HIX	4817	Dijon-04
	Castel	5155	
	Target and Clipper	5183, 5191	Paris-04 ^b , Edgmond-04, La Brosse-04 ^{bc}
	Divine	3836	
	Irena	4399	

^a Based on the GGE biplots each subset data separated the mega-environments shown in this Table.

^b Environments with larger projection on Average Tester Coordinate X-axis give better discrimination of the cultivars.

^c Environments with smaller projection on Average Tester Coordinate Y-axis give better representation of the overall environment.

^d 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

Figure 1. GGE biplot based on the yield data of 12 faba bean cultivars grown at 10 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 (%).