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Adaptation of spring faba bean types across European climates

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ABSTRACT

Faba bean (*Vicia faba* L.) is a cool season grain legume whose acreage has constantly declined in traditional producer countries as it has been replaced by more productive cereal crops. However, faba bean is still considered to have great potential as rainfed crop. In order to satisfy the renewed interest in faba bean cultivation yield stability should be improved by exploiting different germplasm types and sowing seasons.

In order to understand of genotype by environment interactions and to compare cultivar performance over years and locations a spring faba bean network was established with twenty cultivars grown over three crop seasons at thirteen contrasting locations covering most of Europe. Analysis was performed by heritability-adjusted genotype plus genotype $\times$ environment interaction (HA-GGE) biplot analysis. HA-GGE biplot analyses identified that the effect of genotype by environment interaction was higher than the effect of genotypes, allowing identification of three mega-environments, namely Continental, Oceanic, and Mediterranean, in which cultivars performed differently. This supports the need for specific breeding for each specific geoclimatic area. Espresso was the highest yielding cultivar, being also highly stable over the Oceanic and Continental mega-environments. Cultivars Fuego, Hobbit and SR-1060 had also good yield but with a moderate unstability in both Oceanic and Continental mega-environments. Baraca and Alameda yielded poorly at all environments although were the best yielders at Mediterranean locations. Environments as Sumperk and Premesques were identified as the best core test locations for Continental and Oceanic mega-environments, respectively, being the locations in which best genotypes could be most easily identified.

KEY WORDS: genotype $\times$ environment interaction; yield stability; *Vicia faba*

1. Introduction

Faba bean (*Vicia faba* L.) is a cool season grain legume used as a source of protein in human diets, as a forage crop for animals, and for boosting nitrogen in the biosphere (Duc et al., 2010). However, world faba bean acreage has declined from circa 5.5 million ha in 1960 to 2.5 in 2010 (FAOSTAT). This decline in cultivation has been constant in traditional producer countries in Europe, North Africa, West Asia and China and has been ascribed to instability of yields. More productive cereal crops are preferred by farmers. However, the productivity of cereal-based cropping systems is strongly dependent on N fertilizer what requires fossil energy for manufacture, transport and spreading (Smil, 2001). The limited resources of fossil energy and renewing health and environmental concerns reinforce the role of faba bean as a source of N for future cropping systems (Jensen et al., 2010). In fact, faba bean cultivation is increasing in Australia's cereal based farming systems, as growers appreciate its benefits to the fertility and health of soils and as new grain export markets and higher fertilizer prices increase their profitability (Paull et al., 2011).

Yield stability should be improved to satisfy the renewed interest in faba bean cultivation. Faba bean has potential as rainfed crop in continental, oceanic, and Mediterranean climates by exploiting different germplasm types and sowing seasons (Annicchiarico and Iannucci, 2008; Stoddard and Hämäläinen, 2011; Flores et al., 2012). Faba bean germplasm can be grouped into spring and winter types according to frost tolerance, what delimits target climatic zone and sowing time (Lawes et al., 1983; Stoddard et al., 2006). As a particular type, the Mediterranean germplasm is a subtype of spring faba bean adapted to autumn sowing in Mediterranean regions. Significant genetic variation exists within numerous faba bean germplasm lines maintained and

many traits of interest have already been incorporated into modern cultivars (Duc et al., 2010; Rubiales, 2010).

For quantitative traits such as yield, for which the relative performances of cultivars often change from one environment to another, extensive testing is required for identifying genotypes with minimal interaction with environments, or that possess greatest yield stability. The comparison of cultivar performance over years and locations in multi-environment trials is needed to understand genotype by environment interactions, which in turn assist in developing appropriate breeding strategies. Photoperiod and temperature requirements highly influence cultivar performance among sowing dates and locations (Stutzel, 1995a,b; Confalone et al., 2010). A significant genotype by environment interaction not only results in changes in relative ranking or performance of genotypes from one environment to another, but also hinders breeding progress while selecting and advancing genotypes to subsequent stages of selection (Pham and Kang, 1988). Different procedures have been used in the study of genotype by environment interaction (Flores et al., 1998). GGE biplot method (genotype plus genotype by environment interaction) (Yan et al., 2000) graphically represents the genotype main effects plus genotype by environment interaction effects. Many studies have used GGE biplot analysis mainly for mega-environment evaluation, cultivar evaluation, and assessment of varietal stability (Rubio et al., 2004; Butron et al., 2004; Samonte et al., 2005; Navabi et al., 2006; Dehghani et al., 2006; Setimela et al., 2007; Blanche et al., 2007; Baxevanos et al., 2008; Mohammadi et al., 2009; Villegas-Fernández et al., 2009; Zhe et al., 2010; Silva et al., 2011, Fernández-Aparicio et al., 2012; Villegas-Fernández et al., 2012; Rubiales et al., 2012; Flores et al., 2012).

GGE biplot removes the effect of the environment main effect and focuses on the effect of genotype plus genotype by environment interaction components relevant to

cultivar evaluation (Yan, 2002). A secondary goal of GGE biplot is to determine whether the target cropping region is homogeneous or can be meaningfully divided into different megaenvironments (Yan et al., 2000). Investigation of mega-environments is a prerequisite for meaningful cultivar evaluation and recommendation (Yan et al., 2000), helping to discern how many breeding programs are needed to address varietal and germplasm needs.

The objectives of this research were to evaluate the performance and stability of yield among spring faba bean cultivars, to examine the possible existence of different mega-environments within Europe and in such a case to identify the winning genotype for each mega-environment.

2. Materials and methods

Plant material and experimental design

The spring cultivars network was made up of 20 cultivars (Table 1) grown over three crop seasons (2003, 2004 and 2005) at 13 contrasting locations covering most of Europe, from United Kingdom to Austria and from Estonia to Spain (Table 2). An environment was defined as the combination of a year and a location. The cultivars tested in each year were different because of the usual practice of discarding inferior genotypes and adding new cultivars every year (Table 3).

At each location a randomized complete block design with two to four replications was used. Sowings were carried out between February (France) and May (Estonia) according to local practice, at a sowing density of around 30 seeds m⁻². Following local practise, due to its mild winter and hot spring Spanish trials were winter sown.

2.2 Statistical analysis

Because different sets of cultivars were tested in different years (Table 3), the analysis was first conducted by year, followed by other analysis within each mega-environment identified,. A combined ANOVA for randomized complete-block designs within each year and within each mega-environment identified was carried out using SAS ® 9.3 (SAS Institute Inc.). Prior to each ANOVA, tests for normality and equality of variance were conducted for each dependent variable. For each environment, the genotypic variance (σ_g^2) and error variance (σ_e^2) were estimated using Proc Varcomp of SAS ® 9.3 (SAS Institute Inc.). Broad sense heritabilities (H) were calculated as:

$$H = 1 - \frac{\sigma_g^2}{b\sigma_g^2 + \sigma_e^2}$$

where b is the number of replicates. For this study, H was considered a measure of the usefulness of the trial in genotype evaluation in which differences among genotypes might entirely due to genetic effects ($H=1$) or only to random error ($H=0$) (Yan and Holland, 2010).

Different GGE biplots can be generated depending on how the data are scaled prior to singular value decomposition (Yan et al., 2007). In our case, that the environments have different heritabilities (data not shown) for the same trait is appropriate to use the HA-GGE biplot (Yan and Holland, 2010) to study the genotype by location (within each year) and the genotype by location-year environment interaction (within each mega-environment) of faba bean yield. The genotype by location and genotype by environment two-way tables were first centered with the respective environment means and then multiplied by H and then divided by the SD (standard deviation) of the respective environment. A two-dimensional biplot called HA-GGE biplot (heritability-adjusted genotype plus genotype by environment interaction) was constructed using the

first two principal components derived from subjecting the previous environment-standardized 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).

According to Yan and Holland (2010) the vector length of an environment will be proportional to H , and the cosine of the angle between two environments in the HA-GGE biplot approximates the genetic correlation (r) between them (Fig.1). Thus, graphically the HA-GGE displays the relative utility of environments in terms of selection response.

A “Target Environment Axis” (TEA) was defined by Yan (2001) as a virtual environment which is the point on the biplot that has the average coordinates of the all environments (Fig. 1). In a HA-GGE biplot the projection of the vector of an environment onto the TEA abscissa (TEA_a in Figures) should approximate $r H$ (Fig. 1) (Yan and Holland, 2010) which is an overall measure of the usefulness of an environment (Allen et al., 1978). Inspection of the angle formed by two environmental vectors (r in Fig. 1) in an HA-GGE biplot visually conveys the following information: An acute angle (close to 0°) implies a high positive genetic correlation. A right angle (90°) implies no genetic correlation between the two environments. An obtuse angle (close to 180°) implies a high negative genetic correlation. When strongly negative correlations exist among test environments, one should investigate whether the target environments can be divided into meaningful mega-environments (Yan and Holland, 2010). Test environment evaluation and genotype evaluation are meaningful only within a mega-environment (Yan et al. 2007). Thus, the smaller the angle between years (r) within a test location, the more repeatable the test location (Fig. 1). The smaller the

angles between years within a test location and the TEA_a of a mega-environment (in Fig. 1), the more representative the test location (Yan et al., 2011). Cultivars and environments were displayed in the same plot. This HA-GGE biplot could identify broadly adapted cultivars that offer stable performance across all mega-environments identified, as well as cultivars that perform well under specific mega-environments in the spring faba bean network. The average yield and stability of the cultivars were examined, thus the average yield of the cultivars is approximated by the projections of their markers onto the TEA abscissa and the stability is measured by their projection to the TEA ordinate (Fig. 1). The greater the absolute length of the projection of a cultivar, then less stable it is.

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

The analysis of variance results for each year are presented in Table 4. Location (L), genotype (G), and genotype by location interaction (GL) main effects were all highly significant ($p < 0.0001$). As is typical in most multilocation trials, faba bean yields were significantly influenced by location which accounted for 70% to 86% of the total variation ($G + E + GE$),. The effect of GE interaction was greater than the effect of genotypes. The ratio of G over $G + GL$ was 34% in 2003, 38% in 2004, and 30% in 2005 suggesting the possible existence of multiple faba bean mega-environments in Europe, in which cultivar rankings are different from other mega-environments (Yan et al., 2000). The partitioning of $G + GE$ through HA-GGE biplot analysis showed that the first two principal components were significant factors in all years, explaining 73% to 87% of total $G + GE$ sum of squares (Table 4).

To conduct test environment evaluation, it is essential to first conduct a mega-environment analysis, that is, to investigate whether the covered growing region can be divided into mega-environments, because test environment evaluation as well as genotype evaluation becomes meaningful only when conducted within mega-environments (Yan et al. 2007). In 2003, the HA-GGE biplot (Fig. 2) reveals that Gleisdorf and Sumperk locations were clearly distinct from the rest of locations. However, locations had a right or obtuse angle with each of the remaining locations, suggesting that the two groups of locations were not associated or were negatively associated. Gleisdorf and Sumperk locations formed a mega-environment, hereafter referred to as mega-environment 1 (ME1) named XXXXX and remaining locations (Toft, Bersée, Brosse, Paris, Hohenlieth and Jogeve) may be referred to as mega-environment 2 (ME2) named YYY. The distinctiveness of the Sumperk location from the ME2 locations was also apparent in 2004 (Fig. 3). On the other hand, Cordoba and Escacena locations were also clearly distinct from the two previous mega-environments (ME1 and ME2), therefore, these two locations may be referred to as mega-environment 3 (ME3) that we named Mediterranean mega-environment (ME3). Similar mega-environments were earlier identified in winter faba bean trials (Flores et al., 2012). 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.

Figure 5 shows the HA-GGE biplot involving only the year-location combinations in ME1. It is clear that genetic correlation (r) and the square root heritability ($\sqrt{H}$) must be considered simultaneously in assessing the usefulness of a test

environment (Allen et al. 1978; Yan and Holland, 2010). A test environment is not useful if its H is very low or its genetic correlation with TEA is small or negative (wide or obtuse in Fig. 1). Figure 5 shows that Sump04 had the longest vector, therefore, it had the highest H , followed by Sump05 and Gleis05. While, the projection of each test environments onto TEA (Fig. 5) approximate its r_H , and are a measure of its usefulness in selecting superior genotypes for the mega-environment ME1. Thus, the usefulness of the three environments can be ranked as: Sump04 > Sump05 > Gleis05 (Fig. 5). Thus by this criterion, Sumperk location (Fig. 5) was the most usefulness and ideal for selecting superior genotypes within mega-environment ME1.

A test location must be repeatable across years in ranking genotypes for it to be considered as highly representative (Yan et al. 2011). This was be visualize in the HA-GGE biplot. Sumperk location had a high repeatability as shown by the acute angle between both years (r in Fig. 1). Sumperk was generally representative of the ME1 as indicated by its acute angles with the TEA (in Fig. 1). To summarize, Sumperk can be regarded as highly representative, which is also highly repeatable by definition (Yan et al. 2011). Such representativelocations were classified as Type I by Yan et al. (2011) being considered the ideal test locations for use as core test location for a mega-environment. This type de test locations are crucial for a breeding program particularly for early generation selection when amount of seed is limited and not are available multilocation trials.

Figure 5 is also the most appropriate for genotype evaluation as well as for test environment evaluation. HA-GGE biplot (Fig. 5) for faba grain yield shows a seven-sided polygon formed by the union of the identified cultivars that were further away from the biplot origin, so-called vertex cultivars (cvs. Merkur, Fuego, Marcel, Melodie, Baraca, Jageva and GL-0303).

The projection of the genotype vector onto the TEA axis abscissa (TEA_a), with an arrow pointing to a greater value based on their mean performance across all environments within mega-environment ME1. The double arrowed line (TEA_o) separates entries with below-average means from those with above-average means (in Fig. 5, those cultivars that are on the left of the perpendicular have a low grain yield value), and either direction away from biplot origin indicates greater genotype by environment interaction effect and reduced stability (Fig. 5). Therefore, for mega-environment ME1, the best cultivars are Fuego and Espresso as shown by their highest grain yield (positive projection on TEA_a) and the highest stability over ME1. Cultivars Baraca, Jovega, Alameda, Melodie and GL-0303 yielded poorly in ME1. Cultivars Merkur, Hobbit and SR-1060 were unstable for seed yield as they performed well at Gleisdorf environments but only moderately at Sumperk. Cultivar Marcel was also unstable but performing well at Sumperk and near the average at Gleisdorf.

In ME2 (Fig. 6) Paris, Premesques and Bersée were the most repeatable locations as shown by the acute angle between years. Premesques and Bersée were the most representative of the mega-environment as indicated by its acute angles with TEA, while location Paris was moderately representative. Therefore, Premesques and Bersée can be considered as good (Type I) test locations for ME2 (but Premesques had the most high usefulness (r_H)) that the rest of environments classified as of Type II according to Yan et al. (2011). Such locations type II are useful in the multilocation test stage for selecting against unstable genotypes. The highest yielding genotypes ME2 were Espresso and Fuego (Fig. 6). The most stable cultivars were Espresso, SR-1060, Maya and Marcel. Baraca and Alameda yielded poorly at all environments of ME2.

Figure 7 represent a HA-GGE biplot involving only the Mediterranean mega-environment (ME3) The three studied environments had high projection onto TEA_a

indicating its usefulness (r_H) in selecting superior genotypes for this mega-environment. The studied locations (Córdoba and Escacena) were representative of ME3. Escacena had a moderate repeatability between years, being classified as type II according to Yan et al. (2011). Baraca and Alameda were the best performing cultivars in ME3 (Fig. 7). Both cultivars were moderately unstable. Remaining cultivars yielded poorly very below-average, showing that continental cultivars are poorly adapted to the Mediterranean area. The poor adaptation in Mediterranean areas could be attributed to the lateness longer and lower drought tolerance of these cultivars bred in Continental and Oceanic environments relative to the Mediterranean germplasm (Kittlitz et al., 1993; Link et al., 1996). In Mediterranean climates which have a short growing season, early sowing is essential to minimise yield losses from moisture- and high temperature-stress during reproductive development (Loss et al., 1997). As a cool season legume, high temperatures at flowering are likely to reduce pollen viability in faba bean, and interact with moisture stress to cause flower, ovule and pod abortion (Hall, 1992). Baraca and Alameda were the earliest flowering cultivars at Escacena and Cordoba (average 76 days to first flowers, compared to >100 days in remaining cultivars). This earliness can contribute to avoid such heat and drought. Also, it has been shown that floral design and display of the flowers of these cultivars do not fit to the local pollinator (*Eucera numida*) (Susó, 2004) whereas in other parts of Europe principal pollinators are honeybees (*Apis mellifera*) and bumblebees (*Bombus* sp.). However, it is uncertain the role this would play in other Mediterranean regions where different pollinators are present (Marcellos and Perryman, 1990).

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 HA-GGE biplots revealed three apparent

groups of cultivars in terms of their response to the mega-environments (Figs. 5, 6 and 7). Group 1 consisted of six cultivars, namely Fuego, Espresso, SR-1060, Merkur, Hobbit and Mistral that performed well in the Continental mega-environment. Group 2 consisted of four cultivars, Fuego, Espresso, SR-1060 and Hobbit that performed well in the Oceanic mega-environment. Group 3 consisted of two cultivars, namely Baraca, and Alameda that performed well in the Mediterranean mega-environment. Similarly poor yields in Mediterranean areas were previously described for most winter faba bean cultivars (Flores et al., 2012).

Sumperk and Premesques were identified as highly representatives (location type I, according to Yan et al., 2011) of Continental and Oceanic mega-environments, respectively. Escacena was identified as location type II for Mediterranean mega-environment, which may be used for selecting against unstable genotypes.

An ideal genotype should have the highest mean performance and stability (i.e. perform the best in all environments). Although such an ideal genotype may not exist in reality, it can be used as a reference for genotype evaluation. A genotype is more desirable if it is located closer to the TEA_a axis. In this study Espresso was ideal genotype for both Oceanic and Continental mega-environments.

4. Conclusion

In order to satisfy the renewed interest in reintroducing faba bean in rainfed cropping systems yield stability should be improved by exploiting different germplasm types and sowing seasons (Duc et al., 2010; Rubiales, 2010). Many traits of interest have already been incorporated into modern cultivars and breeding effectiveness is expected to increase with the adoption of the new improvements in marker technology together with the integration of comparative mapping and functional genomics (Dita et al., 2006;

Torres et al., 2006; Risipail et al., 2010; Alghamdi et al., 2012). These advances in cultivar development ought to be accompanied with refinement of integrated pest management strategies (Pérez-de-Luque et al., 2010; Stoddard et al., 2010) and adjustments in cropping practices (Jensen et al., 2010).

The HA-GGE biplot allowed identification of three mega-environments, namely Continental, Oceanic, and Mediterranean in which cultivar rankings are different, supporting the need for specific breeding for each mega-environment rather than across the whole continent.

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

Cultivar	Characteristics	Source
Alameda	Coloured flowers, medium seed size, adapted to dryland conditions, low vicine content, medium covicine content	INIA, Spain
Baraca	Coloured flowers, medium seed size, intermediate resistance to broomrape	INIA, Spain
Disco	Low tannin, vicine and covicine content	INRA, France
Divine	Low vicine and covicine content	INRA, France
Dixie	Small seeds, early flowering	INRA, France
Espresso	Coloured flower, high standing ability, high yield potential, big seeds	NPZ, Germany
Fuego	Coloured flower, high standing ability, high yield potential, big seeds	NPZ, Germany
GL 0303	Colored flowers, small seeds	SZ Gleisdorf, Austria
Gloria	White flowers, high protein, resistant to root diseases, small seeds	Serasem, France
Hobbit	Coloured flower, short, big seeds, high yield potential	NPZ, Germany
Jõgeva	Coloured flower, medium to high protein, medium seed size	Jõgeva, Estonia
Marcel	Short, high standing ability, big seeds	Toft, Denmark
Maya	Control, ha, short, big seeds	Serasem, France
Melodie	Low vicine and covicine content	INRA, France
Merkur	Colored flower, moderate lodging resistance, medium seeds size	Agritech, CzR
Mireille	White flowers	Serasem, France
Mistral	White flowers, medium to high protein, high lodging resist, medium seeds size	Agritech, CzR
SR 1060	Low vicine and covicine content	Serasem, France
Valeria	White flowering, medium to high protein, small seeds	SZ Gleisdorf, Austria
Victoria	prot> 3% / Maya, White flowers	Serasem, France

Table 2. Description of the environments (combination of location and season) of the trials for the multi-environment study. Climatic data are provided for the growing season. Average maximum and minimum temperatures.

Environm.	Location	Latit.	Long.	Altitude (m ASL)	Growing season	Weather during growing season		
						Max. T (°C)	Min. T (°C)	Rain (mm)
BERSE03	Bersée, France	50.39°N	2.57°E	29	26 Febr – 13 Aug	28	3	242
BERSE04	Bersée, France	50.39°N	2.57°E	29	16 March – 20 Aug	26	3	287
BERSE05	Bersée, France	52.59°N	2.05°W	150	18 March – 18 Aug	29	6	282
BROSE03	La Brosse, France	48.2°N	3.01°E	93	25 Febr – 24 July	27	4	216
BROSE04	La Brosse, France	48.2°N	3.01°E	93	14 Febr – 06 Aug	24	-1	228
BROSE05	La Brosse, France	48.2°N	3.01°E	93	17 March – 03 Aug	27	6	139
CORD04	Córdoba, Spain	37.86°N	4.8°W	117	18 Nov – 14 June	29	3	527
EDGMON05	Edgmond, UK	52.59°N	2.15°W	150	20 Febr – 30 Aug	28	1	320
ESCA04	Escacena, Spain	37.38°N	6.42°W	171	12 Nov – 06 June	29	3	572
ESCA05	Escacena, Spain	37.38°N	6.42°W	171	15 Nov – 10 June	29	6	147
GLEIS03	Gleisdorf, Austria	45.10°N	15.71°E	361	27 March – 28 Jul	28	0	269
GLEIS05	Gleisdorf, Austria	45.10°N	15.71°E	361	04 April – 09 Aug	27	7	368
HOHEN03	Hohenlieth, Germany	54.25°N	9.53°E	23	22 March – 12 Aug	26	2	256
HOHEN04	Hohenlieth, Germany	54.25°N	9.53°E	23	02 April – 04 Sept	24	6	344
HOHEN05	Hohenlieth, Germany	54.25°N	9.53°E	23	01 April – 02 Sept	26	4	276
JOGE03	Jogeva, Estonia	58.44°N	26.23°E	72	12 May – 03 Oct	26	6	426
JOGE04	Jogeva, Estonia	58.44°N	26.23°E	72	03 May – 21 Sept	23	2	427
JOGE05	Jogeva, Estonia	58.44°N	26.23°E	72	06 May – 10 Sept	21	6	338
LOGRO04	Logroño, Spain	42.45°N	2.28°W	342	12 Febr – 22 July	26	0	254
LOGRO05	Logroño, Spain	42.45°N	2.28°W	342	17 Nov – 12 July	26	-3	190
PARIS03	Paris, France	48.43°N	2.07°E	120	11 March – 27 Jul	27	2	183
PARIS04	Paris, France	48.43°N	2.07°E	120	02 March – 11 Aug	26	3	234
PARIS05	Paris, France	48.43°N	2.07°E	120	19 March – 11 Aug	27	4	158
PREME04	Premesques, France	50.65° N	2.95° E	33	20 Febr – 23 July	25	2	259
PREME05	Premesques, France	50.65° N	2.95° E	33	16 March – 30 Aug	27	4	335
SUMP03	Sumperk, Czech Republic	49.10°N	17.10°W	315	23 April – 05 Aug	23	8	332
SUMP04	Sumperk, Czech Republic	49.10°N	17.20°W	315	22 April – 04 Aug	28	3	356
SUMP05	Sumperk, Czech Republic	49.10°N	17.10°W	315	19 April – 09 Aug	26	3	328
TOFT03	Toft, Denmark	56.72° N	8.97° E	27	03 April – 24 Aug	23	0	312
TOFT04	Toft, Denmark	56.72° N	8.97° E	27	15 April – 31 Aug	23	3	301
TOFT05	Toft, Denmark	56.72° N	8.97° E	27	15 April – 09 Sept	21	6	360

Table 3. Mean grain yield (kg/Ha) and standard error (SE) of 20 faba bean cultivars grown at 32 location-year environments from Spring EUFABA Network.

	Faba bean cultivar																					
Environments	ALAMEDA	BARACA	DISCO	DIVINE	DIXIE	ESPRESSO	FUEGO	GL-0303	GLORIA	HOBBIT	JOGEVA	MARCEL	MAYA	MELODIE	MERKUR	MIREILLE	MISTRAL	SR-1060	VALERIA	VICTORIA	Mean	
BERSE03	M	M	M	6735	M	M	M	M	6332	M	M	6423	6202	7251	M	5442	M	M	M	6735	6446	
BERSE04	4707	3962	6888	7115	5395	8124	8189	5893	6660	6895	5131	7838	7348	6537	7058	6800	6466	8180	5652	7706	6627	
BERSE05	4757	4211	5082	5682	4346	6455	6201	4557	4766	6009	3771	5355	5789	5980	5961	M	5486	5880	4810	5965	5365	
BROSE03	M	M	M	4394	M	M	M	M	3868	M	M	3892	3961	4861	M	2979	M	M	M	4013	3995	
BROSE04	3598	2735	5191	5811	5145	5446	5933	3998	4571	5707	2706	4739	5620	6339	4988	4832	5000	5800	4484	5400	4902	
BROSE05	3212	3449	3270	3322	2448	4121	3408	2240	2998	3634	1979	3628	3901	4271	3681	M	3959	4149	3085	3669	3426	
CORD04	2776	1884	M	266	M	221	235	475	611	711	57	138	338	M	595	250	464	649	779	911	668	
EDGMON05	4947	5247	5533	4567	3902	3143	3429	5256	4178	2603	4996	4920	4440	4762	4735	M	4120	4977	4423	4073	4434	
ESCA04	1993	1490	M	45	M	70	200	92	215	237	4	8	18	55	159	120	135	113	360	225	308	
ESCA05	1203	1633	M	25	M	23	52	M	M	50	61	M	M	M	M	M	M	M	M	M	435	
GLEIS03	M	M	M	2201	M	M	M	M	3103	M	M	2203	2555	2199	M	2390	M	M	M	2721	2482	
GLEIS05	1093	1253	2793	2133	1653	2667	2950	3487	3050	3397	1993	387	613	613	3543	M	2430	3093	2347	2447	2273	
HOHEN03	M	M	M	5133	M	M	M	M	4693	M	M	4841	4881	5062	M	4630	M	M	M	4740	4854	
HOHEN04	3547	1646	3529	4255	3781	5560	6182	4742	4057	5781	4909	5643	5284	4779	4576	4068	3883	4615	3148	3768	4388	
HOHEN05	2352	3221	2649	4341	4432	5005	5490	4438	3737	5044	4372	4899	4474	4495	4367	M	4208	4914	3846	4016	4255	
JOGE03	M	M	M	4413	M	M	M	M	2729	M	M	3588	2582	4085	M	3404	M	M	M	3255	3437	
JOGE04	923	969	2550	4413	2448	4906	4437	2770	3690	2909	2824	2766	2777	3814	3998	4000	2511	4700	3621	2931	3198	
JOGE05	1429	1575	2265	2703	1653	2702	2909	1554	2370	2663	2017	3133	2639	3766	3302	M	2723	3442	2176	3251	2571	
LOGRO04	3846	2555	M	M	M	3127	3489	2616	2477	3257	M	2769	2913	3153	3048	2747	2416	3253	3375	2935	2998	
LOGRO05	3284	3042	1963	2979	1988	2079	3321	2404	2733	2417	M	3654	2296	1604	M	M	M	2842	1709	3663	2642	
PARIS03	M	M	M	3562	M	M	M	M	3169	M	M	3081	3363	4012	M	2742	M	M	M	3152	3297	
PARIS04	2850	2673	4364	4026	3986	4750	4715	3599	3911	4037	1941	4736	4168	4503	4901	4394	4636	4666	3309	4413	4029	
PARIS05	3106	3555	3886	4353	3506	5004	4825	3388	3936	4705	2443	4016	4993	4828	4098	M	4416	5029	4074	4578	4180	
PREME04	4517	4250	7417	6550	5792	8250	8025	6025	6725	7583	5484	6934	7484	6817	7533	5975	6692	8008	6925	6984	6698	
PREME05	3810	4248	5514	6338	4919	7634	7276	4705	5810	7248	4424	6324	6276	5867	5810	M	6105	6281	5900	5848	5858	
SUMP03	M	M	M	4751	M	M	M	M	5081	M	M	5608	6193	5614	M	4073	M	M	M	4383	5100	
SUMP04	3180	3155	3908	3352	3707	4530	4642	3333	3694	4029	2868	4356	3784	2839	4070	3778	4145	4283	3673	3968	3765	
SUMP05	4309	2511	5382	5467	5054	6073	6106	4698	5026	5639	3480	5824	5656	5125	5893	M	5843	6076	5117	4792	5141	
TOF03	M	M	M	2988	M	M	M	M	3012	M	M	2926	2535	2748	M	2527	M	M	M	2651	2770	
TOF04	4536	4095	3934	5969	4223	6107	6175	4679	4544	6044	5085	5517	5593	5730	4885	4392	5078	5827	3737	4684	5062	
TOF05	2915	2166	4472	5409	4140	5351	5617	4544	4399	5471	4390	4906	4602	5051	5043	M	3641	4660	4805	4092	4532	
Mean	3108	2820	4144	4095	3740	4354	4451	3546	3874	4102	2987	4182	4109	4353	4392	3714	4053	4605	3654	4077	3952	
SE	153	138	197	187	165	273	261	188	150	251	202	184	192	184	213	202	213	225	187	166	45	

M: missing data

Table 4. Genotype (G), location (L) and genotype by location interaction (GL) terms for yield for the spring faba bean performance trials (EUFABA Network), 2003 to 2005 years.

Dataset	Source of variation	df ^a	Mean Squares ^b	G/(G + GL) (%) ^c	% of PC1 + PC2 ^d
Year 2003	L	7	38199969***	34	57+19
	G	6	2360815***		
	GL	42	658265***		
Year 2004	L	10	126121022***	38	74+13
	G	14	6791924***		
	GL	140	1119340***		
Year 2005	L	10	46284875***	30	56+17
	G	15	4183104***		
	GL	150	967393***		

^a degrees of freedom

^b *** Significant at the 0.001 level of probability.

^c Percentage G sums of squares respect from the total sums of squares (G + GL)

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

Fig. 1. Each environment is a location-year combination and is represented by a straight line. Only two locations (SiteA and SiteE) are labeled for clarity. The display shows as the vector length of a test environment approximates its square root heritability ($\sqrt{H}$), its genetic correlations (r) and (ρ) with other test environment and with a target environment (TEA), respectively, and as the projection onto TEA axis approximates values of $r \sqrt{H}$. An example of a highly repeatable test location was SiteE, which had acute angles (r) between years. An example of a low repeatability location was SiteA, which had wide angles between different years. The angle θ is a measure of its representativeness, it can be seen that each of the environments within SiteE was more representative of the mega-environment than those within SiteA.

Fig. 2. HA-GGE biplot based on the yield data of faba bean cultivars grown at all locations for the 2003 data from Spring EUFABA Network. See Table 2 for full location names. The cultivar markers located away from origin were connected with straight lines to form a polygon. PC, principal component. TAE_a, Target Environment Axis abscissa.

Fig. 3. HA-GGE biplot based on the yield data of faba bean cultivars grown at all locations for the 2004 data from Spring EUFABA Network. See Table 2 for full location names. The cultivar markers located away from origin were connected with straight lines to form a polygon. PC, principal component. TAE_a, Target Environment Axis abscissa.

Fig. 4. HA-GGE biplot based on the yield data of faba bean cultivars grown at all locations for the 2005 data from Spring EUFABA Network. See Table 2 for full location names. The cultivar markers located away from origin were connected with straight lines to form a polygon. PC, principal component. TAE_a, Target Environment Axis abscissa.

Fig. 5. HA-GGE biplot based on the yield data of faba bean cultivars grown at all locations-year combination for the Mega-environment 1 data from Spring EUFABA Network. See Table 2 for full location names. The cultivar markers located away from origin were connected with straight lines to form a polygon. PC, principal component. TAE_a, Target Environment Axis abscissa.

Fig. 6. HA-GGE biplot based on the yield data of faba bean cultivars grown at all locations-year combination for the Mega-environment 2 data from Spring EUFABA Network. See Table 2 for full location names. The cultivar markers located away from origin were connected with straight lines to form a polygon. PC, principal component. TAE_a, Target Environment Axis abscissa.

Fig. 7. HA-GGE biplot based on the yield data of faba bean cultivars grown at all locations-year combination for the Mega-environment 3 data from Spring EUFABA Network. See Table 2 for full location names. The cultivar markers located away from origin were connected with straight lines to form a polygon. PC, principal component. TAE_a, Target Environment Axis abscissa.