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RESEARCH ARTICLE

Pedoclimatic, knowledge and management factors drive European soybean and faba bean yields

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Abstract
The low usage of grain legumes in European cropping systems is often attributed to yield gaps due to limiting pedoclimatic conditions, sub-optimal management practices, and farmers' limited experience and knowledge in growing these crops. The relative contributions of these factors to current grain legume yield gaps at European scale and, in particular, the difference between yields achieved by experienced farmers and those achieved by novices remain unknown. We therefore explored the relationship between yields and these different factors, to identify areas where farmers require more support to close the yield gaps in grain legume production. To this purpose, we conducted a large-scale online farmer survey in nine European countries with a focus on soybean and faba bean. For both crops, classification and regression tree analysis identified country of production as the primary explanatory variable of yield variation and confirmed the hypothesis that greater experience and knowledge is associated with higher yields. However, the effect of several factors differed between the crops, showing the need for legume-specific strategies. Experience and knowledge were particularly important for soybean, although also relevant for faba bean in low-yielding environments. Other important factors identified to determine yield for soybean included farm specialization, agroclimatic zone, the number of years growing grain legumes and the size of farmland, while for faba bean these important factors were pest management and perceived soil fertility. Farmers highlighted drought, weed infestation, and soil characteristics as having critical impacts on yields for both crops, as well as inoculation and irrigation for soybean. Both soybean and faba bean growers emphasized the need for more information on plant protection and cultivar selection. The results indicate the potential to increase legume yields by supporting farmers in the first years of growing grain legumes, especially for crops that have a shorter history in Europe such as soybean.

Keywords European farmers' survey · Decision trees · Yield gap · Protein crops · Knowledge · Crop management

1 Introduction

The current simplification of agricultural systems has led to several detrimental environmental impacts such as reductions in water quality, soil degradation, and loss of habitat and species diversity (Burchfield et al. 2019). Crop diversification is proposed as a solution to reverse this, with legumes being seen as an important element of this endeavor due to their potential to increase productivity of crops in the rotations, lead to reduced use of fertilizers and pesticides, increase the resilience of cropping systems and farm businesses, and contribute positively to protein self-sufficiency and nutritional objectives (Stagnari et al. 2017). Nevertheless, and despite these high potentials, grain legumes are underutilized in European cropping systems (Watson et al. 2017). This is often attributed to yield gaps (i.e., the difference between attainable yields under optimal conditions and the yields achieved by farmers) and yield variability in legume production (Rubiales and Mikic 2015; Cernay et al. 2015; Reckling et al. 2018). These are in turn associated with diverse factors, such as pedoclimatic conditions (Pandey et al. 1984; Araújo et al. 2015; Scheelbeek et al. 2018), management practices (Muoni et al. 2022), biotic and

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abiotic stresses (Sinclair and Vadez 2012; Rubiales et al. 2015), limited advances in breeding (Siddique et al. 2012), and farmers' lack of experience and knowledge in growing grain legumes (Graham and Vance 2003).

Previous research has shed some light on the impact of these diverse factors on grain legume yields. As their impact varies across different grain legumes, most studies are crop-specific. For example, several studies have explored the influence of biotic and abiotic stresses (Wrather and Koenning 2006; Anthony et al. 2012), management choices (Pedersen and Lauer 2004; De Bruin and Pedersen 2008), cultivar selection (Egli 1993; Kahlon et al. 2011), or several of these factors (Specht et al. 1999; Liu et al. 2008) on soybean yields in specific environments. Similar factors have been explored in the case of other crops such as faba beans, for example in the studies by López-Bellido et al. (2005) or Alharbi and Adhikari (2020). Most of these studies have employed field experiments or literature review approaches, to explore the influence of a limited number of factors on legume yields and to focus on specific combinations of localities and crops.

Other studies have typically used crop simulation modelling, modified water balance calculations or estimations of yields of adapted cultivars to explore the importance of environmental factors, breeding, and management on reducing yield gaps (Anderson et al. 2016). Such analyses are available for major cereals and soybean (Sentelhas et al. 2015; Nendel et al. 2023), but little information is available for faba bean and other grain legumes (Mínguez and Rubiales 2021). A major recurring conclusion is that there is space to improve yields and reduce yield gaps if farmers adopt existing technology (e.g., Bhatia et al. 2008; Battisti et al. 2018). An important question remains in understanding what prevents farmers from tapping into this existing technological potential to secure greater grain legume yields.

A call for more knowledge exchange, advice and means for appropriate interventions to improve farmers' capacity to grow grain legumes is well emphasized in the literature. Several studies have highlighted the need for extension services and technology transfer to support legume growers (Abtew et al. 2016), and have noted that farmers lack support in selecting legume species best adapted to their local environmental conditions and determining their place in the rotation (Magrini et al. 2018). Furthermore, the lock-in around the major cereal crops leads to deficits in both the technological innovation chain for legume cropping and the agri-food chain for legume products (Voisin et al. 2014; Cholez and Magrini 2023). It has been suggested that learning and peer-networking are critical factors for farmers transitioning to legume-supported farming systems (Mawois et al. 2019), but few studies have explored the influence of farmers' knowledge in growing grain legumes and their associated knowledge requirements (e.g., Von Richthofen et al. 2006 in selected European countries; Zimmer et al. 2015 in Luxembourg; Muoni et al. 2019 in East Africa). Nevertheless, the consideration of socio-economic factors for yield gap analysis is gaining attention in the literature (e.g., van Dijk et al. 2017), which suggests that pedoclimatic factors and management are more often taken into account to explain the yield gap than farm or farmer characteristics and socio-economic factors, although the latter, when considered, often explain the yield gap (Beza et al. 2017).

Despite the rich body of literature exploring the factors affecting grain legume yields on the one hand, and the need to improve farmers' know-how and understand the impact of socio-economic factors on the other hand, the relative contributions of these factors to current grain legume yield gaps at European scale remains unknown. Many studies are limited by their focus on individual location, crop or factors in isolation. In particular, the difference between yields achieved by experienced farmers and those achieved by novices has not been explored, although its assessment would allow evaluation of the potential contribution of knowledge in closing the yield gaps and reducing yield variability in grain legume production. Indeed, with previous studies identifying a lack of knowledge in cultivating grain legumes in individual countries (Zimmer et al. 2015 in Luxembourg; Haarala and Luttinen 2018 in Finland), gaining a better understanding of the influence of this factor on yield gaps is critical.

Hence, we set out to investigate farmers'knowledge and attitudes to grain legumes, particularly soybean and faba bean (Figure 1), in an online survey covering nine European countries. We aimed to identify the importance of different underlying drivers of yields in legume production considering pedoclimatic, structural, knowledge, and management factors and to evaluate, for the first time, the influence of farmers' knowledge on yields. To do so, we used Classification and Regression Tree (CART) analysis, an appropriate technique to integrate data gathered on a wide range of variables that include attitudes as well as hard data.

2 Materials and methods

2.1 Survey design and implementation

An online farmer survey was conducted in nine European countries that comprise areas with different history in cultivating soybean and faba beans and represent varied agro-climatic zones across Europe: Finland, France, Germany, Latvia, the Netherlands, Poland, Spain, Sweden and the UK. The survey was run between February 2020 and May 2021 within the frame of the ERA-NET SusCrop project 'LegumeGap' (https://legumegap.zalf.de/). Participants were reached by consortium members through social media and mobilization of their networks with a focus on legume

Figure 1 Soybean (left) and faba bean (right) cultivation. © Moritz Reckling, ZALF.

growers. The survey was developed in English and its final version was translated by the consortium members into the official languages of the survey countries. The survey included questions about farm characteristics and land use, demographics, the farmer's previous experience with legume growing, and two dedicated sections on soybean and faba bean with questions on yields, management, and perceptions on yield-impacting factors (see Table 1 and Table S1 for an overview of the survey questions).

2.2 Overview of data and statistical analysis

The data were summarized using descriptive statistics and subjected to CART analysis. The use of descriptive statistics about the main characteristics of the farm sample and yields illustrated the factors that farmers consider important in determining their yields and obtaining more support in growing the crop. The CART analysis allowed determination of the factors leading to yield variation in the survey sample.

Both numeric and categorical data were used for the analysis, reflecting a range of pedoclimatic, structural, knowledge, and management factors (Table 1). The data was managed in Stata and stored in Excel sheets. The data analysis and visualization were conducted using the statistical software R (version 4.2.2).

The different responses were attributed to agroclimatic zones according to NUTS II regions following a classification by Metzger et al. (2005) and discussion with experts as follows:

Atlantic: Netherlands, UK, Northwestern France (Normandie, Bretagne, Centre-Val de Loire, Île-de-France, Hauts-de-France, Pays-de-la-Loire, Nouvelle Aquitaine); characterized by year-round rainfall and mild temperatures. Autumn-sown and spring-sown versions of cool-climate crops produce very high yields, often of world-record values. Warm-climate crops seldom get enough heat units to achieve their potential.

Boreal-Nemoral: Finland, Latvia, Sweden; limited by a short growing season, during which occasional cool nights limit the potential of warm-climate crops. Cool-climate crops are grown and breeding programs give high priority to earliness of maturity so the crops can be harvested.

Continental: Germany, Poland, Central France (Grand Est, Auvergne-Rhône-Alpes, Bourgogne-Franche-Comté); has warmer summers and colder winters than the Atlantic region. Depending on the regional climate and length of growing season, both warm-climate and cool-climate crops are sown in spring and harvested in autumn.

Mediterranean: Spain, Southern France (Corse, Occitanie, Provence-Alpes-Côte d'Azur); characterized by winter rainfall and summer drought. Cool-climate crops such as wheat and faba bean are sown in the autumn and harvested in the spring, and warm-climate crops such as maize and soybean are grown with irrigation.

Due to its climatic diversity, France was treated as three separate segments in the analysis. All other countries were represented by one segment per country.

For soybean, very few records were observed for some countries. In order to protect the anonymity of respondents, records for these countries were merged with other segments with similar yields. Specifically, four records from Spain were merged with those of Southern France, three records from the UK were merged with those of Northwestern France, and the records from the Boreal-Nemoral countries (two records from Finland, two from Latvia and six from Sweden) were clustered together.

CART (Breiman and Ihaka 1984), a nonparametric method, was used to explain the association between

Table 1 Overview of variables used for the descriptive statistics and CART analyses and corresponding survey questions. Variables with an asterisk were included in the CART analysis. The survey questions corresponding to these variables can be seen ordered as in the survey in Table S1.

Category	Variable	Survey question	Type of question	Variable type
Yields	Soybean/Faba bean yield*	What is your average soybean/faba bean grain yield?	Open-ended quantitative	Numeric: t ha^{-1}
	Diverse yield-impacting factors	How important are the following factors for the level of your soybean/faba bean yields in your experience?	Matrix	Categorical: Very important, Important, So-so, Less important, Not important, Not sure/Don't know (for each factor below): Temperature limitations Drought Soil structure or deficiencies (e.g. compaction, salinity, acidity, waterlogging) Soil texture (e.g. too sandy) Occurrence of pests Occurrence of weeds Occurrence of diseases Suitability of available cultivars Experience in growing the crop Other
Pedoclimatic	Country *	Where is your farm located?	Dropdown	Categorical: The countries included in the study (with France being treated as three country segments in the analysis)
	Agroclimatic zone* (mapped to NUTS II regions)	Where is your farm located?	Dropdown	Categorical: Atlantic, Boreal-Nemoral, Continental, Mediterranean
	Perceived soil fertility*	Are soils on your farm generally fertile?	Single-answer multiple choice	Categorical: Fertile, Average, Infertile
Structural	Arable land* Arable land/Total land*	How much land are you farming in a typical year (owned and leased)? Hectares of arable land Hectares of pasture land	Open-ended quantitative	Numeric: ha
	Farm specialization*	What is your farm specialization?	Single-answer multiple choice	Categorical: Specialist in arable crops, Mixed cropping, Other
	Area of legumes*	What is the area share of your farm devoted to grain legumes in a typical year?	Matrix	Categorical: 0-25%, 26-75%
	Education level*	What is your highest level of education?	Dropdown	Categorical: Primary school, Secondary/High school, Technical/Vocational school, University
	Gender*	What is your gender?	Single-answer multiple choice	Categorical: Male, Female, Other, I would rather not say
Knowledge	Age of the farmer*	How old are you?	Open-ended quantitative	Numeric: number of years
	Years of farming*	For how many years have you been farming?	Open-ended quantitative	Numeric: number of years
	Years of growing legumes*	For how many years have you grown grain legumes (harvested for grain) in total?	Open-ended quantitative	Numeric: number of years
	Years of growing soybean/faba bean*	For how many years have you grown soybean/faba bean (harvested for grain) in total?	Open-ended quantitative	Numeric: number of years

Table 1 (continued)

Category	Variable	Survey question	Type of question	Variable type
	Frequency of growing legumes*	How often do you grow grain legumes (harvested for grain) on your farm?	Single-answer multiple choice	Categorical: Every year, Every second year, Every three or more years
	Perceived knowledge on legume growing*	How do you rate your knowledge and skills about growing grain legumes?	Single-answer multiple choice	Categorical: Good, Average, Limited
	Information sources*	Where do you mainly acquire information about growing grain legumes?	Three-answer multiple choice	Categorical: Farming community (own experience, other farmers), Advisory services (state and commercial), Published info (magazines, internet), Research collaboration, Other
	Required information	For which aspects of growing grain legumes would you like to have more information?	Three-answer multiple choice	Categorical: Market outlets, Environmental effects, Legume growth and physiology, Cultivar selection, Plant protection, Pre-crop effects, Other management, Other, All, None
Management	Frequency of applied management practices*	How often do you follow each of the management practices below for growing soybean/faba bean? Irrigation Rhizobium inoculation Pest management Disease management Weed management (chemical) Weed management (mechanical) Intercropping Double cropping	Matrix	Categorical: Usually, Infrequently, Never (separately for each practice)
	Farm production orientation*	What is your production orientation?	Single-answer multiple choice	Categorical: Conventional, Organic or in conversion, Both
	New management*	How likely are you to try out new crops, new management practices or new machinery/technology on your farm in the coming 5 years?	Single-answer multiple choice	Categorical: Likely, Neutral/Not sure, Unlikely
	Management yield-impacting factors	Which of the following management factors are the most important for the level of your soybean/faba bean yields in your experience?	Three-answer multiple choice	Categorical: Irrigation Rhizobium inoculation Management of pests, diseases and weeds Cropping mode (intercropping, double cropping) Years between successive soybean/faba bean crops Cultivar choice Sowing date, depth and rate Other

Table 1 (continued)

Category	Variable	Survey question	Type of question	Variable type
	Cultivar Improvement	What are the main aspects where soybean/faba bean cultivar improvement is needed?	Three-answer multiple choice	Categorical: Evenness of maturity Higher protein concentration Lodging resistance Higher yields Disease resistance Drought resistance Biological nitrogen fixation Reduced anti-nutritional factors Competition with weeds Frost resistance Greater yield stability Other

the yields of soybean and faba bean and the pedoclimatic, structural, management and knowledge variables marked with asterisks in Table 1. CART uses a binary recursive partitioning technique to split the dataset into groups based on the values of explanatory variables. The analysis was conducted in R using the *rpart* package (Therneau and Atkinson 2025). Briefly, this method explores the interactions in the numerical and categorical variables to cluster the yields to define homogenous groups. The optimal model minimised the complexity parameter and was identified by tuning the number of data points required to make a split and the maximum number of terminal nodes.

Variables with an asterisk were included in the CART analysis. The survey questions corresponding to these variables can be seen ordered as in the survey in Table S1.

3 Results and discussion

3.1 Description of the farm sample

In total, 216 responses were collected for soybean and 547 for faba bean from farms across nine EU countries (Figure 2). Almost half of the respondents on soybean were from France (46%), with large shares also from Germany (27%) and Poland (13%). In terms of agroclimatic zones, 57% of responses on soybean came from the Continental zone, 26% from the Mediterranean, 12% from the Atlantic and 5% from the Boreal-Nemoral. For faba bean, most responses came from Sweden (39%), followed by France (21%) and Germany (10%). More than half of the responses on faba bean were collected from the Boreal-Nemoral zone (53%), followed by the Atlantic (20%), the Continental (18%) and the Mediterranean zones (8%).

The vast majority of farms specialized in arable crops (70% of soybean and 59% of faba bean farms) (Table S2). Mean arable land was 194 ha for soybean farms and 263 ha for faba bean farms (Table S3). The mean percentage of arable land over total farmed land was around 90% for both soybean and faba bean farms. Just above 60% of farms were strictly conventional and about a quarter of them strictly organic or in conversion to organic, with the rest of them having areas of both (Table S2). On over half of the farms, soil fertility was perceived as average or respondents were unsure, while a large proportion of farmers perceived soils on their farms as fertile (38% soy, 41% faba).

The mean age of farmers growing soybean was 46 years compared with 48 years for faba bean (Table S3). Most farmers had either graduated from a vocational or technical school (39% soy, 33% faba) or had a university degree (26% soy, 33% faba) (Table S2). Most of the surveyed farmers were male (68% soy, 75% faba).

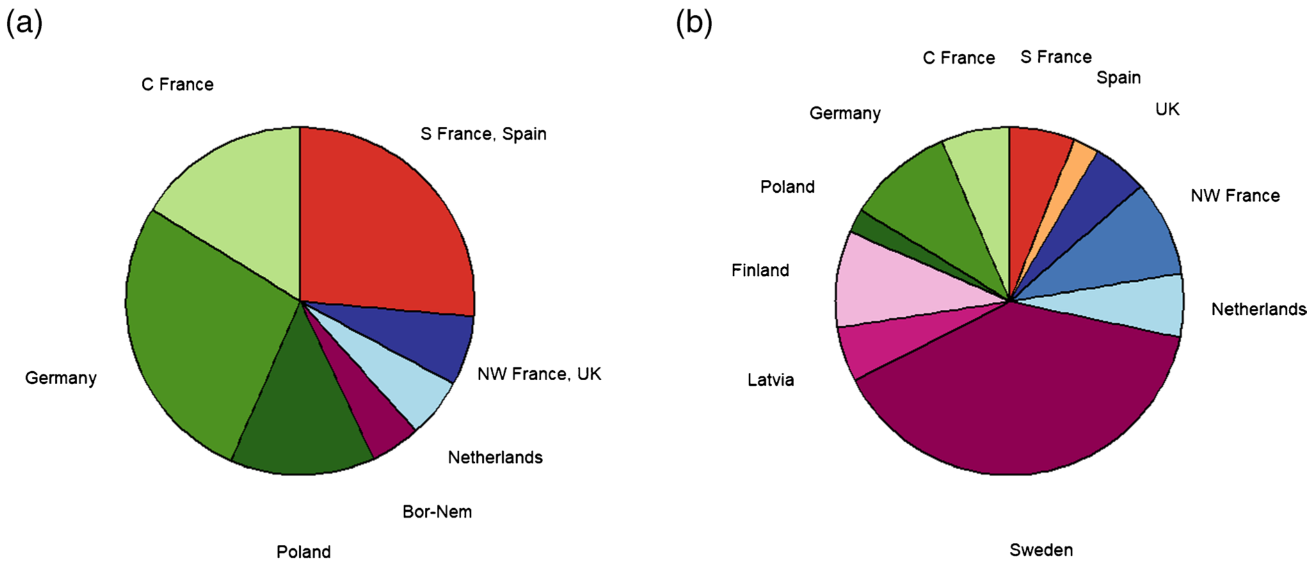

Figure 2 Responses per country segment for soybean (left) and faba bean (right). Country segments in green are attributed to the Continental zone, those in red/orange to the Mediterranean, in blue to the Atlantic, and in purple to the Boreal-Nemoral zones. S France: Southern France, NW France: Northwestern France, C France: Central France, Bor-Nem: Boreal-Nemoral zone.

Regarding the knowledge variables, the mean number of years of farming was 21 and 24 years for soybean and faba bean farmers, respectively (Table S3). The mean number of years of growing grain legumes was 13 years for soybean farmers and 15 years for faba bean farmers, while the mean number of years growing the specific crop was eight years for soybean and nine years for faba bean farmers. Most farmers grew grain legumes every year (82% soy, 74% faba) and devoted less than 25% of their arable land to grain legumes (82% soy, 88% faba) (Table S2). More than half of the farmers perceived their knowledge of growing grain legumes as good (66% soy, 55% faba) and less than 10% as limited, with the remainder of the sample answering that their knowledge was average or being unsure. The principal channel for acquiring knowledge on growing grain legumes was fellow farmers (76% soy, 81% faba), followed by advisory services (54% soy, 60% faba).

3.2 Observed yield levels

The highest mean soybean yields were observed in the Mediterranean zone (Southern France and Spain, 3.0 t ha^{-1}) (Figure 3, Table S4). Mean yields for the Continental and Atlantic zones were 2.7 and 2.4 t ha^{-1}, respectively. For the group of countries within these two zones, yields were higher in Germany, the Netherlands, and Poland, followed by Central and Northwestern France and the UK. The lowest yields were observed in the Boreal-Nemoral zone (0.9 t ha^{-1}).

The highest faba bean yields were observed in the Atlantic zone (3.7 t ha^{-1}), followed by the Boreal-Nemoral (3.4 t ha^{-1}) and the Continental zones (3.2 t ha^{-1}). Important differences were observed for the countries within these zones, with the highest yields in the Netherlands, followed by the UK (Figure 3, Table S5). Yields were high also in Germany, Sweden, Poland, and Latvia, while lower yields were observed in Northwestern France, Finland and Central France. The lowest yields (2.3 t ha^{-1}) were observed in the Mediterranean zone (Spain, Southern France).

3.3 Legume growers' management practices

For both crops, chemical weed control was used more than mechanical weed control, except in the Boreal-Nemoral zone (Table 2, Table 3), where soybean yields are low and the organic product commands a sufficiently premium price to make the crop at least potentially profitable. In the other three zones, 75%−80% of soybean growers managed weeds mostly chemically, as opposed to 40% of farmers in the Boreal-Nemoral zone. Mechanical weed control was practiced by 23–40% of soybean farmers, depending on region and intensity of practice, showing that some used it in combination with herbicides in an integrated weed management approach. Similarly to soybean growers, the largest shares of faba bean growers in the Atlantic, Continental, and Mediterranean zones practiced chemical weed control frequently (56-68% depending on the region), with about a quarter of them answering that they never practice it. The respective shares in the Boreal-Nemoral zone were 35% (frequently) and 45% (never) of farmers. Mechanical weed management was mostly used in the Boreal-Nemoral zone (40% of farmers frequently practice it) while in the other three regions about half or even more than farmers never use it. These

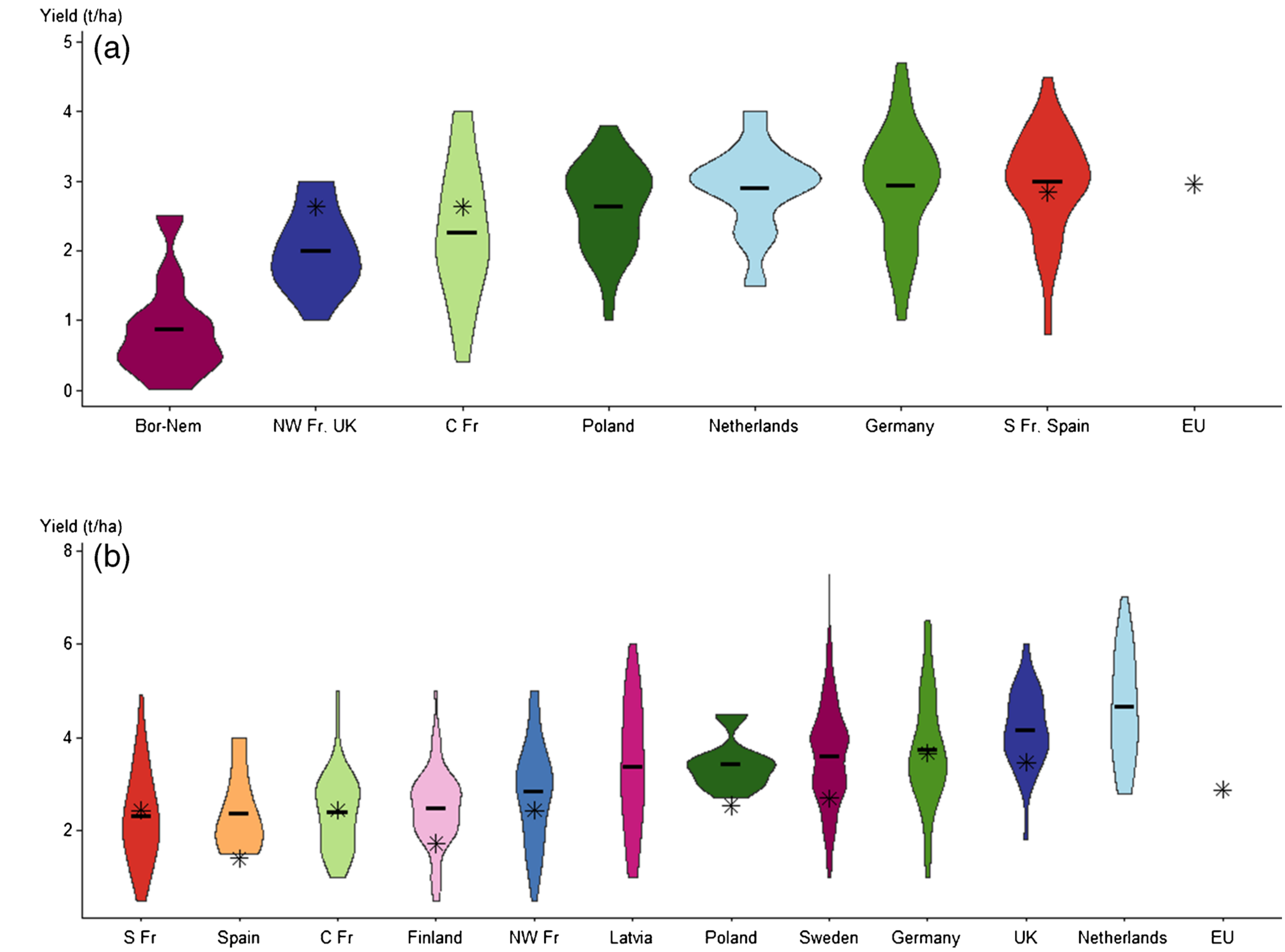

Figure 3 Soybean (**a**) and faba bean (**b**) yields by country segments based on the data collected via the survey. The asterisks display mean crop yields calculated using the five-year mean (2017-2021), reported by Eurostat (2024). Bor-Nem: Boreal-Nemoral zone, NW Fr: North-western France, C Fr: Central France, S Fr: Southern France.

shares differed between conventional and organic farmers. For example, 97% or conventional soybean farmers practiced chemical weed management frequently, while 84% of organic or in conversion soybean farmers practiced mechanical weed management.

Disease control was seldom seen as necessary in soybean but was widespread in faba bean (Table 2, Table 3), on which a range of diseases is endemic (Stoddard et al. 2010). Pest management intervention showed little difference between crops or regions, except a slightly higher share of farmers never undertaking such management in the Boreal-Nemoral zone. That share was 75% for soya bean and 56% for faba bean, while in the other regions it ranged between 38%−55% and 29%−39%, respectively. Farmers using it "infrequently" or "usually" ranged between 14%−38% depending on crop and region.

Irrigation was extensively used for soybean in the Mediterranean zone, with 75% of soybean growers irrigating their fields very frequently (Table 2). In contrast, more than 75% of respondents never irrigated their soybean fields in the Continental and Boreal-Nemoral zones, while results varied in the Atlantic zone. As a summer crop, soybean may be exposed to drought wherever it is grown, and irrigation can increase yield (Karges et al. 2022). Regardless of the zone, less than 5% of faba bean growers irrigated their fields frequently (Table 3). As an autumn-sown crop in the Mediterranean and Atlantic zones, it is more likely to escape late spring or summer droughts than spring-sown crops. When spring-sown, however, it is as exposed to droughts as soybean is, and its yields suffer accordingly (Belachew et al. 2023).

Inoculation was very frequently used on soybeans in the Continental zone (96%), followed by the Mediterranean (90%), the Atlantic (87%) and the Boreal-Nemoral zones (83%) (Table 2). This practice was seen as less relevant for faba beans, where more than 85% of farmers never inoculate their crops (Table 3). Nevertheless, in on-station experiments in many countries, inoculation of faba bean is

Table 2 Percentages of frequencies of application of management practices used on soybean in four agroclimatic zones. The percentages express the share of responses for three different frequency levels (never, infrequently, usually) over the total number of responses per management category (e.g., disease management, double cropping, etc.).

Category	Frequency	Boreal-Nemoral	Atlantic	Continental	Mediterranean
Irrigation	Never	100	40.9	74.2	13.8
	Infrequently	0	27.3	7.2	11.7
	Usually	0	31.8	18.6	74.5
Disease management	Never	60	31.8	70.6	60.0
	Infrequently	0	45.5	17.6	20.0
	Usually	40	22.7	11.8	20.0
Weed chemical management	Never	60	13.6	22.4	20.0
	Infrequently	0	9.1	2.8	0
	Usually	40	77.3	74.8	80.0
Weed mechanical management	Never	20	40.9	40.0	33.3
	Infrequently	40	22.7	25.7	33.3
	Usually	40	36.4	34.3	33.3
Pest management	Never	75	54.5	41.0	38.0
	Infrequently	0	31.8	34.3	36.0
	Usually	25	13.6	24.8	26.0
Inoculation	Never	0	8.7	3.8	3.9
	Infrequently	16.7	4.3	0	5.9
	Usually	83.3	87	96.2	90.2
Double cropping	Never	75	61.9	65.4	62.0
	Infrequently	0	23.8	16.3	22.0
	Usually	25	14.3	18.3	16.0
Intercropping	Never	75	85.7	84.0	89.6
	Infrequently	25	14.3	16.0	6.2
	Usually	0	0	0	4.2

associated with 10–30% increases in yield, depending on the time since the previous legume crop (Belachew et al. 2023).

The percentages express the share of responses for three different frequency levels (never, infrequently, usually) over the total number of responses per management category (e.g., disease management, double cropping, etc.).

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3.4 Important factors for grain legume yield and required support according to farmers

For both crops, over 80% of farmers identified droughts as the most important yield-reducing risk factor. This was followed by weeds and problems with soil structure and degradation processes (e.g., compaction, salinity, acidity, waterlogging) (Figure 4). The availability of suitable cultivars and experience in growing the crop were considered either very important or important by more than half of the respondents. Temperature limitations were considered important for soybean, but less so for faba bean, whereas additional factors of importance for faba beans included soil texture, along with pests and diseases.

Optimal sowing (date, depth, rate) was the most important management factor indicated by the farmers for both crops (Figure 5). Inoculation with rhizobium came a close second for soybean. Other important factors for soybean include cultivar selection, control of biotic stresses, and irrigation. For faba bean, control of biotic stresses was second, followed by cultivar choice and rotational interval.

Appropriate cultivar choice was clearly important for both crops (Figure S1). Soybean is characterized into maturity groups, and farmers may need to test a few to find the one that best suits their environment and management (Simon-Miquel et al. 2024). According to the analysis of survey results, farmers used a large range of soybean varieties from different maturity groups. Late maturity groups of I-II were mostly used in the Mediterranean regions, early groups of mostly 000 in the northern regions and maturity groups of 00 across central Europe. For faba bean, the variation in varieties was much less than in soybean. Faba bean cultivars are highest yielding in the pedoclimatic region for which they were developed and usually perform poorly in other regions (Flores et al. 2013).

Table 3 Percentages of frequencies of application of management practices to cultivate faba bean in four agroclimatic zones. The percentages express the share of responses for three different frequency levels (never, infrequently, usually) over the total number of responses per management category (e.g., disease management, double cropping, etc.).

Category	Frequency	Boreal-Nemoral	Atlantic	Continental	Mediterranean
Irrigation	Never	91.0	83.0	89.9	92.3
	Infrequently	5.2	13.6	6.3	2.6
	Usually	3.9	3.4	3.8	5.1
Disease management	Never	58.5	21.8	33.3	17.9
	Infrequently	27.8	16.1	26.2	35.9
	Usually	13.7	62.1	40.5	46.2
Weed chemical management	Never	45.0	25.3	27.4	23.1
	Infrequently	19.8	6.9	6.0	20.5
	Usually	35.1	67.8	66.7	56.4
Weed mechanical management	Never	27.3	52.3	48.7	60.0
	Infrequently	32.5	25.6	20.5	27.5
	Usually	40.2	22.1	30.8	12.5
Pest management	Never	55.6	37.9	28.6	38.5
	Infrequently	30.1	34.5	33.3	35.9
	Usually	14.2	27.6	38.1	25.6
Inoculation	Never	91.4	84.9	86.9	94.9
	Infrequently	6.5	10.5	4.8	0.0
	Usually	2.2	4.7	8.3	5.1
Double cropping	Never	83.7	86.6	93.4	76.9
	Infrequently	6.9	9.8	3.9	10.3
	Usually	9.4	3.7	2.6	12.8
Intercropping	Never	79.4	61.6	63.0	50.0
	Infrequently	16.3	20.9	24.7	27.5
	Usually	4.3	17.4	12.3	22.5

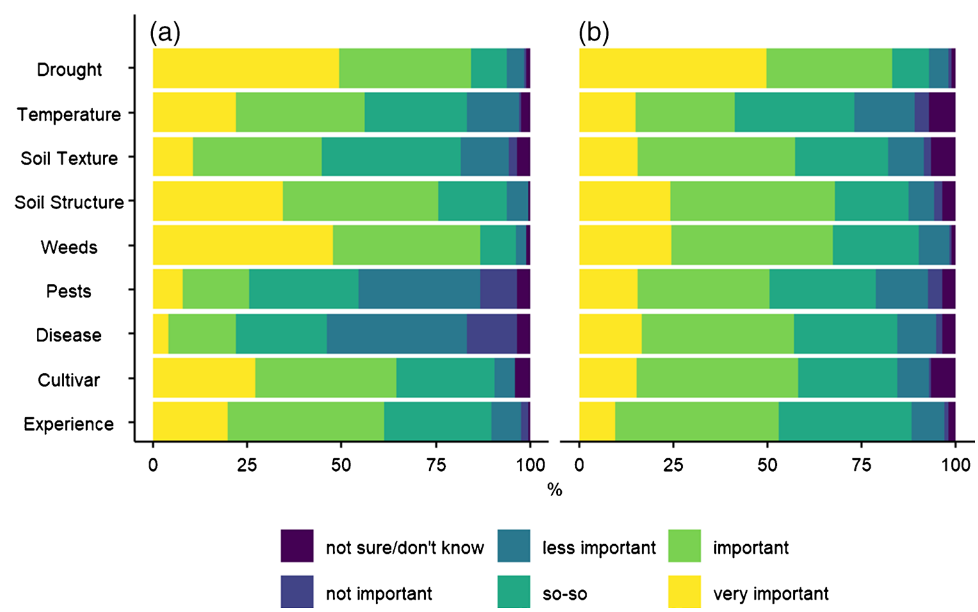


Figure 4 Importance of factors determining soybean (**a**) and faba bean (**b**) yields according to growers. Temperature: Temperature limitations, Soil texture: Soil texture (e.g. too sandy), Soil structure: Soil structure or deficiencies (e.g. compaction, salinity, acidity, waterlogging), Weeds: Occurrence of weeds, Pests: Occurrence of pests, Disease: Occurrence of diseases, Cultivar: Suitability of available cultivars, Experience: Experience in growing the crop.

Respondents identified several aspects where cultivar improvement is needed. Drought resistance, improved yield and yield stability, and competitive ability against weeds were the most prominent aspects for both crops (Figure 6). In addition, improvements related to disease resistance and evenness of maturity were raised as relevant in the case of faba bean.

When respondents were asked for which aspects they would like to have more information about growing grain legumes, they mostly emphasized the need to know more regarding plant

Figure 5 Importance of management factors determining soybean (**a**) and faba bean (**b**) yields according to growers. The stacked bars indicate the number of responses per management factor, decomposed into the responses from each of the four agroclimatic zones. The management factors considered are the following: Cultivar: Cultivar choice, Inoculation: Rhizobium inoculation, Yrs: Years between successive soybean/faba bean crops, Sowing: Sowing date, depth and rate, Crop prot: Management of pests, diseases and weeds, Inter/double: Cropping mode (intercropping, double cropping).

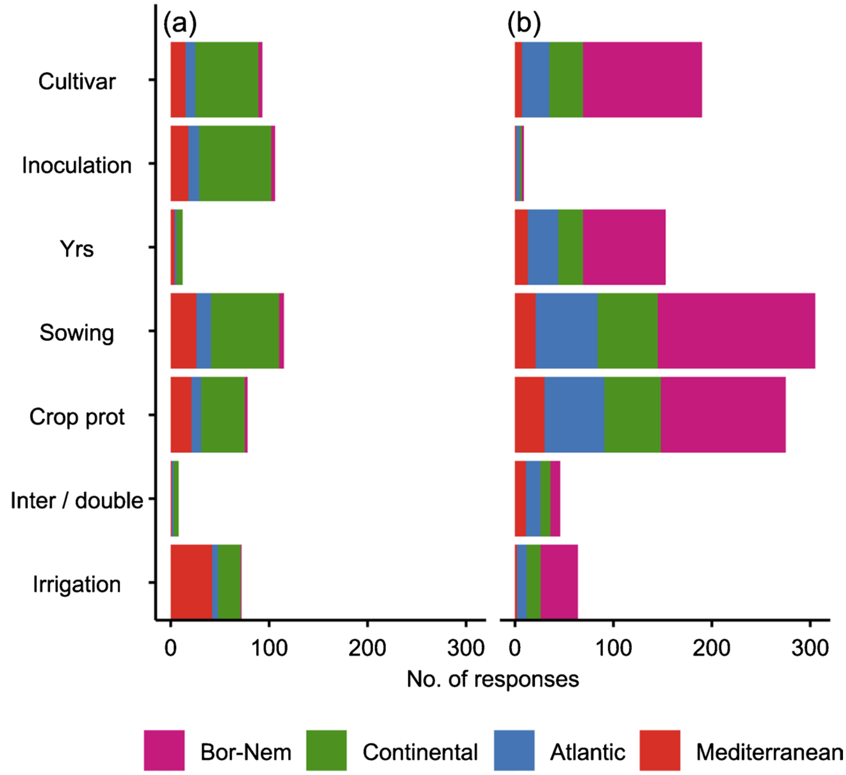
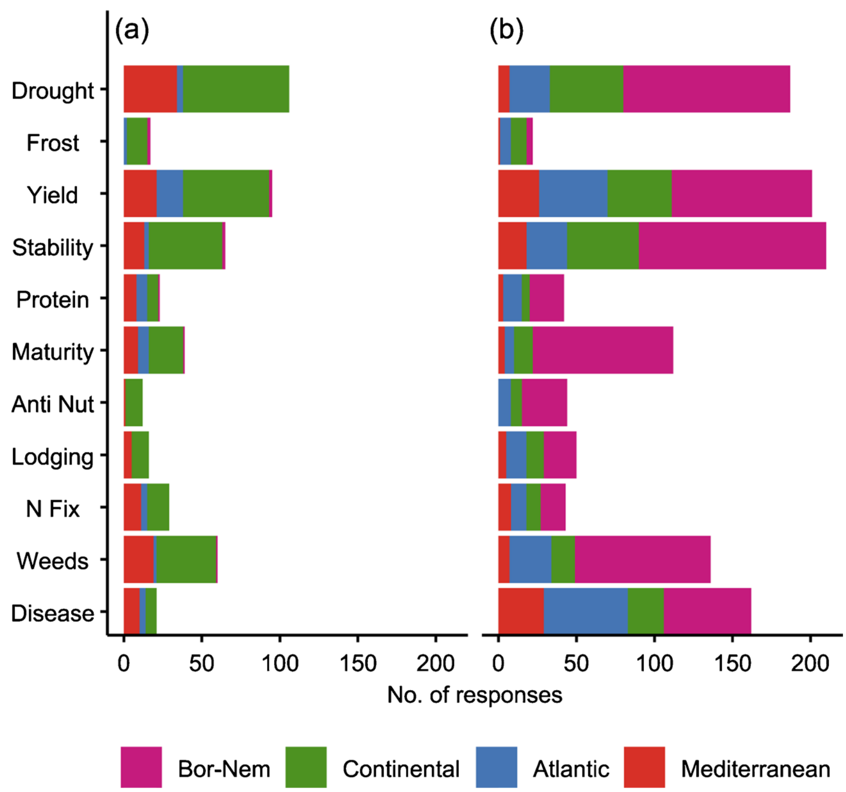


Figure 6 Factors where cultivar improvement is needed per country segment for soybean (**a**) and faba bean (**b**). Drought: Drought resistance, Frost: Frost resistance, Yield: Higher yields, Stability: Greater yield stability, Protein: Higher protein concentration, Maturity: Evenness of maturity, Anti Nut: Reduced anti-nutritional factors, Lodging: Lodging resistance, N Fix: Biological nitrogen fixation, Weeds: Competition with weeds, Disease: Disease resistance.



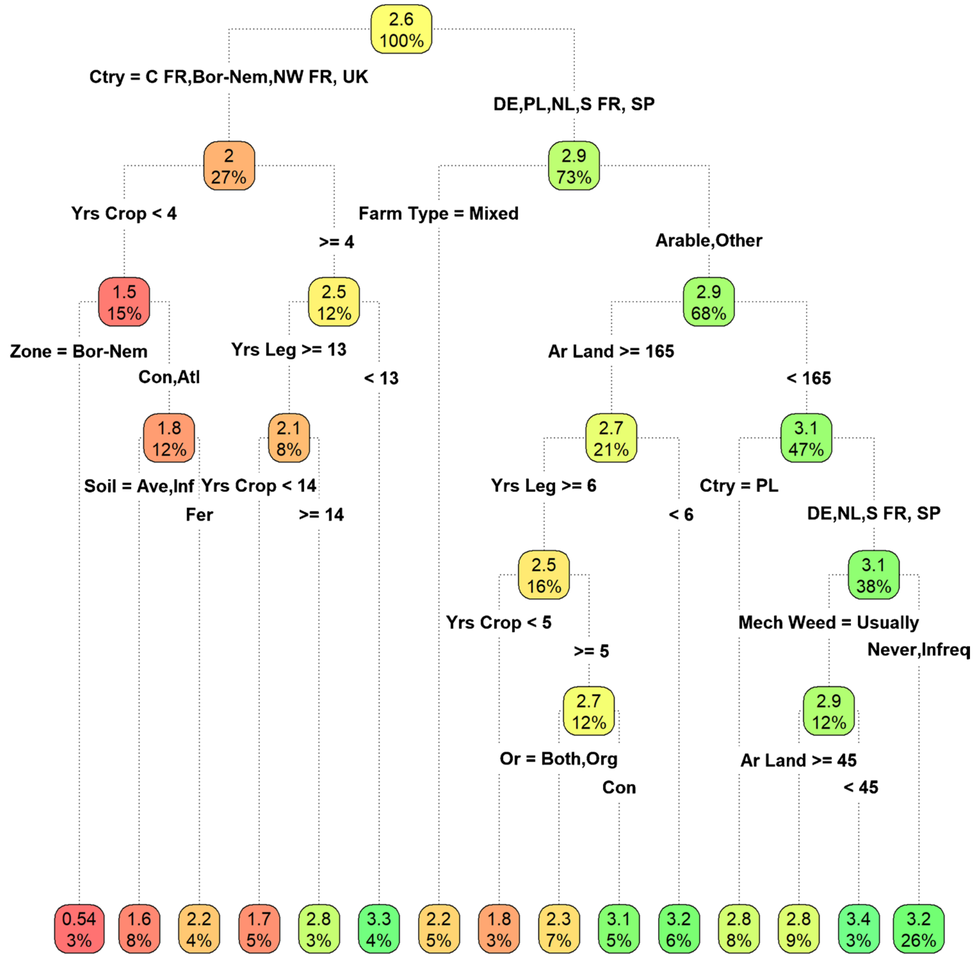


Figure 7 Decision tree on variables related to soybean yields. The variables for which the branches split are indicated on the left side of the split. The abbreviated variables are Ctry: Country; Yrs Crop: Years of experience growing the crop; Yrs Leg: Years of experience growing grain legumes; Ar Land: Area of arable land; Soil: Perceived soil fertility; Mech Weed: Frequency of mechanical weed management; Or: Production orientation. The countries and zones abbreviations are C FR: Central France; Bor-Nem: Boreal-Nemoral; NW FR: Northwestern France; UK: United Kingdom; DE: Germany; PL: Poland; NL: Netherlands; S FR: Southern France; SP: Spain; Con: Continental; Atl: Atlantic. Other abbreviations include Ave: Average; Inf: Infertile; Fer: Fertile; Org: Organic; Con: Conventional; Infreq: Infrequently.

growth and physiology, cultivar selection, plant protection and pre-crop effects (Figure S2). Aspects such as information about market outlets and environmental effects were also highlighted.

3.5 Determinants of yield variation according to CART analysis

The CART analysis for the soybean yields displayed fifteen terminal nodes and fourteen splitting nodes (Figure 7). The overall mean yield was 2.6 t ha^{-1}, while in the fifteen terminal nodes it ranged from 0.5 t ha^{-1} to 3.4 t ha^{-1}. The three principal factors determining this variation were the country where the crop was grown, the number of years growing soybean, and farm specialization. These factors were followed by the agroclimatic zone, the number of years growing grain legumes and the area of arable land. Soil fertility, weed management and organic versus conventional production were also found to play a role. First, countries were partitioned into those with a mean yield of 2.0 t ha^{-1} (Central and Northwest France, countries in the Boreal-Nemoral zone, UK) and those with a higher yield of 2.9 t ha^{-1} (Spain, Southern France, Germany, Poland, Netherlands).

In the low-yielding countries, short experience with soybean (< 4 years) was associated with 1.0 t ha^{-1} lower yield. Less-experienced farmers in the Boreal-Nemoral region had the lowest yields, while those in the UK, Northwestern and Central France achieved over three times as much. In the latter areas, above-average soil fertility was associated with one-third higher yield. Longer experience with soybean in the low-yielding countries, combined with medium-term experience with other grain legumes (< 13 years), achieved 50% higher yields than combined with longer experience with other grain legumes. Of those with long experience with grain legumes, more than 14 years of experience with soy led to about 50% higher yield than less soy experience. These results indicate that familiarity with other grain legumes was not beneficial to those starting to grow soybean in these marginal regions.

In the high-yielding countries, mixed-cropping farms were associated with about 25% lower yields than specialist arable and other farms. For the latter group of farms, those with more than 165 ha of arable land were associated with almost 15% lower yields than smaller ones. In these larger farms, yields were almost 25% lower for farmers that had been growing grain legumes for longer (> 6 years). For this group of farmers, those with longer experience with soybean (> 5 years) attained almost 1.0 t ha^{-1} higher yields. Thus, experience with other grain legumes was not necessarily helpful for soybean growers, while more years of experience specifically with soybean was helpful. The yields of this last group were about one third higher for conventional farms compared to organic (fully organic, in conversion, or both organic and conventional). For farms smaller than 165 ha, yields were about 10% lower in Poland than in other high-yielding countries. In these other high-yielding countries, yields were lower by about 10% when farmers frequently applied mechanical weed management, and in this group, yields were lower by almost 20% for farms with more than 45 ha of arable land. Thus, large farms were associated with lower yields.

The CART analysis for the faba bean yields displayed ten terminal nodes and nine splitting nodes (Figure 8). Mean faba bean yields were 3.3 t ha^{-1}, while in the ten terminal nodes they ranged from 2.4 t ha^{-1} to 4.5 t ha^{-1}. Country, followed by pest management practice and perceived soil fertility were the principal determinant factors of yield variability. Other important factors were the size of arable land versus grassland, disease and weed management, the number of years growing faba beans, and farmers' age. Yields were lower in Finland, France and Spain (mean 2.5 ha^{-1}) than in Latvia, Sweden, the UK, Germany, the Netherlands and Poland (mean 3.7 t ha^{-1}).

In the low-yielding countries, farmers who regularly controlled pests achieved 25% higher yield than those who did not. Much of this yield benefit was associated with having at least 5% of their land as grassland instead of running a 100% arable farm, as the latter had 1.6 t ha^{-1} lower yields than the former.

In the high-yielding countries, farms with soil fertility perceived to be above average achieved almost 25% higher yields. For farms with lower soil fertility, frequent disease management allowed over 25% higher mean yields compared to cases with infrequent disease management. When disease management was infrequent, farmers with more than 4.5

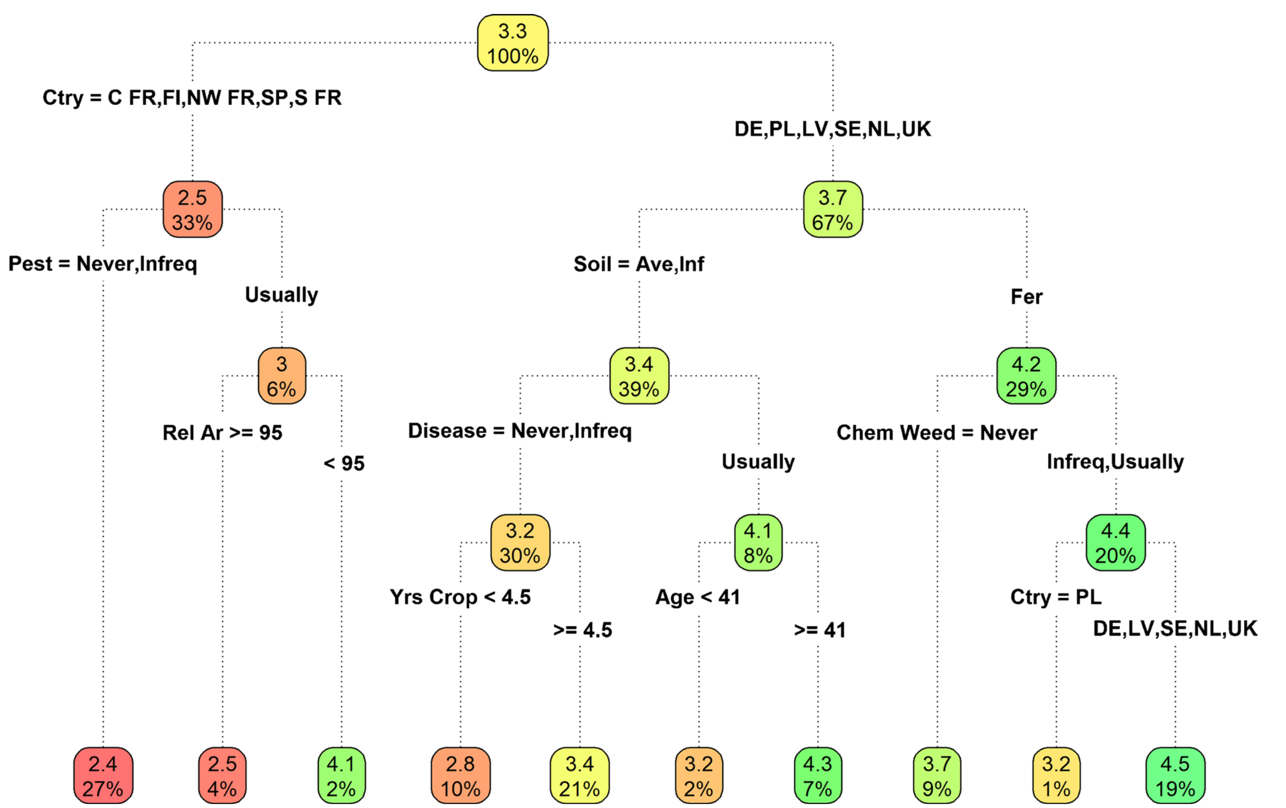


Figure 8 Decision tree on variables related to faba bean yields. The variables for which the branches split are indicated on the left side of the split. The abbreviated variables are Ctry: Country; Pest: Frequency of pest management; Soil: Perceived soil fertility; Rel Ar: Arable Land/Total Land; Disease: Frequency of disease management; Chem Weed: Frequency of chemical weed management; Yrs Crop: Years of experience growing the crop; Age: Age of the farmer. The countries and zones abbreviations are C FR: Central France; FI: Finland; NW FR: Northwestern France; SP: Spain; S FR: Southern France; DE: Germany; PL: Poland; LV: Latvia; SE: Sweden; NL: Netherlands; UK: United Kingdom. Other abbreviations include Infreq: Infrequently; Ave: Average; Inf: Infertile; Fer: Fertile.

years of experience in growing the crop achieved about 20% higher yield than those with fewer years of experience. When disease management was frequent, older farmers (> 41 years old) achieved 1.1 t ha^{-1} higher yields than younger ones. For farms with higher soil fertility, mean yields were about 15% lower when farmers never controlled weeds chemically. For those that used herbicides, yields were lower by 1.3 t ha^{-1} in Poland than in the rest of the high-yielding countries.

3.6 Summary and discussion of key findings per factor

3.6.1 Pedoclimatic factors

Pedoclimatic factors are clearly of predominant importance for the yields of both crops. The country and agroclimatic zone where the crop was grown were identified as key drivers from both the yield survey data and the CART analysis. Conditions for soybean were most favorable in the Mediterranean and part of the Continental zones, while those for faba bean were in parts of the Atlantic and Continental zones.

For both crops, drought was identified as the most important yield-impacting risk factor, and drought resistance as one of the main areas where cultivar improvements are needed. As the timing of the survey (2020-2021) followed on two major widespread drought periods (2018, 2019), the risks of droughts and the urgency of drought management might have been fresh in farmers' minds (Blauhut et al. 2022). Temperature limitations were considered an important factor for growth of soybean as a summer crop, but less so for faba bean with its tolerance to cool temperatures. The effects of climate change are reflected in more frequent, more intense and longer periods of drought (e.g., 2022), which could have a major impact on soybean productivity in the areas that were initially the most productive ones (i.e., the Mediterranean and part of the Continental zones) and further increase dependence on irrigation. At the same time, areas that are currently identified as low to moderately productive could become more favourable (Guilpart et al. 2022).

Soil structure or deficiencies featured in the top three factors affecting the yields of both crops according to farmers. Soil texture was also evaluated as important by faba bean growers. This was echoed in the CART analysis, where lower perceived soil fertility resulted in more than half a ton lower yields for both crops.

3.6.2 Management factors

Several management factors emerged as important in the analysis of the survey. For both crops, farmers identified weeds as the second most important yield-impacting factor (Figure 4). They also expressed the need to obtain more information and knowledge on plant protection options (Figure 6). Weed management emerged as an important factor also in the CART analysis for both crops, and particularly for faba bean. Indeed, the main form of biotic stress management for both crops was chemical weed control, except in the Boreal-Nemoral zone, where weeds were managed more frequently mechanically due to a higher share of organic farms in the sample. Overall, the importance of biotic stresses as a yield-impacting factor is more pronounced in the case of faba bean than in soybean. Disease and pest management were identified as important management factors by farmers and the CART analysis for faba bean, but not for soybean. In particular, disease control was seldom seen as necessary in soybean, but was widespread in faba bean. This is supported by the literature, as many pathogens are endemic in Europe where faba bean has been grown for more than two thousand years (Stoddard et al. 2010).

According to the growers, appropriate cultivar choice and correct sowing dates are of apparent importance (Figure 5), as phenology must match the growing season. For both crops, the availability of suitable cultivars was considered either very important or important for their yields by more than half of the respondents, and it was included in the top three most important management factors identified by the farmers. Cultivar selection was also an area in which farmers explicitly expressed the need to acquire more knowledge.

Irrigation was identified by farmers as an important management factor to deal with drought for soybean, which is grown in drier and warmer environments than faba bean. Although farmers identified drought as one of the most important yield-limiting factors, irrigation was used systematically by soy farmers in the Mediterranean zone but by few farmers elsewhere. Only a handful of faba bean farmers used irrigation anywhere in the study area. Thus, many farmers who recognize the importance of drought in limiting crop yield have few options to alleviate its impacts outside the Mediterranean zone.

Inoculation was recognized as one of the most important management yield-impacting factors for soybean but less so for faba bean (Figure 5). That was echoed in the observation that almost all soybean growers inoculated their seeds, whereas few faba bean farmers did so. It is well known that symbiotic fixation takes place thanks to different bacteria, for soybean by *Bradyrhizobium* species that are not found naturally in European soils (Albareda et al. 2009). Inoculation is therefore necessary and, even if for most European soils, the bacteria could survive several years after introduction (Revellin et al. 1996), the improvements in yield and biomass observed by frequent and systematic inoculations of soybeans have led agricultural advisors to strongly encourage this practice, explaining why most farmers mentioned it as very important in our survey.

Soybean yields in organic farms were lower for a subset of the sample in the CART analysis. In the literature, yield gaps are observed for legumes grown organically, but these are smaller than in other crop categories e.g. 8% for soybean and 9% for other pulses such as faba bean (de Ponti et al. 2012). This is probably due to the lower reliance of legumes on external inputs and the narrower range of available agrochemicals for legumes compared to cereals. Some studies also report higher yields under organic conditions (Wilbois and Schmidt 2019). Other reasons for lower soybean yield, especially in organic farming, could be linked to weed management, which is carried out mechanically only, leading to lower levels of regulation than those obtained by chemical control with herbicides. Hence, competition of weeds for water and light resources remains impactful.

3.6.3 Knowledge factors

Experience and knowledge in growing the crops were considered either very important or important by more than half of the respondents for both crops and emerged as critical determinant factors in the CART analysis. The importance of knowledge and experience for growing soybean was considered greater than that for faba bean in our results, as soybean is a more recent introduction to Europe especially in central and northern parts (Karges et al. 2022).

The importance of knowledge variables seemed evident, especially under less favorable conditions in our study where experience can play a critical role in managing the crop. For soybean, the number of years of experience of growing the crop emerged as the most important factor for the low-yielding countries and, in some cases, one of the important factors for the high-yielding ones. In these cases, farmers with more than 4-5 years of experience achieved 50%−70% higher yields than those with fewer years of experience. For faba bean, the same variable was important in cases with limited soil fertility and disease management and control, with 4-5 years of experience appearing as the threshold for achieving yields that are higher by 20%.

Our findings on the role of experience highlight the need for knowledge transfer, as is emphasized in other studies (Specht et al. 1999), particularly in the case of resource-poor farmers (Graham and Vance 2003; Siddique et al. 2012; Anderson et al. 2016). Development of research programs together with rapid adoption of technologies emerging from agricultural research by producers has been shown to be useful in boosting legume yields (Liu et al. 2008). There are also indications that farmers are increasingly skeptical about expert advice from research programs, suggesting that a proper linkage with the network of farmers is essential (Rust et al. 2022).

Unexpectedly, the number of years of growing other grain legumes appeared to affect negatively soybean yields in our results, indicating differences in crop growth requirements for this grain legume compared to others. The CART analysis revealed other important characteristics about farm structure. For soybean, in the high yielding countries, mixed cropping farms and larger farms were associated with lower yields. This may indicate that soybean is a technical culture, where lack of experience, dedication and specialisation of the production system plays a negative role. In the case of faba bean, the age of farmers was important, with older farmers achieving higher yields for a subset of the sample.

4 Conclusions

This study aimed to identify the importance of different underlying drivers of yields in legume production considering pedoclimatic, structural, knowledge, and management factors and to evaluate, for the first time, the influence of farmers' knowledge on yields. By surveying farmers on a transect of European agroclimatic environments, and combining simple descriptive statistics with deeper CART to analyze the results, we have shown that some yield limitations apply across climates and crops, whereas others are more specific or depend on the farmer's management. The descriptive statistics revealed factors that were considered important by farmers, while the CART analysis identified factors that explained variability within the farm sample.

Pedoclimatic factors are the main determinants of crop yields, with conditions for soybean being most favorable in the Mediterranean (with irrigation) and Continental zones, and those for faba bean in the Atlantic and Continental zones. Soil fertility aspects have a large impact on yields of both crops. Weed management was the most important biotic stress control for both crops, because grain legumes are poorer competitors than cereals, with chemical weed control being widely used in most zones. Overall, biotic stresses limited yields of faba bean far more than those of soybean, as many of its pests and pathogens are endemic in Europe where the crop has been grown for more than two thousand years. Cultivar selection was an area for which farmers explicitly expressed the need to have more support and also saw a need for cultivar improvement. Water management is important for both crops, with irrigation being used for soybean in the Mediterranean region, but not for either crop elsewhere in Europe where it would be equally valuable. As we hypothesized, experience and knowledge in growing the crop were shown to be important, especially for soybean, which is more novel in Europe than faba bean, as well as under unfavorable conditions, where experience plays a critical role in crop management.

These results highlight that the development of legumes in Europe will involve (i) strengthening advice on varietal choice, while climate change affects, negatively and positively, current production areas; (ii) developing tools at system or crop rotation scales to better manage the biotic pressures clearly noted by farmers and to rationalize the insertion of legumes within the cropping systems; and (iii) rethinking the strategies for allocating irrigation water resources between crops to support legume production and protein autonomy in Europe, especially in regions with high potential but severe water constraints. Improving the knowledge of farmers in growing grain legume crops in the first years of their cultivation can act as a lever to close yield gaps and increase the confidence and motivation of farmers for further integration of these crops in European agricultural systems.

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Authors' contributions All authors contributed to the study conception and design. Material preparation and data collection were performed by I.M. together with C.F.E.T., L.A., P.C., M.R., F.L.S., C.A.W., S.L., G.S.M., F.K., C.J.E.S., A.K, D.P.B. Data curation was performed by S.J., I.M., C.F.E.T. The formal analysis methodology was conceived by I.M., C.F.E.T., S.J. Data analysis and visualisations were prepared by C.F.E.T., I.M., S.J. The original draft was prepared by I.M. The draft was reviewed and edited by F.L.S., C.A.W, M.R., C.F.E.T, S.D.B.K., L.A., D.P.B, P.C., C.J.E.S., F.K., S.L. Supervision of the overall or parts of the work were provided by F.L.S., C.A.W., S.D.B.K, M.R., C.F.E.T, C.J.E.S., D.P.B. Funding was acquired by F.L.S., I.M., C.A.W., S.D.B.K., M.R., D.P.B., C.J.E.S., S.L.

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Data availability The datasets generated during and/or analyzed during the current study are not publicly available.

Code availability The code used during the current study is available from the author(s) having conducted the relevant research on reasonable request.

Declarations

Ethics approval Approved by the appropriate institutional research ethics committees.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication Not applicable.

Competing interests The authors have no conflicts of interest to declare that are relevant to the content of this article.

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