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Grain legume production in Europe for food, feed and meat-substitution

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ABSTRACT

Partial shifts from animal-based to plant-based proteins in human diets could reduce environmental pressure from food systems and serve human health. Grain legumes can play an important role here. They are one of the few agricultural commodities for which Europe is not nearly self-sufficient. Here, we assessed area expansion and yield increases needed for European self-sufficiency of faba bean, pea and soybean. We show that such production could use substantially less cropland (4–8%) and reduce GHG emissions (7–22% current meat production) when substituting for animal-derived food proteins. We discuss changes required in food and agricultural systems to make grain legumes competitive with cereals for farmers and how their cultivation can help to increase sustainability of European cropping systems.

1. Introduction

It is widely understood that global food systems need to be transformed to reduce their substantial adverse environmental impacts, e.g., methane emission from livestock and N_2O emissions from fertilizer use at crops (Campbell et al., 2017). The production of meat-sourced proteins is of particular concern, as their environmental impact is around ten times greater on a mass basis and has CO_2 emissions around 30 times more than those of plant-based proteins (Poore and Nemecek, 2018). At the same time, there is currently increased interest in plant-based proteins, due to awareness that a protein transition from animal-to plant--based would enhance healthy and sustainable diets (Aiking and de Boer, 2020; Willett et al., 2019). Grain legumes are protein-rich and a good source of nutrients (Curran, 2012; Erbersdobler et al., 2017). It is estimated that European consumers would be willing to replace around a quarter of the meat consumption with grain legumes (Henn et al., 2022). The European-Commission (2020) is promoting EU-grown plant proteins within the Farm to Fork strategy as part of the European Green Deal

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in recognition of the environmental and health benefits associated with production and consumption of plant protein.

Currently, European demand for grain legumes, specifically soybean, is high and the European Union together with the UK imports about 14 million tonnes (Mt) of soy beans and 18 Mt of soy meal (Eurostat, 2023; FAO, 2023). Over 95% of the imported soybean is used for animal feed, and this is considered unsustainable from an environmental perspective because of the conversion inefficiency involved in animal production and because of (in)direct land use change in the soybean exporting countries. Domestic production of grain legumes should therefore increase (Zander et al., 2016). For the purposes of this analysis, we consider Europe to be all European countries west of Russia and Turkey.

Sufficient internal European production of grain legume crops is amongst the first steps in the protein transition. Faba bean (*Vicia faba* L.), pea (*Pisum sativum* L.) and soybean (*Glycine max* (L.) Merr.) are, by far, the three most widely grown grain legumes in Europe (Eurostat, 2023; Kezeya Sepngang et al., 2020). Yet, current harvested areas of those legumes are small, only ~2% of the European cropland is used for soybean cultivation and ~1% for pea and faba bean jointly (FAO (2023), average 2015–2020). This is in sharp contrast to cereals which cover 46% of the European cropland (FAO (2023), average 2015–2020). Increased European legume production could be realised by both intensification and/or area expansion. Intensification of current production has the advantage that it will not lead to competition for land use with the production of other food crops (although legumes can also be grown on marginal land (Gogoi et al., 2018)) nor to expansion into natural ecosystems. Initial estimations for soybean suggest relatively low production efficiency of grain legumes (51% of potential yields) in comparison to cereals (58% of potentials) in Europe (Schils et al., 2018; van Ittersum et al., 2023; Watson et al., 2017). At the same time, area expansion of legumes will lead to more diverse cropping systems, which is advocated by many (Francis and Clegg, 2020; Nemecek et al., 2008; Preissel et al., 2015). Additionally, due to climate change, significant areas may become more suitable for soybean production in the future due to climate change (Fodor et al., 2017; Nendel et al., 2023).

As a consequence, we devise two scenarios to increase grain legume production, (1.) narrowing the yield gap, i.e., the difference between what farmers actually produce (Ya) and the potential yield (Yp) in irrigated systems or the water-limited potential yield (Yw) in rainfed systems; and (2.) expanding the areas of grain legumes at current yield levels. In this study we will investigate how increased European grain legume (i.e., faba bean, pea, soybean) production, through either Scenario 1 or 2, could contribute to greater supply of plant-based protein and substitution of consumption of meat-based proteins, together with impacts on their land footprint and GHG emissions. We consider a relatively short time horizon in potential production scenarios, assuming no major genetic changes or climate change effects.

2. Materials and methods

The two scenarios for consideration are yield gap closure and area expansion. In Scenario 1 we assume that the yield gap of the three legume crops (i.e., faba bean, pea, soybean) will be narrowed to 80% of the yield potential. This level is the exploitable yield gap and is generally indicated as the upper limit of the attainable yield due to diminishing returns and increasing inefficiencies (Van Ittersum et al., 2013). In this scenario, it is assumed that legume production will take place only on the area where these three crops are currently grown. In Scenario 2, we assume that current yields are maintained, and that 1/12th or 1/6th of the total cropland area is used for the three grain legumes.

2.1. Scenario 1: 80% yield gap closure

Potential yields for grain legume crops in Europe were estimated using two methods, i.e., Method 1) running simulations with a crop growth simulation model together with following the bottom-up approach of the Global Yield Gap Atlas (GYGA, www.yieldgap.org; Grassini et al., 2015; Van Bussel et al., 2015) and Method 2) employing a regression model that uses the potential yield outputs of the crop growth simulation model as input to extrapolate simulated yields to other countries. Method 1 uses a number of sites explicitly chosen to best represent the spatial distribution of the current crop production area, so it was used for the main producing countries. The method employs local weather, soil and agronomic data in a spatial framework capturing key production areas, as input for crop growth modelling to estimate the potential yield (Yp) in case of irrigated systems and the water-limited potential yield (Yw) in case of rainfed systems. This approach with relatively high data requirements (e.g., local agronomic data such as sowing dates, harvest dates, cultivar used) relied on involvement of local experts and was feasible for a limited number of countries, therefore Method 2 was also required to get complete coverage for Europe. Details are provided in Table S1.1 on which method was used for which crop x country combination.

2.1.1. Method 1) yield potential estimation – Global Yield Gap Atlas methodology

First, we selected those countries that best represent the dominant spatial distribution of crop production area (see Table S1.1 for the crop-country combinations where Method 1 was used and Table S1.1.1 for data sources of harvested area selection). With those country areas we covered 69%, 62%, 97% of the total area in Europe of faba bean, pea and soybean, respectively. Next, key climate zones (CZ; defined by a combination of growing degree days, temperature seasonality, and aridity index (Van Wart et al., 2013)) for each country and crop combination were selected based on harvested area and information from local agronomic experts. Within those key CZs, weather stations were identified to provide weather data characterising the climate zone. Next, a 100-km radius 'buffer' surrounding each weather station was created and clipped by the borders of the key CZs and country to ensure that the buffer zone is located within a unique CZ and country. Reference weather stations (RWS) were selected based on harvested area of crop area masks. For faba bean and pea, crop area masks were generated based on national statistics at the finest spatial scale available (NUTS3) for the average harvested area in the five most recent years available. For soybean, the crop area mask of SPAM2010 (IFPRI and Dataverse, 2019) was employed in combination with information from national agronomic experts and, if required, national statistics at the finest spatial scale available (NUTS3) were also used (Table S1.1.1).

Daily observed weather data was collected for each RWS (Table S1.1.1). If suitable weather stations with adequate data were not available, gridded weather data were used (Table S1.1.1). For missing precipitation values, gap filling was carried out, while for other variables propagation of weather data was used to fill data gaps following the method of Van Wart et al. (2015).

For each of the RWSs with their 100 km radius, cropping system information was obtained via national agronomic experts about the water regime (rainfed, irrigated), period of sowing and harvest, planting density and main maturity type of cultivars.

Soil data were obtained for rainfed systems only and consisted of the three dominant Soil Map Units (SMUs) within the buffer of each RWS, based on the generated (faba bean, pea) and available (soybean) crop masks. Each SMU comprises a varying number of Soil Type Units (STUs) of which the soil parameters (Table S1.1.1 for data source) were used as input to the crop growth model.

Finally we carried out simulations of Yw for faba bean, pea and soybean for each STU within a RWS buffer and of Yp for each RWS buffer for pea and soybean. The Simple Simulation Model, SSM-iCrop2, (Soltani, 2012; Soltani et al., 2020; https://ssm-crop-models.net/ssm-icrop2/) was used as the crop growth model. Model calibration and validation was done using European datasets, for details see Table S1.1.2 and Fig. S1.1.1.

The simulation results were up-scaled successively to SMU, RWS, CZ and country, using harvested area per STU based on the crop mask as the weighting factor. All simulated crop yields are presented with standard moisture content, 14% for faba bean and pea, and 13% for soybean. All results have been evaluated and deemed acceptable by national agronomic experts.

2.1.2. Method 2) yield potential estimation – linear regression

For the remaining crop x country combinations which have legume areas not covered by Method 1, we used linear regression to obtain Yw, and for Yp we used the weighted average Yp as predicted via Method 1 (due to limited data availability) (Table S1.2.1). The legume area used was FAO (2023) average over the years 2015–2020 (FAO, 2023). Data available in GYGA of Yw at CZ level for the entire world was used for the linear regression. The linear regression models used Yw of grain legumes as the response variable and the Yw of a commonly grown cereal in the same CZ as the predictor variable (faba bean ~ barley, pea ~ barley, soybean ~ maize), using the lm function in R (Table S1.2.1). This linear regression model was then used to estimate the Yw of the grain legume at CZ level across the crop x country combinations not covered via Method 1. It was assumed that the spatial distribution of the grain legume area within CZs in a country was similar to that of the cereal. Second, we analysed the accuracy of the linear regression model by comparing the simulated legume Yw data for the European countries for which we applied Method 1 to the estimates from the linear regression function (see Table S1.2.1 for Normalized Root Mean Square Error). See Supplementary Material 1.2 for all outcomes.

2.2. Scenario 2: grain legume area expansion

In Scenario 2, actual yields of grain legumes were taken from FAO (2023) (average over the years 2015–2020), and we assumed that area expansion will take place until 1/12th or 1/6th of the cropland area per country is covered by the three grain legumes. We took 1/12th as the area which seems attainable in the short term and 1/6th as the upper limit for the grain legume area in Europe given crop rotation requirements. The area of individual grain legume crops is unevenly distributed across European countries (Watson et al., 2017), therefore per individual country the increase in harvested areas of the three grain legumes was estimated and was based on the current ratio of harvested areas of faba bean, pea and soybean in that country.

2.3. Protein transition from animal- to plant-based

We estimated how increased European production of the three grain legumes via Scenarios 1 and 2 contributes to the demand for plant-based protein and the substitution of meat-based protein. We converted all products (plant-based: faba bean, pea, soybean; meat: beef, chicken, pig) to total amounts of human digestible proteins, in order to allow for substitution calculations. This was done by multiplying the amount of product by its protein content and by its PDCAAS (Protein Digestibility Corrected Amino Acid Score) (Table S1.3.1).

We first defined the contribution of Scenarios 1 and 2 to the current demand for plant-based protein. We defined the current demand for legumes by summing the amounts of the three different legumes imported and home-produced and subtracting the export (FAO (2023) data 2015–2020). The ratio of what is used for food and feed was obtained via the FAO (2023) food balance sheets (average 2015–2020).

Next, we estimated the effect of substitution of animal- by plant-based protein on land released and GHG emission savings. Here, we first defined how much extra plant-based digestible protein was produced in Scenarios 1 and 2 compared to the current situation. Second, the reduction in meat consumption per country was estimated using the current consumption ratios for the different types of meat (beef, chicken, pig). Amount and type of meat consumed per country was obtained from FAO (2023) food balance sheets (average 2015–2020). An upper limit of 25% was set for the amount of meat that could be substituted per country, as this was estimated to be the maximum substitution of meat consumption by grain legumes acceptable to European citizens (Henn et al., 2022). Finally, land and GHG emission savings were estimated through multiplying the amount of substituted meat by conversion factors obtained from Poore and Nemecek (2018) (Tables S1.3.2 and S1.3.3). For the conversion factors we took the 5th percentile of the Poore and Nemecek (2018) global dataset, as we assumed that this would best represent European conditions, which will generally have more efficient livestock production than the global average (Tables S1.3.2 and S1.3.3 contain data and Table S2.1 results of not only the 5th percentile, but also the 10th percentile and median conversion factors). Land saving indicates the land used for substituted meat production (for more details see Poore and Nemecek, 2018), i.e., net land savings, thus minus the land used for extra grain legume production in case of Scenario 2. GHG emissions from substituted meat production includes emissions from the whole supply chain, from land use change, to feed crop production, livestock raising, processing, packaging, retail, to losses (for details see Fig. S1 in Poore and Nemecek (2018)).

3. Results

3.1. Scenario 1: Water-limited and irrigated potential yields

For rainfed faba bean in Europe, Yw (weighted average based on harvested area per climate zone) was estimated at 5.2 Mg ha^{-1}, and showed less variability across climate zones and countries than pea and soybean (SD = 0.63) (Fig. 1e).

For rainfed pea, weighted average Yw was 4.4 Mg ha^{-1}, and showed somewhat more variability across climate zones and countries than faba bean (SD = 0.67) (Fig. 1a). Lowest values were found in climate zones in Mediterranean Europe (Spain, Portugal, Greece; 2–3 Mg ha^{-1}), while highest values prevailed in northwestern Europe (Belgium, Ireland, UK; around 6 Mg ha^{-1}). Crop water availability (i.e., amount of water supply during the crop growing season) was a reason for these differences in yield across the climate zones (Fig. S2.1), given the significant positive correlation between yield and crop water availability ($R^2 = 0.61$). Note that the relationship between crop water availability and Yw could only be assessed for those Yw estimates obtained from Method 1, and not those from Method 2. In the case of irrigated pea, weighted average Yp was 6.0 Mg ha^{-1}, and showed little variability across climate zones and countries (SD = 0.30), but estimations were done for only two countries including five CZs (Fig. 1b). Yields were on average 62% higher when irrigation was applied, for those countries which had both rainfed and irrigated yields predicted (i.e., Spain and Ukraine).

For rainfed soybean, weighted average Yw was 3.1 Mg ha^{-1}, and showed the highest variability across climate zones and countries compared to the other two legumes (SD = 0.77) (Fig. 1c). Lowest values were found in south eastern Europe (Bosnia Herzegovina, Moldova, Ukraine; 2–2.5 Mg ha^{-1}), while highest were found in central Europe (Austria, Switzerland, Slovenia; around 5 Mg ha^{-1}). Also for this crop, total water availability was a reason for these differences in yield across the climate zones (Fig. S2.1), given the significant positive correlation between yield and crop water availability, although the low correlation coefficient ($R^2 = 0.34$) points at the importance of other factors as well, e.g., the temporal distribution of water availability. Weighted average soybean Yp was 5.8 Mg ha^{-1}, and showed little variability across climate zones and countries (SD = 0.32) (Fig. 1d). Yields were on average 80% higher when irrigation was applied, for those countries where both rainfed and irrigated yields were predicted (i.e., Austria, France, Romania, Ukraine).

3.2. Scenario 2: Area expansion

None of the European countries already had 1/6th of their cropland devoted to the three grain legumes; on average only 3% was cropped with the three legumes in years 2015–2020. While 1/12th was reached

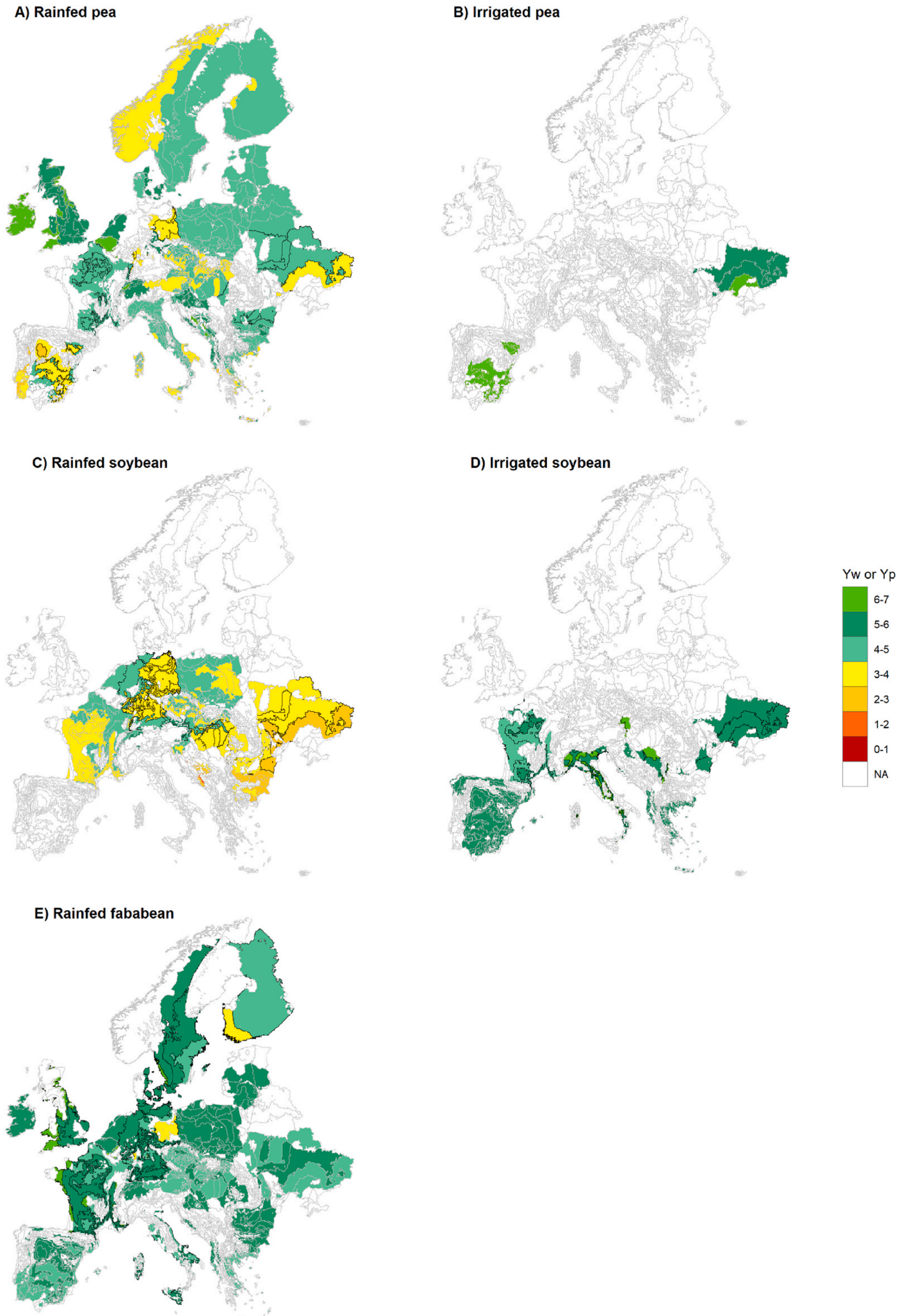

Fig. 1. Water limited potential yield (Yw; left panels) and potential yield (Yp; right panels) in Mg ha^{-1} of pea (top panels), soybean (middle panels), faba bean (bottom panel) at climate zone level (note, Yw and Yp are presented for the whole climate zone but cultivation does not take place everywhere in that climate zone [e.g., no crop growth in the very north of Europe]). Black line around a climate zone means that data is estimated through crop growth simulations models (Method 1), while a grey line indicates results from the regression model (Method 2).

by Croatia (9%), many countries currently have <1% of their cropland covered by the three legumes, e.g., Portugal, Norway, Poland (Fig. 2). Thus, in all countries a large increase in cropland allocated to legumes will be needed to reach the targeted 17% of Scenario 2. The partitioning among total legume area was for faba bean, pea and soybean 7, 30, 63%, respectively (data not shown).

3.3. Production increases through yield increase and area expansion

In order to achieve 80% Yg closure in Scenario 1, average Ya of faba bean, pea and soybean have to increase by 41%, 44% and 69%, respectively (Fig. 3a vs 3b). With the scenario of 80% Yg closure, the largest production increases are possible in Ukraine, Italy and France

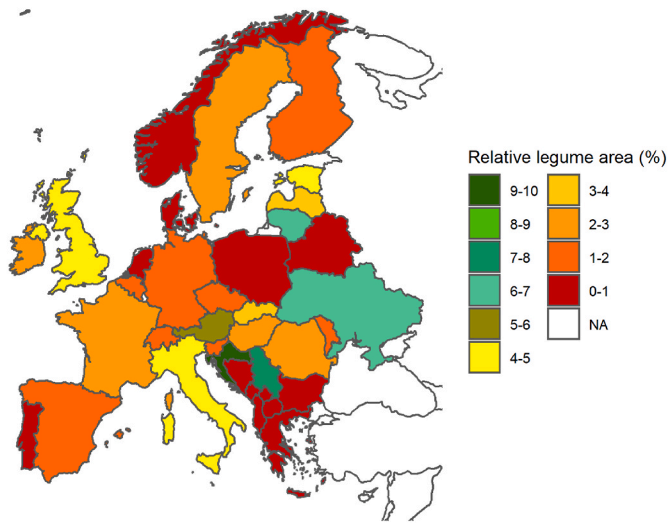

Fig. 2. Percentage of the total cropland area where the three grain legumes are grown in Europe (average over years 2015–2020).

(Fig. 3a vs 3b). However, in a large part of Europe, only limited areas are covered by grain legumes, so production increases with this scenario will be small (e.g., Norway, Portugal, Slovenia).

In the area expansion Scenario 2, the current area of faba bean, pea, soybean must increase from 4.9 to either 13.7 or 27.3 M ha, which is 8.7 (+177%) or 22.4 M ha (+455%), to fulfil the assumption of either 1/12th or 1/6th of the cropland being occupied by the three legumes. Largest relative increases are needed in Portugal (+5089% or +10331% current area for either 1/12th or 1/6th), Norway (+1994% or +4088%), and Belarus (+1712% or +3524%), while the relative increase needed is much smaller for Croatia (+0% or +80%), Serbia (+10% or +123%) and Estonia (+31% or +204%) as they already grow the three legumes on a large share of their cropland (Fig. 3a vs 3c). Large absolute increases apply to Ukraine (0.7 or 3.5 M ha increase for either 1/12th or 1/6th), France (1.1 or 2.7 M ha) and Spain (1.2 or 2.6 M ha; Fig. 3a vs 3c).

3.4. *Self-sufficiency estimations*

Current legume production meets 20% of the European demand, while with 80% Yg closure on present grain legume area it would reach 32%. In case of 1/12th of the cropland devoted to grain legumes and current yields it would be 52%, and with 1/6th of the cropland the European demand can be fully met (Fig. 4). Currently, only 26% of the total European consumption is used directly as food and 76% of that demand is met by European production. In all scenarios, more than enough plant protein can be produced to meet the demand for direct human consumption (Fig. 4).

For Europe as a whole, 11% of the beef, chicken and pork consumption could be replaced by closing the yield gap on existing land with the three legumes if all the extra legume production was consumed as food by European consumers. On average this means a reduction of 3, 7, 13 g per person per day of beef, chicken and pork meat respectively. For Scenario 1 this meat reduction would result in 6 M ha less cropland used, which equals 4% of the current cropland (Fig. 5). At the same time

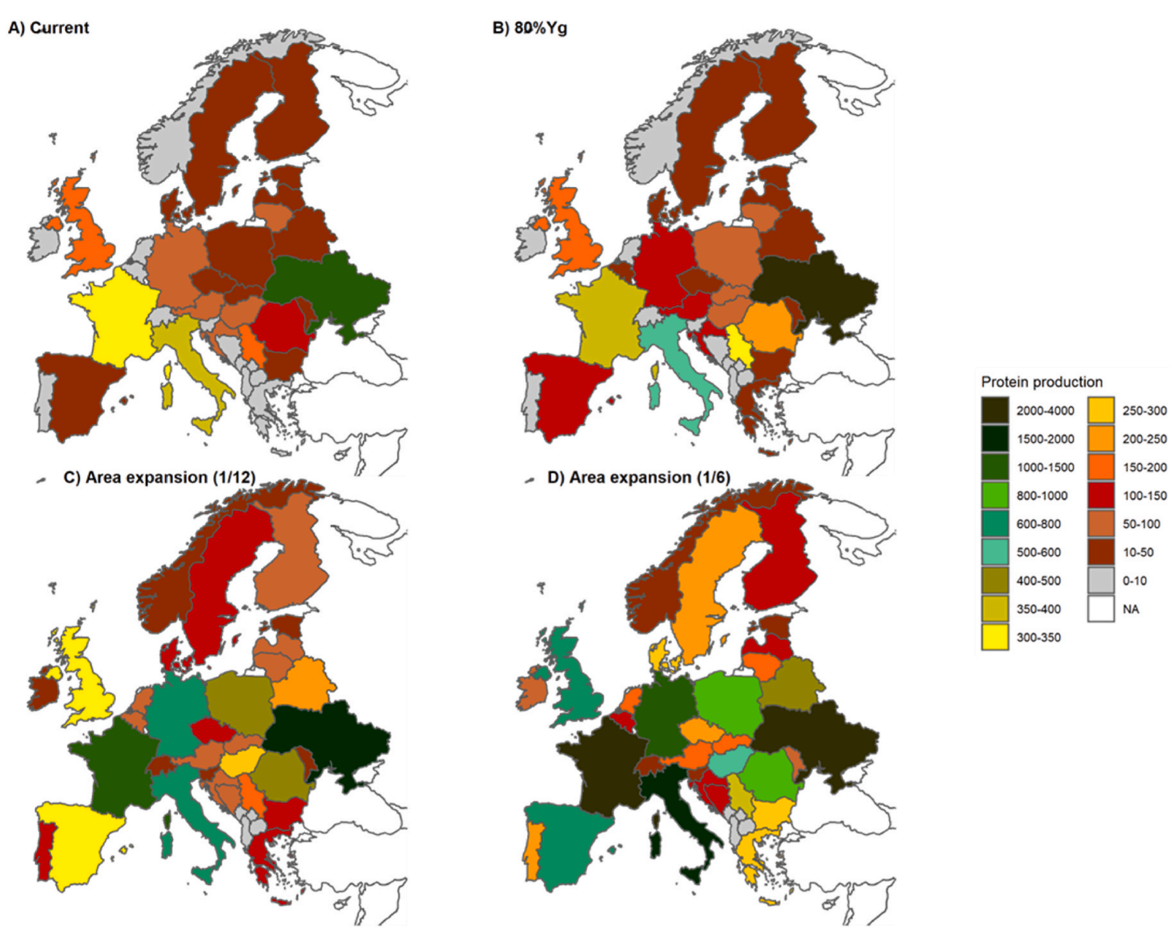

Fig. 3. European digestible protein production (in 10^9 g) from faba bean, pea, soybean with current area and yields (a), in a scenario of 80% yield gap closure (Yg) (b), in a scenario of area expansion to1/12th of the area with faba bean, pea and soybean (c) and in a scenario of area expansion to1/6th of the area with faba bean, pea and soybean (d).

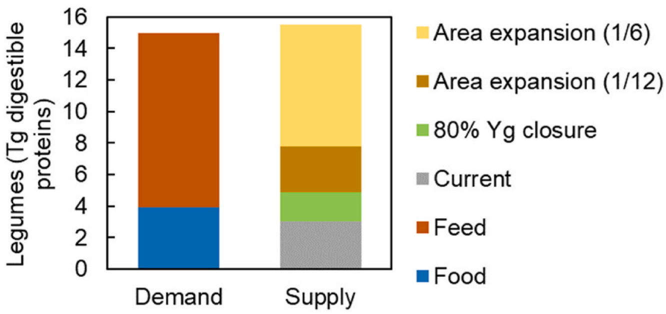

Fig. 4. Total European legume (faba bean, pea, soybean) demand as used for food and feed, and different scenarios of total legume supply: current situation, 80% yield gap closure (Yg), area expansion legumes (1/12th or 1/6th of cropland with faba beans, peas or soybean).

this reduction in meat consumption leads to a reduction in GHG emissions from meat production of 25 Tg CO_2 eqv. or 7%. For Scenario 2, theoretically all meat consumption could be replaced by the extra grain legume production and consumption for 1/6th area expansion and 76% when 1/12th of the cropland is occupied by legumes (Fig. 5). However, if we employ the upper limit of 25% meat substitution, this means on average a reduction of 9, 15, and 24 g per person per day of beef, chicken and pork meat respectively. The result is 11 M ha less cropland used, which equals 8% of the current cropland (Fig. 5). At the same time this reduction in meat consumption leads to 74 Tg CO_2 eqv. less emissions which equals 22% reduction in emissions from meat production (see Table S2.1 for sensitivity analysis on less favourable conversion factors).

4. Discussion

There are many arguments in favour of increasing grain legume production and consumption in Europe. First, grain legumes are one of the few agricultural commodities for which Europe is not self-sufficient, and the shortfall is huge as we show here. Europe imports much of its consumption from the Americas, where much (indirect) land-use change is attributed to increased soybean production (Boerema et al., 2016). From a cropping system perspective, crop diversification is increased and dependence on external nitrogen inputs is reduced (Zander et al., 2016). In our analysis, we showed that self-sufficiency of grain legumes for food can be easily achieved by either a 61% yield increase on current grain legume areas or by a 2.8 times greater area (i.e., to 1/12th of the cropland being occupied by legumes). Self-sufficiency for both food and feed is widely achieved with a 5.5 times greater area (i.e., to 1/6th of the cropland being occupied by legumes). How robust are our estimations and what do they imply?

4.1. Assumptions and data limitation

Several methodological assumptions and data limitation may affect the outcomes of our study. We assumed that the current ratio of area devoted to faba bean, pea and soybean is maintained in our scenarios. This implies that the area of soybean is largest, followed by that of pea and faba bean (Fig. S2.2). However, it is expected that the area of soybean in northern Europe will increase to a larger extent than the other legume crops (Karges et al., 2022). An alternative model would for example be to choose the crop with the highest protein yield potential for each region. In our current study, when considering the demand for legumes we assumed that faba bean, pea and soybean are mutually substitutable. We only considered the digestible protein content, and did not consider dietary preferences or other nutritional aspects such as the content of different essential amino acids or fibers (Domić et al., 2022).

Additionally, we only considered the main grain legumes, faba bean, pea and soybean. Diversity of cropping systems is important, as higher diversity is associated with higher resilience of the cropping system as a whole (Divéky-Ertsey et al., 2022). Therefore, for further studies, it is relevant to consider a broader range of grain legumes that can be cultivated in Europe. For example, areas of lentil, chickpea, lupin, and common bean exceed 10 thousand ha in several European countries (Eurostat, 2023; FAO, 2023).

For our yield gap estimations, we needed to discriminate between irrigated and rainfed production areas. Data on rainfed and irrigated areas is scarce in official datasets, and we obtained estimates from country experts, which were sometimes uncertain and often pointed at low shares of irrigated areas. Uncertainties regarding potential yield predictions can be reduced, especially for faba bean and pea, if potential yields of more countries could be estimated through the use of a crop growth model and following the Global Yield Gap Atlas methodology (Method 1). While we cover more than half of the harvested area of the three legume crops through estimations via this methodology, some main producing countries for faba bean (e.g., Lithuania), pea (e.g., Lithuania, United Kingdom) and soybean (Slovakia) are estimated through regression (Method 2).

Despite uncertainties, our results clearly show that both higher yields and in particular area expansion of grain legumes are needed for Europe to become (more) self-sufficient in plant proteins for human consumption and certainly when including feed demands. This evidently leads to the question, why are current areas limited, and why are yields relatively low compared to their potential?

4.2. Grain legume area

Today, the average share of European cropland devoted to grain legumes is only 3%. One of the causes of this small share is that over the years agricultural systems in Europe have become specialized, focusing on crops with a high and/or stable market value instead of grain legumes which have a relatively low market competitiveness and more variable yields (Magrini et al., 2016; Zander et al., 2016). Using data from www.yieldgap.org, we estimate the average coefficient of temporal variation of cereal yields in Europe to be 16% while that of grain legumes is 28%. Low market competitiveness goes partly back to earlier versions of the Common Agricultural Policy (CAP) of the European Union, which subsidized cereals but not grain legumes (Martin, 2014). In addition, grain

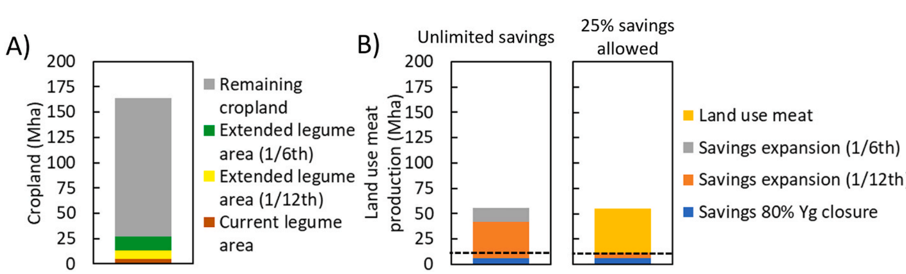

Fig. 5. A) Total cropland divided into current legume area, area required for 1/12th and for 1/6th of cropland being occupied by legumes. B) Total land use for meat production and its savings under the scenario of 80% yield gap closure (Yg), area expansion legumes (1/12th or 1/6th of cropland with faba beans, peas or soybean) when either unlimited meat savings are allowed or when maximum is set to 25% (dashed line).

legumes are generally perceived as low yielding and less profitable crops, thus less competitive with imports (Ghelfi and Palmieri, 2017). The areas of faba bean and pea fluctuate a lot across years (25% and 23% coefficient of temporal variation during the 2002–2020 period, respectively (Eurostat, 2023)). Recently, faba bean area has particularly declined in France, Romania and Spain, while the area of peas has decreased markedly in France, Ukraine and Spain. If the area of these grain legumes returned to the 2017 level in all countries, the area of faba bean would increase by 44% (+0.3 Mha) and the area of pea by 64% (+0.8 Mha) (Eurostat, 2023). Interestingly, since the CAP reform of 2013, the soybean area has increased throughout Europe by 0.15 M ha year^{-1} (Eurostat, 2023), and is likely to increase even more in future as it is projected that 31% more area will become suitable for soybean cultivation in Europe (i.e., as production risks due to cold temperature become less) (Nendel et al., 2023). The area may also expand due to increased demand for locally produced high quality feed and food (Murphy-Bokern and Font, 2022). The awareness that plant proteins are healthier and more environmentally friendly than animal proteins may help to drive an increased areas of all three grain legumes. Obviously, major changes in human consumption and the entire production chain are a prerequisite for such food system transitions to be realised.

4.3. Grain legume yield

4.3.1. Yield defining factors

The level of water-limited potential yield and the potential yield are determined by yield defining factors, in which cultivars play an important role. Investment in breeding effort on pea and faba bean is a tiny fraction of that on cereals and oilseeds (Magrini et al., 2016). Genome sequences of pea (Kreplak et al., 2019) and faba bean (Jayakodi et al., 2023) are expected to provide the necessary background information for considerable acceleration in breeding progress of these crops, while the genome of soybean was sequenced much earlier (Schmutz et al., 2010). Global investment in breeding has greatly exceeded that in other grain legumes and is easily translated to European conditions, with cultivar development proceeding in France and Austria (AGES, 2023). Very early-maturing cultivars have been developed, which can help to avoid conditions of heat and water stress during critical periods of crop growth and development (flowering, bean filling) (Malii, 2022). Other new cultivars have increased resistance to drought and cold, allowing earlier sowing, which is important for optimal use of early spring moisture reserves in the soil (Petrychenko, 2009).

4.3.2. Yield limiting factors

We found that variability in water-limited potential yield can be partly attributed to crop water availability for pea and soybean. Although the present data set could not test the effect of water availability on faba bean yield, it is well established in the literature. Faba bean is considered more sensitive to water deficit and less to water surplus than pea (Stoddard et al., 2006), and a recent cultivar trial showed a strong correlation between yield and growing-season precipitation, confirming the major role of drought in limiting faba bean yield (Skovbjerg et al., 2020). Uncertainties regarding the effect of crop water availability could be reduced if water-limited potential yields of more countries could be estimated through the Global Yield Gap Atlas methodology (Method 1).

Irrigation is a solution to increase yields significantly when low water availability limits yields. Recent experiments have shown that irrigation can increase soybean yield by 41 % (Karges et al., 2022) and a literature survey found increases in faba bean yield averaging 33–53%, depending on the tool used to estimate water need (Belachew et al., 2023). In future conditions with climate change, production of legumes could benefit greatly from irrigation, which may become a necessity in some parts of Europe. Nendel et al. (2023) predicted that for soybean, the area under drought risk in the period 2040–2069 will be almost 30% greater than in 1981–2010. In addition, irrigation might improve and stabilize pea yields in the more continental parts of Europe (Nendel et al., 2014).

4.3.3. Yield reducing factors (weeds, pest and diseases, nutrients)

Other causes of low productivity of grain legumes relate to limited options for weed control in comparison to cereals and oilseeds, which is a consequence of the small areas and the economic value of these crops limiting serious investment in control chemistry (Watson et al., 2017). In addition, improved genetic resistance to key diseases (e.g., broomrape *Orobanche crenata* on faba bean) is needed for grain legumes, because chemical treatment is prohibitively expensive when gross margins are low (Dima, 2015; Mínguez and Rubiales, 2020).

4.3.4. Economic competitiveness with other crops

de Visser et al. (2014) investigated the extent to which legume yields need to increase to be economically competitive with cereals. They found that on average across Europe, yields of faba bean, pea and soybean need to increase by 69, 76, 30%, respectively, to be competitive with wheat (for the price ratios at that time). Note, that to obtain 80% yield gap closure for faba bean, pea and soybean, our estimated yield increases are 41, 45, 69% respectively. Since 2014, the market price of protein has decreased while prices of oil and starch crops have increased (IndexMundi, 2023), so it is evident that across Europe it remains difficult for faba bean and pea, and less so for soybean, to be competitive with imported proteins. Nevertheless, since 2023, farmers in the Netherlands can obtain a higher premium if they incorporate protein crops in their rotation (GLB, https://www.rvo.nl/onderwerpen/glb-2023/conditionaliteiten), which has already led to some increase in acreage of grain legume crops. Thus, policy support can help to make legumes more attractive in economic returns and may lead to immediate area expansion.

4.4. The value chain

Large increases in plant protein production cannot happen instantaneously, and growth will most likely be gradual, perhaps starting at the local scale by bringing together small companies with local and regional markets (local value chains). Furthermore, co-operation between all actors (e.g., farmers, advisors, researchers) involved in the supply chain is s needed to improve knowledge and effectiveness of increased European protein production. Donau Soja Organisation is a good example of such an initiative (Schreuder and de Visser, 2014) and many informal networks have been developed in various individual countries by national and European projects such as Legumes Translated, TRUE and LegValue. Realising the desired increase in European grown plant protein thus requires several factors to come together including agricultural knowledge, innovation, policy support, and public awareness.

4.5. Benefits of increased legume production

Although from an economic perspective and current price ratios it can seem unrewarding to increase production of grain legumes in Europe, other, including economic, benefits of grain legumes must also be considered. The effect of biological N fixation, and delivery of ecosystem services by enhanced crop protection against pests and diseases thanks to a more diverse cropping system and consequent yield enhancement of subsequent crops in the rotation, are often underestimated by farmers (Zander et al., 2016). This is likely to become more important now that fertilizer prices have increased and European policies target the reduction of external inputs and emissions (European-Commission, 2020).

There may be clear geo-political reasons to increase grain legume production in Europe (Nemecek et al., 2008), such as the volatility of world soy prices, the competition from China as a major buyer on the world soybean market, and recent disruptions to world trade from pandemics and warfare. The substitution of mineral nitrogen fertilisers through biologically fixed nitrogen by grain legumes will also lower GHG emission in agriculture (Magrini et al., 2016; Rosa and Gabrielli, 2023).

Substantial extra environmental benefits can be achieved when legumes are directly used for human consumption, instead of indirectly by conversion through feed into livestock. We estimated the GHG savings to be ca. 25–74 Tg CO_2 eqv. (7–22% reduction in emissions from meat production), and land savings ca. 6–11 M ha (4–8% of current cropland) depending on the production scenario chosen. Such dietary changes require significant changes in the food system, human nutrition and associated behaviour, which will require substantial time and incentives.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is available on www.yieldgap.org

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2023.100723.

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