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Could domestic soybean production avoid Europe's protein imports in 2050?☆

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Abstract – The European Union has a high demand for plant proteins for food and feed. Its self-sufficiency rate is about 5% for soya crude proteins. The European Union and its Member States have launched initiatives for reducing soya imports that come mainly from South America and promoting domestic production of protein-rich crops. In the future, climate suitability for soybean cultivation is likely to increase in oceanic and continental Europe. The recent AE2050 study (INRAE. 2020. Role of European agriculture in world trade by 2050: Balancing climate change and global food security issues. Summary report of the study. INRAE (France), 12 p; Tibi A, Forslund A, Debaeke P, *et al.* 2020. Place des agricultures européennes dans le monde à l'horizon 2050 : entre enjeux climatiques et défis de la sécurité alimentaire. Rapport de synthèse de l'étude. INRAE (France), 159 p + Annexes) concluded that, in some parts of Europe (defined here as the European Union-27 plus other Balkan countries, Switzerland, Norway and the United Kingdom), cropland requirements in 2050 may be lower than "2010" cropland areas given possible changes in European food demand (related to glooming demographic growth and under the assumption of healthy diets) and in crop yields (influenced by technological developments and climate change). In this study, we examine to what extent this "cropland surplus" could be used to increase soybean production in Europe and reduce the dependency ratio on protein imports. Only in the case of a Healthy Diets scenario (less meat consumption, inducing less animals fed with cakes), substantial soybean acreages could be envisaged to reduce the European reliance on imports. In addition to the surplus allowed by increasing yields, land surplus was also made available by the reduction of livestock production and its grain feed requirements. The best-case scenario, combining healthy diets and trend-based yield growth, would reduce European imports to only 15% of its total domestic requirements *versus* 45% for the Trend-based Diets scenario. This can be compared to a dependency rate of 51% in our base year "2010", and of 53%–54% for the two 2050 scenarios without growing soybean on cropland surplus. If the range of these quite optimistic estimations of surplus land dedicated to soybean was reduced to more plausible levels (limited to 10% of annual field cropland in 2050) and considering current soybean yield levels ("2019" instead of "2010"), the decrease in Europe's oil cake imports levels would be lower. However, its dependency rate could still be reduced from 54% to 46% in the Trend-based Diets scenario, and from 53% to 38% in the Healthy Diets scenario. One important conclusion is that adopting healthy diets would allow a significant reduction of imports of soybean cakes from abroad with expected environmental benefits in Europe and overseas. On the supply side, challenges for a higher self-sufficiency rate of proteins in Europe resulting from the development of soybean domestic production will come from both available and suitable crop areas, attainable yields and relative profitability.

Keywords: protein self-sufficiency / Europe / climate change / yield projection / cropland surplus

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☆ Contribution to the Topical Issue "Soybean / Soja"

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Résumé – Produire plus de soja en Europe pourrait-il éviter les importations de protéines de la zone en 2050 ? L'Union européenne a une forte demande en protéines végétales pour l'alimentation humaine et animale. Son taux d'autosuffisance est d'environ 5 % pour les protéines de soja. L'Union européenne et ses États membres ont lancé des initiatives visant à réduire les importations de soja qui proviennent principalement d'Amérique du Sud et à promouvoir les productions nationales de cultures riches en protéines. À l'avenir, l'aptitude climatique de la culture de soja devrait augmenter en Europe océanique et continentale. La récente étude AE2050 (INRAE. 2020. Role of European agriculture in world trade by 2050: Balancing climate change and global food security issues. Summary report of the study. INRAE (France), 12 p : Tibi A, Forslund A, Debaeke P, *et al.* 2020. Place des agricultures européennes dans le monde à l'horizon 2050 : entre enjeux climatiques et défis de la sécurité alimentaire. Rapport de synthèse de l'étude. INRAE (France), 159 p + Annexes) a conclu que, dans certaines parties de l'Europe (définie ici comme l'Union Européenne à 27 plus les autres pays des Balkans, la Norvège, la Suisse et le Royaume-Uni), les besoins en terres cultivées en 2050 pourraient être inférieurs aux surfaces cultivées en « 2010 », compte tenu des changements possibles de la demande alimentaire (liée à une croissance démographique faible et dans l'hypothèse de régimes alimentaires plus sains) et des rendements des cultures (influencés par les progrès techniques et le changement climatique). Dans cette étude, nous avons examiné dans quelle mesure ce « surplus de terres cultivées » pourrait être utilisé pour augmenter la production de soja en Europe et réduire son taux de dépendance aux importations de protéines. Ce n'est que dans le cas d'un scénario de régimes alimentaires sains (moins de consommation de viande, induisant moins de besoins en tourteaux), que des surfaces importantes en soja pourraient être envisagées pour réduire la dépendance aux importations. Au-delà du surplus permis par l'augmentation des rendements, la réduction de la production animale et de ses besoins en céréales libère des terres. Le scénario le plus optimiste, combinant des régimes alimentaires sains et une croissance soutenue des rendements, réduirait les importations européennes à seulement 15 % de ses besoins domestiques totaux, contre 45 % dans le scénario des régimes alimentaires tendanciels. Cela peut être comparé à une dépendance de 51 % pour l'année de référence « 2010 », et de 53 %–54 % pour les deux scénarios 2050 (régimes sains ou tendanciels) sans culture de soja sur l'excédent de terres. Si la part des surfaces consacrées au soja était limitée à 10 % des grandes cultures en 2050, et si l'on tenait compte des niveaux de rendement actuels du soja (« 2019 » au lieu de « 2010 »), l'impact sur les importations européennes de tourteaux serait plus modeste. Toutefois, le taux de dépendance de l'Europe pourrait encore être réduit de 54 % à 46 % dans le scénario des régimes alimentaires tendanciels, et de 53 % à 38 % dans le scénario des régimes alimentaires sains. Une conclusion importante de ce travail est que l'adoption de régimes alimentaires sains en Europe permettrait une réduction significative des importations de tourteaux de soja en provenance de l'étranger, avec des bénéfices environnementaux tant en Europe que hors Europe. Du côté de l'offre, les défis à relever pour atteindre un taux d'autosuffisance en protéines plus élevé en Europe, résultant du développement de la production domestique de soja, proviendront à la fois de la disponibilité en terres, des rendements accessibles et de la compétitivité de la culture.

Mots clés : autosuffisance en protéines / Europe / changement climatique / projections de rendements / surplus de terres cultivées

Highlights

- In a scenario of healthier diets, substantial soybean acreages could be developed in Europe by 2050 to reduce the reliance of the zone on protein imports.
- In 2050, European imports could represent up to 54% of protein domestic requirements without expansion of domestic soybean production on available land.
- More cultivated soybean could reduce this dependency down to 15%–46% depending on yield, land use assumptions and diet scenarios.
- A higher self-sufficiency rate of proteins in Europe would likely be limited by available land, attainable yields and crop profitability.

1 Introduction

The European Union (EU) has a high demand for plant proteins, amounting to around 27 million tons of crude proteins in 2017. Today, the EU-27's self-sufficiency rate varies substantially depending on the protein source among oil-protein crops (79% for rapeseed, 42% for sunflower but only 5% for soya), (European Commission, 2018). Consequently, EU-27 imports annually around 17 million tons of crude proteins (of which 13 million tons are soya based corresponding to 30 million tons of soya beans equivalent), essentially from Brazil, Argentina and the USA. In addition, until 2022, the EU imported about 1.5 million tons of crude proteins from sunflower and up to one million tons from rapeseed, both mostly from Ukraine.

Although animal feed (mainly for poultry, pig and dairy cattle) remains largely the most important outlet in Europe (93%), the market for plant proteins has experienced

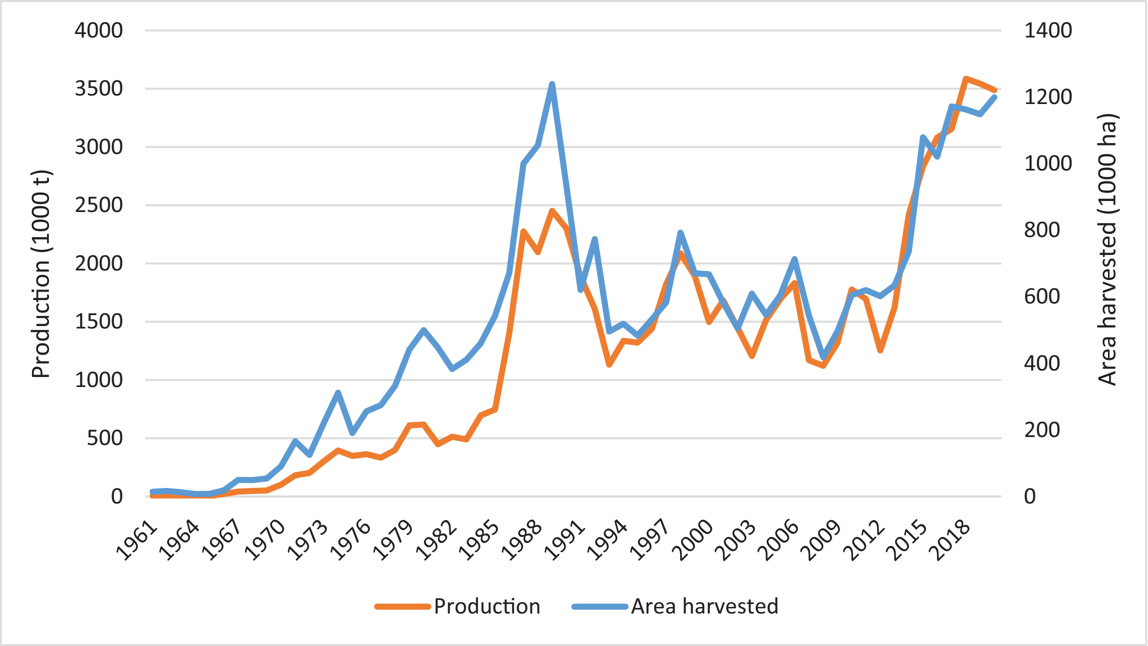

Fig. 1. Evolution of soybean harvested area (in 1000 ha) and production (in 1000 tons) in an enlarged EU from 1961 to 2020. Enlarged EU is EU-27 plus the other Balkan countries, Switzerland, Norway and United Kingdom (see Figure SI-1 for more details on countries). Source: FAOSTAT (2022).

increasing segmentation with demand in high-value feed and food sectors growing rapidly; the food market for plant proteins has been driven by increasing demand for meat and dairy substitutes (European Commission, 2018).

The EC has issued a strategy to reduce the dependency on proteins imported from overseas in a context of healthier diets (less meat) and with the ambition to reduce deforestation in South America (European Commission, 2018). The recently launched Green Deal (European Commission, 2019) has confirmed this orientation by promoting soybean and other legumes as key constituents of the diversification strategy proposed for the agroecological transition and the reduction in agricultural greenhouse gas (GHG) emissions. On 17 July 2017, 14 Member States signed the “European Soya Declaration” that committed them to promote sustainable and certified soybean (and other legumes) production and markets in Europe. In France, the “Charte Soja de France” initiative for a certified, non-genetically modified (non-GM) soya and traced value chain was launched in 2018 with similar objectives (Terres Univia, 2018).

In response to this rising demand and support, especially for locally produced and non-GM soybeans, dedicated areas across Europe have increased rapidly in recent years. In the EU-27, they have doubled to almost one million hectares (ha) since 2013, with a production up to 2.9 million tons in 2018 (FAOSTAT, 2022). The soybean production area in the EU-27 exceeded 1 million ha in 2021 for the first time since the “golden” period of 1987–1989. In line with the AE2050 study (INRAE, 2020; Tibi *et al.*, 2020), we will consider in this paper an “enlarged EU” (*i.e.*, adding the other Balkan countries, Switzerland, Norway and United Kingdom to EU-27 [Figure SI-1]). In this enlarged EU, the soybean area already exceeded 1 million ha in 2015 and covered 1.9 million ha in 2020 for a total production of 3.5 million tons (Fig. 1).

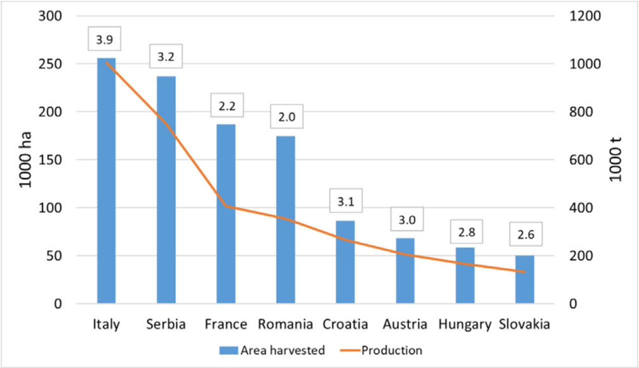

Fig. 2. Soybean harvested areas (1000 ha) and production levels (1000 t) for the eight most important producing countries in the enlarged EU in 2020. Corresponding yields (t.ha^{-1}) are given in the tags above the histogram bars. Source: FAOSTAT (2022).

In 2020, the main soybean producers in this enlarged EU were Italy, Serbia, France and Romania in 2020. However, considering continental Europe, the largest soybean producing countries were Russia and Ukraine that have both favourable climatic conditions and large amounts of available land of good agronomic quality. Therefore two-thirds of continental European soybean production took place outside the EU-27.

Soybean yields in 2020 ranged from 2.0 to 3.9 t.ha^{-1} among the eight most important producing countries in the enlarged EU (Fig. 2).

Promoting vegetable proteins means greater production of legume crops in Europe (Watson *et al.*, 2017). Among these crops, soybean exhibits the largest potential of development thanks to its high grain protein content ($>$ 40% dry matter), the wide temperature and photoperiod ranges in which it can be cultivated due to the diversity of available germplasm (Kurasch *et al.*, 2017), and existing agronomic knowledge from other continents (Grassini *et al.*, 2021). In addition to increased demand for local non-GM soybean, climate change, adapted varieties, and better technological expertise all provide relevant reasons to introduce more of this protein-rich crop in Europe, especially in northern regions above the typical soybean distribution area (Pannecoucque *et al.*, 2018; Lamichhane *et al.*, 2020; Nendel *et al.*, 2020; Boulch *et al.*, 2021; Coleman *et al.*, 2021; Toleikiene *et al.*, 2021; Karges *et al.*, 2022).

In the near future, climate suitability for soybean cultivation is likely to increase in regions located at northern latitudes while vast areas in low latitudes may become progressively unsuitable with more drought periods (Rojas *et al.*, 2019; Lu *et al.*, 2021; Silva Soares *et al.*, 2021). Such estimates on future soybean cropping opportunities in Europe are mostly based on the projection of soybean phenology under future climate, using simple photo-thermal algorithms (Lamichhane *et al.*, 2020; Schoving *et al.*, 2020). Data-driven approaches based on climatic variables and soybean yield statistics also suggest that the soybean production potential in Europe will significantly increase in the future with global warming (Guilpart *et al.*, 2022). From yield projections by 2050, the latter estimated the necessary cropland area to be devoted to soybean in the future to reach 50% and 100% of self-sufficiency in Europe. Nendel *et al.* (2020) used a set of crop growth models with an ensemble approach to simulate on a 25 x 25 km grid cell (i) potential (irrigated) and water-limited soybean yields in Europe, (ii) optimal maturity groups to plant and (iii) growth-limiting factors for current and future climates. These studies considered the climatic suitability of soybean in Europe, the potential and water-limited yields and the response to some adaptations (*e.g.*, maturity group) to climate change. However, they did not assess the fraction of land available for soybean cultivation.

In this paper, we estimated the potential for reducing the dependency on protein imports of the enlarged EU from cropland areas that were cultivated in "2010" (average of 2009, 2010 and 2011) but would no longer be cultivated in 2050. We based our calculations on the recent AE2050 study (INRAE, 2020; Tibi *et al.*, 2020), which concluded that cropland requirements in 2050 in some parts of Europe could be lower than "2010" cropland areas given possible changes in food demand (especially due to slow demographic growth and under the assumption of healthier diets) and in agricultural productivity (influenced by technological developments and climate change). Here we examined to what extent these areas, which can be called "cropland surplus", could be used preferably to increase soybean production and reduce Europe's dependency on protein imports.

2 Material and methods

The AE2050 study (INRAE, 2020; Tibi *et al.*, 2020) was inspired by the foresight study Agrimonde Terra on global food security conducted previously by INRAE and CIRAD (Le Mouël *et al.*, 2018) but with a specific emphasis on an enlarged EU. To that end, Europe was divided into eight regions to reflect the diversity of European agricultural systems (Figure SI-1). Potentials of these sub-European systems were then examined in terms of both their contribution to global food security in 2050 and environmental issues associated with the expansion of cropland, given the uncertainty around the consequences of climate change and technological developments, constraints regarding the possibilities of expanding cropland areas, and impacts of demography and changes in diets. To do so, the biomass balance model GlobAgri-AE2050 (Box 1) was used to project four reference scenarios from the "2010" base year until 2050, combining assumptions on two evolutions of human diets ("Trend-based diets" and "Healthy diets") and two crop yield evolutions ("high" *versus* "moderate" yield growth) in a "business as usual" climate context (RCP 6.0) and under different constraints on possibilities of cropland expansion.

Box 1. GlobAgri-AE2050: a balance model for agri-food products at the global level

GlobAgri-AE2050 is a supply/utilization biomass balance model for agricultural and agri-food products. For each of the 21 world regions and each product (33 agri-food products and 5 fodder products), the model equates domestic production plus imports to domestic utilizations (food, feed and other uses), plus exports, losses and waste, and inventory changes. Simplified equations are defined for fodder products that are not traded. Domestic productions are assessed to meet food and non-food human demands, plus demand for agricultural products intended for feed. Demand for feed is driven by the consumption of animal products in human diets, and is computed within the model as a linear function of production, combined with changes in animal feed efficiencies. For each region and product, gross imports are calculated as a proportion of total domestic demand, while gross exports are defined as a share of the product's world market. World trade (imports and exports) is balanced.

Establishing the supply/utilization equilibrium in each region for each product in 2050 will also depend on the available cultivable land in the region. In cases where cultivable land constraints offer enough flexibility to satisfy any desirable expansion of cultivated areas in 2050, the model is balanced by equalizing, for each product, total supply and total utilizations, in each region and at the global level. Harvested areas are calculated from required productions *via* crop yields, and cultivated areas are then obtained by using cropping intensity ratios. Thus, as long as cultivable area is not saturated in a given country, import dependencies and export market shares of all products in the country are kept constant (as in the base year "2010"). The dynamics change when one or several regions reach a point where the need for cultivated areas exceeds local available cultivable land in 2050. In that case, the equilibrium is obtained, first by reducing these regions' export market shares so as to reduce gross exports, second, if this initial adjustment mechanism fails to bring the cultivated area in the region below available land, by increasing gross agricultural import rates so as to increase gross imports.

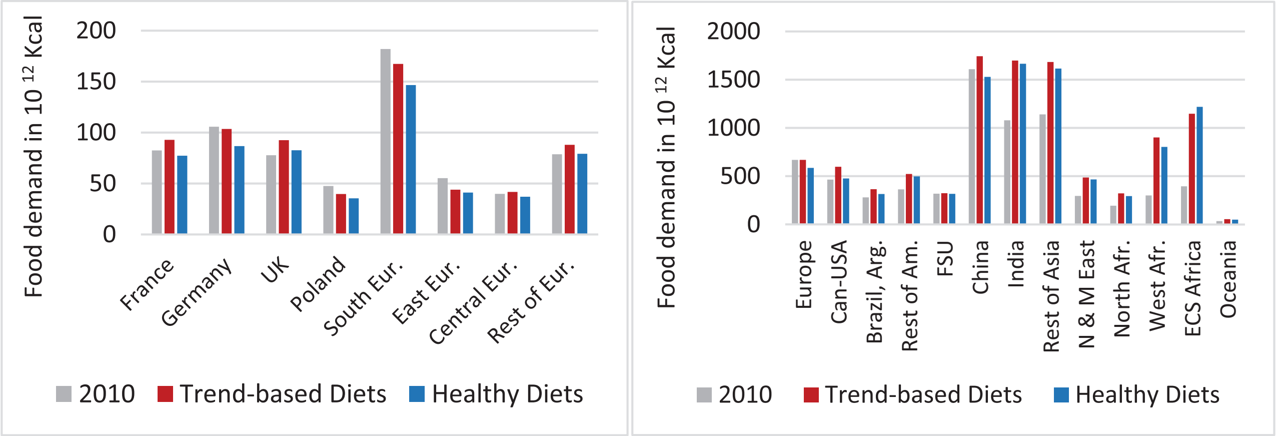

Fig. 3. European (a) and global (b) food demand in "2010" and 2050 (in 10^{12} Kcal). Source: Tibi *et al.* (2020).

The so-called "Trend-based" diets for 2050 were defined as an extension of past regional trends based on FAO projections in Alexandratos and Bruinsma (2012). In this scenario, individual calorie intakes are supposed to stagnate in developed regions, in the Former Soviet Union, in North Africa and in the Near and Middle East; they are supposed to increase in other emerging and developing regions, however not enough to close the nutrition gap in East, Central and South (ECS) Africa. Regional individual caloric intakes would thus vary between 2600 Kcal/person/day in ECS Africa up to almost 3800 Kcal/person/day in North America. In regions where intakes stagnate, the composition of the diets remains almost unchanged compared to "2010", while in other regions the transition towards more meat, more sugar and oils in diets would continue (except in sub-Saharan Africa where diets remain poor in animal products).

The so-called "Healthy" diets illustrate a generalised transition towards healthier diets that follows nutritional recommendations of the World Health Organization (WHO). There would be convergence of regional caloric intakes between 2750 and 3000 Kcal/person/day, supposing also a nutritional catch-up in ECS Africa. In this scenario, daily energy needs are met with better-balanced and more diversified diets containing larger quantities of secondary cereals, fruits and vegetables, and pulses, and less vegetable oils, sugar and meat. The consumption of animal-based products would decline in Europe and other developed regions compared to "2010"; it would increase in sub-Saharan Africa, India, and, more moderately, in North Africa.

Combined with different regional dynamics in population growth between "2010" and 2050, the trends in total food demand, which fuels cropland demand, would be very different between world regions (Fig. 3).

In the AE2050 study, focus was also on characterising uncertainties related to crop yields in 2050, under the combined impacts of global warming and technological developments. Impacts of climate change on yields were estimated through a statistical relationship measuring the effects of changes in average temperatures, annual average precipitation, and atmospheric CO_2 concentration (Makowski *et al.*, 2020). Impacts of technical change on yields were assessed based mainly on FAO projections for 2050, specifically FAO (2018) for the "moderate" yield growth assumption and Alexandratos and Bruinsma (2012) for the "high" or "trend-based" yield growth assumption. However, in the European regions (as well as in a few other countries; for more details on yield assumptions, see INRAE, 2020; Tibi *et al.*, 2020), historical trends (1995–2015) were directly used to project technical changes to 2050 (thus taking into account the yield slowdown at a high level or inversely the catch-up in average yield growth in recent years in different parts of Europe). To reflect uncertainties about the dynamics of technological developments until 2050 on the one hand, and the capacity of crops to benefit from the CO_2 fertilising effect in the field on the other, crop yields were thus projected based on two distinct assumptions:

- a "high" or "trend-based" yield growth assumption with a steady pace of technological developments all over the world and plants reaping the full benefit of the CO_2 effect;
- a "moderate" yield growth assumption with a moderate pace of technical progress and plants not benefiting from the CO_2 effect.

The resulting yield values retained for three major crops in Europe (wheat, maize, oilseed rape) were presented in Table SI-1.

The AE2050 study concluded that potential "cropland surplus" could be an opportunity for Europe, either to develop oil and protein seed crops – thereby reducing its reliance on plant-based protein imports and limiting the induced deforestation – or to transition towards agroecological cultivation systems while maintaining adequate production levels to meet demand.

In this paper, we explored the opportunities for developing soybean production in Europe in 2050. We used the same modelling framework as in the AE2050 study and the same geographical definition of Europe (enlarged EU) divided into eight sub-regions (Figure SI-1). As a starting point for the estimate of the cropland that could be available for soybean production in Europe, we re-simulated the four AE2050 reference scenarios combining two yield assumptions and two diets assumptions. To that end, we adopted the same assumptions as in the AE2050 study for all variables except for cropping intensity ratios that were now held constant in each region compared to "2010". The availability of suitable land for cropland extension was made for all regions under the “no deforestation assumption” which also excluded potentially urbanized areas on suitable land. Here we focussed attention on the results for the different European regions.

3 Results

3.1 How much cropland could be potentially available for soybean production in Europe (enlarged EU) in 2050?

Our simulation results show that by 2050, when crop yields evolve according to the “moderate” yield growth assumption, cropland would extend in all European regions compared to “2010” whatever the assumption on diets, such as no land would be available for developing other productions. However, when crop yields change according to the “trend-based” yield growth assumption, the need for farmland in some European regions – East Europe, Poland and Germany – would diminish compared to current levels (Tab. 1). The extent of the cropland surplus would vary considerably according to the diet assumption.

In the Trend-based Diets scenario, three European regions would experience a reduction in cropland needs compared to “2010”: Poland (−0.9 million ha), East Europe (−2.5 million ha) and South Europe (−3 million ha), (Tab. 1). However, the reduction in cropland in this latter region compared to “2010” is in fact due to a decrease in land suitable for crop production due to climate change and when potentially urban areas on suitable land are deduced from this land[1]. Thereby this land cannot be considered as freed land available for soybean production. The total potential cropland area available in 2050 in this scenario is thus shared between Poland and East Europe with a total of 3.5 million ha (Fig. 4).

In the Healthy Diets scenario, potential cropland surplus in 2050 would be much greater. This is mostly due to reduced demand for animal products leading to less feed demand. In this scenario, cropland could be available in Germany (1.4 million ha), Poland (2.6 million ha), East Europe (5.9 million ha) and Central Europe (0.3 million ha), (Tab. 1). The results for South Europe show a reduction in cropland of 5.5 million ha as the cropland needs of this region establish below suitable land. However, as explained above, the major part of the cropland reduction is due to a decrease in suitable land for crops. Furthermore, as already emphasized in Forzieri *et al.* (2014), Alfieri *et al.* (2015) and Rojas *et al.* (2019), this region would face very high water deficit until 2050 with a strong pressure on water resources for irrigation, which would make more soybean cultivation questionable. For these reasons, South Europe was excluded from the land surplus potential. Summing over all regions, 10.2 million ha could thus be available in Europe in 2050 (Fig. 4).

The total crop area that could potentially be available in Europe for soybean production would thus vary between 3.5 million ha and 10.2 million ha according to the assumptions made on diets, and supposing that crop yields change following the “trend-based” growth assumption.

Table 1. Changes in cultivated crop areas by 2050 (in million ha and in brackets in % compared to “2010”) in the different European regions under the combined effects of diet changes (“Trend-based” *versus* “Healthy” Diets) and yield evolutions (“trend-based” yield growth), given maximum available cultivable areas in 2050 assuming “no deforestation”.

European regions	Trend-based Diets	Healthy Diets
France	+6.9 (+36%)	+2.9 (+15%)
Germany	+1.1 (+9%)	−1.4 (−11%)
United Kingdom	+1.5 (+24%)	+0.7 (+11%)
Poland	−0.9 (−8%)	−2.6 (−22%)
South Europe	*−3.0 (−8%)*	*−5.5 (−15%)*
East Europe	−2.5 (−13%)	−5.9 (−29%)
Central Europe	+0.8 (+12%)	−0.3 (−5%)
Rest of Europe	+5.6 (+37%)	+2.8 (+18%)
Total Europe	+9.5 (+7%)	−9.4 (−7%)
Total cropland potentially available in Europe (excluding South Europe)	3.5	10.2

Source: Simulation results.

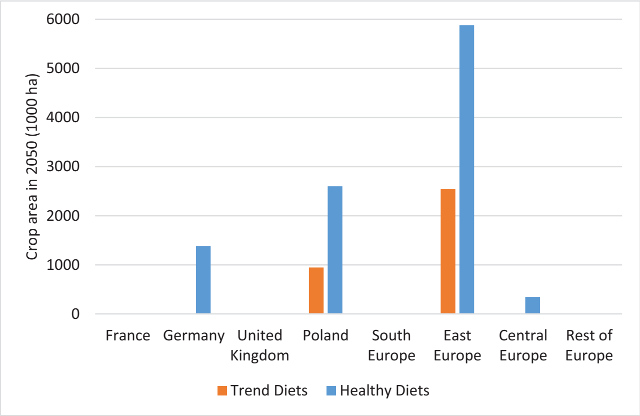

Fig. 4. Potentially available cropland areas (“cropland surplus”) in the different European regions in 2050 (1000 ha) according to diets (“Trend-based” Diets *versus* “Healthy” Diets). Source: Simulation results.

According to these results, no “cropland surplus” would be available by 2050 in France, the UK and the Rest of Europe. According to United Nations’ (UN) demographic projections (UN, 2017), these regions would experience a more dynamic evolution of their population compared to the average of the whole Europe zone (respectively, +12%, +19% and +12% compared to +0.1% for total Europe), which supports total food and feed demand, and thus favours demand for cropland in these regions. Furthermore, the results also rely on the assumption that the international trade structure was maintained constant throughout the projection period. More specifically, we assumed that regional export shares in world trade were maintained constant. As a result, when world trade increases, boosted by the demand from net importing countries, net exporters of agricultural products, like France, increase their export levels and thus their cropland areas.

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[1] Projections of land suitability for cropland taking into account climate change are based on FAO/IIASA GAEZ data (version 3.0), the SRES B2 scenario in 2050. See Forslund *et al.* (2020) for more details.

3.2 How much soybeans and soybean cakes could potentially be produced on European “cropland surplus” in 2050?

If the available cropland surpluses in 2050 resulting from our simulations were optimally used to produce soybeans (that is, assuming all area would and could be harvested), what would be the level of soybean production in Europe? Four European regions could potentially contribute to local soybean production on potentially available croplands in 2050: Poland and East Europe (Serbia, Bulgaria, Hungary, Romania) in the Trend-based Diets scenario; and Germany, Poland, East and Central Europe (Switzerland, Austria, Czech Republic, Slovakia) in the Healthy Diets scenario.

To estimate the European production potential of soybeans in 2050, we considered in a first approach that soybean yields in these regions achieved in the base year (“2010”) would remain stable on available cropland in 2050 (Fig. 5). By using these “2010” yields, we ignore the positive effect of the CO_2 fertilization and yield improvement allowed by progress in management and breeding by 2050. As a result, this constitutes a floor level for soybean yields by 2050.

The highest yields in “2010” were observed in the Po Valley (South Europe), in the Pannonian region (Central and East Europe) and in South-West France where fertile alluvial soils, irrigation availability, late-maturing cultivars and warm climate all result in the most favourable conditions for soybean production. In northern parts of Europe, yield levels are limited by cold conditions and early-maturing cultivars. Moreover, in Germany and Poland, the cultivation of soybean is relatively recent with limited experience from farmers and their advisers.

Based on these yield assumptions, soybean production on “cropland surplus” in Poland and East Europe could lead to a production of 7.9 million tons of soybeans in 2050 in the Trend-based Diets scenario (Tab. 2). Using crushing ratios observed in “2010” (0.79 for Poland and 0.70 for East Europe), the production of soybean cakes could reach 5.7 million tons in 2050, which is equivalent to 2.6 million tons of proteins. In the Healthy Diets scenario, using the same assumptions on yields and crushing ratios (0.80 for Germany and 0.79 for Central Europe), the production of soybeans would reach almost 21.8 million tons and the production of soybean cakes would be 15.9 million tons, which is equivalent to 7.2 million tons of proteins. These figures can be compared to the actual European soybean production observed in “2019” (average 2018–2019–2020) of 3.5 million tons, harvested from 1.17 million ha, mostly situated in East and South Europe (FAOSTAT, 2022).

3.3 How much of Europe’s protein imports in 2050 could be substituted by local production on “cropland surplus”?

In the base year “2010”, imports of soybean cakes in Europe (enlarged EU) were estimated to 20.1 million tons, that is, 9.1 million tons in protein equivalent. Extra and intra-European trade flows were distinguished by the authors based on Eurostat data. These imports represented 88% of total European imports of cakes.

In 2050, in the Trend-based Diets scenario, European soybean cake imports would increase by +46% with respect to “2010” to reach 29.4 million tons (total imports of cakes would increase by +44% in protein equivalent). This simulation result is linked to the evolution of animal production levels in Europe that continue to increase by +40% in energy equivalent compared to “2010”. The European dependency rate for cakes (imports of cakes/total use of cakes) would reach 54% in this scenario, compared to 51% in “2010”.

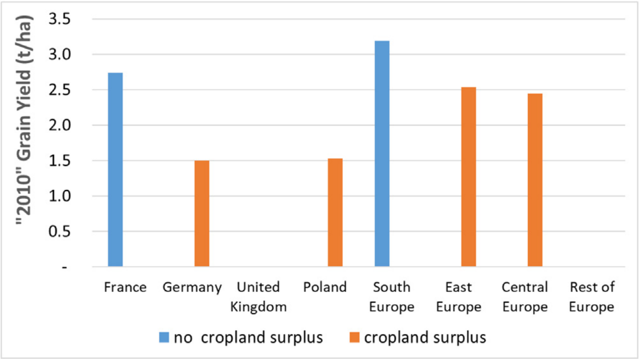

Fig. 5. Soybean yields observed in “2010” (t.ha^{-1}), (average 2009–2011) for the different European regions with or without cropland surplus. No soybean production (and yield) was observed in the United Kingdom and in the Rest of Europe in our base year (“2010”). Source: Tibi *et al.* (2020).

By contrast, in the Healthy Diets scenario, European imports of soybean cakes would decrease by −4% compared to “2010”, reaching 19.3 million tons. This result is consistent with the reduction of the European consumption of animal products in that scenario, which induces a decline in animal production and feed demand for cakes. The total European production of animal products would be reduced by −6% in energy equivalent compared to “2010”; only the production of poultry meat and aquatic animal products would increase in this scenario. The dependency rate would increase slightly to reach 53% in 2050.

Considering that proteins in soybean cakes could substitute proteins from all types of cakes, total imports of cakes in 2050 could be 17% lower in the Trend-based Diets scenario (from 14.9 to 12.4 million tons of protein) and 73% lower in the Healthy Diets scenario (from 9.9 to 2.7 million tons of protein). These figures correspond to a reduction of the cake dependency rate from 54% to 45% in the Trend-based Diets scenario, and from 53% to 15% in the Healthy Diets scenario (Fig. 6).

These results assume intra-European trade of cakes, with regions developing their local production of soybeans and soybean cakes exporting to regions with no available “cropland surplus”. This was already the case in “2010”, when intra-regional imports in Europe represented large shares of total imports of soybean cakes in many European regions[2].

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[2] According to our estimations from Eurostat statistics, intra-regional imports of soybean cakes represented between 24% and 98% of total imports of soybean cakes for most European regions. Only in South and the Rest of Europe this share was weak, 1% and 5% respectively. Source: https://ec.europa.eu/eurostat/web/international-trade-in-goods/data/database.

Table 2. Potential soybean production on “cropland surplus” in 2050 (“2010” yields are the average of the 3 years 2009, 2010, and 2011).

Regions	Available cropland in 2050		Soybean yields in “2010”	Potential soybean production		Crushing ratios	Potential production of soybean cakes	
	Trend Diets	Healthy Diets		Trend Diets	Healthy Diets		Trend Diets	Healthy Diets
	1000 ha	1000 ha	t.ha^{-1}	1000 tons	1000 tons	(0–1)	1000 tons	1000 tons
Germany	–	1384	1.5	–	2076	0.80	–	1658
Poland	946	2599	1.5	1447	3974	0.79	1143	3140
East Europe	2541	5882	2.5	6445	14 917	0.70	4510	10 438
Central Europe	–	348	2.4	–	850	0.79	–	669
Europe	3488	10 214		7892	21 818		5653	15 905

Source: Simulation results. Crushing ratios were calculated from FAOSTAT base yearly data.

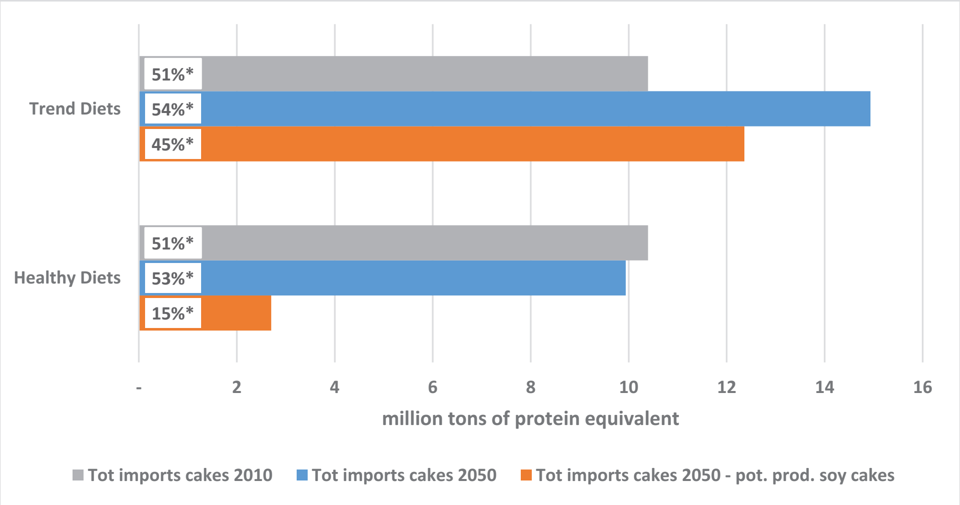

Fig. 6. European (enlarged UE) imports of cakes in “2010” (grey bars), in 2050 in the Trend-based Diets scenario and the Healthy Diets scenario (blue bars), and in 2050 in the two scenarios of diets when potential production of soybean cakes on “cropland surplus” is deduced (orange bars), in million tons of protein equivalent. Soybean yields were assumed unchanged at “2010” levels. *dependency rate = imports of cakes/total use of cakes (in percent).

3.4 What level of soybean yields would be necessary on “cropland surplus” to reduce the Europe’s cake dependency ratio to zero?

Considering the potentially “cropland surplus” in 2050, would it be possible to produce enough soybean in Europe to reduce its imports of cakes to zero? We tried to answer this question by estimating the level of soybean yield that would be necessary to attain on available land for both the scenario of Trend-based Diets (Tab. 3) and the scenario of Healthy Diets (Tab. 4).

In the Trend-based Diets scenario (Tab. 3), Europe would need to produce 13.4 million tons of proteins on “cropland surplus” (equivalent to 29.4 million tons of soybean cakes) to suppress its soybean cake imports in 2050, and 14.9 million tons of proteins (equivalent to 32.8 million tons of soybean cakes) to suppress all oilseed cake imports at that date. To produce these volumes on “cropland surplus” (3.5 million ha), soybean yields would have to increase by 400% to 500% compared to the average yield in “2010”, meaning soybean yields would have to reach between 11.8 to 13.1 t.ha^{-1} in 2050 which is obviously out of all realistic expectations.

The picture would be much more optimistic in the Healthy Diets scenario (Tab. 4). In that second scenario, Europe would need to produce 8.8 million tons of proteins to reduce its imports of soybean cakes in 2050, which is equivalent to 19.3 million tons of soybean cakes. To produce these amounts on available cropland, the soybean yield would need to reach 2.6 t.ha^{-1}, a +21% increase compared to the average soybean yield in “2010” (2.1 t.ha^{-1}). If the aim is to suppress all imports of cakes, the increase in soybean yield would be +37% (up to 2.9 t.ha^{-1}). This would substitute for all proteins in the imports of cakes, with a potential soybean cake production in Europe reaching 9.9 million tons of protein, equivalent to 21.8 million tons of soybean cakes.

Table 3. European soybean yield on “cropland surplus” required to suppress Europe’s imports of soybean cakes and imports of total cakes in 2050 in the Trend-based Diets scenario.

	Cropland surplus 2050 (*)	Soybean yield	Additional potential production of soybean 2050 (**)	Additional potential production of soybean cakes 2050 (**)	Additional potential production of soybean cakes 2050 (**)	European imports of soybean cakes 2050	Total European imports of protein cakes 2050
	1000 ha	$t.ha^{-1}$	1000 tons	1000 tons	1000 tpe (***)	1000 tpe (***)	1000 tpe (***)
Soybean yield in “2010” (average of soybean yields in regions with surplus cropland)	3488	2.3	7892	5653	2572	13 391	14 934
Soybean yield required to suppress European soybean cake imports in 2050	3488	11.8	41 086	29 431	13 391	0	1543
Soybean yield required to suppress all European imports of protein cakes in 2050	3488	13.1	45 820	32 821	14 934	0	0

[*] “Cropland surplus” in the Trend-based Diets scenario.

[**] The additional potential production of soybeans and soybean cakes adds to the projected production of soybeans and soybean cakes in the Trend-based Diets scenario in 2050. The latter production is already accounted for in the scenario’s projected imports.

[***] tpe = tons of protein equivalent.

Table 4. European soybean yield on “cropland surplus” required to suppress Europe’s imports of soybean cakes and imports of total cakes in 2050 in the Healthy Diets scenario.

	Cropland surplus 2050 (*)	Soybean yield	Additional potential production of soybean 2050 (**)	Additional potential production of soybean cakes 2050 (**)	Additional potential production of soybean cakes 2050 (**)	European imports of soybean cakes 2050	Total European imports of protein cakes 2050
	1000 ha	$t.ha^{-1}$	1000 tons	1000 tons	1000 tpe (***)	1000 tpe (***)	1000 tpe (***)
Soybean yield in “2010” (average of soybean yields in regions with surplus cropland)	10 214	2.1	21 818	15 905	7237	8790	9940
Soybean yield required to suppress European soybean cake imports in 2050	10 214	2.6	26 500	19 318	8790	0	1150
Soybean yield required to suppress all European imports of protein cakes in 2050	10 214	2.9	29 970	21 847	9940	0	0

[*] “Cropland surplus” in the Healthy Diets scenario.

[**] The additional potential production of soybeans and soybean cakes adds to the projected production of soybeans and soybean cakes in the Healthy Diets scenario in 2050. The latter production is already accounted for in the scenario’s projected imports.

[***] tpe = tons of protein equivalent.

3.5 Which self-sufficiency rate could be obtained by combining higher soybean yields with more plausible contribution of soybean areas?

Revision of yield assumptions. Previous estimations were run with the "2010" average yields in the European regions concerned by a situation of "cropland surplus" (Fig. 5). The resulting values of 2.1 t.ha^{-1} (Healthy Diets) or even 2.3 t.ha^{-1} (Trend-based Diets) are relatively low compared to 2.8 t.ha^{-1} and 3.0 t.ha^{-1} observed for the enlarged EU in "2010" and "2019" (average 2018–2020), respectively (FAOSTAT, 2022).

This is due to Germany and Poland, two countries in which soybean production is recent and which had very low yields in "2010" (1.5 t.ha^{-1}). Since that date, German yields progressed a lot to reach 2.7 t.ha^{-1} in "2019"; by contrast, yields remained stagnating around 2 t.ha^{-1} in Poland. In their three-year experiment in Northern Germany, Karges *et al.* (2022) confirmed average yields of 2.7 t.ha^{-1} for early-maturing cultivars in rainfed conditions, and 3.5 t.ha^{-1} with irrigation. Gawęda *et al.* (2020) observed yields in Poland from 2.1 to 3.3 t.ha^{-1} in conventional systems over 4 years. Moreover, the other regions with "cropland surplus" had higher soybean yields in "2010" (2.4–2.5 t.ha^{-1} for Central and Eastern Europe) and experienced slight increases over the 2010 decade to reach 2.7 t.ha^{-1} (Central Europe) and 2.9 t.ha^{-1} (Eastern Europe) in "2019". Using the "2019" yield for these "cropland surplus" regions would have resulted in an average yield of around 2.6 t.ha^{-1}, which also could have been a plausible option to test.

Yields in 2050 should likely be positively impacted by improvements in genetics and crop management, as well as by the beneficial effect of temperature rise in northern parts of Europe and increased atmospheric CO$_2$ concentration (Kothari *et al.*, 2022). However, in southern and eastern parts of Europe, heat waves, prolonged droughts and irrigation restrictions could negatively affect grain yields, in any case more than in the northern part of the continent.

Makowski *et al.* (2020) developed a statistical model to predict the effect of climate change using two different calibrations: one for C3 plants (*e.g.*, wheat, soybean) and one for C4 plants (*e.g.*, maize). These models were applied to the regions and climate scenarios in the AE2050 study. For C3 plants, they showed a possible +2% to +8% increase in yields in 2050 in the different European regions with respect to "2010" when considering beneficial CO$_2$ effects; by contrast, yields would decreased by −2% to −7% when the effect of CO$_2$ was omitted and when, in addition, there was no adaptation to these negative effects of climate change. This directly reveals the effect of reduced crop duration with increasing temperature and possible precipitation shortage. When including the effect of technological developments (genetic, agronomic and technical improvements), an increase of +27% to +47% (between "2010" and 2050) was estimated for yields depending on the importance of technological improvements and the CO$_2$ effect (INRAE, 2020; Tibi *et al.*, 2020). This would result in soybean yields in 2050 ranging from 2.5 to 3.5 t.ha^{-1} for the regions concerned by "cropland surplus".

The study of Guilpart *et al.* (2022) based on yield and climatic data resulted in yields around 2 t.ha^{-1} in 2050 with RCP 8.5 for continental Europe. However, these authors considered soybean only as a rainfed crop and did not predict how improved crop management or variety choice might impact these yields in the future (especially maturity groups). In addition, daylength, soil type and atmospheric CO$_2$ concentration were other factors not accounted for in their model that could significantly modify their yield estimates.

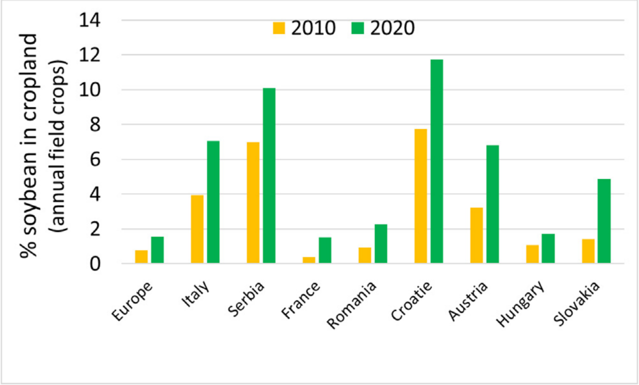

Fig. 7. Share of soybean in total harvested areas of annual field crops (%) in Europe (enlarged EU) and in the eight most important European producers. Source: FAOSTAT (2022).

In our study, in the Healthy Diets scenario, we estimated that the average soybean yield in regions concerned by a "cropland surplus" would have to reach 2.6 t.ha^{-1} to suppress European imports of soybean cakes in 2050, and 2.9 t.ha^{-1} to suppress European imports of all oilseed cakes. If a yield level of 2.6 t.ha^{-1} seems attainable even in northern European countries, 2.9 t.ha^{-1} could be difficult to secure everywhere, especially without irrigation.

Revision of potential soybean areas. Our simulation results of the Trend-based Diets scenario suggest that 8% and 13% of "2010" cropland could be available for soybean in 2050 in Poland and Eastern Europe, respectively. In the Healthy Diets scenario, 11%, 22%, 29% and 5% of total cropland could be devoted to soybean in Germany, Poland, Eastern and Central Europe, respectively (Tab. 1). Considering only land used for annual field crops (*i.e.*, total cropland minus areas devoted to fruits and vegetables, temporary meadows and other cultivated forages), these shares would be higher: 10% and 14% in Poland and East Europe in the Trend-based Diets scenario, and 15%, 28% and 33% in Germany, Poland and Eastern Europe in the Healthy Diets scenario.

In 2010 and in 2020, the average shares of soybean areas on annual field cropland were 0.8% and 1.6%, respectively, which is far from the ratios cited above (Fig. 7). In 2020, some producing countries already experienced higher proportions of their annual field cropland sown in soybean (12% in Croatia, 10% in Serbia, 7% in Italy and Austria). Therefore, we can expect that more soybean could be grown in Eastern Countries, especially in Romania (2.3% in 2020) and Hungary (1.7%), but also in Bulgaria where soybean areas increased up to 100 000 ha in the 1970s but covered less than 5000 ha in recent years (0.2%) with yields less than 2 t.ha^{-1}. In northern countries (Germany, Poland), the substitution of cropland would require a significant improvement in soybean yields as more limitations exist in terms of temperature and photoperiod. However, substantial breeding progress is going on for this part of Europe (Kurasch *et al.*, 2017; Pannecoucque *et al.*, 2018). In addition, there is a huge potential for growing more soybean in cereal-based systems and in northern regions where global warming offers new opportunities for this summer crop.

A revised calculation of the self-sufficiency rate. As a function of the elements exposed above (current soybean yields, limited areas for growing soybean), we considered an intermediate option in our analysis. We re-evaluated the impact of an additional soybean production on European oilcake imports in 2050 using, on the one hand more optimistic levels for soybean yields than "2010" levels, and on the other hand less optimistic estimates for cropland areas available for soybean production.

First, we considered soybean yields more consistent with levels observed in recent years. Instead of using "2010" yields, we used the average yield levels observed in the years 2018, 2019 and 2020 ("2019"), which correspond to the latest data available from FAOSTAT at the time of our study. Second, we limited the share of soybean in the regional cultivated areas of annual field crops estimated in 2050 to 10%, which can be considered as more plausible estimates given that these percentages were already achieved in some European regions where soybean is well introduced.

Based on these alternative assumptions, the available cropland for soybean production would be slightly reduced in the Trend-based Diets scenario, from 3.5 to 2.6 million ha, notably because of the decrease in the land share available in East Europe (from 14% to 10% of annual field crops[3]), (Tab. 5). In the Healthy Diets scenario, the available cropland would be reduced by more than half, from 10.2 to 3.3 million ha, by limiting the shares of land available to 10% in East Europe, but also in Germany and Poland[4].

The use of "2019" soybean yields in the different regions with "cropland surplus" would lead to an average yield of 2.6 $t.ha^{-1}$ in both the Trend-based and Healthy Diets scenarios. The additional soybean production would finally amount to 6.8 and 8.6 million tons of soybeans in the Trend-based Diets and Healthy Diets scenarios, respectively. This would lead to a production of 4.9 and 6.4 million tons of soybean cakes, which could substitute for approximately 2.2 and 2.9 tons of protein equivalent of European oilcake imports.

With these new estimations, Europe's total oilcake imports would still be reduced in the Healthy Diets scenario by −29% (equivalent to 2.9 million tons of proteins), compared to −73% previously with "2010" yields and no limit on soybean in crop rotations. They would not significantly change in the Trend-based Diets scenario (−15% *versus* −17% previously).

With these more plausible assumptions, the European dependency rate for oilcakes would range from 38% in the Healthy Diets scenario (15% with previous assumptions) to 46% in the Trend Diets scenario (45% with previous assumptions). Compared to the rates observed in "2010" (51%) and those of the baseline scenarios (53% and 54%), the opportunity to reduce the European reliance on oilcake imports would still be significant.

Table 5. Potential soybean production in 2050 with average soybean yields "2019" (average 2018–2020) and available areas limited to 10% of annual field crops in 2050.

		Trend-based Diets				Healthy Diets			
	Soybean yields "2019"	Cropland surplus	Additional potential production of soya (**)			Cropland surplus	Additional potential production of soya (**)		
	($t.ha^{-1}$)	(1000 ha) (*)	Beans (1000 t)	Cakes (1000 t)	Cakes (1000 tpe***)	(1000 ha) (*)	Beans (1000 t)	Cakes (1000 t)	Cakes (1000 tpe***)
Germany	2.67	0	0	0	0	873	2335	1864	848
Poland	1.98	932	1849	1460	664	755	1498	1184	539
East Europe	2.90	1715	4974	3481	1584	1309	3797	2657	1209
Central Europe	2.69	0	0	0	0	348	937	737	335
Total Europe		2647	6822	4941	2248	3285	8567	6442	2931

* "Cropland surplus" estimated by considering 10% of the areas occupied by annual field crops in 2050 in the Trend-based and Healthy Diets scenarios with trend-based yield growth.
** Additional potential production of soybeans and soybean cakes adds to the projected production of soybeans and soybean cakes in the Trend-based and Healthy Diets scenarios in 2050. The latter productions are already accounted for in each scenario's projected imports.
*** tpe = tons of protein equivalent.

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[3] Land used for additional soybean production in Poland was very slightly decreased from 946 000 ha to 932 000 ha to be limited to 10% of annual field cropland.

[4] In Central Europe, the initial surplus area was left unchanged as the share in annual field cropland did not exceed 10% (approximately 7% of cropland dedicated to annual field crops in 2050).

4 Discussion and conclusion

In this study, we evaluated the impact on European imports of oilcakes of an expansion of soybean areas on European "cropland surplus" in 2050 resulting from our estimations based on the AE2050 study (3.5 to 10.2 million ha in Europe according to assumptions on diets). We found that this expansion could substantially reduce the reliance on imports from overseas and hence increase Europe self-sufficiency in proteins used for food and feed, especially if healthier diets were adopted. Opting for healthy diets would have a double benefit in terms of protein self-sufficiency by allowing (i) the decrease in European protein demand thanks to a lower meat consumption and (ii) the freeing-up of land used for producing feed crops to grow more legumes, notably soybeans.

However, "cropland surplus" would only be available with a "trend-based" yield growth between 2010 and 2050, reflecting the continuation of historical trends, moreover taking into account the impact of CO_2, which would allow sufficient increases in all crop yields to free up some lands for other uses.

Projecting yields at 2050 is really a challenge due to numerous uncertainties about GHG emission scenarios, accuracy of climatic models, future technological developments (breeding, crop management), socio-economic conditions (prices), and European agricultural policy. However, the trend-based yields we used in this study are plausible. Across all crops, the range of yield projections selected for this study is equivalent to an annual rate of change in average crop yield of +0.6% ("moderate yields") to +1.0% ("high or trend-based yields") globally and of +0.4% to +0.9% respectively in Europe. This range of values is consistent with the rates found in the literature by Le Mouël and Forslund (2017), which range from +0.8% to +1.0% per year globally. Note that the majority of foresight studies reviewed by the authors does not incorporate the effects of climate change on yields.

The obstacles to a higher self-sufficiency rate of proteins in Europe based on domestic soybean development will probably be due to attainable yields but also to constraints on areas that could be sown with this oil-protein crop. This is because other factors could limit soybean land expansion: soil and climate restrictions, access to irrigation, and the competitiveness of the crop (compared to well established crops).

The extension of soybean in northern Europe would probably not require the development of irrigation although some extra-yields were observed with irrigation in northern Germany (Karges *et al.*, 2022); but it would absolutely do so in south-eastern countries (*e.g.*, Romania or Bulgaria) where, in spite of often deep soils, supplemental irrigation will be required to sustain production. Increasing irrigated areas in southern and eastern parts of Europe could have negative impacts on water resources in a context of water scarcity and conflicts of use reinforced by climate change (Garrote *et al.*, 2015; Rojas *et al.*, 2019). This was also a reason for excluding Southern Europe from croplands where soybean could expand in the future. In the same time, irrigation requirements could increase with climate change (higher evaporative demand, less precipitation, late-maturing cultivars) in the regions were irrigation is already applied in soybean. However, possibilities to grow soybean with deficit-irrigation programs (instead of full-irrigation programs) have been demonstrated (Torrion *et al.*, 2014) and should be disseminated to reduce the irrigation requirements.

Although this was not tested here, introducing soybean as a double crop is also an option to increase soybean area and production in Europe (Seifert and Lobell, 2015). This could be modelled within the framework used in this paper by increasing the cropping intensity coefficients. Large uncertainties surround possible evolution of these coefficients in the future, in Europe as in other parts of the world (IIzumi and Ramankutty, 2015). Furthermore, due to the late sowing of soybean in double cropping systems, supplemental irrigation would be required absolutely; this will increase the issue related to water access outlined in the previous paragraph.

The analysis framework of the paper based on the use of the global biomass model GlobAgri deserves attention, notably because the model does not explicitly include prices, and actors' and markets' reactions to price changes. Even if the way international trade is modelled seeks to mimic how imported and exported volumes would react to implicit price changes, the structure of the trade module of the model is rigid, projects the future of trade essentially on the basis of past trends in imports and exports, and thus does not capture the possibility that European soybean imports could react differently. In the same way, estimating a soybean production potential in Europe does not mean that European producers will fully exploit this possibility: they could prefer other crops or simply choose not to cultivate some "cropland surplus" areas that would be insufficiently profitable. In addition, as pointed out by Meynard *et al.* (2013), the development of soybean in Europe could be hindered by socio-technical lock-ins along the value chains that tend to favour dominant crops of the continent.

The agronomic and environmental impacts of inserting more soybean into European crop rotations have not been evaluated specifically in this study. Numerous reports have concluded to potential benefits of introducing legumes (including soybean) in cereal-based cropping systems (Peoples *et al.*, 2009; Voisin *et al.*, 2014; Schneider and Huyghe, 2015; Zander *et al.*, 2016; Guinet *et al.*, 2020; Ditzler *et al.*, 2021). Producing more non-GM soybean in Europe would thus reduce the use of nitrogen (N) fertilizers and greenhouse gas (GHG) emissions (Guilpart *et al.*, 2022), as the recommendation is to avoid N applications on soybean and optimize the N fixation capacities of the crop through inoculation. In spite of lower amounts of residual soil N following soybean as compared to pea or fababean, this could be mentioned as a favourable effect for the N economy of the rotation (Debaeke *et al.*, 1996; Guinet *et al.*, 2020). Including more soybean in the rotation could also reduce the use of pesticides, as this legume crop requires few chemical treatments: its Treatment Frequency Index (TFI) is equal to 1.8 in France, which is the lowest value among the different field crops (Agreste, 2019). In addition, introducing a break summer crop is an efficient lever for controlling pests, weeds and diseases in winter-based cropping systems.

Developing the protein self-sufficiency of Europe by growing more soybean and reducing the import dependency could limit the climate and environmental impacts of transport by ships and of soybean-planted areas in the USA and South America. The concerns raised by this intercontinental market and the impact on sustainability in the producing countries have been discussed in several papers (Fearnside, 2001; Boerema *et al.*, 2016; Salembier *et al.*, 2016). In non-European countries, soybean cultivation is often associated with GM-monocultures and the intensive use of glyphosate, and in Brazil to grassland and forest destruction. The positive consequences of a more local soybean production in Europe would be strengthened if other major importers of soybean cakes and notably China adopted the same policy. However, contrary to some European regions, China would be, according to our simulations, constrained by its maximum cultivable area in 2050.

As soybean accounts for more than 80% of European oilseed cake imports in "2010" (and 88% in protein equivalent), this specific crop was used here as the most representative example of local development of protein-rich crops. However, the development of a combination of oil-protein or grain legumes would likely be a more plausible and interesting option that we could have explored too, in relation with more diversified cropping systems in Europe (including various proportions of oilseed-rape, sunflower or field peas, depending on growing environments).

For expanding soybean production in Europe, outlets, markets and value chains will have to be developed and secured in new producing areas, and intra-European trade must be promoted from new soybean producing regions to regions with no available cropland for additional soybean production.

Finally, it will be interesting to complete the analysis by considering how our results could be modified by the European Green Deal (European Commission, 2019). The latter could substantially affect European agriculture and food systems. Its objectives are materialized into quantitative targets related to climate, environment and health issues for agriculture, with substantial reductions in the use of pesticides, fertilizers and antibiotics, and large increases in agricultural land under organic farming, high-diversity landscape features and protected land areas. Objectives go far beyond the farm gate by adopting a whole food chain approach, generalizing the application of circular bio-economy principles, reducing food waste and losses, and encouraging a shift towards healthy and environmentally friendly food diets though without setting quantitative targets. This could substantially affect European consumption, production and trade.

Supplementary Material

Table SI-1. Yields (t.ha^{-1}) in 2010 and 2050 (RCP 6.0) for three major field crops (wheat, grain maize and oilseed rape) in Europe (enlarged EU) and the eight sub-regions according to "moderate" and "high" yield increase assumptions.
Figure SI-1. Composition, population (millions) and farmland (million hectares) of the eight European regions in "2010".

The Supplementary Material is available at http://www.ocl-journal.org/10.1051/ocl/2022031/olm.

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Declaration of interests

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.

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