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Legume-based pathways reveal opportunities and limits of protein self-sufficiency in the EU and UK

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The European Union and United Kingdom (EU+) remain heavily dependent on imported high-protein feed, primarily soybeans, raising concerns about supply resilience and environmental impacts. We assess three legume-based pathways—trade, policy support, and dietary shift—against a 2030 projection horizon, using integrated regional agro-economic, farm-level, and life cycle assessment models. The trade pathway, simulating a complete interruption of protein imports, provides an analytical upper bound for domestic EU+ legume production. It drives substantial land reallocation (+1.5 million ha legume area) but fails to fully replace imports, resulting in higher prices (+150% for soybeans) and reduced livestock output (-3%), exposing systemic vulnerabilities. Farm-level results underscore economic incentives over agroecological potential. Policy support moderately increases legume cultivation with limited market impacts but improves farm-level viability where conditions are favourable. Dietary shifts increase pulse imports (+100%) but reduce global GHG emissions more effectively than supply-side measures. Overall, the results highlight legumes' potential, limits of self-sufficiency, and the complementary roles of economic incentives and demand-side measures for sustainable and resilient EU+ food systems.

Mounting concerns over greenhouse gas (GHG) emissions, environmental degradation, and human nutrition bring the transition towards more sustainable food systems increasingly into focus[1–4]. In the European Union (EU) and United Kingdom (UK) (hereafter EU+), aligning agriculture with climate and sustainability objectives, and the broader ambition to build resilient food systems, is a central feature of policy frameworks such as the European Green Deal[5], the EU's Vision for Agriculture and Food[6], and the UK Environment Bill[7].

A critical component of this food system transformation involves reducing the EU+'s strategic dependence on imported high-protein sources, particularly soybeans and meals used in livestock production[6,8]. While the EU+ maintains a high overall self-sufficiency in feed protein—driven largely by roughage (grass, silage maize, and forage legumes), which accounts, for example, for 41% of the total EU protein balance[9]—this aggregate figure obscures a critical structural deficit in concentrated high-protein sources. Roughage is predominantly domestically produced and nearly 100% self-sufficient, but it is high in fiber and suited primarily to ruminants; it cannot serve as a primary protein substitute for monogastric livestock. Ruminant sectors do utilize protein meals, particularly in high-yield dairy and beef systems, but their reliance is comparatively limited because forage-based diets can meet a substantial share of their nutritional requirements. By contrast, monogastric sectors depend heavily on externally sourced concentrated high-protein feeds: poultry and pigs alone consume approximately 67% of all high-protein feed used in the EU, reflecting their more demanding amino-acid profiles and higher requirements for digestible protein. As a result, the EU imports approximately 95% of its soybeans and meals (around 14 and 16 million tonnes annually[9]), while the UK imports ~3 million tonnes of soybean derivatives[10]. This structural

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dependency exposes EU+ producers and consumers to risks from global price volatility and supply chain disruptions. Agri-food supply chain vulnerabilities were highlighted during recent global events, including the COVID-19 pandemic[11–13] and the war in Ukraine[14,15]. Furthermore, escalating geopolitical tensions, including US tariff measures and potential retaliatory trade actions[16], threaten to fragment international trade, raising costs, and reinforce concerns about the resilience of global supply chains. High import concentration exacerbates this vulnerability: 50% of EU soybean imports originate from Brazil and 35% from the US, while soybean meal primarily originates from Brazil (46%) and Argentina (39%)[17]. The UK holds a similar pattern, sourcing soya primarily from Argentina (38%), Brazil (31%), and the US (11%)[10].

Calls to reduce reliance on protein feed imports are also driven by environmental considerations. Soybean production in South America is closely associated with agricultural expansion and deforestation in ecologically sensitive regions, including the Amazon, Cerrado (Brazil), and Gran Chaco (Argentina)[18–21]. Responding to deforestation concerns, the EU deforestation-free regulation[22] and the UK Environment Act[7] set out legislative frameworks which require verification of deforestation-free supply chains for imports of key commodities (including soy)[23]. While these legislations aim to reduce the environmental footprint of imports and incentivise sustainable practices in exporting countries, they will also introduce additional uncertainty into global supply chains.

Increasing EU+ domestic protein production, however, extends beyond mitigating import-dependency. Enhanced integration of legume crops, including soybeans and pulses such as peas, beans, and lupins, into crop rotations is widely recognized as a key strategy for sustainable agriculture[24,25]. Legumes contribute to biological nitrogen fixation and improved soil health, thereby enhancing productivity of subsequent crops[25–27]. In addition, their cultivation offers potential environmental benefits, such as reduced GHG emissions due to lower fertilization requirements[28–30].

Beyond their agronomic benefits and use in animal feed, legumes also hold substantial nutritional value and offer a sustainable alternative to animal-based proteins in human diets[31–33]. Pulses are rich in fiber, low in glycaemic index, and associated with numerous health benefits, including improved cardiovascular health, diabetes management, and reduced obesity-related risks[32–34]. Thus, shifting dietary patterns towards greater consumption of plant-based proteins could improve public health and mitigate environmental impacts associated with livestock production, while reinforcing the agronomic benefits of legume integration into farming systems[33,35,36].

Against this background, we assess three forward-looking legume-based pathways for EU+ agriculture with a projection horizon of 2030. The pathways are designed as a complementary set, spanning the spectrum from a theoretical upper-bound stress test to empirically and institutionally grounded near-term scenarios, thereby jointly covering the main mechanisms through which legume production and consumption in the EU+ could be expanded or restructured. The three pathways are: (1) a trade pathway, simulating a complete interruption of soybean and soya meal imports into the EU+ (modeled as import restriction), aimed at establishing the theoretical upper bound for import substitution capacity and enhanced resilience in the face of trade disruptions; (2) a policy support pathway, where all EU+ countries allocate 2% of their direct payments to protein crop cultivation to enhance competitiveness and stimulate domestic production, representing a feasible incremental adjustment within the existing agricultural policy framework; and (3) a consumer dietary shift pathway, modeling an 11% reduction in EU+ meat-protein consumption replaced by plant-based alternatives, grounded in EU+ consumer preference surveys and reflecting a short-term demand-side signal of realistic magnitude for voluntary dietary substitution, consistent with broader public health and sustainability objectives.

For the assessment, we apply a top-down analytical framework integrating sectoral agro-economic modeling, farm-level analysis, and life cycle assessment (LCA) to generate a comprehensive understanding of the potential economic, agronomic, and environmental effects of the pathways. All three pathways are assessed using the CAPRI model, which simulates agricultural production and market effects across EU+ regions (Nomenclature of territorial units for statistics, NUTS 2) and globally. This is complemented by the EFEM model, which provides a detailed farm-level case study for Germany, illustrating how sector-level impacts translate into farm-level outcomes, and identifying the specific opportunities and challenges farmers may face under each pathway. We selected Germany for its diversity in farming systems and agro-climatic conditions, which are broadly representative for the EU+. The analytical framework is further complemented by an attributional LCA, which is conducted exclusively for the trade pathway, comparing the environmental burdens of soybeans production in Germany and Brazil. This focus is analytically justified because a comparison of domestic versus imported soy production is most meaningful under the scenario where large-scale domestic substitution of soy imports is explicitly induced, and the environmental competitiveness of domestically produced soy is therefore directly policy relevant.

Results

Land use and production

Across all three pathways, agricultural land allocated to legumes increases in specific EU+ regions, though the extent and type of legume cultivation vary. In the policy support and consumer dietary shift pathways, some countries reallocate land between soybean and pulse crops in response to changes in relative profitability. For example, France reduces its soybean area by 2% while increasing pulses by 14%, reflecting changing economic incentives for crop producers. In contrast, under the trade pathway, Poland expands soybean (+50,000 ha) and rapeseed (+92,000 ha) areas, primarily for feed, while reducing pulses by 11,000 ha. A particularly notable shift occurs in the trade pathway, where 7.4% (0.7 million ha) of fallow land is brought back into agricultural use, facilitating a 2.4 million ha increase in legume area, compared to 0.9 million ha in the baseline. Countries such as Lithuania, UK, and France exceed domestic pulses demand under the consumer pathway (Fig. 1), indicating export-oriented production to meet EU demand.

Among the three pathways, the trade pathway shows the most substantial changes in land use and legume expansion. However, the overall EU + growth in legume production remains modest due to existing constraints such as lower commercial competitiveness and coupled support ceilings. Soybeans represent a partial exception in the trade pathway, as legume area expands for domestic feed in response to the zero soy imports, slightly displacing cereals, vegetables, and permanent crops. Additionally, total utilized agricultural area increases slightly across the EU+, with France, Italy, and Romania showing the greatest potential for significant soybean expansion (Fig. 1, see also Table SI1 and Fig. SI1).

Trade and prices

The trade pathway results in a substantial surge in the EU+ soybean price (up by 150%). This translates directly into a significant increase in feed costs, leading to a 50% reduction in soybean feed use, constrained livestock production (down by 2–3%), and increased EU+ meat imports between +4% (beef) and +31% (poultry). Despite the legumes production increases in France, Italy, and Romania, EU+ legume supply remains insufficient, resulting in a deteriorated pulses trade balance, with a substantial increase in imports (Fig. 2). This reflects challenges in securing alternative protein feed sources to satisfy domestic demand. While EU+ feed costs rise, global soybean prices increase only by 2%. This moderate price increase can be attributed to limited global market disruption: EU-bound soybean exports represent only 15% of the volumes exported to China, whose imports remain relatively unaffected. Consequently, Brazilian agricultural land contracts rather moderately (−0.14%, 0.4 million ha), with partial reforestation.

By contrast, the policy pathway leads to an improved EU+ trade balance for pulses. EU+ pulses exports increase by 0.1 million tonnes (+42.5%), mainly directed to Mediterranean countries (Tunisia, Algeria, Egypt, Israel) and India. Lower pulses prices and improved production

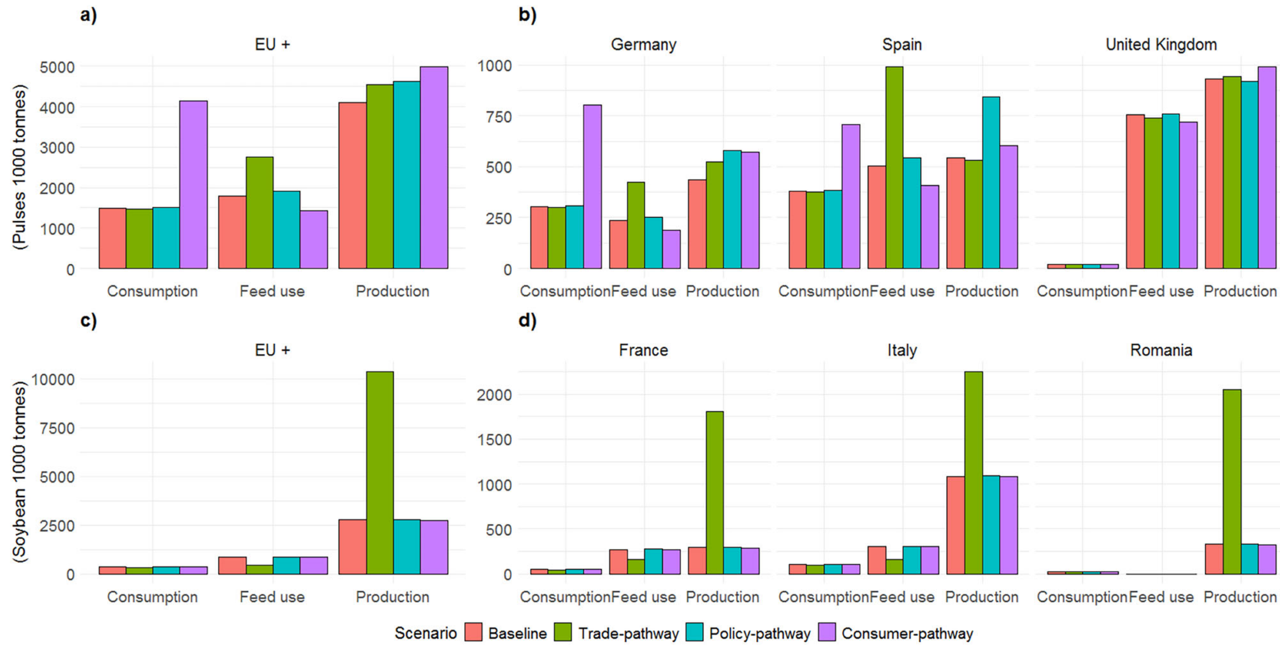

Fig. 1 | Total production, human consumption and feed use (in 1000 tonnes) of pulses (top) and soybeans (bottom). Panels show data for the EU+ (**a**, **c**) and respective top producers (**b**, **d**) in 2030 across four scenarios: baseline (business-as-usual), trade pathway (no imports), policy pathway (protein crop subsidy), and consumer pathway (dietary shifts).

efficiency make EU+ exports more competitive (≈50% of Indian prices), leading to reduced production and trade in some major global producing and exporting countries (such as India). Increased production in Spain and Germany and reduced imports result in a 7% decline in domestic pulses producer prices. Nonetheless, these changes have only a minimal impact on global prices (less than −1%) due to the relatively small share of pulses in global agricultural trade compared to other agricultural products. Importantly, lower EU+ pulses prices incentivise substitution of cereals and oilseed cakes in feed rations, while livestock production remains stable, indicating improved resilience of livestock production under the policy pathway.

The consumer pathway triggers complex trade outcomes: pulses imports into the EU+ more than double, particularly from North America and Argentina, as EU+ demand for plant-based protein increases and non-EU producers prioritize pulses for human consumption. Reduced EU+ meat consumption improves the region's trade balance, while dairy consumption increases due to favorable protein-price ratios. This trend, alongside relatively higher producer margins in the dairy sector, leads to EU + dairy herd expansion. EU+ producer prices for pulses increase by 13%, driven by higher demand and increased input costs from intensified production, whereas soybean prices decrease slightly with reduced feed demand.

GHG emissions

While the modest overall production changes under the policy pathway cause minimal changes in EU+ agriculture GHG emissions, the consumer and trade pathways result in relatively higher reductions. The extent of these reductions primarily reflects changes in livestock production. At the EU+ level, the trade pathway generates a proportionally larger agricultural emission reduction (−2.9%) than the consumer pathway (−1.4%), despite the latter generating larger declines in meat output. This is explained by differences in emission mechanisms: the trade pathway's sharp rise in high-protein feed costs creates strong incentives for the adoption of efficiency-enhancing feeding practices, including feed additives, aimed at optimizing feed rations and improving feed conversion efficiency[37]. These optimized rations reduce crude protein intake and, consequently, methane emissions from ruminants and nitrous oxide emissions related to manure management. However, this EU+ level comparison captures only a partial picture. When global net mitigation is considered, the picture reverses: the trade pathway's domestic emission savings are largely offset by leakage, with about 72% of EU+ emission savings being offset by increases in emissions in non-EU+ countries (+7.6 million tonnes CO_2e), effectively diminishing the EU+ net mitigation to −0.8%. This emission leakage is mainly due to lower EU+ exports, which are replaced by more emission-intensive production in other world regions. By contrast, the consumer pathway leads to net mitigation beyond the EU+: reduced EU+ meat demand leads to global production decreases due to decreased meat imports and increased exports of meat and cereals from the EU+ (Fig. 3), generating a global net reduction in agriculture GHG emission of 18.8 million tonnes CO_2e (compared to 2.9 million tonnes CO_2e in the trade pathway), equivalent to an EU+ net mitigation of –5.2% (Fig. 3).

Germany—a case study

To assess the pathways' farm-level impacts, it is essential to account for heterogeneity across regions and farm types. Legume cultivation depends on agronomic suitability (climate and soil conditions) and relative competitiveness with alternative crops in arable systems or alternative feedstuffs in livestock farms. The representative farm model EFEM was employed, reflecting typical farming systems and biophysical conditions across Germany. The analysis focuses specifically on arable and pig fattening farms (Table SI2). While poultry and ruminant sectors are significant protein consumers, pig fattening represents the most analytically sensitive intersection for this study. Unlike ruminants, which can leverage forage-based legumes, pigs are strictly dependent on high-density protein concentrates, placing pig production at the center of the competition between domestic grain legumes and imported soy. Furthermore, the prevalence of integrated arable-and-pig systems in Germany allows for an assessment of internal shadow prices and nutrient-cycling trade-offs, dynamics that are often absent in the highly specialized and vertically integrated poultry sector. Consequently, these farm types are the most sensitive to the structural and price changes induced by the pathways, serving as a high-resolution proxy for the broader challenges of an EU+ protein transition. Five regions were selected to capture the diversity of growing conditions relevant to legume cultivation (Table SI2 and Fig. SI2). Southern, western, and central Germany

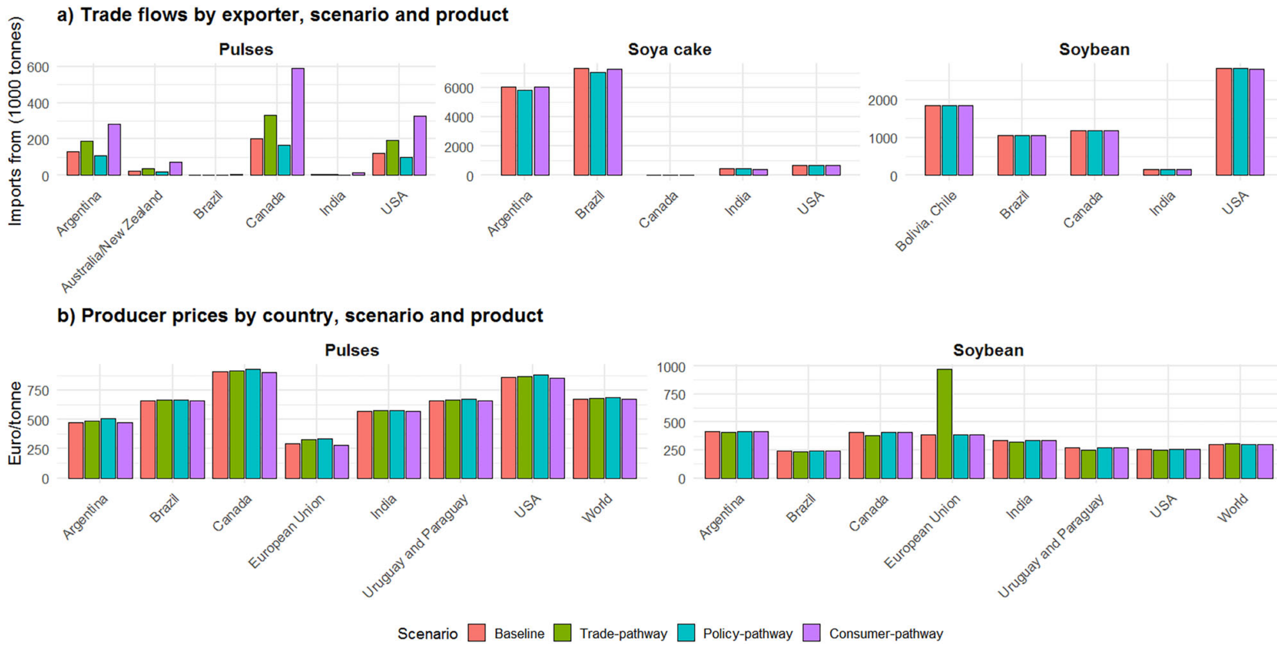

Fig. 2 | Soy product and pulse trade flows and producer prices. Import flows (in 1000 tonnes) of soy products and pulses into the EU+ from major producing and exporting regions (**a**) and corresponding producer prices (in Euro/tonne) per country or country block (**b**) in 2030 across four scenarios: baseline (business-as-usual), trade pathway (no imports), policy pathway (protein crop subsidy), and consumer pathway (dietary shifts).

offer favorable conditions for various crops, including soybeans. Conversely, northern and eastern regions face climatic and edaphic constraints, limiting soybean suitability but allowing beans and peas cultivation. Particularly in the east, sandy soils and dry weather conditions reduce yield potential and favor extensive cultivation systems. In pig fattening farms, livestock density varies substantially by region, from <1 in the east to 2.5 livestock units/hectare in the north, shaping the regional economic importance of pig farming. Figure 4 shows the crop rotations and gross margins under the baseline and the pathways, reflecting pathway-specific price dynamics.

The relative competitiveness of legumes and competing crops is influenced differently by the three pathways, in line with their different effects on agricultural product prices. The trade pathway induces the strongest price increases, particularly for oilseeds and legumes, making soybean cultivation highly profitable where agronomically viable and constrained only by rotation limits. In less suitable regions, pulses become marginally more attractive, especially in eastern pig farms. Gross margins on arable farms with substantial soybean areas increase markedly (40–100%). However, pig farming, particularly in the north with high livestock density and no on-farm soybean viability, faces rising feed costs. Gross margins on these farms decline significantly (−40%), whereas southern and western pig farms are able to partially offset feed cost increases through higher arable production returns.

The consumer pathway yields negligible arable price changes, resulting in limited changes in crop allocation and farm-level margins. Only the northern arable farm responds to an 11% increase in field bean prices by integrating beans into the rotation at a small scale. However, lower pork prices reduce gross margins in pig farms by 12–15%, highlighting a weak transmission of changing consumer preferences to farm-level incentives. Although demand-side shifts reduce animal product prices, they do not generate market signals strong enough to alter crop choices. Therefore, arable farmers receive little economic motivation to adjust cultivation patterns, despite evolving downstream demand structures.

The policy support pathway generates the smallest market price changes but includes a €110/ha area payment for legume cultivation in Germany. This support renders legume cultivation economically viable across most farms. Arable farms with suitable soybean conditions expand soybean areas up to rotational thresholds, while pig farms universally adopt field beans or peas within rotational constraints. Given the relatively narrow profit margins under this policy-driven incentive, overall farm contribution margins remain largely unchanged. This outcome illustrates that modest policy incentives can achieve legume uptake without substantial income effects, provided that agronomic conditions are favorable.

Farm-level GHG emission reductions, including agricultural production and upstream sectors (production of mineral fertilizers, plant protection products, seeds, and purchased feed) are largest under the trade pathway: up to −22% in arable and −17% in pig farms (Table 1). These reductions are directly related to the increased legume cultivation, which lowers synthetic nitrogen fertilizer requirements and reduces feed purchases. Notably, where pig farms such as in the west shift from feed to cash crops cultivation, due to price incentives, external feed purchases rise, leading to emission increases of around 17%. The policy pathway also leads to a reduction in GHG emissions, particularly in central arable farms (up to −17%), through increased legume cultivation. In contrast, the consumer pathway has little impact on farm-level emissions due to unchanged cropping patterns.

Environmental impacts of import substitution: a comparative LCA of soybean production in Germany and Brazil

The Germany-focused analysis is further extended through an attributional LCA comparing the environmental burdens of soybean production in Germany and Brazil. This analysis is conducted exclusively for the trade pathway, as the environmental competitiveness of domestically produced soy relative to Brazilian imports is most analytically relevant under the scenario in which large-scale import substitution is explicitly induced. This LCA component directly enriches the trade pathway analysis by providing an evidence base for evaluating whether import substitution achieves net environmental benefits across the full supply chain, including land use change emissions associated with soy expansion in Brazil.

The attributional LCA shows that environmental burdens associated with imported Brazilian soybeans are two to three times higher than those of domestically produced German soybeans across key impact categories, including acidification, climate change, marine eutrophication, and fossil fuels resource use (Table 2; full results in Tables SI5 and SI6). Land use burdens are more comparable across the two systems, though they remain

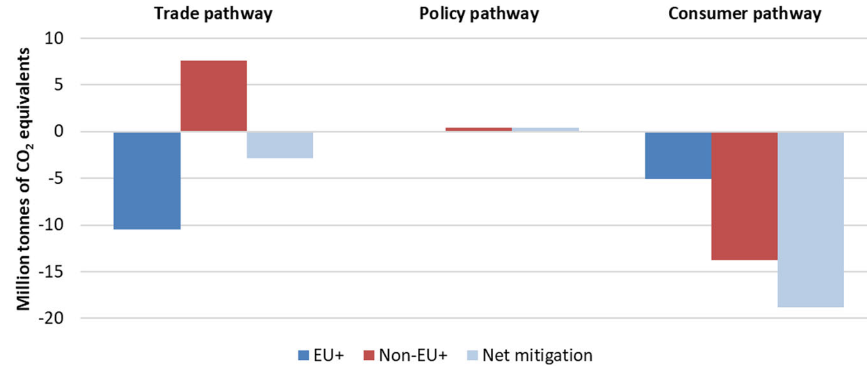

Fig. 3 | Changes in agricultural GHG emissions in the pathways compared to the baseline. Emissions are derived from the CAPRI model and aligned with the UNFCCC Common Reporting Format (CRF) "Agriculture" sector. This scope primarily encompasses non-CO_2 emissions, specifically nitrous oxide (N_2O) from managed soils and manure management, and methane (CH_4) from enteric fermentation and manure management.

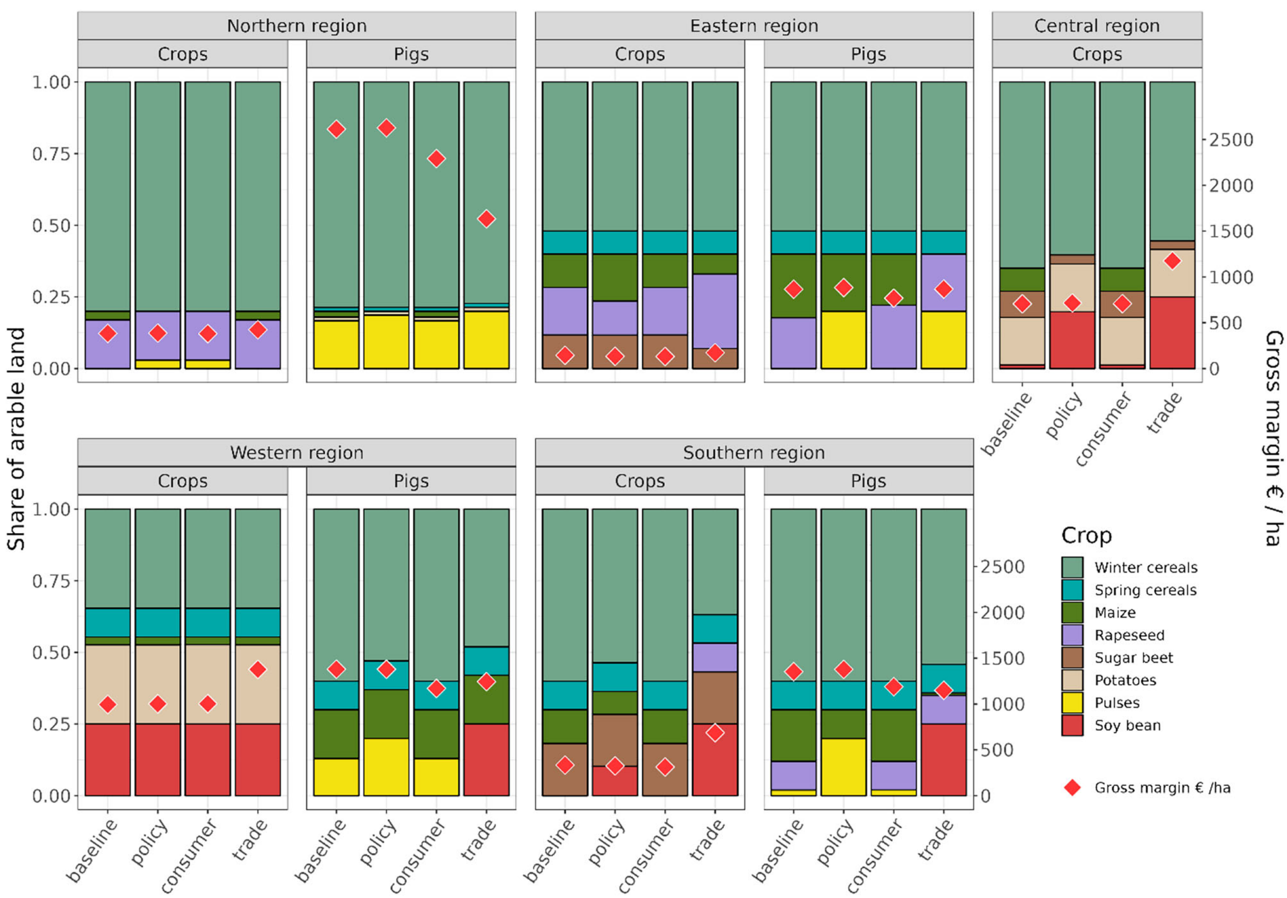

Fig. 4 | Crop rotations and gross margins of arable farms and pig farms in Germany in the baseline and for different pathways (see Table SI2 for the description of the selected farms). Pig farming is a marginal activity in the Central Region; therefore, representative FADN data on pig farms is unavailable for this region.

still higher for Brazil. The only category in which German soybean production performs worse is water scarcity, reflecting the specific irrigation requirements or regional hydrological stress associated with the domestic production context.

The comparatively higher environmental burden across most categories in Brazil is mainly due to land use change, including clear cutting of primary forests for arable expansion. For instance, in Mato Grosso, which produces 30% of Brazil's soybeans, land use change contributes 39% of the climate change burden, with 73% of that fraction attributable to forest conversion. Soybeans from other Brazilian regions exhibit similar trends, though with a lesser extent of land use change. Overall, the production of one tonne of Brazilian soybean entails 1088 kg CO_2e due to soil and biomass carbon stock changes alone. It should be noted that additional emissions from overseas transport and storage of imported soybeans are not included within the LCA system boundary applied here; their inclusion would further amplify Brazil's comparative environmental footprint.

Discussion

The EU+ aims to align agriculture with climate and sustainability objectives while enhancing the resilience and sustainability of food systems. In this context, legumes represent a promising lever for achieving environmental and agronomic goals. However, the current share of land allocated to legume cultivation remains limited across the EU+, while the region remains highly dependent on imported soybean-based high-protein feed, making it vulnerable to global supply disruptions. We simulate three stylized pathways (trade, policy support, and consumer dietary shift) to assess their implications for EU+ legume production, sectoral restructuring, and environmental outcomes.

Table 1 | GHG emissions of arable and pig farms in Germany and changes compared to the baseline.

	Crop farms					Pig farms			
	Norh	East	South	West	Central	North	East	South	West
Baseline (kg CO_2eg/ha)	4137	3110	3855	2877	4215	12,419	4015	7953	5609
Policy pathway (% change)	−0.2	1.7	−5.4	0.0	−17.2	0.2	−9.9	−6.3	−1.1
Consumer pathway (% change)	−0.2	0.0	0.0	0.0	0.0	0.0	−1.7	0.0	0.0
Trade pathway (% change)	0.0	−1.2	−20.6	0.0	−22.0	−0.4	−6.1	−17.3	17.0

Pig farming is a marginal activity in the Central Region; therefore, representative FADN data on pig farms is unavailable for this region. Emissions are modeled using EFEM and comprise both agricultural non-CO_2 emissions and upstream process-related emissions. Agriculture emissions include direct N_2O emissions from managed soils and manure management, and indirect N_2O emissions from leaching, runoff, and atmospheric nitrogen deposition. Upstream emissions include those from the production of mineral fertilizers, plant protection products, seeds, and purchased feed.

Table 2 | Selected environmental burdens associated with the production of one tonne of soybeans in Germany and Brazil (see Tables SI4 and SI5 for the full results).

Parameters	Germany	Brazil
Acidification (mol H^+_{eq})	1.3	3.6
Climate Change (kg CO_2e)	497	1600
Eutrophication, marine (kg N_{eq})	5.8	10
Land use (point)	87,917	95,600
Resource use, fossils (MJ)	1602	3110
Water scarcity (m^3 depriv.)	568	127

The trade pathway, simulating a complete disruption of EU+ soybean imports, produces the most far-reaching systemic adjustments. This pathway shows a significant land use reallocation within the EU+, primarily from cereals and other crops towards domestic legume production, to compensate for lost imports. However, domestic soybean production remains insufficient to fully replace imported soybeans, leading to substantial declines in EU+ livestock production and price increases for soybeans, pulses, cereals, and meat. These results highlight the EU+'s structural dependence on external protein sources and the vulnerability of its livestock sector to trade disruptions—a concern particularly pertinent in light of recent geopolitical and economic instabilities. This pathway serves as a critical analytical stress test, revealing the upper bounds of EU+ legume production capacity and highlighting main vulnerabilities within the current EU+ agri-food system related to high-protein import dependency.

At the regional level, results from the German case study illustrate the limitations of interpreting sectoral model outcomes in isolation. Despite favorable agroecological conditions in regions like southern Germany, factors such as crop profitability, market access, and socio-technical path dependencies strongly influence farm-level decisions. Farm-level modeling results consistently confirm that legume uptake depends on market conditions that make cultivation financially competitive with alternative crops. This has concrete relevance beyond what the gross-margin optimization framework alone implies: the agroecological benefits of legumes are insufficient on their own to drive adoption without corresponding economic returns. Both CAPRI and EFEM account for biological nitrogen fixation by reducing mineral fertilizer requirements and incorporating the pre-crop yield benefits for subsequent crops. These modeled agronomic benefits contribute to the emission reductions of up to −22% in arable farms under the trade pathway, yet they do not independently close the gross-margin gap with competing crops across many regions and rotations. Legume cultivation therefore increases substantially only when market signals (higher prices under the trade pathway) or targeted subsidies (policy support pathway) sufficiently improve gross margins relative to competing crops. By contrast, the consumer pathway yields only modest legume expansion, mainly pulses in regions such as northern Germany. It has to be noted that additional agronomic benefits of legumes, including phytosanitary effects, improved soil conditions, and nutrient mobilization, as well as the broader ecosystem services they provide, are not incorporated by default. These effects are highly context-dependent, varying across crop rotations, locations, and growing seasons, which constrains their systematic integration into farm-level modeling. Their inclusion, where empirically traceable, would likely improve the modeled competitiveness in individual cases.

The trade pathway also demonstrates the highest agricultural GHG mitigation potential at the EU+ level, primarily through production decreases. However, the increase in the costs of high-protein feed also incentivises more efficient feeding practices, including feed additives and feed ration optimization, lowering emissions from enteric fermentation and manure management. The contraction in EU+ cereals and meat production leads to substantial emission leakage, with 72% of the mitigated agriculture GHG emissions offset by emission increases outside the EU+. Conversely, the reduced EU+ meat consumption under the consumer pathway also leads to production decreases in non-EU+ regions, substantially adding to global GHG reductions. The LCA showcases that the environmental burden per tonne of soybean production is considerably lower (by a factor of two to three across key impact categories) within the EU+ compared to Brazil. This finding reinforces the environmental case for import substitution under conditions of large-scale domestic expansion.

The integrated sectoral and farm-level analysis also highlights significant distributional consequences. Under the trade pathway, arable farms benefit from higher soybean prices, substantially increasing gross margins, whereas livestock farms, such as pig farms, face economic losses across the scenarios due to rising feed costs and lower producer prices. This divergence underscores that transitions towards more sustainable and resilient food systems, while broadly desirable, may entail significant socio-economic trade-offs across farm types and regions.

Our analysis reveals the significant potential, yet practical limitations, of expanding domestic legume production within the EU+. The trade pathway effectively illustrates the extent of EU+ protein dependency and the substantial structural adjustments required to approach higher self-sufficiency, alongside environmental gains (GHG emissions) and rather unintended economic consequences (livestock contraction). The regional analysis highlights the critical role of economic incentives and local context in realizing aggregate potential. Our results complement biophysical assessments (e.g., ref. 38) by integrating economic drivers and market dynamics, offering a more comprehensive understanding of the EU+'s potential to transition towards greater protein self-sufficiency. The results regarding the impact of trade interruptions align with studies assessing broader disruptions within the EU+ agri-food chain[39,40]. Furthermore, the LCA comparing environmental burdens of soybean production in the EU+ and Brazil underscores the need for enhanced international coordination to foster globally sustainable food supply chains[20].

The robustness of results should be interpreted in the context of three principal sources of model uncertainty. First, escalating geopolitical tensions and retaliatory trade measures could further destabilize global soy supply chains and amplify price volatility, altering the baseline conditions against which the trade pathway is assessed, potentially bringing realistic scenarios closer to the upper-bound stress test than the current baseline implies. Second, macroeconomic shocks, including oil price increases and transport cost volatility, affect the relative competitiveness of domestic versus imported protein crops. Higher transport costs would tend to favor domestic supply-side measures and strengthen the case for domestic production and demand-side strategies. Third, climate-related uncertainty, particularly the increasing frequency of extreme weather events, could affect both domestic and non-EU+ legume production in ways that are not well-captured by the trend-based yield projections used in the 2030 baseline. Directionally, none of these uncertainties reverses the principal conclusions of the analysis: in each case they would tend to reinforce rather than contradict the finding that domestic substitution capacity is structurally limited and that demand-side measures achieve more robust and geographically broader emission reductions than supply-side interventions alone.

Specific policy implications emerge from the pathway analysis. The policy pathway shows that coupled support improves the competitiveness of legume production, but its impact on overall EU+ protein self-sufficiency remains limited. The trade pathway illustrates that sole reliance on domestically produced legumes would substantially impact EU+ livestock production, particularly pork and poultry. However, this pathway also reveals significant potential for reducing protein needs in animal feed by improving feed rations and feed conversion efficiency in the EU+, but realizing this potential requires economic or regulatory incentives. The trade pathway's analytical value extends beyond the specific case of total import interruption, because any realistic partial restriction, whether arising from geopolitical trade disruptions, the EU Deforestation Regulation, or voluntary sourcing constraints, generates impacts that fall proportionally between the baseline and trade pathway results, scaled approximately to the share of imports effectively curtailed. The trade pathway therefore defines the outer bound against which more granular, policy-specific assessments can be interpreted, without requiring additional scenario runs.

Consistent with other studies[2,35,41], the consumer pathway further demonstrates that demand-side changes, particularly shifts in dietary patterns, can effectively complement supply-side adjustments, with positive effects on global sustainability by influencing production patterns within and beyond the EU+. Importantly, the 11% meat-protein reduction modeled in the consumer pathway sits substantially below the reductions recommended under current normative dietary frameworks, such as the EAT-Lancet 2.0 Commission. As demonstrated by various studies, dietary shifts of the EAT-Lancet scale[42,43] would generate substantially larger reductions in land-use pressures, livestock output, and agricultural GHG emissions than those observed in our consumer pathway. Our results therefore function as a conservative empirical lower bound: if an 11% behavioral shift already produces measurable effects on legume demand, production, and global emissions, alignment with full EAT-Lancet targets would generate considerably more profound systemic transformation. Of the three pathways assessed, the consumer pathway is therefore the most systematically transformative, operating directly on the root drivers of soy import dependency and livestock-related emissions rather than managing them through supply-side substitution or policy incentives.

Methods

This study integrates a sector agro-economic model (CAPRI) and a farm-level model (EFEM) within a top-down analytical framework to explore the impacts of three legume production pathways on EU+ agriculture. Results from each pathway are compared with a 2030 business-as-usual baseline to determine impacts at both the sectoral and farm levels. Additionally, we conduct an attributional Life Cycle Assessment (LCA) exclusively for the trade pathway, comparing the environmental burdens associated with soybean production in Germany and Brazil.

Models

CAPRI. The Common Agricultural Policy Regional Impact Analysis (CAPRI) model is a global, comparative static, multi-commodity, partial equilibrium model for the agricultural and the primary processing sectors. CAPRI is frequently used to analyze impacts of agricultural, environmental, climate change, and trade-related policies and scenarios, both at the EU and global levels[44–48]. One of the main strengths of CAPRI is the highly detailed and disaggregated representation of regional agricultural production and supply within the EU+. Specifically, the CAPRI EU+ supply module comprises about 280 independent optimization models that represent regional agricultural production activities at the EU+ NUTS2 level. Although CAPRI's spatial framework also covers Norway and Switzerland, these countries are not included in the EU+ grouping. Norway's soy demand is driven primarily by salmon aquaculture, which falls outside the agricultural scope and modeling framework of this study, while Switzerland's monogastric sector and aggregate soy import dependency are substantially smaller in absolute terms. The CAPRI regional supply models reflect profit-maximizing behavior of representative farms, taking into account constraints related to land availability, nutrient balances for cropping and animal activities, and policy restrictions. CAPRI includes a dedicated feed module that determines the allocation of feed inputs. This allocation specifies the quantities, measured in kilograms, of various feed categories (such as cereals, rich protein, rich energy, and other feed) or specific feed materials (e.g. fodder maize, grass, arable fodder crops, and straw) used per animal activity level. The input allocation is guided by nutrient requirement functions, which ensure that the feeding rations satisfy the energy, protein, and other essential nutrient needs of livestock. The input coefficients underlying this allocation are calibrated to align with these nutritional requirements, thereby ensuring biologically consistent feed rations across animal activities. The EU+ supply models are interlinked with a global multi-commodity model of agricultural markets, where the production of about 60 primary and processed agricultural products from the supply module is covered for 77 countries in 40 trade blocks (single countries or country groups). Bilateral trade flows and prices are modeled based on the Armington assumption of quality differentiation. The behavioral functions in the market model represent supply and demand for primary agricultural and processed commodities (including human and feed consumption, biofuel use, and import demand from multilateral trade relations), as well as balancing constraints and agricultural market policy instruments (i.e., import tariffs, tariff rate quotas, producer and consumer support estimates, etc.). The supply and market modules iterate until they converge to an equilibrium (i.e. prices and quantities) in all agricultural markets for all products.

Regarding GHG emissions accounting, CAPRI aligns with Sector 3 (Agriculture) of the UNFCCC Common Reporting Format (CRF). This scope primarily comprises non-CO_2 emissions, specifically nitrous oxide (N_2O) from soils and manure management, and methane (CH_4) from enteric fermentation and manure. CO_2 emissions and removals from land use, land-use change, and forestry (LULUCF), as well as CO_2 emissions from on-farm energy use, upstream input processing (e.g., mineral fertilizer production), and transport, are attributed to other CRF sectors and are not included in the CAPRI emission accounts in this study. Agriculture emissions are endogenously calculated based on inputs and outputs of production activities, following IPCC guidelines. The model also includes a set of technical and management-based GHG mitigation options for the EU agricultural sector. These include livestock-related interventions (e.g., feed additives, improved precision feeding) and crop-based options (e.g., precision farming, nitrification inhibitors). The regional adoption and intensity of the options are endogenous variables, and adoption occurs only if an option leads to an increase in marginal profit[37,44].

EFEM. The Economic Farm Emission Model (EFEM) is a comparative static linear optimization model employing a bottom-up approach, applicable at farm and regional levels[49–51]. The model simulates farm-level management decisions and optimizes farm organization and the allocation of available farm capacities with the objective of maximizing total gross margin. It accounts for regionally typical conditions, including climate parameters and typical yields in arable farming, grassland, and livestock production systems. Producer and factor prices, as well as the agricultural and environmental policy framework, are treated as exogenous parameters.

As a comparative-static framework, EFEM captures rather short-term competitive adjustments within existing farm structures, i.e. changes in the scale and intensity of production given fixed farm capacities. Structural reallocation between animal species, which requires capital investment and involves complex, multi-dimensional business decisions, lies outside the scope of this modeling framework. This is a defensible constraint in the context of this study given its 2030 projection horizon, over which such species-level structural transitions are unlikely to materialize at scale, and over which short-run competitive responses within existing structures represent the primary margin of policy-relevant change.

EFEM incorporates all major arable crops, grassland production systems, and livestock husbandry types relevant to conventional agriculture in Germany. Regarding plant production, the model differentiates between food and feed crop activities on arable land and grassland, varying by fertilization strategies, production intensity, and soil management practices. For the purpose of this study, EFEM has been extended to include new legume cultivation and legume-based feed systems[52], taking into account biological N-fixation as well as agronomic effects of legumes for the subsequent crop.

In this study, EFEM is applied exclusively at the farm level, without regional upscaling. Typical farm models for various farm types and regions in Germany are constructed using individual farm data from the EU Farm Accountancy Data Network (FADN). These models represent average conditions by farm type, following FADN typologies, and are constrained by factor endowments and crop rotation limits within the optimization process. The selected study regions and farm models in Germany are presented in the supplementary Table SI1.

The EFEM GHG emissions boundary spans agriculture emissions and upstream process emissions, but excludes LULUCF emissions and removals, as well as transport, distinguishing it from both the narrower CAPRI accounting and the broader LCA system boundary. Agriculture emissions include direct N_2O emissions from soils and manure management, as well as indirect N_2O emissions from leaching, runoff, and atmospheric nitrogen deposition[49]. Upstream emissions include those from the production of mineral fertilizers, plant protection products, seeds, and purchased feed[53].

To simulate the pathway effects, a soft linkage between CAPRI and EFEM was established. The primary data transferred comprise product and factor price changes under each pathway. The policy pathway also incorporates a fixed area-based coupled payment of 108 EUR per hectare for legume cultivation. Furthermore, to ensure consistency in technical progress assumptions, CAPRI-derived projections of yield growth to 2030 were incorporated into EFEM. EFEM assesses the farm-level implications of the three legume production pathways by incorporating these sectoral price changes modeled by CAPRI (Table SI2), along with the assumed protein crop payment of 108 €/ha for Germany. To account for spatial heterogeneity in the suitability for soybean cultivation, EFEM integrates additional regional crop rotation constraints, derived from the cultivation suitability map (Fig. SI1), in addition to general agronomic limits. As a threshold criterion for whether soybeans can be cultivated in a region, soybean cultivation was only permitted in regions where at least 10% of the arable land is classified as having "good" or "very good" suitability. Based on this criterion, soybean cultivation is excluded in Brandenburg and Schleswig-Holstein.

LCA. The attributional Life Cycle Assessment (LCA) was performed using OpenLCA v.1.10.3[54] with the Ecoinvent 3.11 Cut-Off database as the source of background data[55] The environmental burdens associated with the production of one tonne of soybean from the DE21 South region in Germany (no fertilizer inputs) were compared with those from the market process of soybean provision from Brazil from the Ecoinvent 3.11 "market for soybean, Brazil" process. The processes associated with the German soybean cultivation system are recorded in Table SI4. Emissions of nitrous oxide (N_2O) to air and nitrate to water (NO_{3-}) arising from crop residues were calculated according to the Intergovernmental Panel on Climate Change guidelines[56]. Nitrogen oxides to the air were calculated according to ref. 57. The impact assessment followed the "EF v.3.0" method[58]. Results were normalized using person-year equivalents, based on factors from the European Commission[59], to express impacts as a proportion of average annual per-capita burdens to allow comparison across impact categories of differing units and magnitudes.

Impact categories assessed:

- Climate change: quantified as Global Warming Potential (GWP) in CO_2 equivalents, this indicator measures the radiative forcing impacts of over 100 years.
- Ozone depletion: assessed as Ozone Depletion Potential (ODP) in kg CFC-11 equivalents, reflecting the release of halogenated compounds (e.g. CFCs, HCFCs) that degrade stratospheric ozone.
- Human toxicity, cancer effects and non-cancer effects: toxic emissions are evaluated in Comparative Toxic Units for human toxicity (CTUh), representing the projected increase in disease cases per unit emissions. Carcinogenic (e.g. chromium, nickel) and non-carcinogenic (e.g. cadmium, mercury) effects are assessed separately.
- Ionizing radiation, human health: expressed as Human exposure relative to U^{235}, this category captures health risks from high-energy particle emissions from nuclear and fossil-based activities.
- Photochemical ozone formation, human health: measured in methane, carbon monoxide, and non-methane volatile organic compounds (NMVOCs) equivalents, this reflects ground-level ozone (smog) from VOCs, NOx, and sunlight, with implications for respiratory health.
- Acidification (terrestrial and freshwater): assessed as Accumulated Exceedance (mol H^+ equivalents), indicating acid deposition from atmospheric reactions involving SO_2, NOx, and NH_3, affecting ecosystems and soil chemistry.
- Eutrophication (terrestrial, freshwater, and marine): nutrient overloads, mainly N and P, are captured through: Terrestrial: Accumulated Exceedance (N eq); Freshwater: P-equivalent nutrient transfer; Marine: N-equivalent nutrient transfer. Eutrophication leads to biodiversity loss and oxygen depletion in aquatic systems.
- Freshwater ecotoxicity: measured in Comparative Toxic Unit for ecosystems (CTUe), this reflects potential harm to aquatic species from toxic discharges (e.g. heavy metals, pesticides).
- Resource use (minerals, metals, fossil fuels): abiotic depletion is quantified in antimony equivalents (minerals/metals) and Mega Joules (fossil fuels), representing resource extraction relative to scarcity.
- Water scarcity: expressed in m^3 world equivalent, this indicator measures the potential deprivation of water in a given area after all local withdrawals.
- Land occupation: evaluated with the LANCA® tool[60], which considers five land function disruptions per functional unit: Erosion resistance (soil loss), mechanical filtration (particle retention), physicochemical filtration (cation exchange capacity), groundwater replenishment (infiltration potential), and biotic production (biomass yield potential).
- Particulate matter (respiratory inorganics): quantified as disease incidence per unit of fine particulate matter ($PM_{2.5}$), linked to emissions of nitrogen oxides, sulfur oxides, and ammonia.

With respect to GHG emissions, the LCA analysis extends the emission boundary to its widest scope compared to CAPRI and EFEM, explicitly incorporating agricultural production emissions, fossil fuel use, and LULUCF emissions associated with soybean production in both Germany and Brazil. This makes the LCA the only framework in the study that captures land-use change emissions, which are particularly relevant for the Brazil comparison given the association between soy expansion and deforestation in South American production regions. However, it needs to be noted that additional emissions from overseas transport and storage of imported soybeans are not included within the LCA system boundaries applied here.

Scenarios

We assess three forward-looking legume-based pathways for EU+ agriculture against a business-as-usual baseline, with a projection horizon of 2030. The three pathways are designed to operate at deliberately different points on the spectrum from theoretical stress-testing to empirically grounded realism, providing complementary rather than symmetric analytical coverage of the mechanisms through which domestic legume production and consumption in the EU+ could be expanded or restructured.

Baseline. The baseline scenario corresponds to the CAPRI projection for 2030, calibrated to the European Commission's Medium-term Outlook for agricultural markets, which is itself grounded in the OECD-FAO Agricultural Outlook[61]. This provides a consistent and internationally recognized set of assumptions for agricultural commodity markets, including soybeans and pulses, within a coherent modeling framework. Macroeconomic drivers, such as GDP growth, exchange rates, crude oil prices, inflation, and population growth, are derived from external sources, consistent with the OECD-FAO Agricultural Outlook. The baseline scenario reflects a business-as-usual trajectory to 2030, incorporating agricultural, environmental and trade policies approved and in force at the time of modeling. It represents the current conditions of agricultural production and markets as well as policies, prices, demand, and trade. The baseline serves as the reference point for assessing the impacts of the alternative legume-focused pathways, each of which introduces targeted changes to selected drivers while holding other assumptions of the baseline constant.

Trade pathway. The trade pathway simulates a scenario in which soybean and soymeal imports into the EU+ are entirely disrupted. Thus, this scenario presents a hypothetical condition in which the EU+ is forced to increase its domestic soybeans and pulses production to satisfy the demand of the EU+ livestock industry. The objective of this pathway is to establish the theoretical upper bound of import substitution capacity to stress-test the system's resilience to external trade shocks and global market volatility. Technically, this pathway is implemented by imposing a prohibitively high import tariff on soybeans and soymeal, rendering imports economically unviable within the model. Production conditions and policies outside the EU+ remain unchanged, isolating the domestic supply-side response to this specific trade shock.

Policy pathway. This pathway examines changes in direct support payments to EU+ farmers to incentivize increased domestic legume production under the current agricultural policy rules. Specifically, it is assumed that all EU Member States and the UK fully exploit the option to allocate 2% of their direct payment envelope to support for protein crop production. While the option to provide coupled support for protein crop production is already employed in several EU Member States, the pathway generalizes its use across the entire EU+ region. The scenario assumes a budget-neutral reallocation within the direct payment envelope, i.e., an increase in coupled support is offset by a corresponding reduction in decoupled income support. The supported crops include soybeans and pulses (peas, beans, lupins, etc.), whereas fodder legumes are not included. This pathway assesses the potential for production expansion under existing policy flexibility and highlights the differential incentives for protein crop cultivation under an alternative payment structure.

Consumer pathway. This pathway simulates a demand-side shift in dietary preferences within the EU+ population, consistent with nutritional guidelines promoting a higher intake of plant-based protein sources. We model a voluntary transition among consumers towards healthier and more sustainable dietary patterns, operationalised as an 11% reduction in EU+ meat consumption replaced by plant-based protein alternatives. This parameter is derived from EU+ consumer preference surveys[62–64], documenting willingness to substitute meat with plant-based protein among European consumers. Thus, the 11% figure presents a behaviorally realistic near-term demand-side signal rather than a normative target, reflecting also the different temporal scope of our study compared to other frameworks such as the EAT Lancet. The dietary shift is implemented in the CAPRI model only for the EU+ region and is grounded in Nutrient Density Unit (NDU) estimates[65], which provide a nutritionally consistent basis for converting reduced meat consumption into equivalent plant-based protein demand. Specifically, the model converted the substituted meat consumption (Meat) to additional pulses demand (APulse), such as:

$$11\% \text{ x Meat x } 1.33/1.99 = \text{APulse}$$

where the ratio 1.33/1.99 reflects the relative nutrient density of pulses to meat expressed in NDU terms. The resulting additional pulses demand is added to the baseline level of pulses demand to complete the substitution process of plant-based protein in the model.

This pathway captures the implications of changing consumption patterns for legume demand, agricultural production, and land use. It provides insights into the role of consumer behavior in shaping protein crop development and sustainability transitions.

Data availability

The data supporting the findings of this study are available in the Supplementary Information and Supplementary Datafiles 1 and 2. The complete database of CAPRI is open source and is publicly accessible at https://www.capri-model.org. EFEM is calibrated using data from the EU Farm Accountancy Data Network (FADN), which is subject to confidentiality restrictions under EU legislation and is not publicly available; access is governed by the relevant European Commission regulations (https://agriculture.ec.europa.eu/data-and-analysis/farm-structures-and-economics/fadn_en). This constraint limits full external replication of the EFEM results, though the model structure, parameterization, and key assumptions are described in the "Methods" section to allow methodological scrutiny. The complete foreground inventory for the German soybean LCA system, including all inputs and outputs and the exact names of corresponding Ecoinvent 3.11 background processes, is reported in Table SI4 of the Supplementary Information, enabling reconstruction by any user with access to the Ecoinvent database. The Brazilian soybean market system requires no separate foreground inventory: it is represented entirely by the Ecoinvent 3.11 market process, which can be directly accessed and reproduced within the same database.

Code availability

The CAPRI model codebase is publicly accessible at https://www.capri-model.org. The specific model version used in this study is available upon request via registration on the Subversion (SVN) server hosted at the University of Bonn; access contact: https://www.capri-model.org/dokuwiki/doku.php?id=capri:contact. The EFEM and LCA model codes are available upon request from the corresponding author; note that the FADN-based input data used for calibration cannot be shared due to the confidentiality restrictions described above.

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Author contributions

S.S., M.H., B.Z., E.A., and T.F. designed the research and performed the scenario development. M.H., J.H., S.S., T.F. (CAPRI), E.A., B.Z., E.P. (EFEM), and So.S., M.P.C., D.S. (LCA) carried out the technical implementation, scenario simulations, and first analysis of the results. S.S. and T.F. led the writing of the paper. All authors provided feedback and contributed to the interpretation of the results and to writing the paper.

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Competing interests

The authors declare that no competing interests exist. The views expressed are purely those of the authors and do not represent an official position of the European Commission.

Additional information

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