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The European Green Deal improves the sustainability of food systems but has uneven economic impacts on consumers and farmers

Hervé Guyomard[1], Louis-Georges Soler[2✉], Cécile Détang-Dessendre[3] & Vincent Réquillart[4]

The European Green Deal aims notably to achieve a fair, healthy, and environmentally friendly food system in the European Union. We develop a partial equilibrium economic model to assess the market and non-market impacts of the three main levers of the Green Deal targeting the food chain: reducing the use of chemical inputs in agriculture, decreasing post-harvest losses, and shifting toward healthier average diets containing lower quantities of animal-based products. Substantially improving the climate, biodiversity, and nutrition performance of the European food system requires jointly using the three levers. This allows a 20% reduction in greenhouse gas emissions of food consumption and a 40–50% decrease in biodiversity damage. Consumers win economically thanks to lower food expenditures. Livestock producers lose through quantity and price declines. Impacts on revenues of food/feed field crop producers are positive only when the increase in food consumption products outweighs the decrease in feed consumption.

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[1] INRAE, SDAR, La Motte au Vicomte, 35650 Le Rheu, France. [2] INRAE, PSAE, University of Paris-Saclay, Campus Agro Paris-Saclay, 91120 Palaiseau, France. [3] INRAE, CESAER, Institut Agro, 26 Boulevard Docteur Petitjean, 21079 Dijon, France. [4] TSE, INRAE, Manufacture des Tabacs, Aile Jean-Jacques Laffont, 21 Allée de Brienne, 31000 Toulouse, France. ✉email: Louis-Georges.Soler@inrae.fr

As in other parts of the world, the food system of the European Union (EU) is not sustainable. It generates ~30% of the total greenhouse gas emissions (GHGE) of the region[1]; is a major driver of biodiversity loss[2,3]; wastes large amounts of resources[4]; and favors unhealthy diets, obesity, and related diseases[5].

Many studies have shown that sustainable and healthy food systems require simultaneously changing agricultural practices, reducing losses throughout the food chain, and shifting diets. Such analyses have been developed at both the global[6–9] and European[10–13] scales. These studies have relied on either biophysical mass-flow models or well-established economic models of partial or general equilibrium. At the world level, Springmann et al.[7] connected food demand in 2050 for 62 agricultural commodities and 159 countries to food production across regions by reformulating the quantity equations of the IMPACT partial equilibrium economic model. They showed that synergistically combining supply and demand measures, including changes in farm technology and management, reducing food losses, and shifting consumption toward healthier diets containing more plant-based products would be required "to sufficiently mitigate the projected increase in environmental pressures". At the European scale (EU-27 + Switzerland and United Kingdom), Clora et al.[10] used a slightly modified version of the GTAP-E equilibrium economic model to compare the impact on agricultural GHGE of two supply-side mitigation strategies (extensification vs. intensification) "against a 2050 baseline featuring healthy/sustainable diets adopted by European consumers". They showed that extensification would reduce European agricultural GHGE by around 11% in 2050 relative to the baseline while intensification would increase them by around 2.5%. At the EU level, Poux et al.[14] concluded that agro-ecological production systems and healthy diets would reduce European agricultural GHGE by 40% in 2050 relative to 2010. Their analysis relied on a specific biophysical mass-flow model.

These issues and results led the European Commission (EC) adopting a whole food chain approach within the European Green Deal (EGD) launched in December 2019[15]. In a general way, the EGD aims for climate neutrality and a sustainable future in the EU by 2050 while not leaving anyone behind. It requires the transformation of the entire society, including the food system that is specifically targeted by the Farm to Fork Strategy[16] and the EU Biodiversity Strategy for 2030[17]. At the farm level, these strategies set ambitious quantitative targets by 2030 for pesticide, fertilizer, and antibiotic uses; agricultural land under organic farming; and high-diversity landscape features. Beyond the farm gate, the targets relate to the Sustainable Development Goal (SDG) commitment of the EU to halving per capita food waste at retail and consumer levels by 2030. The EGD also aims to facilitate the shift toward sustainable and healthy diets in the EU but does not explicitly define the latter and a time horizon (Table 1).

This dichotomy between supply, loss, and demand ambitions of the EGD has led analyses to focus on the economic impacts of agricultural quantitative targets only[18–25]. When they were considered, non-market impacts were essentially restricted to GHGE. These analyses relied generally on well-established large economic model of partial equilibrium (such as CAPRI) or general equilibrium (such as MAGNET). They all concluded that extensifying agricultural practices would decrease European agricultural production levels and increase European agricultural prices, with however large discrepancies for a same product depending on the study and for a given study depending on the product. European consumers would be economically negatively affected, while the impact on European producers' income/surplus would be positive for some studies[20,21,23,24] but negative for others[18,19,22]. European agricultural GHGE would be substantially reduced, but the 'carbon leakage' effect would cancel half of this gain for Barreiro-Hurle et al.[20,21] and cancel it in its entirety for Henning and Witzke[23]. This focus on supply measures has been criticized by the EC[26], which underlined that these studies did not assess the full economic impacts of the EGD notably because they did not consider or only partially the two objectives related to reducing food losses and shifting diets.

This study contributes to fill the above gap. It assesses the market (prices, production, consumption, trade, farmers' revenues, and consumers' food expenditures) and non-market (GHGE, biodiversity, and nutrition) impacts of the three main levers of the EGD that specifically target the European food system, that is, the decrease in chemical input uses, the reduction in post-harvest food losses, and a shift toward healthier diets defined here as those containing smaller quantities of animal-based products. Thus, we add to the literature in two ways. First, we complete the existing EGD assessments on the European food system by explicitly incorporating the reduction in post-harvest food losses and the shift toward healthier diets. Furthermore, we extend the assessment domain of past studies by evaluating non-market impacts on not only GHGE, but also biodiversity and nutrition. Second, we pay attention to the economics of the European food system through price changes induced by the three levers. In particular, we assess impacts on agricultural prices vs. consumption prices.

This effort is achieved by developing an original and synthetic economic model of partial equilibrium for the food system of the EU-27 calibrated on the average of the years 2018, 2019, and 2020, hereafter noted simply "2019" (Fig. 1). The scenarios present a counterfactual for this year "2019". The use of a synthetic model with three product aggregates only (see below) has obvious drawbacks. Beyond its simplicity, an advantage is that it explicitly includes the variables targeted by the EGD measures on agricultural supply and food losses. An additional advantage is that

Table 1 Main quantitative and qualitative goals of the European Green Deal related to the food system.

Quantitative targets by 2030 at the farm gate

- Reducing the use and risk of chemical pesticides by 50% and the use of more hazardous pesticides by 50%
- Reducing nutrient losses by at least 50% ("while ensuring no deterioration in soil fertility") and fertilizer use by at least 20%
- Reducing the sales of antimicrobials for farm animals and aquaculture by 50%
- Achieving 25% of total farmland under organic farming
- Dedicating 10% of farmland to high-diversity landscape features

Objectives beyond the farm gate

- Halving per capita food losses at the retail and consumer levels by 2030 (SDG 12.3) and committing to explore ways of preventing food losses at the other stages of the food chain
- Creating a food environment (notably through nutrition and sustainability labeling) supporting sustainable and healthy food choices and diets

Source: EC[15–17].

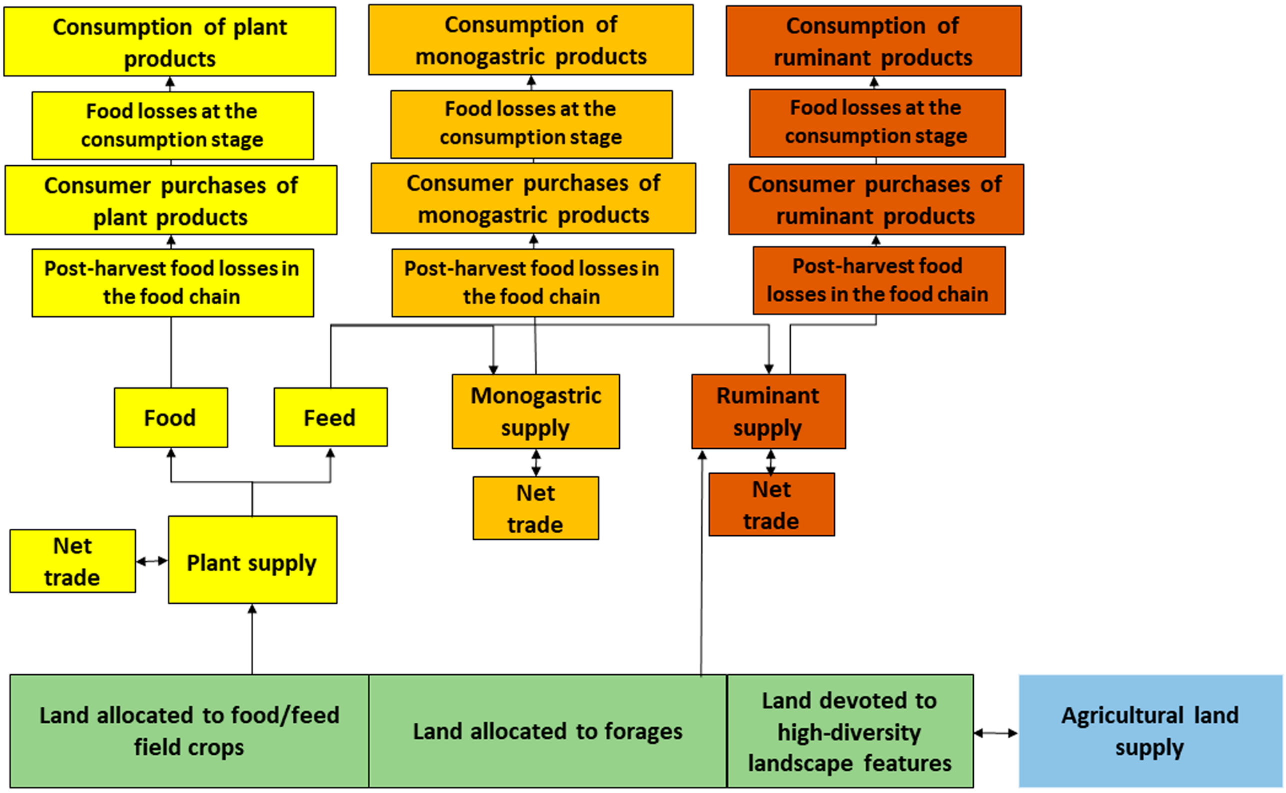

Fig. 1 Structure of the partial equilibrium economic model. Agricultural land supply is variable (blue rectangle) and split into three land uses corresponding to food/feed field crops, forages, and high-diversity landscape features (green rectangles). Land devoted to food/feed field crops determines the domestic plant supply. Total plant supply is defined from domestic plant supply and net trade. This total plant supply is used for food and feeding monogastrics and ruminants (other uses are assumed constant). Food uses determine consumer purchases of plant products by subtracting post-harvest losses in the food chain. Finally, consumption levels of plant products are defined from purchases by subtracting food losses at the consumption stage (yellow rectangles to the left of the figure, from bottom to top). Consumption levels of monogastric and ruminant products are determined in the same manner (orange rectangles for monogastric products and brown rectangles for ruminant products). Forages include permanent grasslands, temporary grasslands and non-herbaceous forages; they are used for feeding ruminant cattle. The aggregate of plant-based products includes cereals, oilseeds, protein crops, rice, sugar beets and potatoes; the aggregate of monogastric-based products includes fresh and processed pork meat as well as poultry- and egg-based products; and the aggregate of ruminant-based products includes milk, dairy products, and ruminant meat.

the logic of the economic effects can be easily traced and explained.

On the consumption side, the model distinguishes three groups of products. The monogastric product group includes pork, poultry, and eggs. The ruminant product group encompasses ruminant meat and milk products. This simple decomposition of animal products makes it possible to evaluate the impacts of a protein transition for European food consumption, implying lower quantities of animal-based products. Such a reduction is a major driver of both healthier diets and decreases in food GHGE in developed countries, including the EU[10,27,28]. The EAT-Lancet Commission[29] recommends not eating more than 300 grams of meat and 250 grams of dairy foods per week as part of a healthy and sustainable diet in a context where Europeans consume, on average, twice as much meat and three times as much dairy products according to FAO statistics (FAOStat database). Since we focus on the protein transition of food consumption, the plant product aggregate excludes fruits and vegetables (F&V) for both the demand and supply sides. This exclusion simplifies the modeling framework but implies that we do not fully address the impacts of healthier diets that encompass an increase in the consumption of F&V[30].

On the production side, agricultural land supply is variable and endogenously allocated to three uses: land devoted to food/feed field crops, land devoted to forages that are cultivated (temporary grassland and other cultivated forages) or not cultivated (permanent grassland), and land devoted to environmental protection through high-diversity landscape features such as embankments, hedges, wetlands, or peatlands. International trade is included through net trade, allowing assessments of GHGE and biodiversity damage embedded in net imports or net exports. Post-harvest losses in food chains make it possible to distinguish the quantities purchased by consumers from the quantities supplied by agricultural producers, while food losses at the consumption stage differentiate the quantities purchased and actually consumed. Losses at the farm level that represent around 11% of total food losses[4] are supposed unchanged at base year levels. Gaps between consumer and producer prices are modeled in the form of constant margins. Each consumption price is thus assumed to be equal to the corresponding production price increased by a margin calibrated on the basis of base year data and assumed to be unchanged in all scenarios.

The model encompasses two ecological indicators, namely GHGE and biodiversity, and approximates food consumption quality through various nutritional indicators. GHGE linked to the consumption of the three groups of products are calculated at the farm gate based on emission coefficients per kilogram of product calculated by Crenna et al.[2]. These coefficients were adjusted following the strategy proposed by Bellassen et al.[31], which made it possible to differentiate emissions according to production practices (conventional vs. agro-ecological) and product origin (domestic and exported vs. imported). The impact on biodiversity is assessed based on biodiversity damage coefficients

Table 2 The scenarios.

Short names of scenarios	Assumptions
Panel a. The three levers of the EGD related to the food system considered in isolation	
‘Agro-ecology’ lever	Lever of agro-ecological practices: - Increase in farmland devoted to high-diversity landscape features - Decreases in the uses of pesticides, fertilizers, and antimicrobials
‘Food losses’ lever	Lever of reducing food losses: - Halving post-harvest food losses
	Lever of diet changes:
‘Anim-’ lever	- Decrease in the demand of ruminant- and monogastric-based products
‘Anim-Plant+’ lever	- Decrease in the demand of ruminant- and monogastric-based products compensated by an iso-protein increase in the demand of plant products
Panel b. The three levers of the EGD related to the food system considered jointly	
‘Agro-ecology, food losses, and Anim-’ scenario	- Joint implementation of the three levers of agro-ecology, food losses, and diet without shock on the demand of plant products
‘Agro-ecology, food losses, and Anim-Plant+’ scenario	- Joint implementation of the three levers assuming an iso-protein compensation of the decrease in the demand of animal products by an increase in the demand of plant products

Note: For more details, see Supplementary Note 2.

calculated by Knudsen et al.[32,33], which allowed us to distinguish the effects by unit of area according to different land uses (food/feed field crops, forages, and high-diversity landscape features), production practices, and product origin. Since we do not include and distinguish all food goods but only the three aggregates of food/feed field crops, ruminant products, and monogastric products, it is not possible to fully assess the nutritional quality of consumers’ diets. However, we provide a set of nutritional indicators (total calories, total proteins, animal proteins, the share of plant proteins in total proteins, fiber, fat, and carbohydrates) associated with the consumption of our three aggregates. Given the nutrient intakes currently observed in the EU and the nutritional guidelines provided by public health agencies, we assume that a decrease in calories, animal proteins, fat, and carbohydrates is positive from a health point of view, while a decrease in fiber is negative (at least as long as the changes are not ‘too’ large, which will be the case in our simulations).

The method section presents the functioning of the economic model, parameters, exogenous and endogenous variables, the calibration process of parameters and variable values in the base period, and the different assumptions used to calculate the non-market indicators in both the base period and the scenarios. Supplementary Note 1 details the model equations, parameters, variables, and indicators as well as data sources and references used for the calibration process. The Archive[34] provides the result of the calibration process (‘calibration’ and ‘non-market impact coefficients’ files of Archive 3.1), a full version of the simulation model and simulation results (‘baseline’ and ‘scenarios’ files of Archive 3.1).

The results are displayed by first considering the impacts of each lever implemented in isolation. The ‘agro-ecology’ lever implements the agricultural components of the EGD, that is, the reduction in the use of pesticides, fertilizers, and antimicrobials and the increase in high-diversity landscape features. The ‘food losses’ lever assumes that post-harvest food losses are reduced in line with the corresponding EGD objective. The third lever assumes a 20% exogenous reduction in the demand for both types of animal products. It is simulated on the basis of two variants; the first does not have a shock to the demand for plant products (‘Anim-’ lever variant), while the second supposes an iso-protein compensation for the decrease in the demand for animal products requiring an increase by 29.5% in the demand for plant products (‘Anim-Plant+’ lever variant). Unlike the first two levers, the third lever of shifting diets is not normative since the EGD does not define a target for diets. The three levers are then combined to define two complete scenarios, without (‘agro-ecology, food losses, and Anim-’ scenario) and with (‘agro-ecology, food losses, and Anim-Plant+’ scenario) iso-protein compensation on demand. The levers and scenarios are summarized in Table 2 and their implementation is detailed in Supplementary Note 2.

Simulation results show that the three levers help to safeguard the climate and the biodiversity by reducing GHGE of European food consumption by around 20% and biodiversity damage in agro- and forest-ecosystems by around 40–50% relative to base year levels. The nutritional indicators of food consumption are improved only thanks to the third lever of shifting diets. The three levers do not have identical impacts on quantities, prices, and finally agricultural producers’ revenues and consumers’ food spending. While the ‘agro-ecology’ lever increases food expenditures by 2.0% and increases revenues of producers of food/feed field crops and livestock by 11.3% and 2.8%, respectively, the ‘Anim-Plant+’ lever reduces food expenditures by 3.4%, increases food/feed field crop producers’ revenues by 13.9%, and diminishes livestock producers’ revenues by 26.2%. When the three levers are used jointly, consumers win economically thanks to lower food expenditures. Livestock producers lose through quantity and price declines. Food/feed field crop producers win when the increase in food consumption of plant products outweighs the decrease in feed consumption (‘agro-ecology, food losses, and Anim-Plant+’ scenario); they lose when the feed effect dominates (‘agro-ecology, food losses, and Anim-’ scenario).

Results

Impacts of reducing chemical input use and increasing high-diversity landscape features (‘agro-ecology’). European farmers react to the ‘agro-ecology’ lever of less intensive farming practices and augmented high-diversity landscape features by expanding total farmland by 4.4 million hectares (Mha) gained on forests. This total farmland expansion effect represents a break in the trend since the amount of land that was used for agricultural production in the EU remained almost unchanged between 2005 and 2022[35]. This expansion effect is, however, lower than the increase in high-diversity landscape features (6.8 Mha). As a result, agricultural areas devoted to food/feed field crops and forages decline by 0.4 Mha and 2.0 Mha, respectively, relative to corresponding areas in the base period (Table 3).

The ‘agro-ecology’ lever reduces European agricultural production more substantially for plant products (11.7%) than

Table 3 Economic impacts of the scenarios.

Market impacts		Reference situation	Levers in isolation				Set of the three levers	
			'Agro-ecology'	'Food losses'	Diet		'Agro-ecology, food losses, and Anim-'	'Agro-ecology, food losses, and Anim-Plant + '
					'Anim-'	'Anim-Plant + '		
Total farmland (Mha)	Food/feed field crop areas	68.9	68.5	68.5	68.7	69.4	68.0	68.6
	Forage areas	70.1	68.1	70.1	69.7	69.5	67.9	67.6
	High-diversity landscape features	6.95	13.78	6.95	6.95	6.95	13.75	13.76
	Total	146.0	150.5	145.6	145.4	145.8	149.6	150.0
Production levels (Mt)	Food/feed field crops	392.7	346.7	382.3	385.7	405.5	330.1	347.0
	Ruminants	48.8	45.1	48.2	44.8	43.9	40.8	39.9
	Monogastrics	42.0	39.9	41.5	39.4	38.7	36.9	36.3
Producer prices (€/t)	Food/feed field crops	211	266	191	196	233	232	265
	Ruminants	870	984	808	680	711	742	770
	Monogastrics	1640	1757	1531	1338	1379	1367	1403
Producer revenues (M€)	Food/feed field crops	82,866	92,266	73,129	75,696	94,349	76,689	91,803
	Ruminants	42,456	44,364	38,922	30,487	31,203	30,256	30,728
	Monogastrics	68,880	70,101	63,552	52,652	53,292	50,467	50,928
Quantities purchased (Mt)	Plant products	101.5	101.1	92.3	100.8	133.4	91.4	121.3
	Ruminant products	38.8	38.6	37.5	30.1	30.1	28.8	28.8
	Monogastric products	23.3	23.3	22.3	18.1	18.2	17.4	17.4
Quantities consumed (Mt)	Plant products	84.6	84.3	84.6	84.0	111.3	83.8	111.2
	Ruminant products	36.0	35.8	36.1	27.8	27.9	27.8	27.8
	Monogastric products	21.3	21.3	21.4	16.6	16.6	16.6	16.6
Consumer prices (€/t)	Plant products	2000	2055	1980	1985	2022	2021	2054
	Ruminant products	4500	4614	4438	4310	4341	4372	4400
	Monogastric products	7000	7117	6891	6698	6739	6727	6763
Consumer expenditures (M€)	Expenditures on plant, ruminant, and monogastric products	541,045	551,925	503,004	451,526	522,714	427,639	493,512
Net trade (Mt)	Plant products (net imports)	41.7	74.4	30,0	32.9	54.5	54.3	73.4
	Ruminants (net exports)	5.3	1.8	7.2	11.1	10.2	9.2	8.4
	Monogastrics (net exports)	5.8	3.7	7.8	11.2	10.5	10.7	10.1

Note: For a synthetic description of the levers and scenarios, see Table 2; for a detailed description of the scenarios and of their implementation within the model, see Supplementary Note 2.

for ruminant (7.6%) and monogastric (5.0%) products. The domestic production of plant products is more negatively impacted than that of animal products because it experiences not only a first effect linked to lower productivity of agro-ecological practices and a decrease in area but also an induced effect linked to reduced feed demand generated by lower animal production. Producer price increases are proportionally larger than production decreases because the supply functions of the three groups of products are price inelastic[34]. These positive price effects outweigh the negative quantity effects so that revenues increase by 11.3% for plant producers, 4.5% for ruminant producers, and 1.8% for monogastric producers. It was not possible to assess the impacts on producer incomes because it was not possible to calibrate production costs for both the initial situation with conventional farm practices and the final situation with agro-ecological farm practices. On this point, it is worth noting that there is no consensus on the profitability of agro-ecological vs. conventional farming[36], with inconsistent results between, for example, on the one hand van der Ploeg et al.[37], who concluded that agro-ecology in the EU would be more profitable than conventional agriculture (on the basis of several case studies), and on the other hand Davidova et al.[38], who reached an opposite conclusion with lower labor returns in low-input farming systems (on the basis of FADN—Farm Accountancy Data Network—samples for different EU countries). Of course, these assessments were based on observed prices and not simulated prices.

Consumer price increases in percent are much lower than corresponding producer price increases in percent because of the margins between the two prices that were supposed to be unchanged. Increases in consumer prices translate into small decreases in quantities purchased because the food demand system is price inelastic[34]. The price effect dominates the quantity effect, resulting in increased food consumption expenditures by 2.0%.

Price increases in the EU improve the price competitiveness of European imports from third countries and deteriorate the price competitiveness of European exports to third countries. As a result, European net imports of plant products increase by 32.7 million tons (Mt) and European net exports decrease by 3.5 Mt for ruminants and 2.1 Mt for monogastrics.

European production-based GHGE associated with the consumption of our three aggregates and calculated at the farm gate decline due to (i) the decrease in domestic production levels and (ii) the decrease in emissions per kilogram (kg) of food/feed field crop production induced by the reduction in chemical input uses, notably fertilizers. The decline in domestic production-based GHGE is partly compensated by the increase in emissions embedded in trade linked to augmented net imports of plant products and diminished net exports of animal products. In total, the GHGE of European consumption of our three aggregates decline by 65 Mt CO_2 equivalent (CO_2 eq), that is, minus 4.9% relative to base period emissions (Fig. 2). The same mechanisms result in a decrease in the biodiversity damage indicator by 17.6%, with a trade effect cancelling half of the reduction in domestic

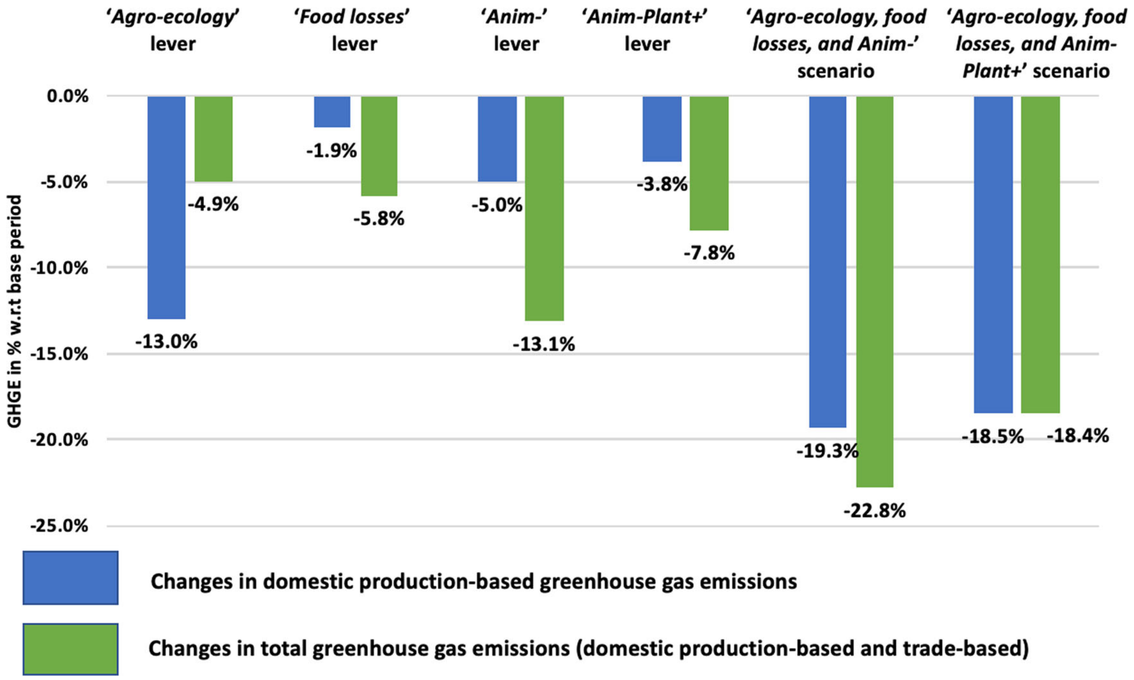

Fig. 2 Substantially improving the climate performance of the European food system requires jointly using the three levers of agro-ecological practices, reducing food losses and shifting toward healthier average diets containing lower quantities of animal-based products. Impacts at the farm gate of the three levers and the two scenarios on greenhouse gas emissions of European consumption of the three food aggregates, in percent with respect to base period emissions. Changes in domestic production-based emissions are in blue. Changes in total emissions (domestic production-based and trade-based) are in green. The three levers and the two scenarios are described in Table 2. For more details on calculating emissions, see Methods and the Archive[34].

production-based damage (Fig. 3). Since the first lever of agro-ecology only slightly increases consumer prices without changing relative prices between the three groups of products, it leaves almost unchanged the quantities consumed and hence the various nutritional indicators (Fig. 4).

Existing studies that did not assume that total farmland was fixed also concluded that farmland expand under the effect of the 'agro-ecology' lever of the EGD[20–23]. All these studies found that European agricultural production declines and that the agricultural trade balance of the EU deteriorates. They also concluded that production level declines are greater for plant products than for animal products (see Table 5 in Wesseler[25]). According to these studies, food expenditures increase while producer incomes improve or deteriorate depending on the study. In total, our simulated economic results fit well with those of existing studies focused on the agricultural components of the EGD. This comparison suggests that our model, although simplified, reproduces the economic mechanisms at work.

Impacts of reducing post-harvest food losses ('food losses'). The 'food losses' lever does not change the farmland area devoted to high-diversity landscape features and has only a small negative impact on farmland area devoted to food/feed field crops that is reduced by 0.5% relative to the base period.

Since pre-harvest losses are assumed unchanged in percent, the 'food losses' lever corresponds to a shift to the left in the domestic demand functions for the three groups of products[39] that decreases the quantities purchased by European consumers, the quantities produced by European producers, and finally consumer and producer prices. Declines in domestic purchases are proportionally more severe than decreases in domestic production because the consumer and producer price declines induced by the demand shift discourage net imports of plant products that diminish by 28.0% and encourage net exports of animal products that increase by 35.8% for ruminant products and 33.1% for monogastric products. Since European producers sell less at a lower price, their welfare is negatively affected with a decline in their revenues by 9.6%. Food expenditures of European consumers decline by 7.0% under the combined effect of the decreases in food purchases and consumer prices. However, the quantities that are actually consumed are almost unchanged as decreases in quantities that were previously lost compensate for decreases in quantities that are purchased.

Because reducing food losses saves resources, the GHGE of European food consumption of our three aggregates decrease by 76 Mt CO_2 eq. Unlike the 'agro-ecology' lever, the 'food losses' lever reduces not only domestic production-based GHGE (by 25 Mt CO_2 eq) but also emissions embedded in trade (by 51 Mt $C0_2$ eq). It also reduces the biodiversity damage indicator by 13% under the combined effect of the decrease in domestic production and the decrease in damage embedded in trade. Similar to the 'agro-ecology' lever, the 'food losses' lever has almost no impact on the different nutritional indicators.

Impacts of shifting diets ('Anim-' and 'Anim-Plant+'). First, we consider the 'Anim-' lever variant where the exogenous reduction of the European demand for both ruminant- and monogastric-based products is not compensated by an exogenous increase in the demand for plant products. The shock is modeled through changes in food demand preferences that directly reduce the quantities purchased and consumed. However, final demand levels for the three aggregates are endogenous as they react to consumer price changes.

The demand shift reduces the quantities purchased, consumed, and produced, as well as consumer and producer prices for both types of animal products. The decreases in quantities purchased require severe declines in producer prices to adapt domestic production to reduced domestic demand. However, domestic

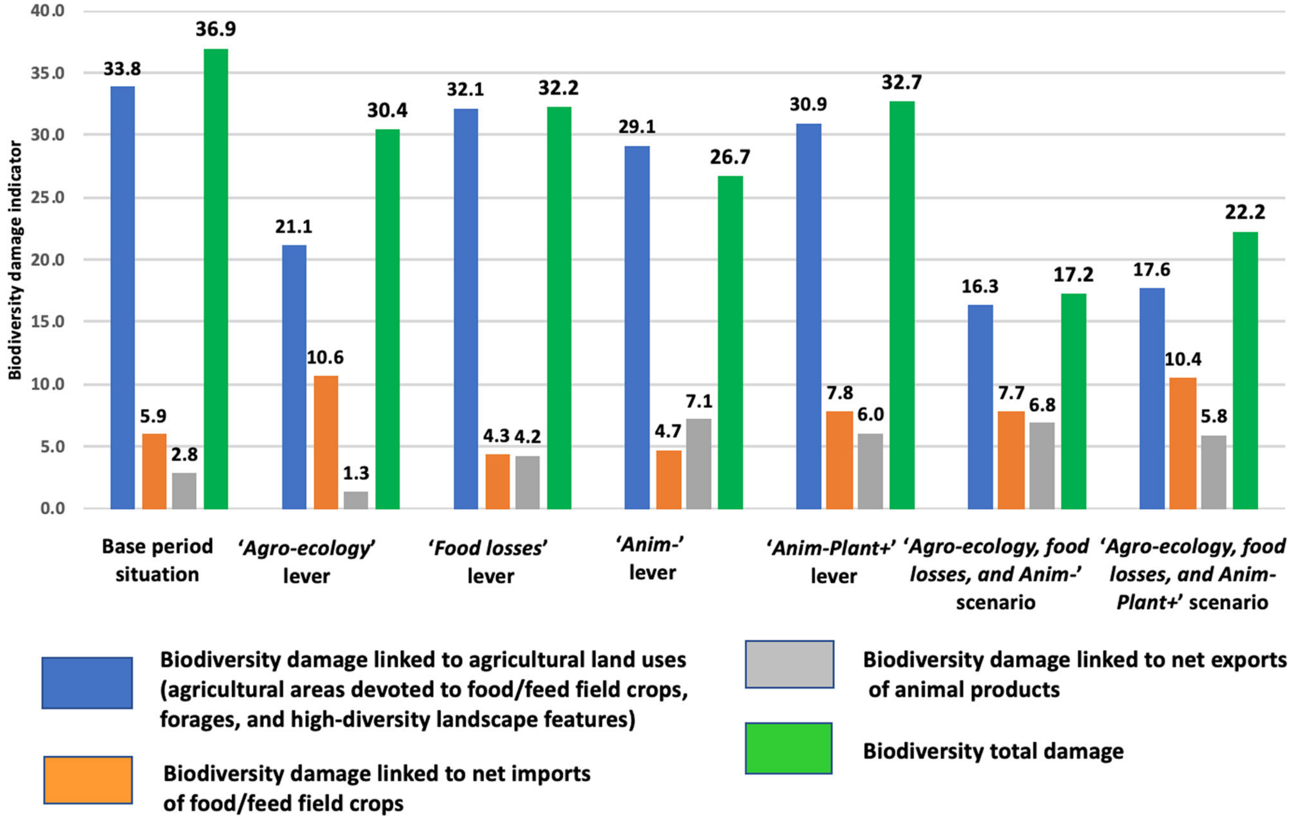

Fig. 3 Substantially improving the biodiversity performance of the European food system requires jointly using the three levers of agro-ecological practices, reducing food losses and shifting toward healthier average diets containing lower quantities of animal-based products. Biodiversity damage in European agro-ecosystems in the base period, the three levers, and the two scenarios. Biodiversity total damage (green column) is defined as the sum of biodiversity damage linked to agricultural land uses (blue column) and biodiversity damage linked to net imports of food/feed field crops (orange column) minus biodiversity damage linked to net exports of animal products (gray column). The three levers and the two scenarios are described in Table 2. For more details on calculating the biodiversity damage indicators, see Methods and the Archive[34].

production declines are much lower than domestic purchase decreases (8.2% vs. 22.5% for ruminants and 6.3% vs. 22.5% for monogastrics, respectively) because domestic producer price declines enhance the price competitiveness of European net exports, which increase by 109.0% for ruminants and 92.2% for monogastrics. The 'Anim-' lever variant penalizes the food/feed field crop production sector because of an strong negative feed effect (less feed demand due to lower animal production levels; see Fig. 5). Producers' revenues decrease much more for ruminants (28.2%) and monogastrics (23.6%) than for producers of food/feed field crops (8.7%). Food consumption expenditures decrease by 16.5% under the combined effect of lower quantities and prices.

The 'Anim-' lever variant reduces the GHGE of European food consumption of our three aggregates by 171 Mt CO_2 eq under the joint effect of (i) lower domestic production-based emissions (minus 66 Mt CO_2 eq) mainly because the domestic supply of animal products diminishes and (ii) lower emissions embedded in trade (minus105 Mt CO_2 eq) because net imports of plant products decrease and net exports of ruminants and monogastrics increase. The same logic applies to the biodiversity damage indicator, which decreases by 27.6%. Unlike the 'agro-ecology' and 'food losses' levers, the 'Anim-' lever variant substantially affects the nutritional indicators. Logically, the consumption of animal proteins decreases (by 22.4%) and the ratio of plant proteins to total proteins increases (from 0.42 to 0.48). Total calories, total proteins, fat, and carbohydrates decrease as well. The fiber intake varies very little since animal products are poor in fiber.

By construction, the 'Anim-Plant+' lever variant maintains the protein content of food consumption at base period level. As a result, food expenditures decrease less in 'Anim-Plant+' (3.4%) than in 'Anim-' (16.8%) because European consumers purchase greater quantities of plant products at higher prices in the second variant than in the first. Unlike the 'Anim-' lever variant, the 'Anim-Plant+' lever variant benefits European producers of food/feed field crops because the positive food effect now outweighs the negative feed effect; their revenues increase by 13.9%. The two variants have very similar effects on the domestic markets of ruminant and monogastric products. Animal production levels are however lower in 'Anim-Plant+' than in 'Anim-' because of a negative feed price effect in the second variant relative to the first. It is the reverse for animal producer prices. In total, quantity and price changes lead to livestock producers' revenues that are almost identical for both variants and therefore substantially lower than those of the base period. While net imports of plant products decrease in 'Anim-', they increase in 'Anim-Plant+' because they are boosted by the increase in corresponding producer prices. Net exports of animal products increase in both variants but less importantly in 'Anim-Plant+' than in 'Anim-' because producer prices are higher in the second variant than in the first.

Iso-protein compensation has an environmental cost. The GHGE of European consumption of our three aggregates decrease by 103 Mt CO_2 eq in 'Anim-Plant+' vs. 171 Mt CO_2 eq in 'Anim-' because reductions in production-based emissions and in emissions embedded in trade are lower in the second variant than in the

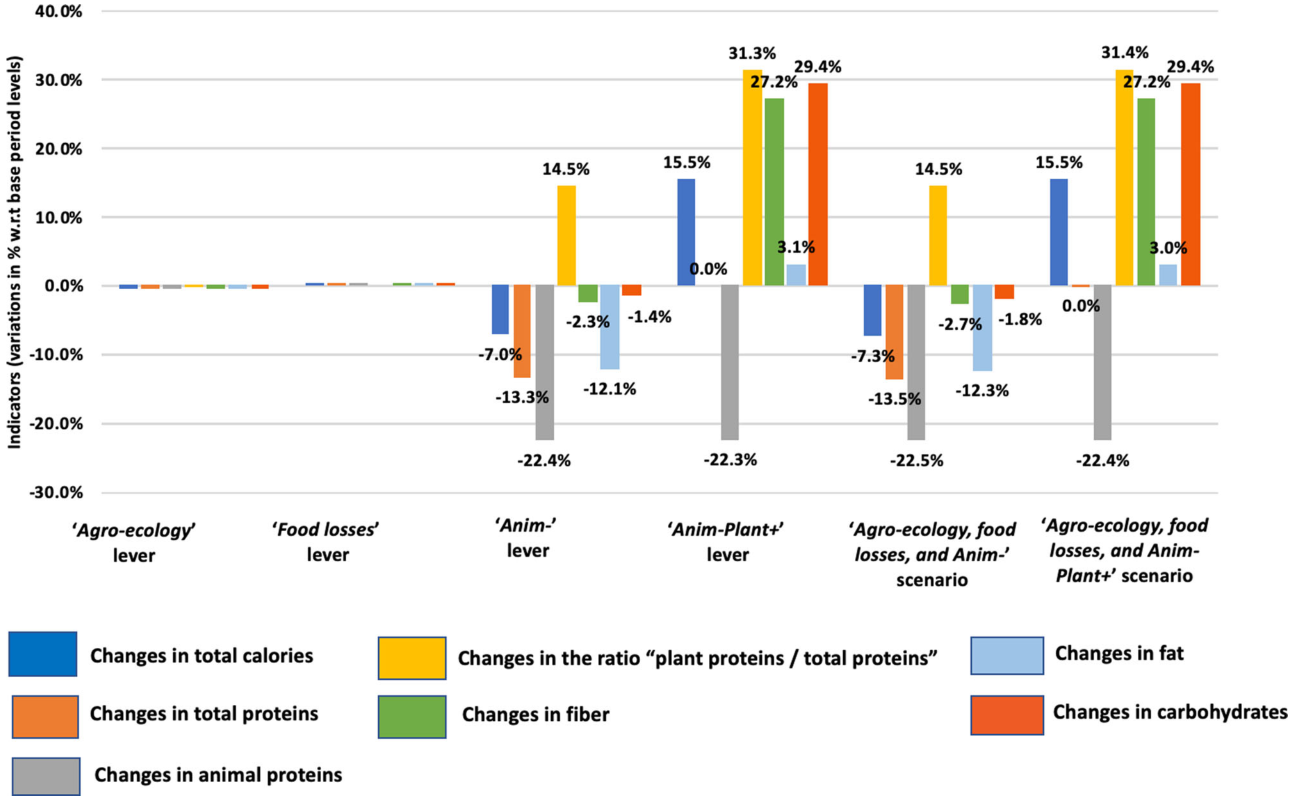

Fig. 4 The improvement in the nutritional indicators used to assess the quality of European food consumption is fully determined by the third action lever regarding the shift in demand toward less animal-based products. Impacts of the three levers and the two scenarios on the nutritional indicators of European consumption of the three food aggregates, in percent with respect to indicator values in the base period. The three levers and the two scenarios are described in Table 2. The colors are used to distinguish the different nutritional indicators: changes in total calories are in blue; changes in total proteins are in brown; changes in animal proteins are in gray; changes in the ratio of plant proteins on total proteins are in orange; changes in fiber are in green; changes in fat are in blue; and changes in carbohydrates are in red. For more details on calculating the different nutritional indicators, see Methods and the Archive[34].

first. Similarly, the biodiversity damage indicator diminishes by 11.3% in 'Anim-Plant+' vs. 27.6% in 'Anim-'. The 'Anim-Pant+' lever variant increases the share of plant proteins to total proteins from 0.42 to 0.55. It also increases the fiber intake by 27.2%. However, total calories, fat, and carbohydrates increase (because our plant aggregate includes a large part of calorie-dense foods).

In summary, the compensation for the decrease in the demand for animal products by an increase in the demand for plant products benefits European producers of food/feed field crops who produce more at a higher price. Climate and biodiversity benefits are positive but lower relative to the variant without compensation. Food expenditures decrease but European consumers spend more for a higher calorie intake in the variant with compensation than in the variant without compensation.

Impacts of jointly implementing the three levers ('agro-ecology, food losses, and Anim-' and 'agro-ecology, food losses, and Anim-Plant+'). Jointly implementing the three levers of agro-ecology, food losses, and diets in the 'agro-ecology, food losses, and Anim-' scenario leads to a reduction in farmland areas devoted to food/feed field crops (0.9 Mha) and forages (2.2 Mha) because the increase in high-diversity landscape features (6.8 Mha) included in the agro-ecology lever is greater than total farmland expansion (3.6 Mha).

This combined scenario leads to declines in domestic production for the three products. For both ruminants and monogastrics, the negative impact on producer prices due to lower food losses and diet shifts outweighs the positive impact of agro-ecology, leading to producer price reductions of 14.7% for ruminants and 16.7% for monogastrics. The reverse occurs for plants, for which producer prices increase by 10.1%. As a result, revenue declines are more severe for ruminant producers (28.7%) and monogastric producers (26.7%), in both cases under the combined impact of negative quantity and price effects, than for food/feed field crops producers (7.5%), for which the negative quantity effect is partly counterbalanced by a positive price effect.

Domestic purchases of the three aggregates decline, to a greater extent for ruminant and monogastric products than for plant products. Food consumption decreases are lower than purchase declines for the three products because of the food loss reduction shock. Consumer price changes are moderate (negative for the two animal products and positive for plant products) under the assumption of constant margins between producer and consumer prices. Combined effects on quantities and prices reduce food expenditures by 21.0%.

European net imports of plant products increase by 30.3% boosted by the European producer price increase of food/feed field crops, and European net exports of animal products increase (by 73.3% for ruminant products and 83.4% for monogastric products) favored by an improved price competitiveness of European animal products. This finding means that the positive effect of agro-ecology on net imports of plant products outweighs the negative impact of the two other levers. It is the opposite for net exports of ruminant and monogastric products, with a dominant positive effect of the reduction in food losses and animal product demand over agro-ecology.

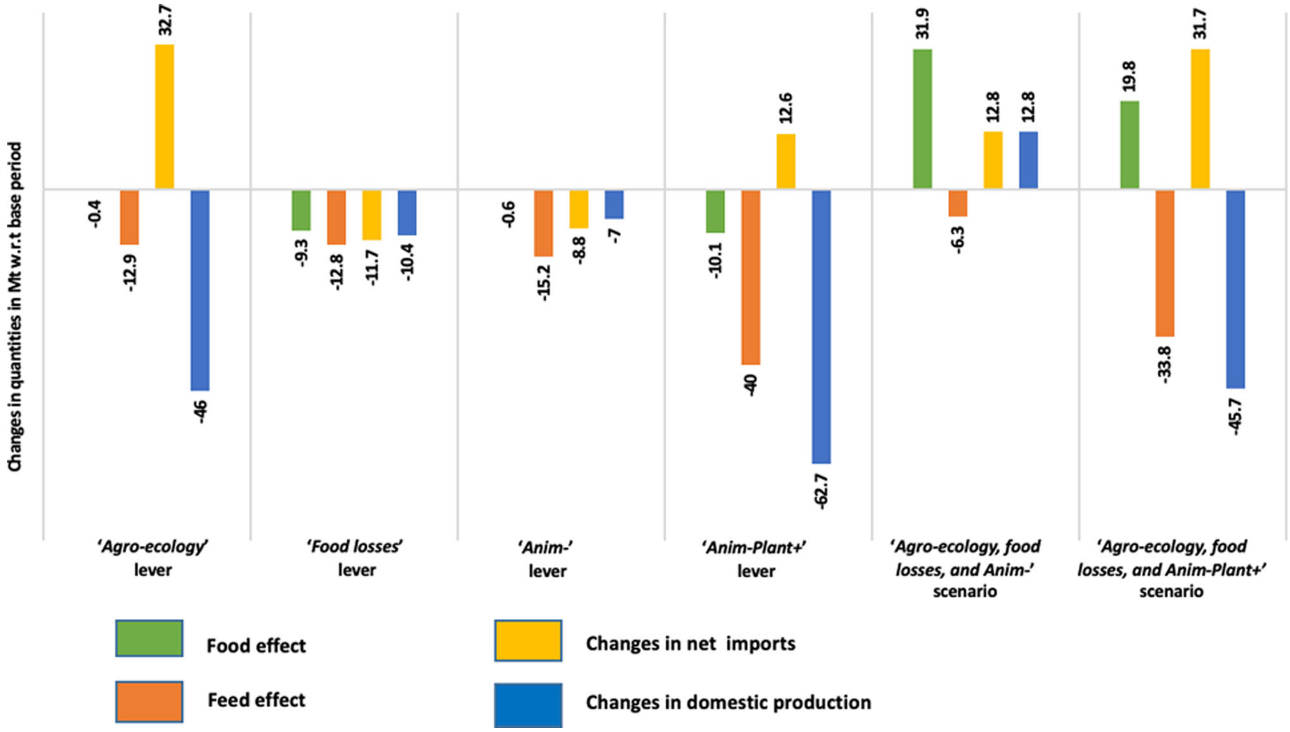

Fig. 5 Impacts of the three levers and the two scenarios on the European market of plant-based products; variations in Mt with respect to base period levels. The three levers and the two scenarios are described in Table 2. The food and feed effects are in green and brown, respectively; changes in net imports are in orange and changes in domestic production are in blue. The 'agro-ecology' lever leads to a very small negative food effect (minus 0.4%) and a much more severe negative feed effect (minus 12.9%); net imports of plant products increase by 32.7% while domestic production decreases by 46.0%. Food is the quantity of plant products at the farm gate used for domestic consumption; it includes all post-harvest losses that occur between the farm gate and the final consumption stage.

The combination of the three levers reduce the GHGE of European consumption of our three aggregates by 198 Mt CO_2 eq under the combined effect of decreases in domestic production-based emissions and emissions embedded in trade. The biodiversity damage indicator decreases by 53.4% under the combined effect of reductions in damage linked to domestic production and trade changes. The animal demand reduction shock of the 'agro-ecology, food losses, and Anim-' scenario changes the nutritional indicators in the same proportions as the 'Anim-' lever variant. Overall, European consumers benefit thus from more balanced and less expensive food consumption.

Relative to the 'agro-ecology, food losses, and Anim-' scenario, the 'agro-ecology, food losses, and Anim-Plant+' scenario increases the domestic production and producer prices of food/feed field crops, as well as purchases, consumption and consumer prices of plant products. The shift to the right in the domestic demand function of plant products is sufficient to increase the revenues of plant producers by 10.8% with respect to the base period level. This improvement in the economic situation of plant producers has a cost for European consumers since food expenditures decrease substantially less in the iso-protein compensation scenario (8.8%) than in the no-compensation scenario (21.0%). The two scenarios have similar effects on the European markets of animal products.

Relative to the 'agro-ecology, food losses, and Anim-' scenario, the improvement of the GHGE and biodiversity footprint of the European food system is lower in the iso-protein compensation scenario. This result is not due to emission and damage increases from the consumption of animal products, which is identical in both scenarios. This result is mainly due to increases in production and net imports of plant products that lead to higher emissions and damage both domestically and through net trade. Relative to the 'agro-ecology, food losses, and Anim-' scenario, the iso-protein compensation scenario makes it possible to increase the share of plant proteins to total proteins and the fiber intake. However, these positive nutritional outcomes are achieved at the expense of increases in calories, fat, and carbohydrates.

Discussion

The simulation results of the 'agro-ecology' lever on production levels, producer prices, and trade are in line with those of other studies focused on this aspect of the EGD alone[18–24].

Agricultural land supply elasticity with respect to land price is a key parameter in determining the market and non-market impacts of the 'agro-ecology' lever, notably because European farmers react to the constraint of increasing high-diversity landscape features by expanding total farmland area. As a result, assuming that the total farmland area is fixed overestimates the negative impacts on production levels and the positive impacts on producer prices. This assumption also results in overestimates of the climate and biodiversity benefits. On the other side, this discussion highlights that there might be environmental reasons for not allowing European agricultural land to expand into forests. In this paper, we used the literature review developed by Tabeau et al.[40] that led us to set the price elasticity of agricultural land supply in the EU to 0.05 (the sensitivity analysis displayed in the Archive[34] presents the consequences of a zero fixation of this elasticity). In the same way, studies such as those of Beckman et al.[18,19] that assumed that the total farmland area was reduced by 10% because of the constraint of increased high-diversity landscape features overestimated the impacts on production levels and producer prices by ignoring that part of the

European farmland area is currently already devoted to such features[41].

Our analysis of the 'agro-ecology' lever highlights that it is important to consider how producer price changes are transmitted to consumer prices. Other studies do not consider or present changes in consumer prices[20,21], or the information is vague focusing only on market prices without precisely defining them[18,19]. The negative effects of the 'agro-ecology' lever for European consumers are dampened in our analysis, which explicitly captures the fact that the cost of agricultural products is only a small part of food prices. However, this result depends on the assumption of constant margins between producer and consumer prices. As noted by Sheldon[42], "vertical contracting between agricultural suppliers and downstream food processors and vertical restraints between food processors and retailers" may affect the transmission of prices in the food chain. A more sophisticated model distinguishing the different actors of the food chain would be required to address these issues.

The simulation results show that the 'agro-ecology' lever of the EGD makes it possible to reduce GHGE of European food consumption and biodiversity damage in European agro-ecosystems even if increases in emissions and damage embedded in trade reduce the domestic environmental benefits associated with the extensification of agricultural practices. Matthews[43] also concludes that the leakage effects of climate policy in European agriculture would be strong with however wide variability according to studies. Because it does not substantially modify absolute and relative consumer prices and thus food consumption patterns, the lever of agro-ecological practices is not accompanied by an improvement in the nutritional quality of European food consumption.

Reducing post-harvest losses increases climate and biodiversity benefits but has no impact on the different nutritional indicators. The order of magnitude of the decline in the GHGE of European food consumption is consistent with that simulated by Scherhaufer et al.[44], and Read et al.[45] Reducing post-harvest food losses benefits European consumers at the expense of European producers who face reduced food demand[39]. Estimates of food losses along the food chain are uncertain[46], even in a high-income region such as the EU[47–49]. Reducing food losses requires strong public policies and substantial changes in actors' behaviors throughout the whole food chain[50,51]. Despite European, national, and local initiatives[52], there is no evidence that food losses are declining in the EU[53].

The improvement in the nutritional indicators used to assess the quality of European food consumption is fully determined by the third action lever regarding the shift in demand toward less animal-based products. However, such a shift raises two potential nutritional issues: a decrease in total protein availability in the 'agro-ecology, food losses, and Anim-' scenario, where the decrease in the demand for animal products is not compensated by an increase in the demand for plant products; and an increase in calorie, fat, and carbohydrate intake in the 'agro-ecology, food losses, and Anim-Plant+' scenario, where the decrease in the demand for animal products is compensated by an iso-protein increase in the demand for plant products. Further improving the nutritional quality of the European diet would require increasing only protein-dense plant products such as legumes[54,55] within the aggregate of plant-based products but not all products within this aggregate. Improvements would also require reducing energy-dense products within this aggregate, for example, through product reformulation[56,57] (which means reducing the content in fat and carbohydrates of most foods included in our plant product aggregate). While the first solution can be addressed in a revised version of our model that would differentiate legumes from other plant products, the reformulation of food products would require a much more complex modeling framework that would notably distinguish the processing stage of the European food chain.

Shifting consumption patterns toward less animal-based products provides climate[1,13] and biodiversity[2] benefits. The lower the compensation for the decrease in the demand for animal products is from increasing the demand for plant products, the higher the climate and biodiversity benefits. However, this diet shift leads to a strong decrease in livestock producer revenues that will induce a deep restructuring of livestock sectors. Strong public policy measures will be necessary to enable their adaptation[58]. Plant producers will experience both a negative feed effect (fewer plant products for animal feed) and a positive food effect that will be higher if decreased consumer preferences for animal-based products are accompanied by greater preferences for plant-based products.

Our simulation results show that the three EGD levers of agro-ecological practices, the reduction of post-harvest losses, and the dietary changes toward diets containing lower quantities of animal-based products contribute to reducing the climate and biodiversity footprint of the European food system. In contrast, only a reduction in the demand for animal-based products substantially affects the nutritional indicators since the two other levers do not truly change European food consumption patterns. Additional nutritional benefits—that have not been simulated—would follow from an improvement in the nutritional quality of the plant product aggregate. Furthermore, our analysis does not include the F&V sector. This omission limits the possibility of fully simulating healthier diets in the EU. In fact, a more relevant scenario from a nutritional point of view would be to compensate, at least partially, the decrease in the demand for animal-based products with an increase in the F&V demand that is rising in the EU but remains below nutritional recommendations[59].

The three action levers considered separately would have strong and contrasting impacts on European food trade and the resulting GHGE and biodiversity damage embedded in trade. Adopting agro-ecological practices substantially deteriorates the European food balance and induces strong GHGE and biodiversity damage embedded in trade. In contrast, diminishing food losses and shifting food consumption decrease net imports of plant products and increase net exports of animal products, and therefore reduce GHGE and biodiversity damage embedded in trade.

The market and non-market effects of the EGD depend on key parameter estimates related to elasticities of agricultural land supply and demands, product supplies, product demands, and trade. These parameters affect changes in three key intermediate endogenous variables (agricultural land uses, feed uses, and trade) that ultimately determine the impacts on the quantities produced and purchased, as well as on producer and consumer prices. The sensitivity analysis displayed in the Archive[34] suggests that the simulation results are reasonably robust for plausible ranges of these elasticity parameters. It shows that the simulation results are more sensitive to the choice of trade parameters than to the calibration of domestic supply and demand parameters.

Our analysis has obvious limitations. The analytical framework integrated agricultural land use, agricultural production, and food and feed demand but relied on only three food aggregates. Therefore, it was not possible to make explicit distinctions, for example, between ruminant meat and milk markets or between cereals and legumes in plant-based products. Furthermore, the F&V was not included. Environmental indicators are easy to interpret but crude. The assessment of economic results is incomplete specifically because we have not estimated changes in production costs and consumer welfare. Finally, we have assumed that consumption changes were driven by spontaneous modifications of consumer preferences and have not considered how public policy instruments could achieve the three shocks. Obviously, this would have consequences on market, welfare, and non-market impacts depending on policy design and redistribution rules.

Despite uncertainties in the elasticity estimates and limitations of the model, we believe that our analysis relying on basic and well-established economic theory is sufficiently robust to highlight the following concluding messages. The EGD will have different market and non-market impacts on the European food system depending on the adoption rates of the three levers of agro-ecology, food losses, and diets. In particular, the lever of agro-ecological practices will lead to different impacts relative to a scenario including lower post-harvest losses and lower consumption of animal products. This lever of agro-ecology will have a minor impact on consumption expenditures and a positive (respectively, negative) impact on producer revenues when the positive producer price effect outweighs (is outweighed by) the negative quantity effect. This lever has only limited climate and biodiversity benefits because of the increases in GHGE and biodiversity damage embedded in trade. Using the two other levers of reducing food losses and shifting diets jointly will further improve the climate and biodiversity benefits of European food consumption, to the benefit of European consumers (lower food expenditures) but to the detriment of livestock producers (lower revenues).

Methods

The market model. The model is a partial equilibrium economic model of the European food system (EU-27) calibrated for the year “2019” (arithmetic average of the three years 2018, 2019, and 2020). Starting from the bottom of Fig. 1, the total agricultural land supply is endogenous and split into three land demand components: two endogenous productive uses (food/feed field crops and forages that include permanent grasslands, temporary grasslands, and non-herbaceous fodder) and one exogenous climatic and environmental use corresponding to high-diversity landscape features. Food/feed field crops are used to produce (i) food for human consumption through the plant-based product aggregate that includes cereals, oilseeds, protein crops, rice, sugar beets, and potatoes and (ii) feed for both ruminants and monogastrics. Forages are used for feeding ruminant cattle that produces the aggregate of ruminant-based products at the food demand stage. This aggregate encompasses milk, dairy products, and ruminant meat. The rationality of this aggregation lies on the supply side, where milk and meat are joint products[60]. Monogastrics—which do not consume forages—include pork, poultry, and eggs, and account for the aggregate of monogastric-based products at the food demand level. This food demand aggregate encompasses fresh and processed pork meat as well as poultry- and egg-based products.

International trade occurs through net trade flows. In the initial situation, the EU is a net importer of food/feed field crop products and a net exporter of ruminant and monogastric products.

Post-harvest food losses are divided into those that occur between the farm and food purchases and those that occur at the final consumption stage (consumers consume only part of their purchases).

Model resolution, endogenous, and exogenous variables. For the three product aggregates, the model equalizes supply (domestic plus net trade) to demand (sum of food demand, feed demand in the case of food/feed field crops, and other non-food demand assumed constant at base period levels). It also equalizes agricultural land supply to demand (land areas devoted to food/feed field crops, forages, and high-diversity landscape features).

Product supplies were derived from three restricted quadratic profit functions (one for each production sector). The food/feed field crop and forage land demand functions were also derived from the food/feed field crop and ruminant profit functions, respectively. To simplify the approach, we assumed that both the ruminant and monogastric sectors bought all concentrated feed (cereals, oilseeds, etc.) from the food/feed field crop sector (domestic or foreign). To reduce the number of parameters to calibrate, we followed a standard approach[61,62] by assuming a Leontief technology (fixed input/output coefficients) with respect to concentrated feed for both ruminants and monogastrics.

Net trade was modeled in a simplified way assuming that net trade flows of each group of products depended on the corresponding European price only (positively for plant products for which the EU was a net importer in the base period and negatively for both ruminant and monogastric products for which the EU was a net exporter in the base period). This modeling does not fix the net trade status of a group of products to that of the base period. For example, the EU may become a net exporter of plant products in a scenario leading to a sufficiently strong decrease in their producer price.

The food demands for the three groups of products were derived from a separable quadratic utility function leading to a three-equation food demand system depending on the three final demand prices. Differences between consumer and producer prices were modeled through constant margins. Post-harvest losses were included in the form of loss coefficients in the three food demand equations.

At equilibrium, the model determines the three consumer prices and the land price, from which we derive the quantities that are domestically purchased and consumed (food and feed), produced, and traded, as well as agricultural land uses, producer prices, producer revenues, and consumer expenditures. Quantity variables are then used to calculate the climate, biodiversity and nutrition indicators.

The exogenous variables are (i) the proportion of agricultural land devoted to high-diversity landscape features, (ii) the uses of pesticides and fertilizers in both the food/feed field crop and ruminant sectors (expressed in the form of the use of these chemical inputs per hectare of food/feed field crops and forages, respectively), (iii) the cost of veterinary expenditures in both the ruminant and monogastric sectors, (iv) the post-harvest loss percentages in the food chain and at the final consumption stage for the three product aggregates, and (v) the consumer preferences for each product aggregate implying that, for example, shifting diets toward less animal-based products can be modeled through a decrease in base period demand levels for both ruminant and monogastric products.

Variable values in the initial situation (base period). The model’s equations summarized in Supplementary Note 1 define the different variables entered in the initial equilibrium situation and the different parameters to be calibrated. Supplementary Note 1 also displays measurement units for variables, and references and data sources for both variables and parameters. The initial values of the variables and the estimated parameters are listed in the calibration table of the Archive[34].

Production and trade data were obtained from various Eurostat databases for the EU-27 over the period of 2018–2020, including land uses and yields for food/feed field crops and forages; production levels of food/feed field crops, ruminants and monogastrics; net trade flows; and the shares of total production of food/feed field crops used for food, feeding ruminants, and feeding monogastrics. Since the three productions considered are aggregates, averages were weighted when necessary by either surfaces (yields) or calories (ruminant and monogastric productions, feed and food shares, and net trade flows).

The ruminant aggregate is expressed in Mt carcass weight equivalent (cwe). Milk production is converted into cwe via calories assuming that one kilogram (kg) of milk is equal to 657 calories and that one kg of ruminant meat is equal to 2457 calories. The monogastric aggregate is defined in the same way with one kg of pork accounting for 2300 calories, one kg of poultry accounting for 2190 calories, and one kg of eggs accounting for 2190 calories. Trade data are estimated using the same aggregation rules. Information on chemical input uses in the three production sectors was calculated from data of the European Farm Accountancy Data Network (FADN) for 2017 and 2018 (the most recent years available). Inputs are expressed in Euros. We assumed that chemical input prices remain unchanged at initial period levels, which makes it possible to simulate the consequences of changes in quantities through changes in values. This assumption was implied by the lack of information on the parameters (price elasticities) of chemical input supply functions.

Food purchases, post-harvest losses, and food consumption levels were more complicated to calculate as the modeling of any food system is still hindered by the difficulty of matching production and consumption data in a consistent way. This challenge can be explained by various factors: heterogeneity of data sources; discrepancy in the way products are categorized, multiple uses of raw materials; lack of processing and waste/loss data; etc. The standard solution to address this challenge is to work with apparent consumption data (domestic production plus imports and stock variation minus exports and non-food uses). This solution provides estimates of quantities consumed, which do not consider processing, distribution, and consumption losses. To address this issue, we proceeded as follows. In the first stage, we calculated the average quantities consumed for each food aggregate (in Mt) from national surveys available on the European Food Safety Authority website (https://www.efsa.europa.eu/en/data-report/food-consumption-data). In the second stage, we started in the opposite direction by using production data and applying (i) conversion rates to go from raw materials to edible products (for example, to go from carcass to meat) and (ii) loss coefficients based on estimates provided by different studies[45,49,63]. Losses considered in the analysis are post-harvest losses that occur after primary production (thus excluding pre-harvest losses that were assumed constant in percent at based period levels). We distinguished two types of loss coefficients: one for the processing, manufacturing, distribution, and retail stages, and one for the final consumption stage. The final consumption loss coefficients made it possible to distinguish the quantities purchased by consumers from those actually consumed. Consumers' food expenditures were calculated based on purchases. In the scenarios involving lower post-harvest losses, we assumed that the two loss coefficients of each aggregate were reduced by the same percentage. The reductions were applied to the edible part of losses. At this stage, it is important to emphasize that food loss estimates vary substantially depending on the study (from 158 to 298 kg/year/capita for the EU according to Corrado and Sala[48]). As a result, in the third stage, we addressed the outcomes of steps one and two and adjusted the loss coefficients and food consumption data to ensure consistency between the quantities produced, purchased, and consumed.

Producer price data were derived from Eurostat databases (averages for the EU-27 over the three-year period 2018–2020). Eurostat publicly provides consumer price indices but not consumer price levels. To overcome this issue, we took the following steps. We started with French data from the Kantar World Panel (https://www.kantar.com/) that have already been described and used to calculate French food prices[64,65]. In the second step, we calculated the average consumer prices of each food aggregate by weighting the price of each component of this aggregate by the quantity consumed. Finally, to estimate representative European consumer prices, we applied a correction coefficient to the second-step estimates to express the relative position of French prices relative to European prices (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Comparative_price_levels_for_food,_beverages_and_tobacco).

Parameter calibration. The parameters of supply, trade, and derived and final demand equations were calculated from estimates of corresponding elasticities, except for the equation constants that were calibrated to reproduce the quantity and price equilibrium in the initial situation. The references used to estimate elasticities are presented in Supplementary Note 1 and in the calibration table of the Archive[34]. In the few cases where elasticity information was lacking in the literature, we made arbitrary but explicit assumptions based on expert opinion that are also displayed in Supplementary Note 1 and the Archive[34]. Sensitivity tests presented in the Archive[34] were performed to check the simulation results' robustness to elasticity values retained in the scenarios.

Nutrition, climate, and biodiversity indicators. The nutritional quality of food consumption was assessed on the basis of a set of indicators: total calories, total proteins, animal proteins, share of plant proteins in total proteins, fiber, fat, and carbohydrates. The information required for this purpose was calculated from the Ciqual Nutrient Database (https://ciqual.anses.fr/), which made it possible to calculate these indicators for 100 g of each food aggregate. Food consumption indicators were then obtained by multiplying the nutrient contents by the quantities actually consumed in each scenario. At this stage, it is worth noting that we did not assess the nutritional quality of the European average diet but only of the European consumption of the three food product aggregates as several food products, notably F&V, were not included in our analysis. Calculations are detailed in the "Non-Market impact coefficients" file of the Archive[34].

The GHGE of European food consumption of the three aggregates in the initial situation and the different levers and scenarios were calculated at the farm gate from the work of Crenna et al.[2]. These authors provided average environmental impacts, including climate impacts, for 32 food products. This information allowed the calculation of GHGE associated with each of our three food aggregates. However, Crenna et al.[2] did not differentiate GHGE at the agricultural production stage according to farming practices, while it is clear that any GHGE assessment of the EGD must take into account how more agro-ecological farming practices impact agricultural GHGE. This step was carried out in this article based on the systematic review of Bellassen et al.[31], who compared the unitary GHGE of agricultural products according to production methods, notably conventional vs. organic. Bellassen et al.[31] concluded that on average in the EU, unitary GHGE of crops relying on organic practices were 20% lower than those associated with conventional practices. We then assumed that unitary GHGE of food/feed field crops relying on agro-ecological practices (per kg of product leaving the farm) were 10% lower than those associated with conventional practices. Bellassen et al.[31] also concluded that unitary GHGE of ruminants of monogastrics were equal for conventional and agro-ecological practices. We made the same assumption. Regarding product origin, we assumed (i) that the GHGE of European imports of plant products were 20% higher than those of food/feed field crops produced in the EU with conventional farm practices and (ii) that the GHGE of European net exports of ruminant and monogastric products were equal to those of quantities sold on the domestic market. At this stage, it is important to note (i) that our estimates of GHGE do not include the impacts of the levers and scenarios on carbon sinks through land use, land-use change and forestry (LULUCF) and (ii) that the choice of percentages of 10% and 20% is an assumption based on expert opinion since the literature review does not provide information for agro-ecological agriculture. Calculations are detailed in the "Non-Market impact coefficients" file of Archive 3.1[34].

Assessing the impacts of the EGD on biodiversity is complex[66]. Despite a large number of studies, there is no consensus on the methods and indicators that can be used for such an assessment. In this paper, we evaluated the impacts on biodiversity of scenarios that encompass changes in agricultural land uses, agricultural practices, agricultural production levels, net trade flows, food losses, and food purchases and consumptions. To that end, we used the works of Knudsen et al.[32,33]. These authors provided information on the potential damage to biodiversity per unit of area according to the type of land use (crops vs. different forages), agricultural production methods (conventional vs. organic), and product origin (European vs. tropical). The reference land use type was chosen to be forest with a damage to biodiversity equal, by construction, to zero. The limitations of the resulting indicators were described in Knudsen et al.[32]. They are mainly related to the partial assessment of some biodiversity components (for example, because they do not include arthropods, birds, or soil biodiversity). Specifically, we assessed the impacts of levers and scenarios on biodiversity as follows. In the first step, we distinguished land areas corresponding to (i) food/feed field crops devoted to domestic uses, (ii) forages devoted to domestic uses of ruminants, (iii) high-diversity landscape features, (iv) net imports of plant products, and (v) food/feed field crops and forages devoted to net exports of ruminant and monogastric products. In the second step, we multiplied these five land uses by the associated biodiversity damage coefficients. For food/feed field crop and forage land areas devoted to domestic uses and net exports of animal products, biodiversity damage coefficients were assumed to be 10% lower in the scenarios relying on agro-ecological farm practices than in the base period with conventional farm practices. As for GHGE, we thus assumed that the biodiversity damage coefficients of agro-ecological practices were between the coefficients of conventional and organic practices. Calculations are detailed in the "Non-Market impact coefficients" file of the Archive[34].

Scenarios. See Table 1 (and Supplementary Note 2 for details).

Data availability

The references and data sources used to calibrate the model (parameters and variable values in the initial situation) are displayed in Archive 3.1 available from the Archive[34]: https://zenodo.org/record/8360349.

Code availability

The model was solved using Excel. Archive 3.1 available from the Archive[34]: https://zenodo.org/record/8360349 allows the reproduction of all simulations. After a short use notice, Archive 3.1 successively presents the model data and parameters; the way the climate, biodiversity, and nutrition impacts were calculated; the simulation results of the different levers and scenarios; and a synthesis table summarizing the market and non-market impacts of the levers and scenarios. This Archive also includes a sensitivity analysis (Archive 3.2).

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Author contributions

H.G., L-G.S., C.D.-D., and V.R. designed the research, developed the model, and performed the analysis. H.G. and L.-G.S. drafted the paper with input from C.D.-D. and V.R. All authors participated in the paper editing.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Louis-Georges Soler.

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