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Unveiling the economic and environmental impact of policies to promote animal feed for a circular food system

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ABSTRACT

Feeding animals with low-opportunity-cost feed (LCF) such as agricultural residues and by-products, and better use of local feed resources are discussed as strategies for transitioning towards more circular food systems. This study incorporates technical characteristics of livestock production into a global economic model to investigate the economic and environmental effects of these circular food system transitions in the European Union (EU27) in relation to the policies used to reach them. We compare the impact of LCF stimulating subsidies, budget-neutrality and import tariffs stimulating domestic sourcing. Providing only subsidies increases circularity and agricultural wages (0.1 to 0.3%), but also animal production (0.1 to 1.5%) with negative indirect effects on land use (0.3 to 1.1%) and emissions (1.3 to 8.0%). Promoting the use of LCF through budget-neutral subsidies and domestic feed sourcing through import tariffs, decreases animal production (-0.1 to -1.6%) and GHG emissions in agriculture (-0.4 to -6.0%). Synergy effects from subsidising DDGS, a biofuel by-product used as feed, increase biofuel production, positively contributing to lower GHG emissions (-0.3 to -0.6%) in 2030. However, budget-neutrality drives land use up (0.1 to 0.5%) while decreasing agricultural wages (-0.1 to -0.3%). This calls for complementary policies to mitigate drawbacks and enhance benefits of a more circular agri-food system in the EU27 in 2030.

1. Introduction

Animal-sourced foods (ASF) dominate the environmental impacts of our food system (ASF) (Hilborn et al., 2018; Herrero et al., 2015; Poore and Nemecek, 2018; Steinfeld et al., 2006). Animal feed plays a major role (Salami et al., 2019), accounting for 45% of greenhouse gas (GHG) emissions from the livestock sector (Gerber et al., 2013), occupying 70% of the global agricultural land (Steinfeld et al., 2006) and utilising 30–40% of human-edible feed crops (Erb et al., 2012). As historically ASF demand increases with rising incomes (Cole and McCoskey, 2013; Schader et al., 2015), expected global population and prosperity growth cause serious environmental concerns. To tackle this challenge, current studies identify solutions in more circular agri-food systems with a particular role for livestock (Röös et al., 2017; van Hal et al., 2019; Van Zanten et al., 2019; De Boer and van Ittersum, 2018). Low-opportunity-cost feed (LCF) such as discarded biomass, plant residues, by-products, and food loss and waste, typically compete less for land or natural resources and represent an important human-inedible feed resource for livestock production (Salami et al., 2019). Upcycling LCF to replace human-edible feed crops in animal diets represents a first strategy for transitioning towards a more circular food system as it mitigates food-feed competition and could contribute to reducing the environmental impacts of global livestock production (van Hal et al., 2019). On top of this, a second strategy for circularity consists in feeding livestock through a better use of local resources (De Schutter, 2017; Stephens et al., 2020; European Commission, 2020). Decreasing feed imports in EU27 can reduce the negative environmental externalities associated with feed production and trade (IPES-Food, 2022), simultaneously increasing the availability and reuse of domestic LCF (Van Zanten et al., 2019).

Despite the recognized environmental benefits of circular agri-food systems (Röös et al., 2017; van Hal et al., 2019; Van Zanten et al., 2019; De Boer and van Ittersum, 2018), limited knowledge exists on the economic implications of policy interventions that foster this transition when market mechanism are taken into account (Ominski et al., 2021). Increasing the reuse of LCF while simultaneously decreasing feed

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imports alters demand for agricultural residues and industrial by-products (such as oilcakes, distillers' dried grains (DDGS) or molasses) suitable as animal feed, affecting agricultural and industrial production systems. Substituting compound feed and feed crops with LCF may jeopardise the income of stakeholders in the agricultural sector, including livestock and animal feed producers. A higher demand for domestic resources and agricultural residues may drive up crop production, intensifying demand for land, chemical fertilizers use, and GHG emissions. Similarly, a higher use of industrial by-products (e.g. from biofuels) as animal feed risks to increase production and supply of primary commodities generating by-products, increasing GHG emissions. In the absence of a parallel increase in demand this may reduce sectoral revenues and in turn affect wages. Effective design of policies thus requires an economy-wide assessment of the potential consequences of transitioning towards a circular food system.

The EU27 stands actively as global promoter of circular policies (European Commission, 2020; 2021), but no official policy has yet been established to achieve circularity within agri-food systems. Policies such as tax incentives for reused products, environmentally-motivated subsidies on loss/waste reuse, and recycled content requirements can promote resource efficiency (European Commission, 2020), incentivizing more sustainable material reuse (OECD-G20, 2021). However, devising policies for circular food systems transitions requires an interdisciplinary understanding of its technical and socioeconomic consequences.

Technical studies (van Hal et al., 2019; van Selm et al., 2022; Van Zanten et al., 2019) outline the possibilities of using LCF as feed or closing nutrient cycles through circular systems (Wiel et al., 2019). However, biophysical optimization models (Muscat et al., 2021; Frehner et al., 2022; van Zanten et al., 2023; Van Selm et al., 2023) frequently employed to explore the effects of adopting circularity, ignore opportunity costs, price changes, and other market responses crucial for devising the effect that policy interventions could have in practice. On the other hand, economic assessments of circular food systems (Pagotto and Halog, 2016; Winning et al., 2017; Donati et al., 2020; Donner et al., 2020) are rather scarce, and often overlook biophysical and technical constraints of circularity as they often rely on economic money-based frameworks. Bridging disciplines, additional studies (Salemdeeb et al., 2017; Tarifouris and Martin, 2021; Awasthi et al., 2022) linked economic optimization procedures or life-cycle assessments (LCA) to technical inquiries on circularity. Several economywide models (Godzinski, 2015; Fujimori et al., 2017; Winning et al., 2017; Stadler et al., 2018) include waste management and material recovery but primarily focus on the upcycling of discarded metals, providing no enquiry on biomass reuse. Van Meijl et al. (2018) incorporate various biobased residues into a global economic framework to formulate policies that promote the use of secondary biomass for bioenergy, but such framework does not account for the potential reuse of these residues as animal feed.

Global general equilibrium (GE) models are useful for analysing circular economy policies that involve multiple agents, countries, and integrated sectors within a market environment (McCarthy et al., 2018; Winning et al., 2017). GE models depict interactions amongst producers along global supply chains and consumer responses to changing prices and incomes, analysing endogenous economic-wide price effects and socioeconomic and environmental impacts crucial for assessing the consequences of circularity measures. However, GE models do not fully account for biophysical or nutritional balances (Pauliuk et al., 2017; Pyka et al., 2022) nor livestock feeding constraints necessary for quantifying the implications of circular policies targeting livestock production. As GE models might misrepresent biophysical flows during simulations (Delzeit et al., 2020; Pyka et al., 2022), their standard framework impedes the accounting of technical features and dietary constrains of different types of livestock when policies changing feed supply and livestock production are applied. While previous studies (Britz and van der Mensbrugghe, 2018; Chepeliev, 2022; Gatto et al., 2023) have integrated physical biomass data into GE models, none has investigated circular food system solutions including a detailed technical modelling of livestock systems.

In this study, we combine economic and technical modelling of circularity in livestock production to evaluate the impact of circular agri-food policies in the EU27. A novelty of this research is the enhancement of a global GE model with physical biomass tracing and improved modelling of the technical requirements of livestock production and feeding. This extension of existing work aims to account for the dietary constraints and nutritional requirements of various livestock species while capturing the behavioural responses of economic actors along global supply chains when policies promote LCF use as feed. In substituting primary feed with LCF we verify feed-conversion-ratios (FCR) and energy supply in animal diets, describing and contextualising cases where energy supply and livestock requirements are imbalanced. This makes a first step towards integrating biophysical balances and livestock feeding constraints into GE models, which is crucial for evaluating circular agri-food system policies.

2. Methods

2.1. Modelling circular flows in livestock production systems

To investigate the impact of policies towards more circular livestock systems in EU27, we use a global GE model. GE models provide economy-wide coverage, offering a detailed representation of value flows throughout the economy which allows an in-depth understanding of economic adjustments when policies favouring the use of LCF are implemented. For this study we use MAGNET[1] (Modular Applied GeNeral Equilibrium Tool), a recursive dynamic variant of the well-known Global Trade Analysis Project (GTAP) model (Corong et al., 2017), with a specific focus on agri-food sectors and the rest of the bioeconomy (Van Meijl et al., 2006, Woltjer et al., 2014. Van Meijl et al. 2020a; 2020b, Leclere et al., 2020, Gatto et al., 2023). The version of MAGNET utilised for this study is based on the GTAP 10 database (Aguiar et al., 2019). We extended the model with livestock and feed specific parameters to capture the dietary constraints and nutritional requirements of various livestock species while modelling the implications of policies to promote the use of LCF and domestic feed sources.

As a first step towards including aforementioned biophysical constraints we distinguished four different feed sectors supplying animal-specific feed based on the suitability of each feed type per livestock category. Livestock type specific feed needs are generally glossed-over by GE models. The additional feed details allow us to calculate the feed-conversion-ratios (FCR), defined as a ratio between feed inputs (Mtons) and livestock production (Mtons), and the energy requirements (gross energy and crude protein) for each livestock sector before and after policies change (detailed calculations are reported in the Supplementary Information). To foster a circular agri-food system, we focus on partly replacing primary feed (i.e. feeding crops and compound feed) with LCF derived from by-products and agricultural residues. By-products comprise oilcakes, molasses, and distillers' dried grains (DDGS) respectively generated from the production of vegetable oils, refined sugars and biofuels, and fishmeal, already largely used as animal feed. Agricultural residues are obtained from agricultural production of several cereals and horticulture commodities. More detailed information on model changes and feed sources in MAGNET is provided in the Supplementary information.

In the integration of physical quantities, we preserve the consistency of a GE framework, while better representing biophysical balances and technical input substitution possibilities. We follow the approach of Gatto et al. (2023) manipulating the standard GTAP-based MAGNET database to obtain a closer representation of material flows. For primary commodities we convert dollar-based quantities to physical units

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[1] For more detailed information visit www.magnet-model.eu

(Mtons) derived from FAOSTAT and World Bank (2014), allowing a complete tracing of physical flows through the global economy. To address nutritional balances in livestock diets we verify our results by calculating FCRs (on the basis of physical quantity, protein, and energy) and compare those to values reported in literature (see Supplementary Information). First, we quantify the production output (Mtons) of livestock sectors in MAGNET, and define the nutritional supply required to produce this output of live animals, in terms of physical quantities, energy, and protein. Then the composition of total feed supplied to each livestock sector is specified, indicating the type of products and their energy and protein content. We then verify that in the processes of substituting primary feed with LCF the overall nutritional supply required for healthy feed remains preserved across model simulations. As we do not fully represent livestock diets by omitting grass, hey, and other types of animal-based by-products and residues, feed-conversion-ratios from literature for certain livestock have been adjusted accordingly. Further model details, nutritional balance calculations, and detailed composition of animals' diets are available in the Supplementary information.

2.2. Towards more circular livestock system scenarios

We use 2020 as base year and define our business-as-usual (BAU) scenario from the IMF-World Economic Outlook projections for GDP and population (IMF, 2022), projecting changes in the global economy towards 2030 (Table 1). We compare our BAU scenario with scenarios simulating different circular policies. To promote higher use of LCF (first strategy) and increase use of domestic feed sources (second strategy) we examine subsidies on LCF use, import tariffs on primary feed (compound feed and feed crops), and combinations of both strategies.

In the base year LCF makes up 10.2% of the total feed supply, while 88.8% of feed is sourced domestically within the EU27. Subsidies can be budget-neutral or non-budget-neutral. Budget-neutral subsidies, in line with the first strategy, are financed through endogenous ad-valorem taxes on domestic non-LCF feed use by livestock sectors in EU27. Non-budget-neutral subsidies are funded from the general government budget, i.e. are non-specific in terms of where the funds are coming from. In the case of budget-neutral subsidies, taxes are levied on domestic compound feed and feed crops. This first of all addresses the fiscal implications of the subsidy, raising the required funds from the livestock sectors benefiting from the subsidy instead of putting this burden on the broader economy. Secondly, by taxing the feed inputs that the circular policy intends to replace, budget-neutrality strengthens the impact of the LCF subsidies. To address the second strategy for circularity we introduce import tariffs to stimulate the use of more local resources of animal feed. Tariffs are levied on imported compound feed and feed crops (cereals and horticultural products) demanded by livestock sectors. Finally, we investigate the combination of LCF subsidies and import tariffs at different levels, addressing two main pillars of circularity: promoting LCF use and stimulating domestic sourcing of animal feed.

First, we investigate which combination of instruments and magnitude of interventions presents the best option for promoting a circular agri-food system without generating significant spillover effects. Following, we analyse the impact of two prototypical policy scenarios in non-food sectors, delving deeper into the economy-wide synergies and trade-offs of circular policies beyond agrifood sectors.

Table 1
Overview of regional macro drivers in our model from 2020 to 2030.

REGION SPECIFIC SHOCK (% change)		Population growth	GDP growth
Macro drivers in BAU scenario^{+}	EU27	0.6	39.1
	BRA	4.8	60.8
	CHN	−0.5	82.8
	USA	3.1	42.9
	SEA	7.2	77.6
	INDA	−2.1	29.0
	NAMO	8.3	58.6
	LAC	7.5	52.4
	REUCA	3.2	48.3
	MENA	11.6	72.5
	SSA	19.4	76.0

Notes: $^{+}$Population and GDP projections from the International Monetary Fund (IMF, 2022) covering the period between 2020 and 2030.
EU27 = European Union-27; BRA = Brazil; CHN = China; USA = United States of America; SEA = Southeast Asia; INDA=Industrialised Asia; NAMO = North America & Oceania; LAC = Latin America & Caribbean; REUCA = Rest of Europe & Central Asia; MENA = Middle East & North Africa; SSA = Sub-Saharan Africa.

3. Results

To address our first research question we test the impact of policies promoting different levels of LCF subsidies, import tariffs, and combinations of both interventions on variables key for a circular agri-food system transition, such as livestock and feed production, land use and GHG emissions. Based on the model's response to different magnitudes of interventions (see Supplementary Information, section "Enhanced modelling of livestock systems and circularity"), we introduce a range of subsidies (both non-budget neutral and budget neutral) varying between 20% and 70% to investigate the first strategy for circularity, and a stand-alone import tariff of 60% to investigate the second strategy. The chosen policy scale is determined by the negligible impact smaller policy changes exert on the analysed variables, and on the fact that stronger policies do not provide additional insights into the interaction between key variables.

3.1. The economic impacts of policies promoting animal feed for a circular food system

Financing subsidies on LCF through general government spending (non-budget-neutral subsidies – blue bars in Fig. 1) increases feed use as livestock production expands in response to the subsidy stimulus (Panel A and D - Fig. 1). The subsidy reduces average LCF costs, increasing its share in total feed (10.2% in baseline) from 12.0% (with a 20% non-budget neutral subsidy) up to a 33.6% (with a 70% non-budget-neutral subsidy) (Panel B - Fig. 1). Regardless of the subsidy level, subsidies to LCF stimulate production of primary crops generating agricultural residues which, due to the expansion of livestock production and thus feed demand, results in a stronger increase in crop production (Panel E - Fig. 1), positively influencing labour demand and average low-skilled wages in agriculture (Panel F – Fig. 1).

Financing LCF subsidies by imposing taxes on compound feed and feed crops (budget-neutral subsidies – orange bars in Fig. 1) decreases livestock feed demand, total feed supply (Panel A - Fig. 1), and livestock production (Panel D - Fig. 1). Taxes increase costs of primary feed inputs, encouraging their replacement with subsidized LCF which increase within total feed supply from a 12.2% (with a 20% subsidy) up to a 40.5% (with a 70% subsidy) (Panel B - Fig. 1). As taxes reduce demand for crops from livestock and compound feed sectors, average unskilled wages in agriculture decline as demand for agricultural products decreases in response to higher prices (+0.1% with a 20% subsidy to +0.7% with a 70% subsidy), and workers transition from relatively more labour-intensive livestock sectors to the crop sectors, which on average rely more on land.

Imposing a high tariff (TAR 60%) on imported feed stimulates the use of domestic feed (Panel C - Fig. 1) while having a small negative impact on livestock production levels (Panel D - Fig. 1). A stand-alone import tariff mainly reduces compound feed due to its relatively large import volume compared to other feed. A lower demand for imported compound feed indirectly increases domestic feed crops demand, resulting in a small increase in total feed use (Panel A – Fig. 1). While not severely affecting livestock production levels (Panel D – Fig. 1) or shares of LCF within total feed (Panel B – Fig. 1), such shift in feed demand can

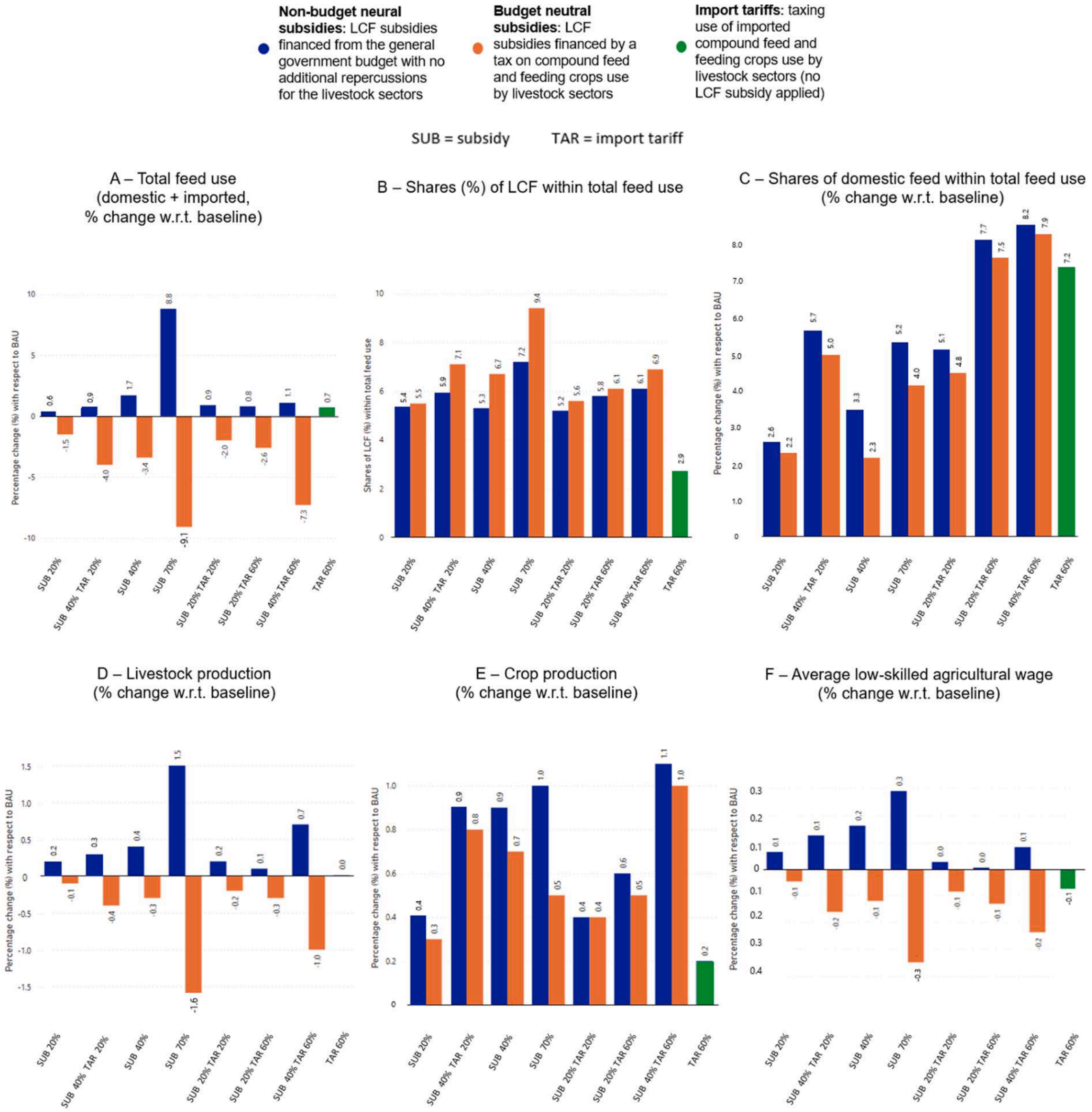

Fig. 1. Overview of the economic impact of policy instruments promoting a circular livestock system in EU27 in 2030. Estimates illustrated in the figure report changes (%) with respect to our business-as-usual (BAU) scenario in 2030. The only exception regards Panel B, where estimates refer to shares of low-cost-opportunity feeds (LCF) i.e. agricultural residues and by-products, within total feed use (domestic and imported) by livestock sectors in the EU27. Panel A illustrates how different policies affect total feed use (domestic and imported) in the EU27. Panel B reports the shares of LCF within total feed supply, illustrating the degree of circularity achievable under each policy combination. Panel C reports the impact of policies on the shares of domestic feed within total feed use by livestock sectors in the EU27. Paned D reports changes of livestock production under different policy combinations. Panel E illustrates changes in crop production under different policy combinations. Panel F illustrates changes in average low-skilled wages in agricultural sectors (crops and livestock) in the EU27 under different policy combinations.

contribute to a circular food system as it promotes domestic feed sourcing. Nonetheless, negative wage effects additionally occur when a stand-alone import tariff is imposed as agri-food prices increase, lowering demand.

Combining subsidies with import tariffs has varying impacts on LCF use and domestic feed production. When subsidies are not budget-neutral, adding a 20% or 60% import tariff boosts domestic feed (crop) and livestock production (Panel C, D and E – Fig. 1). In contrast, combining any import tariff with budget-neutral subsidies further decreases total feed demand and livestock production (Panel A and D – Fig. 1). Here, a rise in budget-neutral subsidies results in a stronger decrease in livestock production compared to rising import tariffs (Panel D - Fig. 1) as budget-neutral subsidies increase costs of domestic primary feed more. Finally, while combining tariffs with budget-neutral subsidies leads to a stronger decrease in agricultural low skilled wages, coupling any level of import tariffs with non-budget-neutral subsidies partially contains the increase in agricultural wages.

As changes by livestock type follow the same pattern we focus the main text on the impact on the total livestock sector, providing in the Supplementary Information detailed results on changing livestock-specific production volumes, diets, feed-conversion-ratios, and energy supply.

3.2. *The environmental impacts of policies promoting animal feed for a circular food system*

Rising non-budget neutral subsidies from 20% to 70% proportionally leads to a higher increase in crop and pastureland within the EU27

(Panel A and B – Fig. 2) due to an expansion of livestock and crop production which parallelly drives GHG emissions from agriculture (Panels D, E, and F – Fig. 2).

Differently, applying budget-neutral subsidies limits the increase in crop production and crop land use within the EU27 (Panel E – Fig. 1 and Panel B – Fig. 2) as taxes shrink demand for feeding crops from livestock and compound feed sectors. Despite budget-neutral subsidies reduce livestock production, the use of pastureland from livestock sectors decreases at a lower rate (Panel A – Fig. 2). This is because financing subsidies through taxes on primary feed indirectly stimulates the use of pastureland for ruminants sectors, maintaining land into production. As a result total land use increases under both subsidy schemes, being higher under non-budget-neutral subsidies given the expansion of both crop and livestock production (Panel C – Fig. 2). Nonetheless, as budget-neutral subsidies reduce livestock production and related GHG emissions (Panel D – Fig. 2), total agricultural emissions in the EU27 decrease (Panel F – Fig. 2). This is primarily driven by decreased livestock emissions which, in the case of budget-neutral subsidies, offsets the increase in crop-related emissions linked to higher crop production volumes (Panel E – Fig. 1 and Panel E – Fig. 2).

While standalone tariffs affect crop production, land use, and emissions (Panels B and E – Fig. 2), these effects intensify when tariffs are combined with any type of subsidy. Particularly, when tariffs accompany non-budget neutral subsidies, there are sharper increases in total land use and agricultural emissions (Panels C and F – Fig. 2) as increasing non-budget neutral subsidies boost the demand for domestic feed and livestock production, exacerbating related environmental impacts. On the contrary, when budget-neutral subsidies are combined with tariffs, there's a more significant reduction in total agricultural emissions (Panel F – Fig. 2). This effect occurs because higher budget-

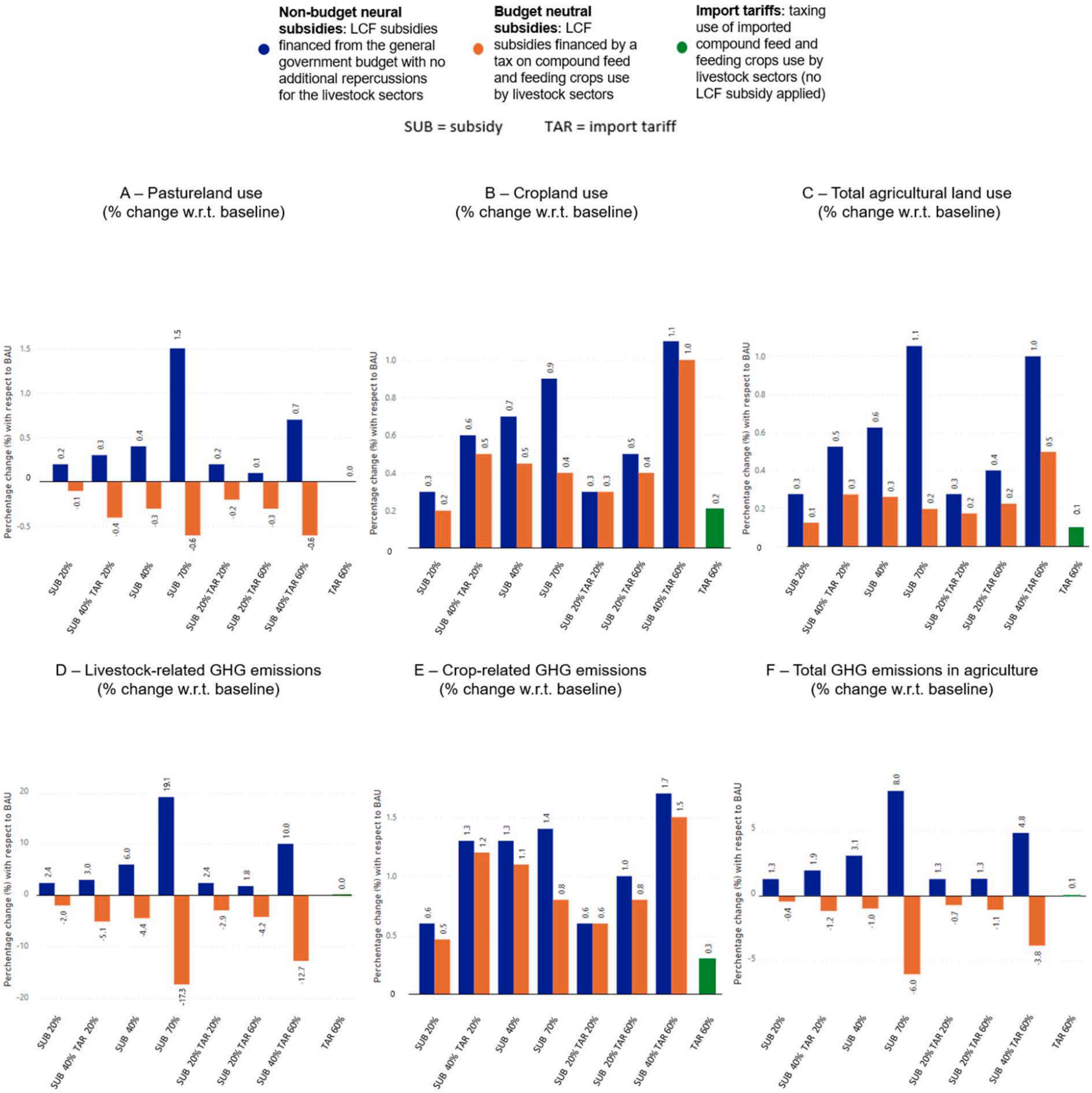

Fig. 2. Overview of the environmental impact of policy instruments promoting a circular livestock system in EU27 in 2030. Estimates illustrated in the figure report changes (%) with respect to our business-as-usual (BAU) scenario in 2030. Panel A reports changes in total pastureland (demanded by livestock sectors) under different policy combinations. Panel B reports the changes in total crop-land (demanded by crop sectors) under different policy combinations. Panel C reports changes in total agricultural land (crop land and pastureland) under different policy combinations. Panel D reports changes in livestock-related emissions (generated by livestock production) under different policy combinations. Panel E reports changes in crop-related GHG emissions (generated by crop production) under different policy combinations. Finally, panel F illustrates changes in total GHG emissions in agriculture (from crops and livestock sectors) associated with different policy combinations.

neutral subsidies reduce livestock production to a greater extent, compensating for the emissions increase resulting from expanded crop production.

3.3. A weak and strong circular economy scenario

From our policy instrument analysis we observe that while budget-neutral subsidies have a slightly negative effect on agricultural wages, they are preferrable to non-budget-neutral subsidies as the budget-neutral subsidies lead to higher levels of LCF within total feed, without increasing feed and livestock production and thus avoiding an increases in GHG emissions. In this section we select two prototypical policy scenarios from the interventions discussed above to illustrate their impacts on biomass trade and non-agricultural sectors. We use these scenarios to showcase impacts on different livestock productions, diet composition, FCRs, and energy requirements, reporting more detailed results in the Supplementary Information. Our prototypical scenarios consist of a "weak circular economy" (WCE) scenario, where a 20% budget-neutral subsidy on LCF use is provided to livestock sectors, and a "strong circular economy" (SCE) scenario where a 40% budget-neutral subsidy on LCF use as feed and an 20% import tariff on compound feed and feed crops is imposed in the EU27. A detailed scenario description is provided in Table 2 below. The WCE scenario is equal to the SUB 20% and the SCE scenario is equal to SUB 40% TAR20% in the section above and impacts on production, land use, low skilled wages and emissions can be found in Fig. 2. The next section discusses additional economy wide impacts beyond agriculture.

3.4. The impacts of policies promoting animal feed for a circular food system on industrial by-products, biomass competition, trade, and economywide GHG emissions

Both the WCE and the SCE scenarios increase demand for by-products as animal feed, leading to an increase in demand and production of the main commodities generating them (Panel A - Fig. 3) as the overall profitability of sectors improves with higher demand and thus prices for by-products. In the WCE scenario, production primarily increases for biofuels generating distillers' dried grains (DDGS) (+15.5%), and processed fish generating fishmeal (+1.1%). The production of molasses (a by-product of refined sugars) increases relatively less (+0.4%) due to the high use of molasses in other production processes (i.e., processed foods) which limits its use as animal feed. In the SCE scenario, we find a more significant increase in the production of biofuels (DDGS, +45.2%), processed fish (fishmeal, +2.6%), and vegetable oils (oilcakes, +1.1%) with again a relatively minor impact on the production of refined sugars (molasses, +0.7%).

Table 2
Overview of magnitude of selected policy interventions to promote a circular agri-food system in the in EU27 in 2030.

Source of input	Feed inputs demanded by livestock sectors	Weak Circular Economy scenario (WCE)		Strong Circular Economy scenario (SCE)	
		TAX (%) (budget-neutral tax rate)	SUBSIDY (%) (budget-neutral)	TAX (%) (budget-neutral tax rate)	SUBSIDY (%) (budget-neutral)
Domestic	CEREALS	2.7*		6.6*	
	HORTICULTURE	2.7*		6.6*	
	COMPOUND FEED	2.7*		6.6*	
	AGRICULTURAL RESIDUES		20.0		40.0
	BY-PRODUCTS		20.0		40.0
Imported	CEREALS			20.0**	
	HORTICULTURE			20.0**	
	COMPOUND FEED			20.0**	
	AGRICULTURAL RESIDUES				
	BY-PRODUCTS				

* Size of the ad-valorem tax levied to finance the subsidy (endogenously computed in the model based on the response to the LCF subsidy).

** Import tariff levied to crops and horticultural products demanded by livestock sectors. Import tariffs do not apply to imported crops and horticultural products demanded by other sectors in the economy.

Expanding biofuel production drives demand for domestic and imported energy crops (WCE +30.1%; SCE +46.5%), contributing to the increase in cropland. The subsidy leads to a higher demand for DDGS (and biofuel), while the tax imposed for financing the subsidy reduces demand for feed, making it more advantageous to cultivate crops for energy production rather than for animal feed. As a result, domestic biomass is redirected towards other uses (including energy), reducing its availability for food and feed production (Panel B – Fig. 3). Compared to BAU, policies in the WCE scenario slightly increase domestic biomass allocation towards other uses (+0.1%), decreasing biomass use for feed (−0.2%) and food (−0.02%). In the SCE scenario changes are more significant, as biomass allocation to other use increases (+0.4%), while decreasing for feed (−0.4%) and food (−0.03%).

The import tariff primarily impacts main feed-exporting regions such as LAC and Rest of Europe & Central Asia (REUCA), decreasing exports of feeding crops (average −19.2%) towards EU27. However, higher imports of food (+2.3%) and non-food biomass (average +2.2%) counterbalance the negative effects of the tariff and result in expanding crop imports in the EU27 (+1.9%). Imports of ruminant and poultry meat increase by an average of 2.1%, mainly from LAC, REUCA, and Southeast Asia. Similarly, the higher production of biofuels drives imports of energy crops (WCE +2.5%; SCE +4.1%), particularly increasing imports of sugar beet/cane from SSA, LAC, Brazil, and REUCA. The crop price increase in both scenarios (WCE +0.4%; SCE +0.9%) drives imports of crops (Panel C – Fig. 3). In WCE, imports increase for primary fresh food (+1.1%) and other non-food uses (average +0.7%), originating primarily from Latin America & Caribbean (LAC) and Sub-Saharan Africa (SSA). Average imports of non-feed crops increase in the SCE scenario (+1.9%) as such crops are not subject to feed tariffs and freeing domestic biomass for feed use. The decrease in imported biomass use for animal feed and the increase in biomass use for food and energy (Panel A - Fig. 3), result in a decrease of imports of grains in favour of sugar beet/cane and wheat, respectively used for energy production and food consumption. Despite this, the regional sourcing of biomass remains largely unchanged, with REUCA, LAC, and SSA remaining the main primary biomass import sources of the EU27.

On the export side, while the crop price increase reduces feed and food biomass exports (WCE −0.3%; SCE −1.4%), the increasing production of biofuels leads to higher exports (WCE +7.2%; SCE +21.5% - categorized under "other use (energy)" in Panel C – Fig. 3), primarily towards Brazil, Industrialized Asia, and United States. Increased availability of biofuels also decreases EU27 demand for refined petroleum products from, both from domestic (WCE −0.3%; SCE −0.5%) and imported (WCE −0.02%; SCE −0.05%) sources. The substitution from fossil to biobased sources occurs mainly in transportation and chemical sectors. As a result non-agricultural emissions decrease across scenarios (WCE −0.3%; SCE −0.5%) and lead to lower total GHG emissions (WCE −0.3%; SCE −0.6%) in the EU27 (Panel D – Fig. 3).

4. Discussion

This study analyses economywide and environmental impacts of policies promoting a more circular food system with a focus on livestock. We use a global general equilibrium (GE) model to explore subsidies and import tariffs on agriculture and non-agricultural products. The novelty of our study revolves around improved modelling of livestock systems by including livestock specific feed constraints in monetary CGE models, addressing a key limitation of these models (Pauliuk et al., 2017; Pyka

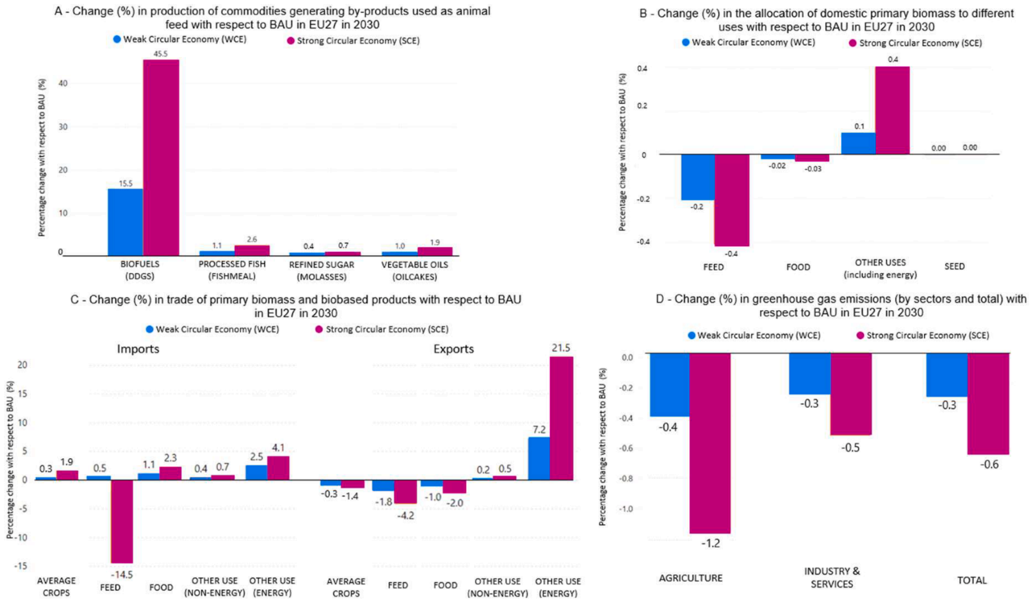

Fig. 3. Changes in production of by-products, biomass allocation, trade, and greenhouse gas emissions in the EU27 in 2030 (by scenario). Estimates refer to percentage change (%) in our circular policy scenarios with respect to our business-as-usual (BAU) scenario in 2030. Panel A illustrates change (%) in production of commodities generating by-products under our policy scenarios in 2030. Panel B illustrates change (%) in the allocation of domestically produced primary biomass in the EU27 to different uses (feed, food, other uses, and seed) under our policy scenarios in 2030. Here "other uses" refers to the use of biomass in industrial non-food sectors such as textile, chemical, and bioenergy sectors. Panel C reports changes in trade of primary biomass and biobased products under our policy scenarios in 2030. "Average crops" refers to a change in the weighted average of all traded crops (cereals and horticulture) in the EU27. The "feed" category refers to feed crops as well as processed compound feed. Similarly, the "food" category refers to trade of primary fresh agri-food products as well as processed foods. The "other use (non-energy)" category refers to trade of biomass products (fresh and processed) used in industrial non-food non-energy sectors such as textile or chemical sectors. Differently, the "other use (energy)" category refers to trade of biomass products used to produce bioenergy, including trade of energy crops as well as biofuels. Finally, Panel D illustrates changing greenhouse gas emissions by sectors and in total under our policy scenarios in 2030.

et al., 2022). The expansion of our economic model in terms of modelling technical aspects of livestock production provides an understanding of the economic feasibility of strategies aiming to improve circularity in agri-food systems while respecting biophysical constraints on livestock production. Our results show that subsidies on LCF use and import tariffs on compound feed and feed crops are able to increase LCF shares in total feed while promoting a higher use of domestically sourced feed, key in a circular agri-food system.

A core finding is that well-designed budget neutrality of policies is crucial as it turns an expansion of livestock production and total feed use induced by a pure subsidy into a contraction, limiting negative indirect production-related effects, such as increased land use and GHG emissions. This becomes especially relevant for the EU27 policymakers as core agricultural policies in the EU27 (e.g. CAP 2023–27, the New Green Deal) often promote subsidies without well-designed accompanying taxes. This neglect of the indirect production stimulating effect of subsidies risks generating potential environmental drawbacks. However, while budget-neutral policies might be preferred for promoting circularity given their positive impact on GHG emissions and land use, the price increase generated by the taxes decreases agricultural low-skilled wages in the EU27. This supports the inverse correlation between rising agri-food prices and agricultural wages (Swinton and Young, 2001; Sumner et al., 2017; European Commission, 2018), and contributes to ongoing debates on circularity in the EU27 (European Commission, 2020; 2021) illustrating that a circular agri-food system transition may come at a labour cost often not accounted for by technical studies (De Boer and van Ittersum, 2018; Billen et al., 2021; Karlsson et al., 2021).

We find lower magnitudes of policy interventions do not significantly increase shares of LCF within total feed use but increasing magnitude of interventions can lead to more severe externalities on land use and agricultural wages. The size of the interventions is therefore crucial and becomes especially relevant when envisioning a livestock sector heavily reliant on LCF (van Zanten et al., 2019; Wiel et al., 2019; van Hal et al., 2019; Sandström et al., 2022). While a stand-alone stronger subsidy (e.g. 40% or 70%) increases negative externalities (GHG, land use), a viable option to increase the degree of circularity of the EU27 food system lies in complementing a budget-neutral subsidy with a low import tariff. This policy combination, tested in our prototypical "strong circular economy" (SCE) scenario, allows to promote LCF and domestic feed use, reduces emissions in agriculture and overall economy within the EU27, without severely affecting land use and wages in comparison to other investigated policy options.

Additionally, we find a positive contribution to lower GHG emissions through interactions with non-agricultural sectors illustrating the relevance of using a GE model. Positive effects in agriculture are observed only when budget-neutral subsidies are introduced as such interventions directly decrease primary livestock production, an important source of agricultural emissions in the EU. While this contributes to the discussion on practical policy tools for promoting circularity to address GHG emissions, it also emphasizes that the GHG mitigation potential of policies to promote LCF and local feed use in livestock production is limited, underscoring the need for more stringent complementary policies to meet the agricultural emission targets outlined in the New EU Common-Agricultural-Policy (CAP27). The analysis of our prototypical scenarios illustrates furthermore that promoting the use of by-products as animal feed may increase the production of main commodities. In the case of biofuels generating DDGS as a by-product, we find mixed effects. A higher biofuel production increases demand for energy crops, contributing to increasing land demand while diverting domestic biomass towards industrial uses. However, higher biomass imports counterbalance the negative effects of feed tariffs on main EU27 trading partners, compensating potential welfare losses abroad. Parallelly, the higher availability of biofuel reduces demand for refined petroleum products, increasing the use of more sustainable biobased energy sources. The total reduction in GHG emissions in the EU27 reinforces the benefits achieved by policies in agriculture, further contributing to economywide EU27 emission targets in 2030.

Finally, while prior economic research on large-scale livestock-focused circular food systems is rather limited, available technical inquiries provide results largely not comparable to those from our analysis. Technical studies often present a different set-up of scenarios, investigating more explorative extreme scenarios in which e.g. livestock systems entirely rely on secondary feed or domestic feed sources (Van Selm et al., 2023). In contrast, our study presents policy scenarios that closely align with current feeding practices, providing a more accurate representation of real-world conditions. For this, reproducing such scenarios into our economy-wide model would result rather unfeasible as monetary constraints as well as rational economic behaviour of agents within our model contrast by design with the extreme scenarios detectable only with biophysical models. Nonetheless, the different approaches can enrich each other's and assist researchers and decision makers by providing different pieces of the same puzzle. While technical approaches may learn, for example, from the potential rebound effects revealed by an economy-driven approach, economic enquiries may benefit from understanding how a sustainable future would look like when non-monetary objectives become leading. In this study, we aimed to bridge part of the gap between disciplines by enhancing the representation of biological systems (animals, crops) in a GE model for an integrated assessment of circularity.

The mixed impacts found across sectors and indicators show that to increase the effectiveness of a transition towards circular food systems complementary policies should be implemented. Taxation on animal-sourced foods (currently applied or debated in several countries) or changes in regulations to allow and favour the reuse of discarded biomass as animal feed (Zu Ermgassen et al., 2016), may constitute viable solutions for decreasing pressures on land in the EU27. Relaxing regulations for upcycling secondary biomass as animal feed can increase LCF supply, limiting the high increase in crop production linked to the higher demand for agricultural residues. This could additionally avoid increasing land use and prices, limiting the rise in agricultural imports and negative spillovers to agricultural wages.

With regards to wage losses in agriculture, a potential approach is to provide temporary compensation through income subsidies, such as the current direct payment system within the EU, recognising the need to safeguard the welfare of the main actors in the food system when policies for sustainability are implemented. In this, policies should facilitate the transition of workers towards non-agricultural sectors by implementing specialized training and educational programs. These initiatives aim to provide workers with better opportunities to explore alternative employment options, particularly in cases where agricultural wages decrease. Finally, while our policies promote an increase in the domestic sourcing of feed, which benefits material and nutritional cycles, targeting only the feed sector leads to a higher dependency on imports of non-feed biomass. This underscores the risks associated with implementing policies focusing on a single sector and emphasizes the need for more comprehensive and cross-cutting policies to effectively address potential spillover effects on agriculture as a whole and the broader economy.

As always, our findings are subject to several limitations. A more detailed distinction between cattle (sheep, horses, others), poultry (broilers, hen, etc.) or aquaculture (marine fish, freshwater fish, molluscs, etc.) would have provided more specific impacts of circular policy measures. Similarly, the inclusion of additional feed types such as pasture grass, hay, animal by-products, minerals, and additional plants, currently beyond the scope of our current modelling framework, would have enhanced the calculation of nutritional balances, enriching our analysis. This limitation becomes apparent when having a closer look at the diets (Tables S10a-g in Supplementary Information). Across our investigated scenarios, FCRs for each livestock sector are close to reference estimates observed in literature. The only exception is represented by bovine cattle which presents a relatively lower FCR compared to literature as several feed products (i.e. hay, pasture grass) are not integrated in our model and thus omitted from nutritional calculations. However, the differences in FCRs and energy and protein content across scenarios, although small, indicate that livestock productivity might be affected. Further research could therefore improve our economic framework by differentiating livestock by productivity level and including species specific requirements such as maximum inclusion levels for certain ingredients. This becomes especially relevant when investigating scenarios with higher shares of LCF or diets that might compromise the productivity of specific livestock production systems. Moreover, further research could improve the modelling of livestock-related GHG emissions. As we quantify GHG emissions from livestock sectors based on the number of livestock, we ignore changing animal emissions linked to livestock dietary shifts, being already included in the national GHG inventory of some EU27 countries.

5. Conclusion

Feeding animals with low-opportunity-cost feed (LCF) such as agricultural residues and by-products, and better use of local feed resources are potential strategies for transitioning towards more circular food systems. We find providing only subsidies increases circularity and agricultural wages but also animal production, exerting negative indirect effects on land use and GHG emissions. Differently, we find promoting the use of LCF through budget-neutral subsidies and domestic feed sourcing through import tariffs, decreases animal production and GHG emissions in agriculture. Relevant synergy effects are found from subsidising DDGS, which indirectly increases biofuel production, positively contributing to lower GHG emissions in 2030. However, we find budget-neutrality drives land use up while decreasing agricultural wages. Thes findings indicate that integrating technical and economic modelling of circularity and adopting an economywide perspective, allows identification of trade-offs of circular policies often overlooked when adopting a technical perspective or focusing solely on the livestock sector. While circularity is an important initial step in mitigating GHG emissions, policymakers need to adopt a multidisciplinary approach to effectively address these trade-offs. This involves implementing complementary policies to tackle negative spillovers and ensure a successful transition towards a sustainable food system in the EU27 by 2030.

Credit author statement

Alessandro Gatto: Conceptualization, Methodology, Software, Writing. **Marijke Kuiper**: Conceptualization, Methodology, Software, Writing. **Corina van Middelaar**: Conceptualization, Methodology, Writing. **Hans van Meijl**: Conceptualization, Methodology, Writing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Alessandro Gatto reports financial support was provided by Wageningen University & Research. Alessandro Gatto reports a relationship with Wageningen University & Research that includes: employment.

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.107317.

References

Aguiar, A., Chepeliev, M., Corong, E.L., McDougall, R., van der Mensbrugghe, D., 2019. The GTAP Data Base: Version 10. J. Glob. Econ. Anal. 4 (1), 1–27. https://doi.org/10.21642/JGEA.040101AF.

Awasthi, S.K., Kumar, M., Sarsaiya, S., Ahluwalia, V., Chen, H., Kaur, G., Sirohi, R., Sindhu, R., Binod, P., Pandey, A., Rathour, R., Kumar, S., Singh, L., Zhang, Z., Taherzadeh, M.J., Awasthi, M.K., 2022. Multi-criteria research lines on livestock manure biorefinery development towards a circular economy: From the perspective of a life cycle assessment and business models strategies. J. Cleaner Prod. 341, 130862 https://doi.org/10.1016/j.jclepro.2022.130862.

Billen, G., Aguilera, E., Einarsson, R., Garnier, J., Gingrich, S., Grizzetti, B., Lassaletta, L., Le Noë, J., Sanz-Cobena, A., 2021. Reshaping the European agro-food system and closing its nitrogen cycle: The potential of combining dietary change, agroecology, and circularity. One Earth 4 (6), 839–850. https://doi.org/10.1016/j.oneear.2021.05.008.

Britz, W., van der Mensbrugghe, D., 2018. CGEBox: A Flexible, Modular and Extendable Framework for CGE Analysis in GAMS. J. Glob. Econ. Anal. 3 (2), 106–177. https://doi.org/10.21642/JGEA.030203AF.

Chepeliev, M., 2022. Incorporating Nutritional Accounts to the GTAP Data Base. J. Glob. Econ. Anal. 7 (1), 1. https://doi.org/10.21642/JGEA.070101AF. Article.

Cole, J.R., McCoskey, S., 2013. Sustain. Sci. Pract. Policy 9 (2), 26–36. https://doi.org/10.1080/15487733.2013.11908112.

Corong, E.L., Hertel, T.W., McDougall, R., Tsigas, M.E., van der Mensbrugghe, D., 2017. The Standard GTAP Model, Version 7. J. Glob. Econ. Anal. 2 (1), 1–119. https://doi.org/10.21642/JGEA.020101AF.

De Boer, I.J.M., Van Ittersum, M.K., 2018. Circularity in Agricultural Production. Wageningen University & Research. https://www.wur.nl/upload_mm/7/5/5/14119893-7258-45e6-b4d0-e514a8b6316a_Circularity-in-agricultural-production-20122018.pdf.

De Schutter, O., 2017. The political economy of food systems reform. Eur. Rev. Agricult. Econ. 44 (4), 705–731. https://doi.org/10.1093/erae/jbx009.

Delzeit, R., Beach, R., Bibas, R., Britz, W., Chateau, J., Freund, F., Lefevre, J., Schuenemann, F., Sulser, T., Ruijven, B.V., Weitzel, M., Willenbockel, D., 2020. Linking Global CGE models with Sectoral Models to Generate Baseline Scenarios: Approaches, Challenges, and Opportunities. J. Glob. Econ. Anal. 5 (1), 34.

Donati, F., Aguilar-Hernandez, G.A., Sigüenza-Sánchez, C.P., de Koning, A., Rodrigues, J.F.D., Tukker, A., 2020. Modeling the circular economy in environmentally extended input-output tables: methods, software and case study. Resour. Conserv. Recycl. 152 (2020), 104508. Article.

Donner, M., Gohier, R., de Vries, H., 2020. A new circular business model typology for creating value from agro- waste. Sci. Total Environ. 716, 137065, 2020.

Erb, K.H., Mayer, A., Kastner, T., Sallet, K.E., Haberl, H., 2012. The Impact of Industrial Grain Fed Livestock Production on Food Security: An extended Literature Review. Commissioned by Compassion in World Farming, The Tubney Charitable Trust and World Society for the Protection of Animals, UK, Vienna, Austria.

European Commission, 2018. Land Prices and Farm Incomes in the EU: Analytical Insights and Policy Options. Retrieved from. https://ec.europa.eu/agriculture/sites/agriculture/files/land-prices-farm-incomes-2018_en.pdf.

European Commission, 2020. European Commission, Directorate-General for Communication, Circular economy Action plan: For a Cleaner and More Competitive Europe. Publications Office of the European Union, 2020. https://data.europa.eu/doi/10.2779/05068.

European Commission, 2021. European Commission, Directorate-General for Communication, European green deal: Delivering On Our Targets. Publications Office of the European Union, 2021. https://data.europa.eu/doi/10.2775/373022.

Frehner, A., Cardinaals, R.P.M., de Boer, I.J.M., Muller, A., Schader, C., van Selm, B., van Hal, O., Pestoni, G., Rohrmann, S., Herrero, M., van Zanten, H.H.E., 2022. The compatibility of circularity and national dietary recommendations for animal products in five European countries: A modelling analysis on nutritional feasibility, climate impact, and land use. Lancet Planet Health 6 (6), e475–e483. https://doi.org/10.1016/S2542-5196(22)00119-X.

Fujimori, S., Hasegawa, T., Masui, T., 2017. AIM/CGE V2.0: basic feature of the model. In: Fujimori, S., Kainuma, M., Masui, T. (Eds.), Post-2020 Climate Action. Springer Singapore, Singapore, pp. 305–328, 2017.

Gatto, A., Kuiper, M., van Meijl, H., 2023. Economic, social, and environmental spillovers decrease the benefits of a global dietary shift. Nat. Food 4 (6), 6. https://doi.org/10.1038/s43016-023-00769-y. Article.

Gerber, P.J., Food and Agriculture Organization of the United Nations, 2013. Tackling Climate Change Through livestock: A global Assessment of Emissions and Mitigation Opportunities. Food and Agriculture Organization of the United Nations.

Godzinski, A., 2015. Circular Economy and Energy: a Computable General Equilibrium Approach. French Ministry of Environment. https://afse2015.sciencesconf.org/61878/document.

Herrero, M., Wirsenius, S., Henderson, B., Rigolot, C., Thornton, P., Havlík, P., de Boer, I., Gerber, P.J., 2015. Livestock and the Environment: What Have We Learned in the Past Decade? Annu. Rev. Environ. Resour. 40 (1), 177–202. https://doi.org/10.1146/annurev-environ-031113-093503.

Hilborn, R., Banobi, J., Hall, S.J., Pucylowski, T., Walsworth, T.E., 2018. The environmental cost of animal source foods. Front. Ecol. Environ. 16 (6), 329–335. https://doi.org/10.1002/fee.1822.

IPES-Food, 2022. The Politics of protein: Examining Claims About livestock, fish, 'alternative proteins' and Sustainability. https://www.ipes-food.org/_img/upload/files/PoliticsOfProtein.pdf.

Karlsson, J.O., Parodi, A., van Zanten, H.H.E., Hansson, P.A., Röös, E., 2021. Halting European Union soybean feed imports favours ruminants over pigs and poultry. Nat. Food 2 (1), 1. https://doi.org/10.1038/s43016-020-00203-7. Article.

Leclere, D., Obersteiner, M., Barrett, M., Butchart, S.H.M., Chaudhary, A., De Palma, A., DeClerck, F.A.J., Di Marco, M., et al., 2020. Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature. https://doi.org/10.1038/s41586-020-2705-y.

McCarthy, A., Dellink, R., Bibas, R., 2018. The Macroeconomics of the Circular Economy Transition: A Critical Review of Modelling Approaches, OECD Environment Working Papers, No. 130. OECD Publishing, Paris. https://doi.org/10.1787/af983f9a-en.

Meijl, H.van, van Rheenen, T., Tabeau, A., Eickhout, B, 2006. The impact of different policy environments on land use in Europe, Agriculture. Ecosyst. Environ. 114, 21–38. https://doi.org/10.1016/j.agee.2005.11.006.

Muscat, A., de Olde, E.M., Ripoll-Bosch, R., Van Zanten, H.H.E., Metze, T.A.P., Termeer, C.J.A.M., van Ittersum, M.K., de Boer, I.J.M., 2021. Principles, drivers and opportunities of a circular bioeconomy. Nat. Food 2 (8), 8. https://doi.org/10.1038/s43016-021-00340-7. Article.

OECD-G20, 2021. The role of G20. A background report prepared for the 2021 G20 Presidency of Italy. https://www.oecd.org/environment/waste/OECD-G20-Towards-a-more-Resource-Efficient-and-Circular-Economy.pdf.

Ominski, K., McAllister, T., Stanford, K., Mengistu, G., Kebebe, E.G., Omonijo, F., Cordeiro, M., Legesse, G., Wittenberg, K., 2021. Utilization of by-products and food waste in livestock production systems: A Canadian perspective. Anim. Front. 11 (2), 55–63. https://doi.org/10.1093/af/vfab004.

Pagotto, M., Halog, A., 2016. Towards a Circular Economy in Australian Agri-food Industry: An Application of Input-Output Oriented Approaches for Analyzing Resource Efficiency and Competitiveness Potential. J. Ind. Ecol. 20, 1176–1186, 2016.

Pauliuk, S., Arvesen, A., Stadler, K., Hertwich, E.G., 2017. Industrial ecology in integrated assessment models. Nat. Clim. Change 7 (1), 13–20. https://doi.org/10.1038/nclimate3148.

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360 (6392), 987–992. https://doi.org/10.1126/science.aaq0216.

Pyka, A., Cardellini, G., van Meijl, H., Verkerk, P.J., 2022. Modelling the bioeconomy: Emerging approaches to address policy needs. J. Cleaner Prod. 330, 129801 https://doi.org/10.1016/j.jclepro.2021.129801, 2022ISSN 0959-6526.

Röös, E., Bajželj, B., Smith, P., Patel, M., Little, D., Garnett, T., 2017. Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures. Glob. Environ. Chang. 47, 1–12. https://doi.org/10.1016/j.gloenvcha.2017.09.001.

Salami, S.A., Luciano, G., O'Grady, M.N., Biondi, L., Newbold, C.J., Kerry, J.P., Priolo, A., 2019. Sustainability of feeding plant by-products: A review of the implications for ruminant meat production. Anim. Feed Sci. Technol. 251, 37–55. https://doi.org/10.1016/j.anifeedsci.2019.02.006.

Salemdeeb, R., Font Vivanco, D., Al-Tabbaa, A., zu Ermgassen, E.K.H.J., 2017. A holistic approach to the environmental evaluation of food waste prevention. Waste Manage. (Oxford) 59, 442–450. https://doi.org/10.1016/j.wasman.2016.09.042.

Sandström, V., Chrysafi, A., Lamminen, M., Troell, M., Jalava, M., Piipponen, J., Siebert, S., van Hal, O., Virkki, V., Kummu, M., 2022. Food system by-products upcycled in livestock and aquaculture feeds can increase global food supply. Nat. Food 3 (9), 9. https://doi.org/10.1038/s43016-022-00589-6. Article.

Stadler, K., Wood, R., Bulavskaya, T., S¨odersten, C.J., Simas, M., Schmidt, S., Usubiaga, A., et al., 2018. EXIOBASE 3: developing a time series of detailed environmentally extended multi-regional input-output tables: EXIOBASE 3. J. Ind. Ecol. 22 (3), 502–515. June 2018.

Schader, C., Muller, A., Scialabba, N.E.H., Hecht, J., Isensee, A., Erb, K.H., Smith, P., Makkar, H.P.S., Klocke, P., Leiber, F., Schwegler, P., Stolze, M., Niggli, U., 2015. Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. J. R. Soc. Interface 12 (113), 20150891. https://doi.org/10.1098/rsif.2015.0891.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., de Haan, C., 2006. Livestock's Long Shadow. FAO, Rome, 2006. https://www.fao.org/3/a0701e/a0701e00.htm.

Stephens, E.C., Martin, G., van Wijk, M., Timsina, J., Snow, V., 2020. Editorial: Impacts of COVID-19 on agricultural and food systems worldwide and on progress to the sustainable development goals. Agric. Syst. 183, 102873 https://doi.org/10.1016/j.agsy.2020.102873.

Sumner, D.A., Matthews, W.A., 2017. The Impact of Land Prices on the Incomes of Farmers and Farm Workers in the United States. Agric. Resour. Econ. Rev. 46 (2), 249–268. https://doi.org/10.1017/age.2017.7.

Swinton, S.A., Young, D.L., 2001. The Effects of Land Prices on the Wages of Farm and Nonfarm Labor in the United States. Am. J. Agric. Econ. 83 (3), 618–633. https://doi.org/10.1111/0002-9092.00183.

Taifouris, M., Martin, M., 2021. Toward a Circular Economy Approach for Integrated Intensive Livestock and Cropping Systems. ACS Sustain. Chem. Eng. 2021 9 (40), 13471–13479. https://doi.org/10.1021/acssuschemeng.1c04014.

van Hal, O., de Boer, I.J.M., Muller, A., de Vries, S., Erb, K.H., Schader, C., Gerrits, W.J.J., van Zanten, H.H.E., 2019. Upcycling food leftovers and grass resources through livestock: Impact of livestock system and productivity. J. Cleaner Prod. 219, 485–496. https://doi.org/10.1016/j.jclepro.2019.01.329.

van Meijl, H., Tsiropoulos, Y., Bartelings, H., Hoefnagels, R., Smeets, E., Tabeau, A., Faaij, A., 2018. On the macro-economic impact of bioenergy and biochemicals – Introducing advanced bioeconomy sectors into an economic modelling framework with a case study for the Netherlands. Biomass Bioenergy 108, 381–397. https://doi.org/10.1016/j.biombioe.2017.10.040.

Van Meijl, H., Tabeau, A., Stehfest, E., Doelman, J., Lucas, P., 2020a. How Food Secure are the Green, Rocky and Middle Roads: Food Security Effects in different world development paths. Kankyo Hen'igen Kenkyu. https://doi.org/10.1088/2515-7620/ab7aba.

Van Meijl, H., Shutes, L., Valin, H., Stehfest, E., van Dijk, M., Kuiper, M., Tabeau, A., van Zeist, W., Hasegawa, T., Havlik, P., 2020b. Modelling alternative futures of global food security: Insights from FOODSECURE. Clim. Change Global Food Secur. 25, 100358 https://doi.org/10.1016/j.gfs.2020.100358.

Van Selm, B., Frehner, A., de Boer, I.J.M., van Hal, O., Hijbeek, R., van Ittersum, M.K., Talsma, E.F., Lesschen, J.P., Hendriks, C.M.J., Herrero, M., van Zanten, H.H.E., 2022. Circularity in animal production requires a change in the EAT-Lancet diet in Europe. Nat. Food 3 (1), 1. https://doi.org/10.1038/s43016-021-00425-3. Article.

Van Selm, B., Hijbeek, R., van Ittersum, M.K., van Hal, O., van Middelaar, C.E., de Boer, I.J.M., 2023. Recoupling livestock and feed production in the Netherlands to reduce environmental impacts. Sci. Total Environ. 899, 165540 https://doi.org/10.1016/j.scitotenv.2023.165540.

Van Zanten, H.H.E., Van Ittersum, M.K., De Boer, I.J.M., 2019. The role of farm animals in a circular food system. Clim. Change Global Food Secur. 21, 18–22. https://doi.org/10.1016/j.gfs.2019.06.003.

van Zanten, H.H.E., Simon, W., van Selm, B., et al., 2023. Circularity in Europe strengthens the sustainability of the global food system. Nat. Food 4, 320–330. https://doi.org/10.1038/s43016-023-00734-9, 2023.

Wiel, B.Z.van der, Weijma, J., Middelaar, C.E.van, Kleinke, M., Buisman, C.J.N., Wichern, F, 2019. Restoring nutrient circularity: A review of nutrient stock and flow analyses of local agro-food-waste systems. Resour. Conserv. Recycl. X 3, 100014. https://doi.org/10.1016/j.rcrx.2019.100014.

Winning, M., Calzadilla, A., Bleischwitz, R., Nechifor, V., 2017. Towards a circular economy: Insights based on the development of the global ENGAGE-materials model and evidence for the iron and steel industry. Int. Econ. Econ. Policy 14 (3), 383–407. https://doi.org/10.1007/s10368-017-0385-3.

Woltjer, G., Kuiper, M., Kavallari, A., van Meijl, H., Powell, J., Rutten, M., Shutes, L., Tabeau, A., 2014. LEI Report 14-057. LEI - part of Wageningen UR (University & Research centre, The Hague.

Word Bank, 2014. Word Bank Database. www.worldbank.org.https://data.worldbank.org/indicator/ER.FSH.AQUA.MT?end=2014&name_desc=false&start=2014.

World Economic Outlook October 2022, 2022. IMF. https://www.imf.org/external/datamapper/datasets/WEO.

zu Ermgassen, E.K.H.J., Phalan, B., Green, R.E., Balmford, A., 2016. Reducing the land use of EU pork production: Where there's swill, there's a way. Food Policy 58, 35–48. https://doi.org/10.1016/j.foodpol.2015.11.001.