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Subsidizing extensive cattle production in the European Union has major implications for global agricultural trade and climate change

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ABSTRACT

Pastureland maintenance is seen as a land-based measure to reduce dependency on feed concentrates and mitigate greenhouse gas (GHG) emissions from livestock production in the EU, while providing other ecosystems services. This paper assesses potential market-mediated impacts, including global Land Use Change (LUC) and GHG emissions, from increased subsidies to pasture-based livestock production in the EU. A *tax recycling strategy* (TRS) is simulated against a baseline up to 2030 under the shared socioeconomic pathway 2 (SSP2). This implies a budget-neutral increase in the level of pasture subsidies in individual Member States, as land subsidies for other cropping activities decrease. We employ the computable general equilibrium (CGE) model GTAP in its recursive-dynamic version, GTAP-RDEM, extended with the Multi-Regional Input-Output (MRIO) database FABIO to disaggregate agri-food sectors from 21 to 31. This approach allows considering price- and income-dependent feedbacks when assessing long-run changes in the global economy, improving the sectoral resolution relative to GTAP v10.

The policy increases pastureland areas and cattle production in almost all EU Member States, whereas cropland and crop production decrease, causing significant changes across EU agri-food markets. Crop prices increase, leading to the reduced output of intensive animal production sectors, mainly pig and poultry. Cropland areas decrease and most EU countries increase imports of grain, oilseeds, and cakes, essentially soybean cake from Brazil and North America. While GHG emissions decrease in those EU countries where pasturelands expand mainly at the cost of croplands, GHG emissions increase in those countries where pastureland expansion comes with forest loss. As a result, net GHG emissions increase in the EU-27 in 2030 (+2.49 Mt CO_2-eq). Emissions from LUC in major non-EU grain- and oilseed-exporting countries increase, e.g., by 102.52 Mt CO_2-eq in Brazil and by 129.17 Mt CO_2-eq in North America. The simulated policy shows that promoting extensive livestock per se does not meet the objectives of the Common Agricultural Policy and the EU Green Deal. The TRS should be complemented with policies to foster crop diversification and promote the use of domestic feed sources (e.g., legumes) to effectively ensure feed self-sufficiency and that extensive cattle production in the EU does not lead to deforestation in carbon-rich countries.

1. Introduction

1.1. Background: market developments for meat, dairy and feed concentrates

Population growth, rising incomes, as well as changes in dietary patterns and production technologies act as main drivers of increased global consumption of livestock products in the last decades (Machovina et al., 2015; Godfray et al., 2018; OECD/FAO, 2019). Global production of meat increased by +44% from 2000 to 2019 (337 Mt), reached a production volume of 316 Mt in 2022 and expected to attain 374 Mt by 2030 (FAO, 2021; FAO, 2023) while the global population grew by 26% in the same time. This went along with a shift to a more intensive livestock production systems relying on housing and nutrients-rich

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concentrate feeding (Gilbert et al., 2020) and a significant decrease in pastureland areas, by 40% between 1982 and 2006 globally (Bao Le et al., 2014). The growing demand for protein from concentrates turned soy into a major feed crop of which around 70% are used for feed globally (Brack et al., 2016). Global consumption of meat and dairy products is projected to increase further: by 40 Mt and 20 Mt (in milk solids equivalent), respectively, in 2028 relative to 2019 (OECD/FAO, 2019). Further intensification of livestock production is also expected to feed the growing world population. According to Friends of the Earth Europe (2018), global soy-cultivated area might increase significantly, to reach 141 million hectares in 2050, essentially in countries such as in Argentina, the United States (US) and Brazil.

In the European Union (EU), projected increases of concentrate feed demand would imply further growth in imports of protein-rich crops (EEA European Environment Agency, 2017). Currently, 95% of the crude proteins in feed are imported, mainly from Brazil, Argentina, and the US, amounting to 17 Mt annually, of which 13 Mt are soy-based (EC European Commission, 2018). Between 2005 and 2017, soy production contributed more than 80% to tropical deforestation embedded in EU imports, associated with loss of carbon-rich ecosystems, either directly or indirectly (Fehlenberg et al., 2017; Escobar et al., 2020). Moreover, livestock intensification and higher reliance on concentrates has led to loss of pastureland, e.g., in Germany by 12% from 1991 to 2017 (Umwelt Bundesamt, 2018); with negative impacts in terms of soil quality, carbon sequestration and other ecosystem services, such as biodiversity conservation (van Swaay et al., 2015; Alliance Environment, 2019).

1.2. The common agricultural policy, pastureland, and proteins

Multiple instruments of the Common Agricultural Policy (CAP) address pastureland maintenance and promote domestic production of plant protein sources. The compulsory so-called "Greening measures" (EC European Commission, 2013) comprise the maintenance of permanent pasture in Member States and support legumes production, as legumes count towards the required Ecological Focus Area.[1] Since 2014, legumes production can receive additionally so-called Voluntary Coupled Support (VCS) [2] (EC European Commission, 2015). The CAP post-2020 reform further reinforces and extends such measures as part of the "Green Deal" (EC European Commission, 2020) towards a" climate neutral EU" by 2050. For example, the European Commission (EC European Commission, 2019) favours a shift from compulsory crop diversification to obligatory crop rotations including proteins, and stricter measures to maintain permanent pasturelands. The European Parliament (2018) also proposed its own "plant protein strategy" as part of the post-2020 CAP to reduce dependency on protein imports, through increased domestic production of plant-based proteins and a strengthened role of pastureland to maintain agricultural sustainability and ecosystem services. Farmers generally welcome these measures linked to income support, as voiced by the COPA-COGECA organization representing farmers and agri-cooperatives in EU decision taking (Guyomard et al., 2020). Other voices, especially some scientists and environmentalists, call for more ambitious support to extensive livestock production systems and protein crop production in the EU, for instance, by targeted opt-in measures under the Pillar II (Dupraz and Guyomard, 2019; Chemnitz, 2019). This reflects fears that decoupled CAP support alone might translate into an expansion of mono-cultural and animal intensive production systems at the expense of extensive farming (Scown et al., 2020).

1.3. Study aims and approach

This study assesses potential market-mediated impacts, including global LUC and GHG emissions, of a budget-neutral increase in pastureland subsidy rates in the EU, with the aim of increasing pastureland areas and improve the environmental sustainability of the EU livestock sector. Budget-neutrality is achieved by decreasing land subsidies to other cropping activities, to avoid an increase in the overall EU budget and to further foster the substitution of cropland by pastureland. Potential impacts from such a *tax recycling strategy (TRS)* have been addressed by Hecht et al. (2016), but at a farm level. To the best of our knowledge, this is the first study to assess both global direct and indirect effects from a TRS, which promotes a shift to more extensive livestock production in the EU. Results could inform the design of the future CAP, highlighting the interaction between the environmental efficiency of CAP payments at the national level and the global spillovers up to 2030.

In order to assess the economy-wide impacts and related spillovers from an increased support to the EU extensive livestock sector, we employ an approach integrating Computable General Equilibrium (CGE) and detailed Multi-Regional Input-Output (MRIO) analysis, which links the well-known GTAP-CGE model (Corong et al., 2017) to the physical MRIO model FABIO (Bruckner et al., 2019). FABIO offers high agricultural detail compared to the GTAP database while CGE analysis overcomes theoretical weaknesses of the MRIO method, as discussed below. It is often argued that CGE modelling is more suitable for policy analyses and long-run assessments of changes in the global economy, such as climate change impacts (Walmsley et al., 2014; Carrico et al., 2020). Recent literature shows only few examples of analyses of agri-food value chains (Walmsley et al., 2014; Carrico et al., 2020) based on a CGE-MRIO approach, reflecting challenges for instance related to data harmonization and consistent balancing. No previous study focusing on the EU livestock sector could be found. A description of recent literature on quantitative approaches to assess environmental impacts from the European livestock industry, including both CGE and MRIO analyses is included in the Electronic Supplementary Material. Examples from previous studies (Gocht and Britz, 2011; Gocht et al., 2016; Heinrichs et al., 2021) on this topic mostly employ supply chain or farm models, which allow for more detailed analysis of local and sectoral effects, but cannot consider price-induced changes outside the EU. Gocht et al. (2016) find that a 5% increase in grassland area generates carbon sequestration of 5.96 Mt CO_2-eq, which is partially offset by an increase of 1.75 Mt CO_2-eq from CH_4 and N_2O emissions.

2. Materials and methods

2.1. Model setting and database preparation

This study employs a recursive-dynamic version of the standard GTAP model (Hertel, 1997), namely the GTAP Recursive Dynamic Extended Model (G-RDEM) (Britz and Roson, 2018; Roson and Britz, 2021), developed to assess long-run dynamics of economy-environment interactions. G-RDEM is available as a module in the modular and extendable platform for CGE modelling CGEBox (Britz et al., 2018). The GTAP-AEZ (Lee et al., 2005) and GTAP-E modules (Burniaux and Truong, 2002) are also implemented in CGEBox to respectively represent conversion of land among productive uses as well as substitution between capital and energy in the production structure of sectors.

In G-RDEM (Britz and Roson, 2018; Roson and Britz, 2021a,b), Total

[1] Farmers with more than 15 ha of arable land are obliged to dedicate 5% of this land to areas beneficial for biodiversity, i.e., Ecological Focus Areas (EFA), such as trees, hedges and land left fallow, which can improve biodiversity and safeguard natural habitats (EC European Commission, 2013).

[2] Although CAP income support has been progressively decoupled, EU countries can still link limited payments (up to 8% of total income support budget, with a possibility of higher budget share under certain conditions) to specific agricultural sectors and products, which are considered as important for social, economic, and environmental reasons. Example of these eligible sectors include cereals, protein crops and grain legumes (EC European Commission, 2015).

Factor Productivity (TFP) is endogenously determined through the baseline generation, driven by exogenous GDP projections. Resulting TFP shifters are taken as exogenous for counterfactuals, whereas GDP becomes endogenous. Besides the usual capital accumulation process considered in recursive-dynamic CGE models, G-RDEM introduces five major features, namely:

1. An empirically estimated An Implicitly Directly Additive Demand System (AIDADS)[3] in replacement of the Constant Difference in Elasticity (CDE) demand system to better simulate income dynamics in demand (especially relevant for agri-food sectors), by means of exponential Engel curves (Ho et al., 2020);
2. Endogenous savings rates driven by income and demographic dynamics.
3. Differentiated productivity growth rates across the three main sectors of the economy, i.e., agriculture, manufacturing and services;
4. Debt accumulation from foreign savings, related to imbalances in the trade balance;
5. Cost-shares that adjust over time according to income changes.

Moreover, an extended version of the GTAP-AEZ model (Lee et al., 2005) is employed, taken from Nong et al. (2020) and Escobar and Britz, 2021 Britz (2021a,b), which considers the possibility to convert natural land cover at the Agro-Ecological Zone (AEZ) level to land in economic use. This version replaces the conventional nested Constant Elasticity of Transformation (CET) structure that maximizes total land rents while keeping total land stock fixed. It combines estimates of total natural land areas potentially converted into agricultural uses per region and AEZ based on (Eitelberg et al., 2015) with country-specific land supply elasticities, which are calibrated based on the FAO (2018) cropland projections and applied to a land buffer with respect to land rents. When land rents increase, new land is supplied to the upper nest of the extended land transformation while land transformation among productive uses is simulated with a 3-tier CET function. The updated land supply function in GTAP-AEZ is shown in figure A1 in the annex.

The production function of the concentrate feed industry (figure A2 in the annex) is also extended by introducing by CES nests that differentiate between energy (sugar- and starch-based) and protein-rich crops (figure A2a). Considering high substitution possibilities among raw materials in the compound feed industry (Manceron et al., 2014), an elasticity of 5 is considered in the two nests. Additionally, substitution between pastureland and different feedstuffs (with a substitution elasticity of 0.25) is introduced in the production structure of livestock sectors (figure A2b) to adjust the intensive margin of livestock production as proposed by Golub et al. (2007). This means that an increase in land rents will translate increased intensification of livestock production by a higher use of feed concentrates and less pasture.

GTAP-AEZ quantifies GHG emissions from land substitution at the AEZ level, as governed by the CET structure. These emissions include CO_2 emissions from energy use and non-CO_2 emissions from agricultural activities, i.e., CH_4 emissions from enteric fermentation and manure management, and N_2O emissions from synthetic nitrogen fertilizer application. Additional GHG emissions arise from changes in carbon stocks due to LUC, which are estimated by the model in each year and then amortized linearly over 20 years, in line with the time horizon considered in the AEZ-EF model (Plevin et al., 2014). This allows estimating both the induced LUC emissions and the changes in annual emissions from economic activities when calculating the net GHG effect of the TRS.

2.2. Database disaggregation

This study is based on the GTAP version 10 database, with the base year 2014 (Aguiar et al., 2019), extended with auxiliary datasets, namely GTAP-AEZ (Lee et al., 2005) to include physical land at AEZ level and CO_2 emissions from carbon stock changes due to LUC; GTAP-E (Burniaux and Truong, 2002)) to estimate CO_2 emissions related to fossil fuel use across sectors; and (Rose and Lee, 2008) to quantify non-CO_2 emissions (CH_4, N_2O and F-Gases) from agricultural and industrial activities, differentiated by sector, country and source. The original GTAP 10 database is aggregated into 36 larger regions, while keeping the full sectoral resolution of 65 sectors. Most EU Member States are kept separate, in line with the objective of the study (table A1 in the annex). The 65 sectors are extended to 75 to cover 31 agri-food sectors, relative to the original 21 sectors in GTAP 10. Specifically, production, consumption and bilateral trade information from FABIO (Bruckner et al., 2019a) is used to consistently split the GTAP sector Oilseeds, Vegetable oils, Vegetables and fruits, and Other food into additional sub-sectors (Table 1), by using the SAM split utility in CGEBox (Britz, 2021a; Britz, 2022). This is based on calculating split factors from FABIO, i.e., shares on output, bilateral trade, land use, final demand, and intermediate demand while the common 'proportionality assumption' (Walmsley et al., 2014) is applied to estimate intermediate and final demand for the new sub-sectors in case of missing information. This relates mainly to intermediate non-agri-food demand. The split of the sector Vegetable oils generates a non-diagonal SAM to represent crushing of specific oilseeds into cake and oil, allowing to distinguish between food and feed applications.

2.3. Simulation design

In recursive-dynamic CGE analysis, effects of an external shock on the economy are analysed against a baseline, here capturing expected economic developments in the medium term. The baseline is constructed over the period 2014–2030 by using GTAP-RDEM. Based on the narrative of the Socio-Economic Pathway 2 (SSP2) (Riahi et al., 2017), which represents a continuation of past economic and demographic trends, projections of growth in GDP, as well as population by age group and education levels under moderate climate change adaptation and mitigation challenges are taken as given from other studies.

The counterfactual scenario captures the re-distribution of existing CAP subsidies from cropland to pastureland. This is modelled in a budget-neutral way, such that increased subsidies on pastureland are offset by lower ones to other crops, as proposed by (EC European Commission, 2018; Hecht et al., 2016). Specifically, it is assumed that subsidies allocated to pastureland are at least two times higher than subsidies to cropland, but not exceeding a subsidy rate of 80%. To ensure budget neutrality, total subsidies to land in each EU country are held fixed at benchmark level. To do so, we exogenize the total subsidy costs for land in each EU country and introduce an endogenous correction variable to the updated subsidy rate according to the shock. This tax-recycling mechanism is also applied during the baseline generation and keeps CAP payments to land fixed in real terms. All other subsidy and tax rates besides land subsidies in EU Member States are kept

Table 1
Additional sectors disaggregated from the original GTAP 10 database (Aguiar et al., 2019) based on relative split factors estimated from FABIO (Bruckner et al., 2019a).

Original GTAP sectors	New sub-sectors based on FABIO data
Oilseeds	Olive; Soybean; Palm oil fruits; Rape and mustard seed Other oilseeds
Vegetable Oils	Olive oil production => olive oil Soybean crushing => Soybean oil, cake Palm oil production => palm oil Rapeseed crushing => Rape seed oil, cake Other oilseed crushing => Other cakes and oils
Vegetables and fruits	Legumes; vegetables, other vegetables, and fruits
Other food processing	Feed concentrate; Other food processing

[3] The latest version draws on Britz (2021a,b).

unchanged.

Simulated impacts are expected to vary across EU Member States, due to differing agronomical conditions and dominating farming systems. Fig. 1 highlights these differences based on a characterization of ruminant livestock sectors in the different EU countries at the benchmark in 2030 considering three main attributes, namely (1) the cost share of concentrate feed, (2) the cost share of land, and (3) the initial subsidy rate on pastureland, which may drive potentially different economic and environmental impacts from the TRS. The first two factors indicate the intensification level of livestock production.

As shown by Fig. 1, low subsidy rates (below 20%) are found in some countries, such as in Belgium (11%), Denmark (16%) and Netherlands (6%), while high support (more than 50%) is observed in Austria (54%), Germany (53%), Sweden (51%) and Ireland (71%). The cost share of concentrate feed is in general high in most of EU Member States, except in certain Eastern EU countries, such as Romania, Latvia and Slovakia, where it does not exceed 5%. These countries have more extensive farming systems, which also implies higher cost shares for land compared to Western-EU Member States. For example, land cost shares do not exceed 2%, in Netherlands, Denmark and Ireland. Where subsidies are already high, the maximum considered subsidy rate of 80% will prevent stronger increases and thus limit the adjustment. In contrast, farmers in countries where initial subsidy rates are low will have higher incentives to convert crop and other land to pastureland. The original intensification level also plays an important part. As concentrate feed costs are expected to increase when crop land subsidies drop and thus crop production costs increase, a high initial cost share of concentrate feed will reduce incentives to expand ruminant production. This can limit the pastureland expansion in response to increased subsidies. Hence, higher expansion rates of grassland-based cattle production are expected in countries with relatively low initial subsidies on pastureland, but also low concentrate feeding, e.g., Romania and Slovakia. Finally, the TRS will lead to larger pastureland expansion in countries where conversion to pastureland is easier.

3. Results

3.1. Baseline results

This section describes the main socioeconomic and environmental outcomes of the baseline over the period 2014–2030, based on the SSP2. The presentation focuses on crop and livestock production and consumption, land areas and prices. LUC results refer to the combination of all price-induced land substitution effects that take place on a global scale until 2030. Driven by changes in GDP and population growth, the baseline shows a continuous growth in the EU demand for agricultural products until 2030 (Fig. 2).

Demand for food and feed crops increases significantly, e.g., 7.51% for wheat, 2.67% for rapeseed, and 8.24% for legumes. An increase in the demand for oilseeds crushing is also projected, namely for rapeseed meal (6.68%) and soybean meal (13.93%). Another driver is the increased use of primary crops to produce biochemicals and biofuels. For

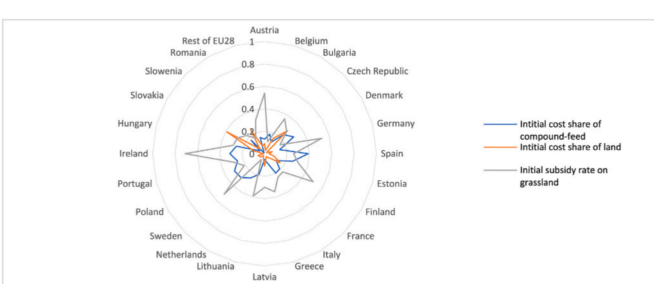


Fig. 1. Characterization of the livestock sector in the EU28 countries based on GTAP10 database.

instance, the input demand for vegetable oils used by the EU chemical industry is projected to rise considerably, e.g., for rapeseed oil by 23.53% and for soybean oil by 20.00%. Consequently, there is a significant increase in the EU supply of food and feed crops (Fig. 2b), e.g., wheat (10.92%), rapeseed (5.40%) and legumes (8.67%). However, for other crops, the increased demand is mainly met through greater imports (Fig. 2c), e.g., total EU imports of soybean rise by 18.64%. This results in an increased production of agricultural commodities in exporting countries with abundant natural resources, such as in South America and Southeast Asia. Crop production increases in the world partly driven by the increased supply in the EU (Fig. 2d).

Figure A3 in the annex shows changes in EU imports of agricultural commodities, namely oilseeds, vegetable oils and meals (figure A3a), and cereals and other crops (figure A3b) by main exporting countries. Brazil shows a drastic increase in its exports of soybeans (48.59%) and derivatives: oil (12.90%) and meal (39.88%). EU imports of cereals and other crops also increase in the medium term, namely wheat from North America (36.11%) and sugar cane from sub-Saharan Africa (79.37%). The projected increase in the EU's demand for primary crops, from both intra- and extra-EU markets, is associated with sizeable global LUC effects. Figure A4 in the annex shows changes in the pastureland and cropland areas up to 2030, relative to 2014. Due to limited land availability, pastureland areas decrease significantly in most EU countries, for instance by 20.67% in parts of Germany) and by 11.45% in parts of France. Pastureland expands in several regions (by up to 5%), mostly outside the EU, such as in Middle East and North Africa (MENA), parts of North America, Central Asia, Southern Africa, South-Eastern Asia (SEA) and Western Pacific as well as in the North-Eastern and central regions of Brazil. Cropland increases in most EU countries, such as in Ireland (up to 28.89%), France (up to 10.28%) and Italy (up to 5.22%) as well as in other regions, such as North America (up to 8.31%), Southern Asia (up to 12.29%) and South America (up to 27.57%).

3.2. Market-mediated impacts of the tax recycling strategy (TRS)

The expected market-mediated effects of the simulated TRS are summarized in Fig. 3, in order to facilitate the understanding of the results below.

Note: Green boxes indicate an increase. Red boxes indicate a decrease. Grey boxes indicate impacts on GHG emissions. Yellow boxes indicate impacts on land market and subsequent effects on the economy.

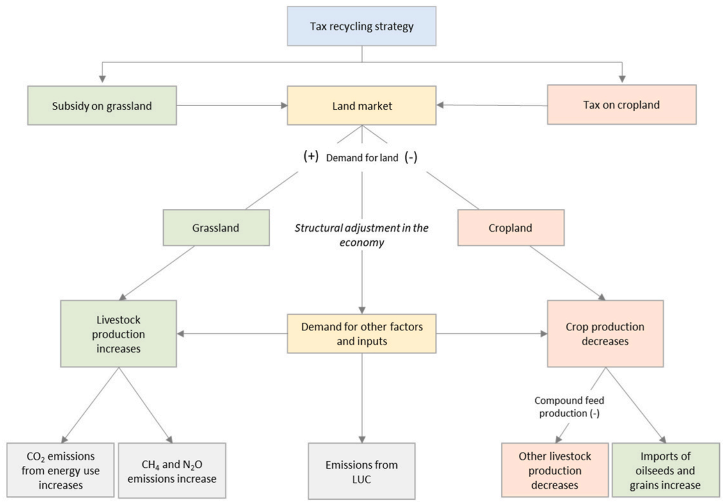
Higher subsidies and thus reduced pastureland prices translate into reduced production costs for ruminant livestock production. This generates an increased demand for land in the EU livestock sector, partly replacing feed concentrates and supplements, and favoring ruminant production over other livestock systems. The TRS has the opposite effect on crop production: cropland uses become more expensive so that arable land use and crop production decrease in the EU. These adjustments entail changes in prices of agricultural commodities, i.e., decreasing prices of livestock products and increasing prices of crops. This has implications in other sectors that use primary crops as intermediate inputs, mainly non-ruminant livestock (i.e., pig and poultry) and concentrate feed production, where production costs increase. Decreases in ruminant meat prices and increases in other agricultural products' prices lead to changes in final demand. The adjustment in production requires a reallocation of production factors and intermediate inputs across sectors, driven by changes in land rents and subject to the degree of substitution between land and other production factors (inputs). Increases in pastureland subsidies decrease the feed use of crops and lead to pastureland expansion. Decreased production costs in cattle production may result in additional adjustments, for instance, by increases in the demand for other production factors and intermediate inputs that are not associated with the use of land, such as labor. It must be taken into account that the extended GTAP-AEZ module (Fig. 1) mitigates this effect, as new land can be brought into productive uses. All these market responses will ultimately have environmental implications

Fig. 2. Projected changes in demand, production, and imports of agricultural commodities relative to the year 2014 (%), in the baseline representing Socio-Economic Pathway 2 (SSP2).

in terms of LUC and GHG emissions, as discussed below. Results from the TRS supporting pastureland-based cattle production are presented as percentage changes relative to the baseline scenario in 2030.

Changes in subsidy rates across EU countries up to the year 2030 are shown in table A2 in the annex. These tax rate adjustments are not uniform across countries. They reflect the original budget allocation between pastureland and cropland: the higher the share of cropland subsidies in total land subsidies, the smaller is the resulting drop. Moreover, as any increase in pastureland subsidies beyond a subsidy rate of 80% is not allowed in the simulation (see section 3.3), countries with a high subsidy rate for pastureland in the baseline show little change in the tax rates, such as in Ireland (+6.96%). Land-based payments to ruminant production increase by almost threefold in countries where initial payments are rather low, such as in Belgium (213.06%), Denmark (196.65%), and Italy (199.52%).

Figure A5 shows simulated output and price effects on the EU ruminant livestock sectors. Market responses are quite diverse across EU countries, with their size depending on the magnitude of the shock, i.e., greater subsidy changes provoke larger market effects. In countries where payments to pastureland are already high in the baseline, such as in Ireland, a minor change in subsidy rate results (+6.96%) in a negligible effect on cattle production (+0.91% in 2030). In countries with



Note: Green boxes indicate an increase. Red boxes indicate a decrease. Grey boxes indicate impacts on GHG emissions. Yellow boxes indicate impacts on land market and subsequent effects on the economy

Fig. 3. Flow chart of economic and environmental effects of increases land-based payments to cattle sector in the European Union (EU) at the expense of cropping activities.

rather low initial payments, significant substitution of pastureland for feed concentrates takes place, as the extensive margin effect prevails, and farmers benefit from increasing pastureland areas. For instance, in Romania, subsidy rates increase by 189.06% and make cattle output in 2030 increase by 7.44%. However, in some other countries, cattle production remains stagnant despite larger increases in pastureland subsidies. This is the case of countries where cattle production is largely based on feed concentrates. Netherlands provides an example, with cattle production increasing by only 0.57% in 2030 relative to the baseline, despite a subsidy increase of 179.57%. Here, cost increases for concentrates due to higher crop prices offset cost savings from reduced pastureland prices. In fact, reducing cropland-based support to boost extensive cattle production in the EU increases crop and feed concentrate prices (See table A3 in the annex). For instance, the price of rapeseed meal increases in Netherlands, Hungary, and Belgium by around 2%. The increase in crop prices, combined with an overall increase in feed concentrates demand in the EU cattle sector contributes to increasing feed prices. For instance, concentrate prices increase in major EU ruminant producers, by 1.57% in France, 1.53% in Germany and 1.41% in Spain. This results in a relatively small expansion of the cattle sector, i.e., production increases by 0.79%, 1.68% and 1.19%, in France, Germany and Spain, respectively.

The pastureland subsidy is detrimental for the EU's supply of non-ruminant livestock (figure A6 in annex), both due to lower prices of ruminant meat and higher concentrate feed cost. Hence, these sectors, encompassing pig and poultry, shrink in many EU countries, mainly in Lithuania (-3.53%) and Estonia (-3.48%), where a significant redistribution of production inputs and factors from non-ruminant to ruminant livestock sectors is observed. In other countries, non-ruminant livestock sectors even slightly expand, such as in Hungary, Poland, Ireland and Netherlands by around 1% in 2030 compared to the baseline.

As explained above, differences in livestock management systems and initial subsidies drive the varying impacts across EU countries from the land subsidy redistribution. The less elastic the land supply, the greater the changes in land rents and subsequent substitution effects among land uses (See table A4 in the annex). Land buffer data are only available at national level, such that the extent of land expansion is not differentiated at the sub-national level. In countries where some additional land is available, such as in Germany, price-mediated effects from the TRS are relatively smaller. Another example of this is the Czech Republic, where the increased support to pastureland triggers a significant increase of cattle production (19.91%), while cropping and other livestock activities are barely affected. However, in countries where data show that agricultural land resources are fully utilized, changes in land subsidy rate provoke more significant price effects. For instance, in Greece, increases in wheat (2.02%) and other cereal prices (1.54%) contribute to a price increase of 2.51% in 2030 for other non-ruminant livestock products. Results also depend on the relative shares of cropland and pastureland in total agricultural land area in the database. For instance, in Spain, where the share of cropland in total agricultural area is quite large (73 % at the benchmark), increasing pastureland subsidies does not require larger decreases in crop land subsidies. Accordingly, only minor changes in crop production are observed, for instance, wheat production drops by 0.06%. The opposite is found in cases where the share of cropland is originally low and where land is scarce. Ireland is an exception, despite the relatively low cropland area share (25%), due to the limited increase in payments to pastureland (6.96%). Overall, the TRS generates a moderate decrease in production of traditional crops in the EU, such as rapeseed and wheat, partly also due to increasing market prices (See table A3 in the annex). At the same time, imports of cereals, oilseeds, vegetable oils and cakes increase to compensate for lower domestic production (Table 2).

As seen in Table 2, the EUincreases its cereal imports. The larger relative changes are observed in the smallest import flows, such as from MENA (+0.01 US$ billion or +12.50%). Similarly, oilseed imports increase, e.g., from Argentina (+0.03 US$ billion or +11.11%) and East Asia (+0.01 US$ billion +6.25%). Imports of vegetable oils and cakes into the EU market also rise, for example, by 0.01 US$ billion or 4.55% from Oceania and by 0.10 US$ billion or 2.78% from Brazil. Intra-EU trade also expands for cereals, oilseeds, vegetable oils and cakes by 0.24 US$ billion (2.13%), 0.12 US$ billion (2.21%), and 0.36 US$ billion (2.16%), respectively. Countries where the subsidy shift has negligible impact on crop prices increase crop exports to other EU countries, such as, the Czech Republic, which increases total wheat exports by 6%. In Ireland, where the TRS results in a minor increase in payments to pastureland, oilseed and cereal exports to other EU Member States rise by 2.15%. The policy makes imported feedstuffs from third countries relatively cheaper than those produced ones in the EU, which results in an increased EU import of such feedstuffs. For instance, the UK increases its rapeseed cake exports to the EU by 3.44%As the major rich-protein feedstuff used in the EU feed industry, soybean cake imports also increase, mainly from Brazil (2.05%) and North America (2.18 %)=.

Table 2
Changes in total EU imports of agricultural products by origin, relative to the baseline in 2030; import values in (US$ billion). MENA: Middle East and North Africa; ROW: Rest of the World; SSA: Sub-Saharan Africa; UK: United Kingdom.

	Cereals		Oilseeds		Vegetable oils and cakes		total imports		
	Baseline value	*absolute change*	*Baseline value*	*Absolute change*	*Baseline value*	*Absolute change*	*Baseline value*	*Absolute change*	*% change*
EU	11.26	0.24	5.44	0.12	16.65	0.36	33.35	0.72	2.16%
UK	0.46	0.01	0.21	0.01	0.6	0.01	1.27	0.03	2.36%
North America	1.71	0.03	1.98	0.05	0.85	0.01	4.54	0.09	1.98%
Brazil	0.11	0.00	2.59	0.07	3.6	0.10	6.3	0.17	2.70%
Argentina	0.04	0.00	0.18	0.02	2.9	0.03	3.12	0.05	1.60%
East Asia	0.03	0.00	0.16	0.01	0.15	0.00	0.34	0.01	2.94%
Southeast Asia	0	0.00	0	0.00	4.62	0.03	4.62	0.03	0.65%
South Asia	0.01	0.00	0.36	0.00	0.78	−0.01	1.15	−0.01	−0.87%
Latin America	0.2	0.00	0.5	−0.01	0.94	0.01	1.64	0.00	0.00%
Australia, New Zealand	0.03	0.00	0.69	0.00	0.22	0.01	0.94	0.01	1.06%
SSA	0.12	0.00	0.19	0.00	0.17	0.00	0.48	0.00	0.00%
MENA	0.08	0.01	0.06	0.00	0.19	0.01	0.33	0.02	6.06%
ROW	1.68	0.04	0.53	0.01	1.39	0.04	3.6	0.09	2.50%

3.3. Global LUC and GHG emissions from the tax-recycling strategy

The aforementioned changes in agricultural production and trade generate considerable LUC both inside and outside the EU (Fig. 4). As expected, pastureland expands significantly in almost all EU Member States (Fig. 4a). This expansion is greater in countries where land resources are readily available, such as in Spain, France, Hungary, and Slovakia with increases of up to 6.81%. These changes refer to the maximum changes found across AEZs. The reduced land availability minimizes the effect in other EU countries, such as Germany, Poland, Czech Republic, Denmark, Romania, Latvia and Italy, where pastureland expands up to 2.25%. Total cropland area decreases across the EU as a result of the policy, by up to 7.20% in Greece and Estonia (Fig. 4b) and up to 1.64% in Spain, France, and Slovakia. However, cropland areas also increase in countries such as Ireland (6.29%), where the subsidy increase for pastureland land is limited, same as Poland, Czech Republic, and Hungary (2.81%).

The increased EU demand for imported crops, essentially rich-protein crops from third countries (Table 2), leads to an expansion of cropland area in major grain producing and exporting countries such as US and Brazil (up to 6.29%), and Argentina (11.61%). Cropland also increases to a lower extent in other countries outside the EU, such as in East Asia (up to +2.81%), or in South-East Asia (up to +0.53%). Unmanaged forest loss is still observed in those EU countries where the TRS causes a significant increase in pastureland areas, such as in Germany (0.43%) and Italy (1.74%). In contrast, managed forestland areas increase in other EU countries, such as France (+0.81%), Greece (+3.46%), and Slovakia (+0.52%). Outside the EU, managed forestland expands in Brazil, Argentina, Canada, US, and Mexico (up to +2.61%), due to the moderate decreases in pastureland areas. At the same time, these effects are driven by the decreased meat exports to the EU and increased exports of grains and soy derivatives. Unmanaged forestland areas decrease slightly in the above-mentioned countries (by up to 0.70%). On the contrary, unmanaged forests increase in Sub-Saharan countries (by 4.65%), as well as in parts of South America and Western Asia, where both pastureland and cropland areas shrink as a result of decreasing demand for crops from these countries. At the global level, there is a decrease in pastureland areas (0.18% or 800 thousand ha), cropland (0.93% or 13,559 thousand ha) and managed forests (0.88% or 431 thousand ha), while unmanaged forests expand (0.51% or 15,728 thousand ha) relative to the baseline in 2030.

The TRS generates significant changes in GHG emissions (CO_2-eq) both inside and outside the EU, resulting from both global LUC and economy-wide adjustments (table A5 in the annex). Net GHG emissions

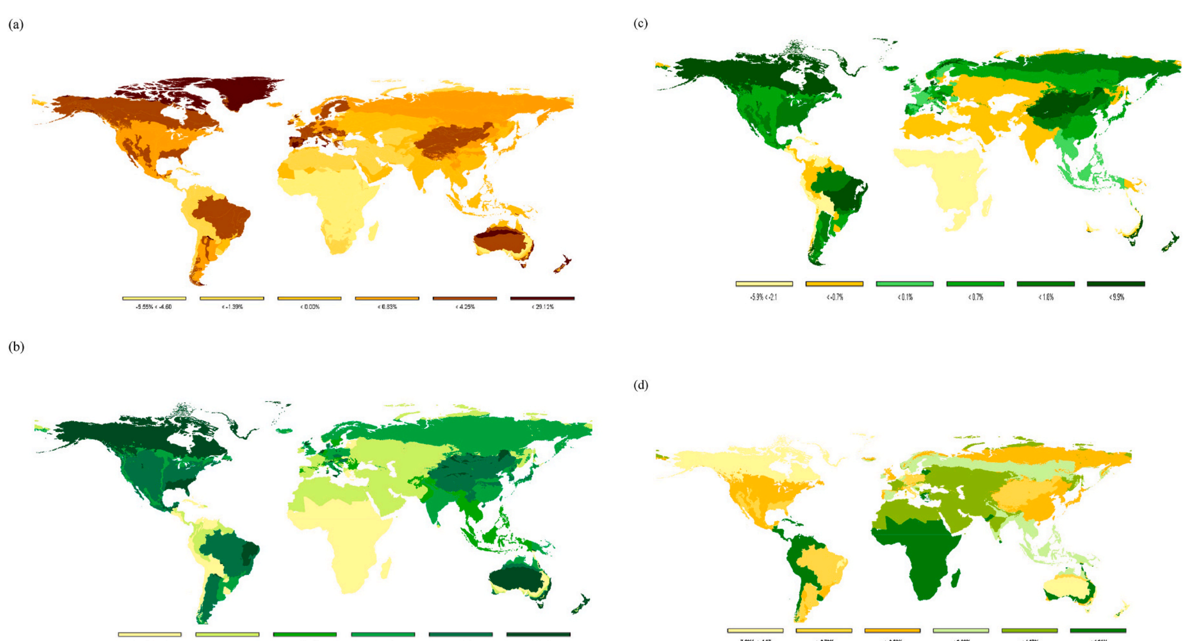


Fig. 4. Changes (%) in land areas of a) pastureland, b) cropland, c) managed forest, and d) unmanaged forest in the year 2030 relative to the baseline.

increase in the EU (2.49 Mt CO_2-eq in 2030), due to the increase in both CO_2 and non-CO_2 emissions (10.95 Mt CO_2-eq in 2030) from all economic sectors, which arise from fossil fuel combustion, and agricultural and industrial activities. The latter emissions offset negative LUC emissions (-8.45 Mt CO_2-eq in 2030) that result from the increase in biomass and soil carbon sequestration. Impacts across EU Member States are highly heterogeneous (table A5). GHG emissions decrease in countries such as in Greece, France, and Lithuania, by 15.35 Mt CO_2-eq, 5.20 Mt CO_2-eq, and 6.19 Mt CO_2-eq relative to the baseline in 2030, respectively. This is due to the expansion of pastureland and forestland, which increases carbon stocks, offsetting the higher CH_4 emissions from ruminant production. For example, in France, pastureland and unmanaged forest areas increase at the expense of cropland (up to 1.64%), and emissions from LUC decrease by 7.55 Mt CO_2-eq in 2030. Also in Greece, LUC decreases emissions by 8.55 Mt CO_2-eq through pastureland expansion. In other EU countries LUC increases GHG emissions, mainly through pastureland expansion at the cost of forests, e.g., in Italy (10.77 Mt CO_2-eq), Poland (5.34 Mt CO_2-eq), Germany (4.39 Mt CO_2-eq), Netherlands (3.10 Mt CO_2-eq), and Denmark (2.16 Mt CO_2-eq).

In EU countries where land resources are readily available, emissions from LUC contribute to increasing GHG emissions, as new land is brought into cultivation. For example, in Hungary, the expansion of pastureland area comes essentially at the expense of unmanaged forest (-68 thousand ha), leading to an increase of emissions from LUC of 1.07 Mt CO_2-eq. In Spain and Ireland, LUC results in small decreases of GHG emissions, by 1.49 Mt CO_2-eq and 0.02 Mt CO_2-eq, respectively, due to pastureland expansion at the cost of unmanaged forests. In Spain, CO_2 and non-CO_2 emissions increase drastically, e.g., CH_4 from cattle production increase by 0.18 Mt CO_2-eq, which represents the second highest increase among all EU Member States, after the Czech Republic. Despite increases in total GHG emissions in the EU (+2.49 Mt CO_2-eq in 2030), the TRS generates a significant decrease in GHG emissions globally (538.86 Mt CO_2-eq in 2030). LUC outside the EU decreases CO_2 emission through tge expansion of pastureland and unmanaged natural forest in many regions, essentially in Sub-Saharan Africa (-557 Mt CO_2-eq in 2030). This offsets potential increases in LUC emissions in other countries, mainly in EU agricultural trade partners such as Brazil and US, where cropland expands to meet the EU demand of protein-rich crops (Fig. 4b). For instance, emissions from LUC increase by 102.52 Mt CO_2-eq in Brazil and by 129.17 Mt CO_2-eq in US.

4. Discussion and policy implications

4.1. Implications of the results in the context of related studies

The recursive-dynamic, extended CGE model applied in this study allows considering global market-mediated spillovers in terms of land use and GHG emissions to estimate the medium-term sustainability of a shifts in land subsidies to promote more extensive cattle production in the EU. Such intervention has been widely discussed in the framework of the CAP as it is expected to improve the sustainability of food production and enhance environmental ecosystem services, for instance, by (1) reducing pastureland degradation, (2) increasing carbon sequestration, and (3) decreasing GHG emissions. However, our results show that the TRS does not necessarily lead to decreased GHG emissions in many EU countries if market-mediated LUC effects are included, while also generating land-use spillovers in other countries in the ROW. In this section, our results are compared to those from previous related studies, while limitations of our own study are discussed. The analysis highlights the importance of considering global and economy-wide effects when assessing the land use and GHG implications of policy support to extensive livestock production in the EU. Previous studies (Gocht et al., 2016; Gocht et al., 2016; Heinrichs et al., 2021) on this topic mostly employ supply chain or farm models, which allow for more detailed analysis of local and sectoral effects, but cannot consider price-induced changes outside the EU.

Results from this study show that an increase of returns to land in the cattle sector motivates farmers to shift more land into grazing, by converting cropland to pastureland. This strategy affects the EU countries differently depending, on the one hand, on the production structure of their cattle sector (more or less intensive); on the other hand, on the availability of additional land to be brought into cultivation. Greater pastureland expansion is observed in those EU countries with similar areas of grassland and croplands. This implies a larger area of grassland reacting to the increased subsidies, and, at the same time, a large buffer of cropland on which to expand. A lower support to pasture relative to cropland under current policies gives room for larger subsidy increases and thus for greater incentives. Accordingly, the TRS has more limited impacts in countries with smaller land buffers, such as in Greece, but also in Member States that rely heavily on feed concentrates instead on pastureland, such as the Netherlands.

The simulated expansion in pastureland area of 2.10% (or around 1 Mha) can be compared to that estimated by Gocht et al. (2016). They employ the PE model CAPRI integrated with the biochemistry CENTURY model to simulate a strategy that encourages EU farmers to increase pastureland area by 5% or around 2.9 Mha, through flexible payments. It is also important to mention that the original area of the EU pastureland in the baseline scenario in Gocht et al. (2016) is 58.5 Mha, while it is around 46.7 Mha in our study. This difference is mainly explained by the non-inclusion of the UK, as a former EU Member State with large grassland areas of around 10 Mha. Gocht et al. (2016) find that a 5% increase in grassland areas generates a carbon sequestration of 5.96 Mt CO_2-eq, which is partly offset by an increase of 1.75 Mt CO_2-eq from CH_4 and N_2O emissions. Our study estimates emission reductions from carbon sequestration of 8.45 Mt CO_2-eq, although these are offset by increases in CO_2 and non-CO_2 emissions. In addition, this greater carbon sequestration in the present study could be also attributed to the scenario design that enforces a simultaneous decrease in cropland subsidies, which is not the case in Gocht et al. (2016). Hence, the TRS implies that more cropland, with lower carbon stocks compared to natural forests, is converted to pastureland. This is in line with the CAP, to avoid EU budget increases. Our study estimates net GHG increases in the EU of 10.95 Mt CO_2-eq, due to increases in economy-wide emissions, mainly from livestock. Gocht et al. (2016) consider GHG emissions from agriculture only, which explains the net decrease in GHG emissions. A CGE-based study as the one presented provides a more comprehensive estimation of the total GHG emissions from a policy promoting grassland in the EU, with effects that spread across sectors. In contrast, CAPRI provides more spatial details by simulating agricultural production at the NUTS-2 level, which reduces potential aggregation bias, and represent subsidies in more detail.

The simulated TRS is detrimental for the EU's supply of pig and poultry and other livestock, due to increasing crop prices, which entail higher concentrate feed costs. As a net effect, EU imports of feedstuffs increase. Demand for traditional feed crops is largely met with intra-EU imports, specifically from those countries that are barely affected by the strategy and where pastureland support is already notable, e.g., Ireland. However, imports of other high-protein feedstuffs from non-EU regions increase, notably soybean cake from South and North America. The increase in import demand for feedstuffs responds to the higher feed concentrate demand from expanded cattle production, which exceeds the substitution effect between grass and feed concentrate in feed use. Demand for feed concentrate at EU level in the cattle sector increases by 0.18% in 2030, relative to the baseline. This side effect from the TRS increases EU's dependence on imported proteins and generates LUC and related GHG emissions, mainly in major feed exporting countries outside the EU. For instance, GHG emissions decreases (8.45 Mt CO_2-eq) from LUC effects in the EU comes with an increase of LUC emissions of 102.52 Mt CO_2-eq in Brazil and by 129.17 Mt CO_2-eq in USA. Such leakage effects reduce the global mitigation potential of the TRS by 348 Mt CO_2-eq or 40%. Trade-mediated carbon leakage has been widely discussed in global economic modelling assessments of agricultural sectors.

However, fewer studies consider induced LUC when addressing GHG emissions reduction potentials in livestock sectors, as most of them use farm-scale models (Schils et al., 2007) or have a limited regional coverage (Jansson and Säll, 2018). Fellmann et al. (2018) address different challenges for the EU agricultural sector to contribute to climate change mitigation. They find that a GHG emission reduction strategies targeting non-CO_2 emissions from agriculture may lead to considerable carbon leakage due to changes in agricultural trade balance. In their study, this effect comes essentially from the global re-allocation of the livestock sector as 90% of the additional emissions outside the EU stem from meat production. From the consumption side, Zech and Schneider (2019) estimate that the mitigation potential of a carbon tax on EU's food consumption is decreased by 43% due to carbon leakage.

4.2. Methodological contribution and limitations

A major contribution of this study is the link of the physical MRIO model FABIO (Bruckner et al., 2019a) to the dynamic GTAP-RDEM model (Britz and Roson, 2018; Roson and Britz, 2021a,b). This offers a powerful framework to increase the sectoral resolution of the GTAP database with regard to agri-food sectors. In this study, FABIO is used to increase the agri-food resolution in the original GTAP 10 data (Aguiar et al., 2019) from 21 to 31. This significantly enhances the analysis of trade-mediated effects in the EU and across the world. The integration of physical MRIO data into the database of a CGE model of economic nature poses methodological and empirical challenges (Walmsley et al., 2014; Wiedmann et al., 2011). This entails, for instance, finding appropriate price vectors to translate physical quantities into economic flows. The link to FABIO can be easily expanded to disaggregate other agri-food sectors to study both supply- and demand-driven shocks to the global agri-food system within the CGEBox framework (Britz et al., 2018). Indeed, an improved version of this link by Britz (2022) increases the agri-food detail to around 50 sectors.

Combining GTAP-based CGE models with MRIO databases is not yet common in the literature, where only a few examples can be found. One of them is the GTAP-supply chain (GTAP-SC) model (Walmsley et al., 2014; Carrico et al., 2020). GTAP-SC uses the GTAP-based MRIO database (Hertwich and Peters, 2009) that employs the Broad Economic Classification (BEC) of the United Nations to differentiate between bilateral trade for intermediate use and for final consumption, at the 6 digit harmonized system (HS) level. Carrico (2017) further improved the GTAP-SC model (Walmsley et al., 2014) by introducing tariff rate differentiation across economic agents. However, the GTAP-MRIO does not provide additional agri-food sector detail beyond the 21 sectors found in the standard GTAP database. A study by Bruckner et al. (2019b) highlights the importance of increasing sectoral resolution for assessing environmental sustainability, especially in the context of an expanding global bioeconomy, which is characterized by complex and highly fragmented bio-based value chains, with high potential to generate land use spillovers and associated environmental footprints.

A key limitation of this study is related to uncertainties in the parameterization of the production functions of the crop and livestock sectors, which may significantly affect results. Pelikan et al. (2015) change the structure of the supply for primary agriculture in a special version of the GTAP model such that it captures the supply response of the farm-type layer of the CAPRI model, which provides high details of the EU agriculture (Gocht and Britz, 2011). Simulated output prices are then exogenously fed into the CAPRI supply models. Such a consistent and structural "hard linkage" approach, as described in Philippidis et al. (2017) may significantly improve the results obtained. Moreover, it allows for more detailed environmental assessments of the TRS at the NUTS2 level in the EU. The aggregation level of AEZs at the level of country or even group of countries in this study might cause aggregation biases, for instance, with regard to carbon stock accounting. A comprehensive review by Hertel et al. (2019) comprises further examples of global economic models, which try to improve the accounting of direct and indirect LUC, such as the PE GLOBIOM-Brazil model (Buurman et al., 2015; Soterroni et al., 2018), adapted from the global economic model GLOBIOM to assess land use policies in Brazil at high spatial resolution. In this model, LUC and related agricultural production are presented at the grid level.

Global CGE models include many parameters, the value of which is not certainly known. For more limited studies, such a comparative-static CGE experiments with lower spatial resolution and/or less products/sectors, sensitivity analysis is recommended to understand the epistemic uncerrtainty affecting the results. Literature in this field generally confirms that broader impacts are robust even with regard to larger parameter changes, see, for instance, Hermeling et al., (2013), which reinforces the robustness of our findings. Britz and Van der Mensbrugghe (2016) indicate significant aggregation biases associated with CGE analysis, which we address by improving the spatial detail for the EU and its relevant trading partners, and employing the FABIO MRIO to provide sectoral detail.

4.3. Policy implications

Increasing the sustainability of the livestock sector, which represents a major contributor to the global GHG emissions and biodiversity loss, remains an enormous challenge for the EU to meet the Paris Agreement and the Sustainable Development Goals (SDGs) (Herrero et al., 2016; Reisinger and Clark, 2018; Mehrabi et al., 2020). Results from this study show that a TRS promoting extensive cattle production in the EU does not necessarily lead to GHG emission mitigation in the EU, where net GHG emissions increase by 2.49 Mt CO_2-eq in 2030, despite GHG emission reductions from LUC. This means that additional initiatives should be promoted in the EU to ensure that environmental objectives of the post-2020 CAP are met. Specifically, the CAP encourages crop rotations, potentially including legumes, to promote feedstock diversification and reduce the dependency on imported commodities and feed concentrates. This could be achieved through alternative strategies beyond subsidies, e.g., capacity building and training to enhance farmers' ability to implement tailored interventions and manage rotations, programs to facilitate farmers' access to resilient and nutritional feed crop varieties and low-impact technologies, etc. (Havet et al., 2014; Rivera-Ferre et al., 2016). It is thus necessary to understand local and regional institutional and cultural factors shaping livestock systems (e.g., in terms of the grass/forage input ratio to the total animal intake, or the relationships between producers and sellers), which in turn determine the feasibility of carbon reduction strategies. In the EU context, these strategies should specifically aim to sustainably increase yield productivity of plant proteins (Kaufmann et al., 2022; Antonio, 2023). Adopting sustainable management practices - including agroforestry and optimized rotating grazing - could contribute to increasing grasslands' sequestration capacity (FAO, 2023). Finally, promoting the One Health in the agri-food system can contribute to increasing livestock productivity while maintaining pasturelands and their carbon sequestration potential. This could be achieved by switching towards a holistic management of agricultural systems, though it would require further investments in infrastructure, policies and regulations to ensure feed/food safety and reduce the risks of animal disease outbreaks (Zira et al., 2022; Thumbi et al., 2015; Mehrabi et al., 2020).

The TRS causes natural land cover loss in countries that are home of carbon- and biodiverse-rich ecosystems, e.g., in Brazil through the increased EU imports of oilseeds and grains. The latter does not align with the EU regulations to promote deforestation-free supply chains (EUDR) in the context of the EU Green Deal, which aims to cap imports of soy that has been linked to deforestation after December 31, 2020, among other commodities. It remains to be seen whether the EUDR will effectively prevent global deforestation, as the EU accounts for a relatively minor share of international feed demand, led by China (Zhao et al., 2021; Govoni et al., 2022; Huang et al., 2019). Additional measures may be needed to ensure that agri-food production in the EU does not lead to LUC globally, such as promoting the use of domestic feed resources (including by-products and waste). More effective forest conservation policies in major agri-food exporting countries, as well as other governance interventions aimed at combating illegal deforestation and land grabbing, remain crucial to tackle deforestation at source (Börner et al., 2020; Zhao et al., 2021).

5. Conclusions

This study assesses potential market-mediated impacts in 2030, including global LUC and GHG emissions, of a budget-neutral increase in pastureland subsidy rates in the EU, aimed at increasing pastureland areas to improve the environmental sustainability and self-sufficiency of the EU livestock sector. The TRS is in line with the CAP's aim to improve maintain/increase pastureland areas in the EU to prevent pastureland degradation and increase carbon sequestration, while maintaining the EU agricultural budget at the cost of agricultural subsidies. We employ a recursive-dynamic CGE modelling framework with higher detail in agri-food sectors (oilseeds, vegetable oils and cakes) compared to the GTAP v10 Database, based on a physical MRIO database that includes more than 130 agricultural products. Results show that GHG emissions increase in the EU, relative to the baseline, due to the increase in agricultural emissions, including those from enteric fermentation. Induced LUC contributes to net carbon sequestration in the EU, despite forestland decreases in some countries. Furthermore, the policy generates global spillovers in terms of agricultural land expansion and GHG emissions, including unmanaged forest loss, in EU-trading partners that increase oilseed and grain exports to the EU, where pastures expand at the cost of cropland. To avoid such unwanted effects and to decrease EU's dependency on imported crops, the simulated strategy should go in parallel and in synergy with increased efforts and policy interventions to diversify feed sources in the EU and sustainably increase the productivity of indigenous crops, mainly legumes, e.g., through more sustainable crop and grasslands management practices, lower-impact technologies, and more circular supply chains. The study also underlines that spillover effects of international trade should not be overlooked when developing regional agricultural policy strategies affecting the increasingly interlinked food-feed-fuel-fibre markets.

CRediT authorship contribution statement

Salwa Haddad: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Neus Escobar:** Formal analysis, Validation, Writing – review & editing. **Martin Bruckner:** Data curation, Writing – review & editing. **Wolfgang Britz:** Conceptualization, Data curation, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141074.

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