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To cite this article: Francesco Clora *et al* 2021 *Environ. Res. Lett.* **16** 124048

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ENVIRONMENTAL RESEARCH
LETTERS

LETTER

OPEN ACCESS

RECEIVED
31 March 2021REVISED
22 October 2021ACCEPTED FOR PUBLICATION
15 November 2021PUBLISHED
3 December 2021

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Impacts of supply-side climate change mitigation practices and trade policy regimes under dietary transition: the case of European agriculture

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E-mail: wusheng@ifro.ku.dk**Keywords:** agriculture system, climate change mitigation, dietary changes, food, trade, European Union, CGE modelSupplementary material for this article is available [online](#)**Abstract**

The European Union's *Green Deal* proposal and *Farm to Fork* strategy call for both demand and supply measures to reduce emissions from the food system. While research clearly illustrates the importance of dietary transitions, impacts of potential supply-side measures are not well understood in relation to competitiveness concerns and leakage effects. This study assesses trade and GHG emission impacts of two supply-side mitigation strategies (intensification vs. extensification) in the EU, UK and Switzerland (EU + 2), against a 2050 baseline featuring healthy/sustainable diets adopted by European consumers. To capture potential leakage effects arising from changing external trade flows, the two supply-side strategies are assessed against three trade policy regimes (i.e. status quo, regional trade liberalization with *and* without border carbon adjustment), resulting in six scenarios formulated with detailed inputs from the EU Calc model and other literature and simulated with a purported-designed CGE model. Results show that intensification, while improving the EU + 2's external trade balance, does not reduce emissions in the EU + 2, compared to the baseline. In contrast, extensification leads to a substantial emission abatement that augments reductions from the assumed dietary transition in the baseline, resulting in a combined 31% agricultural emission reduction in EU + 2 during 2014–2050. However, this is at the expense of reduced net agrifood exports by US\$25 billion compared to the baseline and significant carbon leakage at a rate of 48% (i.e. nearly half of agricultural emission reduction in the EU + 2 'leaked' to elsewhere). Furthermore, implementing the EU + 2's prospective regional trade agreements results in increased territorial emissions. Although a border carbon adjustment by the EU + 2 can improve its trade balance and partially shift mitigation burdens to other countries, the associated reductions in global emissions (and carbon leakage) would be marginal. Finally, different trade and emission effects are identified between the crop and livestock sectors, pointing to the desirability of a mixed agriculture system with intensified livestock sector and extensified crop agriculture in the EU + 2 that balances emission reduction goals and competitiveness concerns.

1. Introduction

The global food system is a significant contributor of global greenhouse gas (GHG) emissions [1]. The move towards emission-intensive diets consisting

of more animal food products in developing and emerging economies due to rising income and population implies that the global food system could emit even more than today, raising the urgency of curbing this trend [2–4] for safeguarding planetary

health [5]. The food system in 2015 generated 30% of the European Union's (EU) GHG emissions [6], mainly due to its generally intensive livestock sector [7] and high per capita dietary emissions [8]. The Farm to Fork Strategy [9] recognizes the importance of supply- and demand-side measures to obtain a sustainable food system and a climate neutral EU [10]. Transitioning towards healthy and sustainable diets consisting of more plant-based food items and having less food waste are widely recognized as demand-side mitigation options [11–16].

On the supply-side, both intensification and extensification practices are proposed as mitigation measures. The choice between the two practices is often based on availability and quality of land and access to internal and purchased inputs [17–19]. Intensification practices can improve yields, technical efficiencies, and intensities in land use and chemical inputs [20–25]. For instance, intensified agriculture reduces land use per unit of output, potentially allowing spare land as carbon sinks, whereas intensified livestock sector also reduces the burden of manure management. However, intensification can negatively affect various environmental indicators, such as biodiversity and global nitrogen cycle [26–28]. Extensive practices are also considered as climate change mitigation strategy [29–33]. For instance, an extensified agroecological system phases out synthetic fertilizers and pesticides and deploys agroforestry practices. However, unilateral extensification may lower crop yields [34], potentially leading to increasing production elsewhere [35]. These complexities suggest that the choice between the two practices should be carefully evaluated in relation to the expected differential yields and output effects and product compositional effects, not the least in conjunction with future dietary patterns.

The EU is highly competitive on world agrifood markets. In 2019 its external agrifood exports and imports amounted to €181.8 and €121.7 billion, respectively, leading to €60 billion agrifood trade surplus [36]. Changes to the EU's production system and dietary patterns may cause imbalances on the EU internal market, resulting in changing external trade patterns and potentially impacting third countries that depend either on imports sourced from, or on exports to, the EU market. This competitiveness concern can be compounded by potential carbon leakages that weaken the EU's intended contribution to global emission reduction⁴. Therefore, it is important to consider the development of the EU's external trade policy. The EU had 41 Free Trade Agreements (FTA) in force with 72 countries as of 2019 and has recently concluded or is currently working on a variety of other agreements [37, 38]. Existing empirical

studies point to ambiguous impacts of trade liberalization on GHG emissions [39, 40]. It is also unclear how climate change mitigation would reshape existing trade patterns. Moreover, the risk of carbon leakage through trade linkages can be counteracted by trade policy instruments such as export rebates for trade-exposed sectors and the so-called border carbon adjustments (BCA; also known as carbon border adjustment mechanism—CBAM) levied on emissions embodied in imports [41, 42]. The BCA has been mentioned in the European Green Deal proposal [10]. Its actual implementation and conformity to relevant WTO trade rules, and possible retaliations from trade partners, largely remain unclear [43, 44].

This paper contributes to the above literature by investigating the GHG emissions and trade-related carbon leakage effects of two alternative supply-side responses (i.e. intensification vs. extensification) to a healthy/sustainable dietary transition pathway in the EU, plus UK and Switzerland (EU + 2). It further explores how the impacts of these supply-side responses—including carbon leakage effects—are contingent on the assumed trade policy regimes. The analysis is conducted in a computable general equilibrium (CGE) framework, with a baseline in which consumers in the EU + 2 transition to a sustainable diet by 2050. Against this baseline, we exploit detailed sector- and country-level data from the European Calculator model (EUCalc)⁵ and other sources to formulate and simulate the effects of different combinations of the two supply-side mitigation strategies and three trade policy regimes (i.e. business-as-usual (BAU), trade liberalization, and trade liberalization with BCA).

2. Methods and data

In this paper, we apply a hybrid approach that allows concrete supply- and demand-side climate change mitigation scenarios built from detailed bottom-up data to be simulated in a top-down static CGE economic model with built-in flexibilities that can accommodate large structural changes in production system and consumption patterns reflected in such scenarios [45]. Based on the GTAP-E model [46, 47], we modify the household demand system to allow for embedded within-budget share shifters for simulating potentially large preference-driven dietary transitions towards 2050⁶. On the supply side, we introduce shifter parameters [48] in the nested production functions to facilitate the implementations of technological and structural changes envisioned in the intensification and extensification scenarios. An aggregate land supply function is implemented to capture land supply responses [49, 50]. We

⁴ Carbon leakage refers to the relocation of GHG emissions from countries with stringent climate policy to other parts of the world subject to no (or weaker) regulations.

⁵ www.european-calculator.eu/.

⁶ For details, see section 1 of the supplementary materials (SM) (available online at stacks.iop.org/ERL/16/124048/mmedia).

also capture changes in non-CO₂ emissions, in addition to CO₂ emissions already included in GTAP-E. Finally, trade policy instruments on GHG embedded in imports are added, for implementing alternative BCAs.

2.1. Data and baseline

The core data sets used are the GTAP-E v10 database [51] and the associated non-CO₂ emissions dataset [52]⁷, with 2014 as the reference year (therefore, all monetary values are denoted in millions of USD in that year). The datasets cover 65 sectors and 141 global countries/regions, including national input-output tables, bilateral trade flows, macroeconomic aggregates, energy, emissions, and trade policy instruments. These databases are aggregated to 12 countries/regions and 31 sectors⁸. We update the GTAP databases to create a baseline in 2050, using assumptions consistent with the ‘middle-of-the-road’ Shared Socioeconomic Pathway SSP2 [53] and in line with the latest available literature [54]. The overall strategy is to replicate at country/region level available long-run GDP projections and either impose or solve for the underlying determinants. More specifically, population [55] and labor force [56] projections are directly imposed in the baseline, while changes in total factor productivity are solved for by targeting GDP projections [57]. Changes in capital stock are endogenously adjusted via the so-called ‘Baldwin equation’⁹ [58]. Additionally, we include differential growth in sectoral productivities¹⁰ [59]. Autonomous energy efficiency improvements are implemented, with a constant exogenous rate of 1% annual growth for all activity sectors and energy carriers. External 2040 fossil fuel prices projections [60, 61] are imposed by endogenizing changes in the productivity of the oil, coal and gas sectors. Changes in crop yields due to a 1 °C increase in temperatures compared to 2014 [53] are also included in our baseline, using estimates by Roson and Sartori [62]. Finally, we exogenously project regional pathways of food consumption from 2014 to 2050, implementing dietary changes in the baseline as shifts in consumer preferences through a model simulation.

⁷ The non-CO₂ emissions database includes, among others, methane (CH₄) and nitrous oxide (N₂O) emissions linked to burning crop residues and savanna (CH₄, N₂O), emissions from cultivation of organic soils (N₂O), crop residues (N₂O), manure left on pastures and applied to soils (N₂O), manure management (CH₄, N₂O), enteric fermentation (CH₄) and intermediate use and production of synthetic fertilizers and pesticides (N₂O).

⁸ For details of the sectoral and regional aggregations, see section 2 of the SM.

⁹ We do not directly target the changes in capital stock, but opt for endogenizing it via the ‘Baldwin equation’ in the model that effectively ensures a fixed savings rate closure with capital accumulation.

¹⁰ Bekkers *et al* (2019) use 2.49 percentage points additional annual growth for agriculture, 1.51 for manufacture and –0.34 for services (relative to average economy-wide TFP growth), at the world level.

Data used to formulate dietary changes in the baseline and for constructing the production system transition scenarios are based on those from the EUCalc model [16]. The EUCalc model belongs to the so-called calculator models [63–70] and is a bottom-up system dynamics model. It represents GHG emissions dynamics and to evaluate the trade-offs and synergies arising from user-defined modifications to supply and demand in key emitting sectors in the EU + 2. It contains a rich set of historical and projected data disaggregated at the EU member state level, capturing drivers of sectoral and system-wide GHG emissions at various mitigation ambition levels; the latter are defined through sectoral expert/stakeholder elicitation and literature studies [71]. On the demand side, we update and extend the dietary projections from the lifestyle module of the EUCalc model [16] to construct the dietary scenario in the baseline (section 2.2). On the supply-side, we harness the rich details of EUCalc’s agriculture module to construct the extensification and intensification scenarios (section 2.3).

2.2. Dietary projections in the baseline

Consistent with the European Green Deal and the Farm to Fork strategy, in our baseline the EU + 2 is assumed to follow a healthy/sustainable diet in 2050 and to reduce food waste. The rest of the world (ROW) continues with BAU dietary developments and imposes no changes in food waste.

The healthy/sustainable diet in this work is based on calories required to maintain adequate body size under moderate physical activity and food group composition in line with dietary guidelines from medical research. At the global scale, diets offering substantial health benefits are found to be associated with significant reduction in agricultural GHG emissions, land clearing and biodiversity loss [3]. In this work we are mainly concerned with the changes in calorie demand resulting from adopting healthy diets used in our baseline. Although quantifying the health benefits of shifting dietary patterns is beyond the scope of this paper, previous research has established these positive benefits both at national and global scales in details [72, 73].

We begin by estimating the basal metabolic rate (BMR) under moderated physical activity level for individual countries, targeting a body mass index (BMI) between 18.5 and 24.9 [74] in 18 age/sex groups in each country, using data from NCD Risk Factor Collaboration [75]. The Schofield equation [76] is then calibrated on data from Hiç *et al* [77] to evaluate the total required amount of calories. The total per capita calories is then fulfilled with 45 different food groups following the Global Dietary Guidelines from Springmann *et al* [78] that reproduce the dietary composition consistent with guidelines from WHO [79] and World Cancer Research Fund [80]. By keeping the relative caloric

contribution of each group in the 2014 diet, we preserve to some extent the specific preferences of countries while implementing the dietary change. As not all food groups considered in this paper are covered by dietary guidelines (e.g. beverages), it is necessary to make some assumption on how these items evolve. We first prioritize the fulfillment of the calorie budget with food groups covered in the dietary guidelines, followed by food groups not included in the guidelines in the same relative proportions as in the 2014 diet and in an amount that observes the total calorie budget. In this way, we further maintain the historical preferences for some food groups.

After the diet composition is determined for each age/sex class, the total per capita calories for a country are determined by aggregation with the respective population. Additionally, we assume that the EU + 2 achieves reductions in food waste at the consumer level (SDG 12.3.1.b), using waste factors in the FAO Global Food Losses and Food Waste study [81].

For ROW, income elasticities of calories—a commonly used method to extrapolate calorie demand in long run projections [82]—at country level during 2000–2015 are assumed to persist in 2050. These are calculated based on the FAO Food Balance Sheets data on calorie availability [83] and per-capita GDP [84]. To project calorie consumption, GDP [57] and population projections [55] are used. These updated diets, measured as calorie demand for 45 food products, are then aggregated to the GTAP commodity classification using the Central Product Classification [85]. The implied changes in demand shares for final consumption and intermediate uses (e.g. food consumed away from home) are then implemented in the baseline as shifts in consumer preferences through model simulations¹¹.

2.3. Scenario design and implementation

We formulate and simulate six scenarios against the 2050 baseline, covering the combinations of agricultural intensification vs. extensification in the EU + 2 on the one side, and three trade policy regimes on the other. These are outlined in table 1 and described next. Note that in these scenarios we assume all crop and livestock sectors are either undergone intensification or extensification.

2.3.1. Alternative agricultural systems in EU + 2

Agriculture systems can be characterized by the intensities of the use of land, energy, and chemical inputs and the associated emission intensities [86]. We construct the intensification and extensification scenarios according to indicators related to the efficiency and requirement in land use (including crop yields, grazing intensity, and livestock yields)

and in input use (covering synthetic fertilizers, pesticides, and energy)¹². Table 2 presents changes to these indicators to be implemented in the intensification and extensification scenarios, obtained and aggregated from more detailed data in the agricultural module of the EUCalc model [87] and detailed in section 4 of the supplementary materials.

Crop yield changes are modeled as ‘land efficiency’ changes by crops, ranging from 1.1% to 2.2% for the different crops under intensification (*INT*), and –14.9% to –24.9% under extensification (*EXT*). Likewise, grazing intensity of livestock products are also modeled as ‘land efficiency’ changes, changing from the baseline level of 1.5 livestock units per hectare (LSU ha⁻¹) to 3.8 LSU ha⁻¹ and 1.0 LSU ha⁻¹ in *INT* and *EXT*, respectively. Alternative agricultural systems are also expected to have different livestock yields, defined as the amount of edible meat produced per livestock unit (measured in kcal/LSU). *INT* is expected to increase livestock yields (by between 4.6% and 8.5%), while *EXT* would lower yields (by between –10% and –22.2%). Changes in the livestock yields are modeled as changes in the efficiency in meat production. Moreover, *INT* (*EXT*) is expected to increase (decrease) synthetic fertilizers and pesticides use. Changes in fertilizers and pesticides uses are modeled via modified cost structures in sectoral production functions. Finally, energy used under both *INT* and *EXT* is expected to decrease. We model such changes by altering shares of the energy bundle in the production functions.

2.3.2. Alternative trade policy regimes

In the first trade policy regime (i.e. BAU), we assume no changes to the EU + 2’s agricultural trade policy from the 2014 level. In the trade liberalization regime (i.e. *FT*), we implement the agricultural trade provisions in 12 potential EU FTAs [37] to study the interplays between trade liberalization and more intensified (*INT_FT*) or extensified (*EXT_FT*) agriculture in EU + 2. The *FT* scenarios track the ‘conservative liberalization’ scenario of Boulanger *et al* [37], based on the consideration that recent setbacks to globalization are likely to linger well in the foreseeable future. No further liberalization is assumed for the ‘other food’ sector because it includes a large and heterogeneous set of processed products that are likely subject to different treatment in different trade agreements [37]. This conservative liberalization scenario only results in noticeable reductions of EU import tariffs on rice, sugar, cattle meats, and dairy (figure 1).

The third trade policy regime contains regional trade liberalization and a BCA on EU agrifood imports, differentiated by the exporting region’s

¹¹ Details on the 2050 baseline diet can be found in section 3 of the SM.

¹² As the intensification scenarios considered here are built on the ‘conventional’ intensification practices (e.g. intensive use of chemical inputs), more sustainable intensification practices (e.g. precision agriculture) are not considered.

Table 1. Scenarios analyzed in this study.

	BAU agricultural trade policy	Trade liberalization (FT)	FT + Border Carbon Adjustment
Intensification	<i>INT</i>	<i>INT_FT</i>	<i>INT_FT_BCA</i>
Extensification	<i>EXT</i>	<i>EXT_FT</i>	<i>EXT_FT_BCA</i>

Note: INT: intensification; EXT: extensification; FT: trade liberalization; BCA: border carbon adjustment.

Table 2. Key indicators in the agricultural intensification and extensification scenarios, % change from baseline.

Indicators	Intensification	Extensification
Crop yields	1.57	−22.03
Livestock yields	6.46	−14.47
Grazing intensity	162.41	−2.69
Fertilizer and pesticide use	28.60	−76.28
Energy use	−11.10	−11.10

Note: Numbers are simple averages across sectors. More details are available in table S6 in supplementary materials.

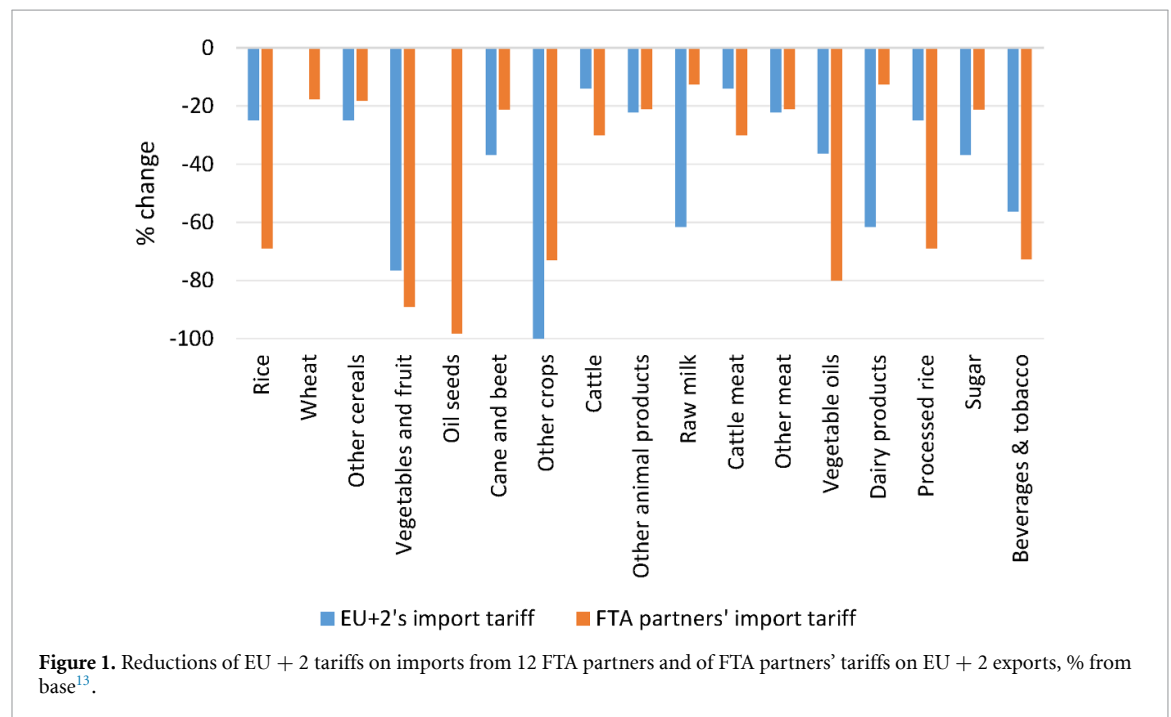


Figure 1. Reductions of EU + 2 tariffs on imports from 12 FTA partners and of FTA partners' tariffs on EU + 2 exports, % from base¹³.

direct sectoral CO₂eq intensity, as in scenarios *INT_FT_BCA* and *EXT_FT_BCA*. These scenarios are used to illustrate whether and to what extent the BCA counteracts potential carbon leakages arising from trade liberalization and agricultural system transition. As an illustration, the BCA is set at 40 USD/ton CO₂eq, the lower bound of the World Bank's estimated minimal price range needed by 2020 to be consistent with achieving the Paris temperature target [88]. In practice, the BCA leads to additional tariffs on EU agrifood imports, with the highest percentage increase in tariff rates in primary agricultural products (figure 2), although unlike processed food they are not intensively traded and do not necessarily

have high initial import tariffs. In contrast, as direct emissions in processed food do not include non-CO₂ emissions from primary agriculture, the BCA tariffs are relatively low for processed food imports (between 0.03 and 1.06 percentage points).

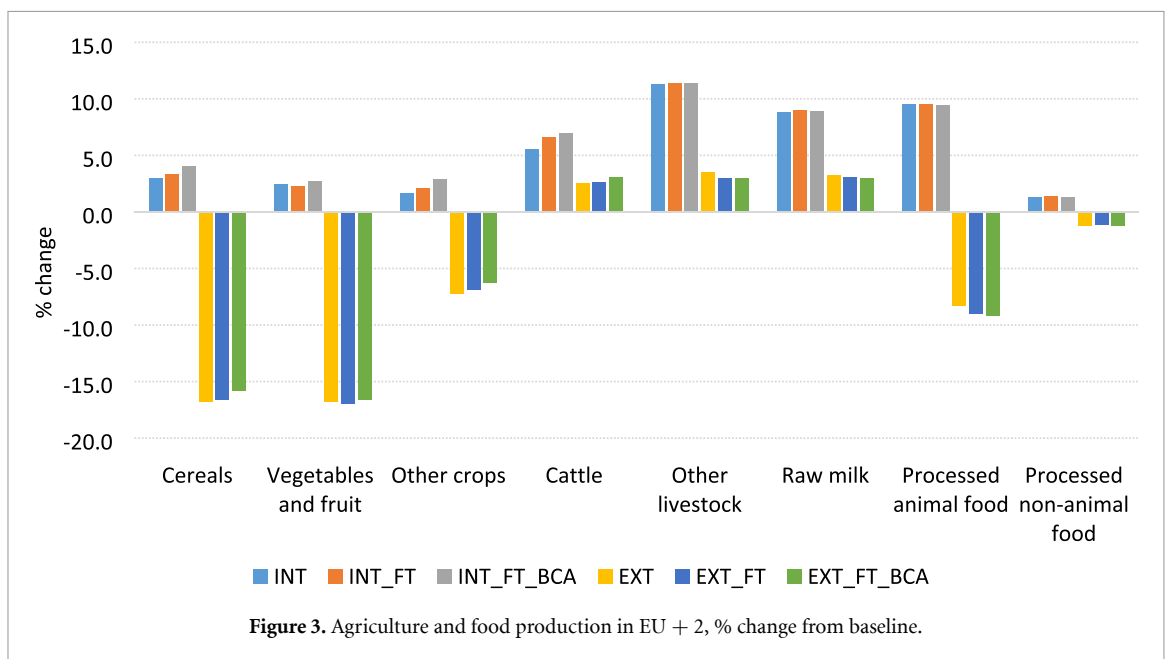
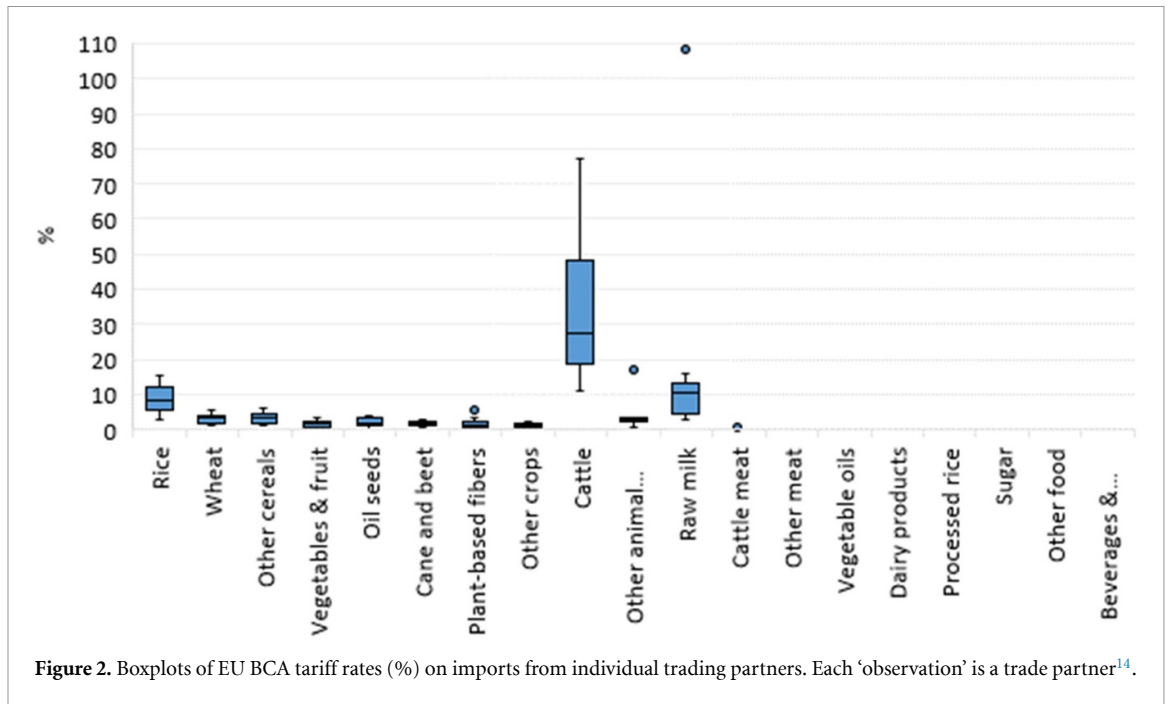
3. Results

We present in this section key simulation results on agricultural production, trade balance and agricultural GHG emissions. All results reported in figures 3–6 are relative to the 2050 baseline.

3.1. Agricultural production

Increasing crop yields due to intensification (the *INT* scenario) increases outputs of cereals, vegetables and fruit, and other crops in the EU + 2

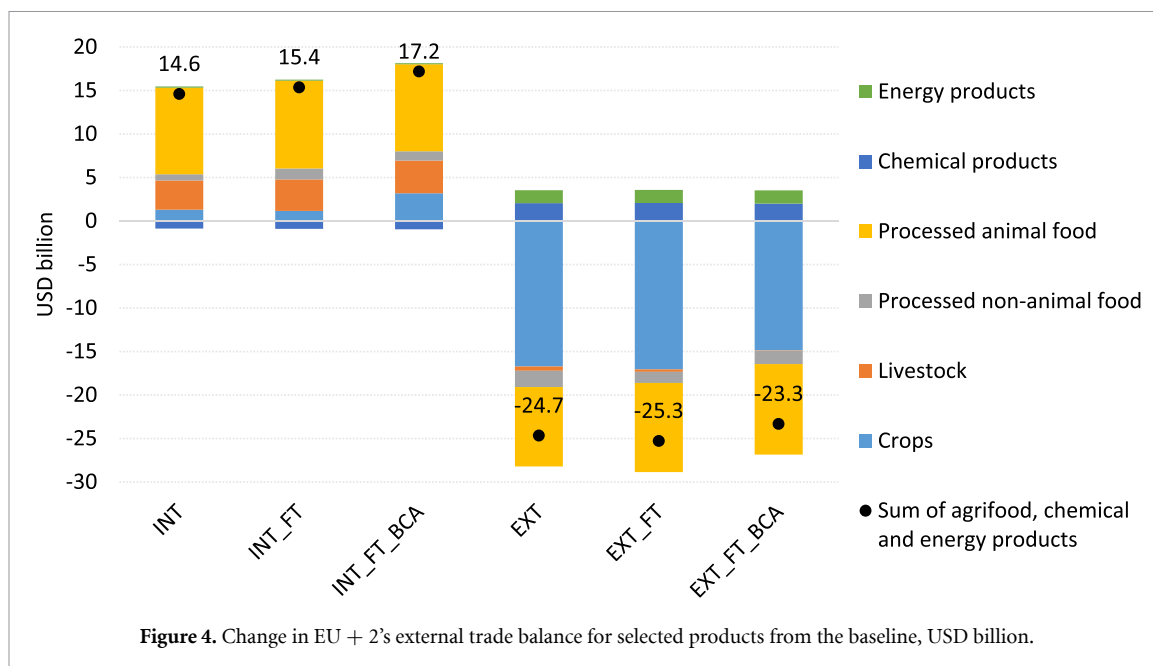
¹³ See section 5 of the SM for further details.



by 2%–3% (figure 3). In contrast, extensification (*EXT*) results in marked reductions in crop outputs (7%–17%), driven by competitiveness losses associated with lowered yields and reduced input uses. In contrast, primary livestock production rises under *INT* (6%–11%) and under *EXT* (2%–3%) but for different reasons, while processed animal food outputs rise (decrease) under *INT* (*EXT*). Under the *INT* scenario, rising grazing intensity and livestock yields improve the EU + 2’s competitiveness and allow its processed animal food sectors to expand export market shares. Conversely, *EXT* implies lower

livestock yield and grazing intensity, leading to the opposite effect: decreasing processed animal food exports due to higher costs and prices; and a larger increase in intermediate demand for primary livestock products for meeting domestic demand due to lower livestock yields. The small expansion of the livestock production under *EXT* is aided by the relatively minor reduction of grazing intensity (2.7%), and the reallocation of resources such as land from the crop sector, as the latter experiences larger decrease in yields and input uses. Finally, processed non-animal food output increases under *INT* (due to cheaper intermediate inputs) but decreases under extensification (due to more expensive intermediate inputs).

¹⁴ See section 5 of the SM for further details.



Adding trade liberalization and BCA to the scenarios (i.e. as in the *INT_FT*, *INT_FT_BCA*, *EXT_FT* and *EXT_FT_BCA* scenarios) alters but does not cause noticeable changes to the output results. Under *INT_FT*, all output levels except that for vegetables and fruit and processed animal food are slightly higher than under *INT*, reflecting that the two-way trade liberalization with the EU + 2's FTA partners will lead to more tariff concessions by the partner countries than by the EU + 2 itself. Under *EXT_FT*, output levels either decrease less or increase more for cereals, other crops, cattle, and processed non-animal food. The BCA acts effectively as an import tariff, protecting domestic producers in the EU + 2 from foreign competition. Hence, output levels under *INT_FT_BCA* and *EXT_FT_BCA* are generally higher than under *INT_FT* and *EXT_FT*, except for processed foods (due to their negligible BCA tariffs in connection their lower direct emission intensities).

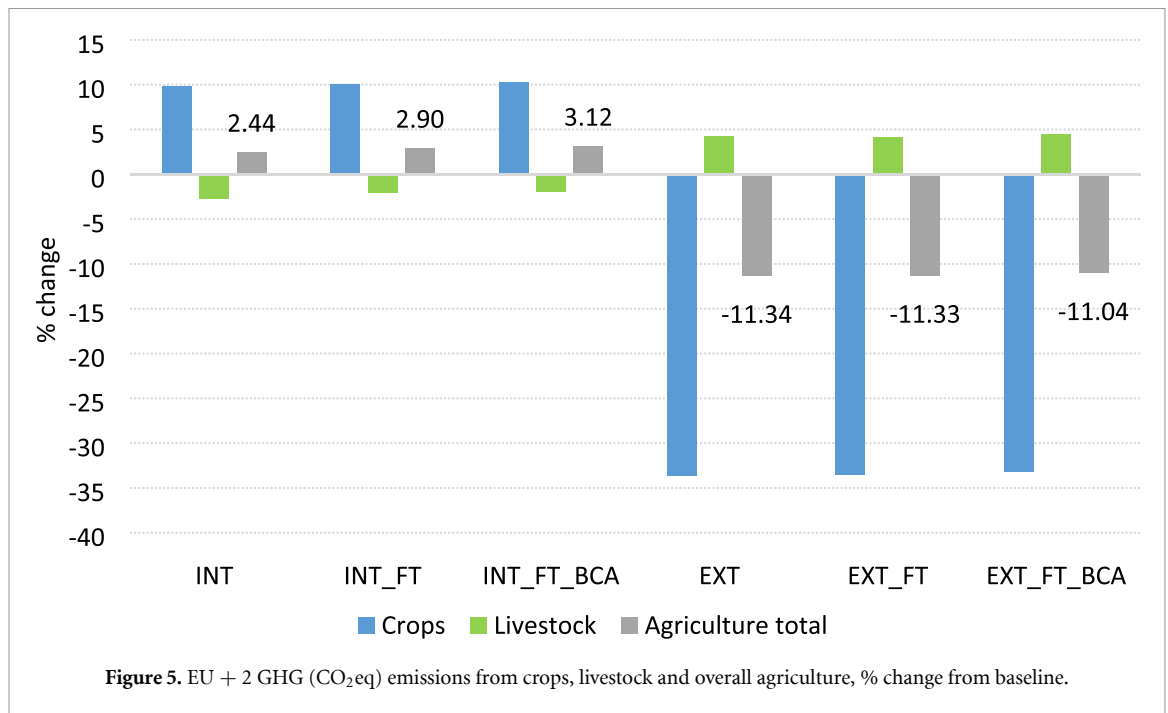
3.2. Trade balance

Changes in production systems and trade policy regimes alter production costs and output levels, which in turn affect the EU + 2's external trade patterns, as captured by changes in trade balance presented in figure 4¹⁵. Relative to the baseline, the EU + 2's agrifood trade balance improves in all intensification scenarios, while worsening under all extensification scenarios. In the intensification scenarios, increasing grazing intensity and livestock yields reduce costs of livestock products and increases their outputs,

leading to increasing exports of processed animal food. Increases in crop yields also improve net exports of crops and processed non-animal food. In the *INT* scenario, the EU + 2's trade balance improves by US\$14.6 billion. In the *EXT* scenario, decreases in crop yields, livestock yields and grazing density lead to worsening trade balance by US\$24.7 billion, despite improved net exports of chemicals and energy due to phasing-out of fertilizer and pesticide use and reduced energy consumption.

Trade liberalization further strengthens the EU + 2's net exporter position in animal and processed food under intensification. In the *INT_FT* scenario, net exports of livestock, processed animal and non-animal foods further increase, while net crops exports slightly decrease. Together with increased net chemical imports, this leads to further improvement of the EU + 2's trade balance (by US\$15.4 billion). When a BCA is imposed (as in *INT_FT_BCA*), the EU + 2's trade balance for agrifood, chemical and energy products improves further, mainly driven by higher crop net exports. In contrast, in the *EXT_FT* scenario, the EU + 2's net exports of chemicals and energy improve further. However, this is outweighed by the larger decrease in net exports of both crops and processed animal food, due to rising domestic costs and declining output levels. On balance, the EU + 2's trade balance decreases slightly more under *EXT_FT* (by US\$26.3 billion), compared to US\$24.7 billion under *EXT*. When using the BCA to counter the large decrease in net exports (as in *EXT_FT_BCA*), a smaller decrease in net crop exports is obtained (by US\$14.8 billion, compared to US\$17.1 billion in *EXT_FT*), resulting in a smaller overall trade balance decrease at US\$23.3 billion.

¹⁵ We focus on the trade balance of agricultural and food products and energy and chemical products used in agriculture. More detailed results can be found in section 6 of the SM.



3.3. GHG emissions

3.3.1. Agricultural emissions in the EU + 2

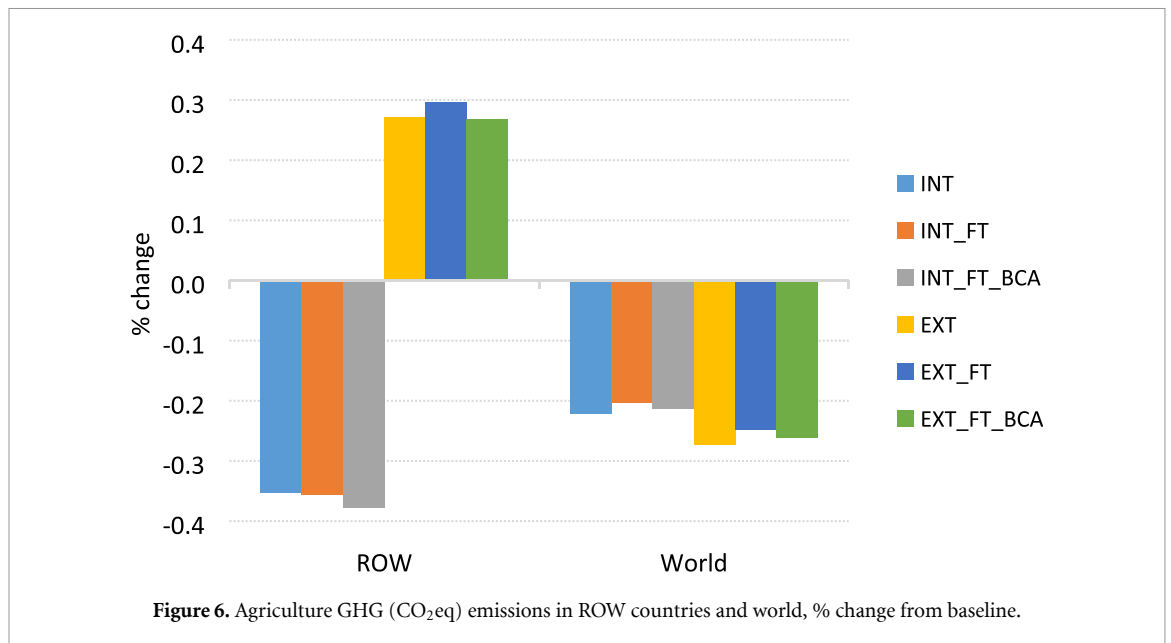
Intensification generally increases GHG emissions in the crop sector due to substantial increases in chemicals input use and rising yields. In the livestock sector, however, GHG emissions decrease slightly, as grazing intensity and livestock yield improvements more than offset rising emissions from increased outputs. As shown in figure 5, the EU + 2's agricultural GHG emissions increase by 2.4% under *INT*, relative to the baseline¹⁶. Adding trade liberalization (as in *INT_FT*) leads to higher agricultural emissions (by 2.9% compared to the baseline), as a result of slightly higher emissions in the crop sectors and smaller emission reduction in livestock sectors. In contrast, under *EXT*, with reduced crops outputs and lowered chemical use, agricultural emissions in the EU + 2 drop by 11.34%. Trade liberalization (as in *EXT_FT*) only slightly lowers the reduction of agricultural emissions (relative to *EXT*). Finally, implementing the BCA allows the EU + 2 to import less and slightly boost EU + 2 production, leading to higher emissions, as compared to *EXT*. Relative to the baseline, agricultural emissions rise by 3.1% in *INT_FT_BCA* (compared to 2.9% increase in *INT_FT*), but decrease by 11.04% in *EXT_FT_BCA* (compared to 11.33% reduction in *EXT_FT*).

¹⁶ Future intensification can deviate from the conventional intensification practices by, for example, adopting precision agricultural practices that reduce chemical inputs. Based on [89], we formulate three extra scenarios in which the use of chemical inputs (mainly chemical fertilizers) in EU + 2 changes by 15%, 0%, and -15%, respectively (and keep all other assumptions unchanged as in *INT*). Simulation results show smaller increases or reductions of GHG emissions from the crop sector (by 5%, -1%, and -7%, respectively).

In summary, our results suggest that an intensified agricultural system in the EU + 2 cannot reduce its agricultural GHG emissions, as reduced livestock emissions are outweighed by increased crops emissions. An extensified agriculture, however, may abate total agricultural emissions, even though it slightly increases livestock emissions. Therefore, an extensive agricultural production system can be considered a suitable option for GHG mitigation when the dietary shift allows for a sufficient decrease in the consumption of land-intensive products. Nevertheless, such a result may not hold if the dietary shift remains too limited and demand for agriculture land rises. This highlights the key role of behaviour changes in the GHG mitigation option portfolio in the agri-food system. Combining the 22% agricultural emission reduction during the baseline projection period 2014–2050 driven mainly by assumed dietary transition and the 11% reduction in the *EXT* scenario (compared to the baseline) leads to a total emission reduction of 31% from the 2014 level. Conversely, the intensification scenarios would marginally offset the emission reduction achieved through dietary transitions, leading to a much smaller overall reduction of 21% in 2050 (compared to 2014). Furthermore, trade liberalization generally opens more markets for the EU + 2's competitive agricultural and food sectors, allowing its net trade position to improve to the extent that its agricultural emissions rise marginally. Finally, implementing the BCA will further increase EU + 2's agricultural emissions.

3.3.2. Agricultural emissions in the rest of world and carbon leakage

In the intensification scenarios, rising EU + 2 agricultural emissions are accompanied by lower



emissions in ROW, resulting in falling global emissions (by approximately 0.2%), due to partially displaced agricultural production from ROW. Reductions of agricultural emissions in ROW are 0.35%, 0.36%, 0.38% in the *INT*, *INT_FT*, *INT_FT_BCA* scenarios (figure 6), respectively, as trade liberalization and the BCA further decrease ROW's emissions. In contrast, a more extensive agricultural system (as in *EXT*) decreases agriculture emissions in the EU + 2 by 11.34% but increases that in ROW by 0.27%, due to rising net agricultural imports to the EU + 2 from the ROW. This is equivalent to a carbon leakage rate of 48%. As a result, global agricultural emissions decrease by about 0.27%. In *EXT_FT*, the EU + 2's agricultural emissions will be slightly higher (−11.33% relative to the baseline) but ROW's emissions will increase more at 0.3%, resulting in a larger leakage rate of 52% and a smaller reduction in global emissions at 0.25%. The BCA in *EXT_FT_BCA* is shown to be modestly effective in reducing carbon leakage rate to 49%, resulting in a 0.26% reduction in global agricultural emissions.

The results show that GHG emissions in the EU + 2 would decrease for the crop sectors under extensification and for the livestock sectors under intensification. Therefore, we simulate an additional scenario to evaluate the potential impact of a mixed system of intensified livestock sectors and extensified crop sectors, with BAU trade policy regime. The EU + 2's agricultural emissions are reduced by 15% compared to the baseline, with decreasing GHG emissions in both crops (33%) and livestock sectors (3%). The EU + 2's trade balance is only reduced by US\$3.9 billion—compared favorably to all *EXT* scenarios—mostly driven by increased net exports of processed animal food. Global agricultural emissions decrease by 1%, larger than in any of the six scenarios

previously presented. Such mixed system appears to strike the right balance in achieving substantial reductions in European and global agricultural emissions and minimizing loss of net exports from the EU + 2.

4. Conclusions

This study provides a new assessment on how agricultural practices can be used as climate change mitigation measures to complement potential transitions to a healthy diet in Europe in reducing European and global agricultural emissions. Recognizing potential carbon leakages with trade linkages from unilateral mitigation actions by the EU + 2, we also investigate impacts of three different trade policy regimes.

Our results show that a full 'conventional' intensification of EU + 2 agriculture would increase its GHG emissions, while decreasing emissions in ROW, mainly due to increased agricultural production in the EU + 2 and improved net agri-food exports that partially displace ROW production. Within agriculture, however, intensification would lead to more crop emissions and reduced livestock emissions. While the result of intensification leading to reduced livestock emissions is in line with some studies [24, 25], the result of increasing emissions from intensified crop production differs from other studies [20, 23]. This is mainly due to the unilateral intensification of European agriculture assumed in our study, as compared to the intensification scenario assumed at the global level in earlier studies. The global CGE framework with bilateral trade linkages used in this study captures the production displacement effects due to expanded EU + 2 production that increases emissions.

In contrast, a shift towards extensification is shown to have the potential of significantly reducing

EU + 2 agricultural emissions, complementing the mitigation effects of the assumed dietary transition in the baseline. Still, the combined emission reduction of 31% during 2014–2050 due to extensification and dietary transition is lower than the 40%–47% reductions reported for 2010–2050 in other studies [30, 31]. One possible reason is that the adjustments through bilateral trade linkages are explicitly considered in our work. Furthermore, we do not assume phasing out of plant protein imports as in these other studies, because this would require erections of additional trade barriers. It is worth noting that although agricultural extensification in the EU + 2 alone would lead to increased net agricultural imports and carbon leakage (as also pointed out by Bellora and Bureau [35]), global emissions still decrease more with extensification than with intensification.

A trade-off between reducing agricultural emissions and maintaining competitiveness and net exports is identified when evaluating intensification and extensification across the crops and livestock sectors. This trade-off points to the attractiveness of a mixed production system of intensive livestock and extensive crop production, as also suggested by previous research [17, 29]. Such a mixed system can lead to greater GHG emission reduction than full intensification or extensification. It would also result in smaller losses of European net exports, compared to the full extensification scenarios. Intuitively, this mixed system with intensified animal agriculture also matches the EU + 2's comparative advantage patterns [90–92].

Trade liberalization that often leads to expanded exports and domestic production in a country's more competitive sector may be undesirable in relation to emission reduction ambitions. Our results show slightly higher European and global agricultural emissions when the EU + 2's preferential trade liberalization expands in both the intensification and extensification scenarios. This is in line with a few studies [40, 93, 94], but in contrast with others [40, 95]. To address carbon leakage and competitiveness concerns, we find that a BCA imposed on the EU + 2's agrifood import would partially shift abatement burdens to ROW, as also shown by others [41, 42, 96], even with agricultural and food trade liberalization.

There are several limitations in the current paper that can potentially impact the results reported. This work uses dietary shifts and changes in BMI as the main pathway to determine future calorie amount and composition of diets that have both GHG and health benefits. Although current diets pose the highest disease burden of lifestyle-related risks [97], other pathways such as decreased blood pressure, lower alcohol or tobacco consumption would lead to even larger health co-benefits. Although total land

supply and within-agriculture land reallocations are captured in the model, carbon stock changes associated with land use changes are not modeled. Thus, our carbon leakage results may very well be understated, particularly in the extensification scenarios (e.g. due to deforestation in ROW). This is an important dimension to be modeled in future work. The BCA in this paper is designed to cover direct GHG emissions embodied in agrifood imports, with an indicative price as we do not model a domestic carbon price on agrifood sectors¹⁷. Ultimately, the design of the BCA, both in terms of emissions covered¹⁸ and carbon price adopted¹⁹, will determine its effectiveness in reducing carbon leakages and protecting domestic outputs. This needs to be explored in future research. The environmental impacts considered in the current paper are limited to GHG emissions. Future work can be extended to cover other environmental indicators, such as biodiversity or water stress to better evaluate potential benefits and drawbacks of each production system. Instead of assuming a BAU scenario for ROW, scenarios with alternative climate change mitigation efforts in ROW can provide additional insights. Finally, future work should be performed to include a systematic sensitivity analysis with respect to the inputs to this modeling exercise.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This study is primarily funded by the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730459 (Project EU Calculator: Trade-offs and pathways towards sustainable and low-carbon European). The authors also acknowledge stimulating discussions with other members of the EU Calc project team. The authors thank the three anonymous reviewers for their thoughtful comments on earlier versions of the paper.

¹⁷ Without an explicit carbon price within the EU, implementing a BCA on agrifood products will be technically and legally challenging. This work does not explicitly consider these complexities and the BCA scenario should therefore be treated as exploratory.

¹⁸ Designing a BCA covering both direct and indirect emissions embodied in agrifood imports would lead to higher additional tariff rates than with the current design, which in turn may better tackle carbon leakages.

¹⁹ To be WTO-compatible, a BCA is expected to have to mimic an explicit domestic carbon price (and even account for foreign explicit carbon prices). At the moment, in the EU, there is no carbon price covering agricultural sectors, making it difficult to justify a BCA to trade partners.

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