Fossil fuel subsidy reforms' impact on land-use

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Note that this work is undergoing substantial changes. More scenarios are being simulated while the method is being extended (to, for example, more accurately depict land-use expansion). If you are interested, please reach out to robin.argueyrolles@unibas.ch

Abstract

Evaluations of fossil fuel subsidy reforms have so far overlooked their impact on land use. Yet, reforms are known to interact with biofuels, whose emission balance is dependent on land use and cover changes. Coupling a Computable General Equilibrium (CGE) model with a biophysical crop growth model, we simulate oil subsidy reforms' impact on the economy, land use, and GHG emissions from fossil fuels, land use, and land cover change. The linking approach captures the feedback between biophysical and socio-economic drivers of land use while accounting for bilateral trade and general equilibrium effects in the economy. At the global scale, the impact of reforms on land use is unlikely to offset their net reduction in GHG emissions. However, land-use change patterns vary geographically at a 0.5° spatial resolution. The assessment of domestic fossil fuel subsidy reforms is accordingly subject to variations that may be especially important given the localized costs of land use for carbon storage. Countries or regions at risk could benefit from complementary policies such as land zoning to mitigate land spillover effects.

Keywords: Fossil Fuel Subsidy, biofuel, land use, emissions, spillover, leakage, climate policy

1. Introduction

Despite 75 carbon pricing mechanisms around the world (World Bank 2024), global greenhouse gas (GHG) emissions reached 59 GtCO2eq in 2019 (IPCC 2022). Fossil Fuel Subsidy Reforms (FFSR) through their impact on prices could successfully lower emissions from fossil fuel consumption (Antimiani et al. 2023; Arzaghi and Arzaghi 2023; Chepeliev and Mensbrugghe 2020) and support the deployment of renewable energies (Bridle and Kitson 2014; IEA 2014; Zinecker et al. 2018). The phase in and out of biofuels being a function of fossil fuel (i.e. oil) prices (Leblanc et al. 2022), reforms can, for example, support biofuels' market and the policies promoting their deployment (Argueyrolles et al. 2025).

While substituting fossil fuels for bioenergy can be an attractive strategy to decarbonize the transport sector (Leblanc et al. 2022), increasing demand for bioenergy crops like maize, soybean, and rapeseed is not without its challenges. Increasing agricultural commodity prices can threaten food security (Rosegrant and Msangi 2014; Thompson 2012) while the growing demand for land can impede biodiversity protection (Behrman et al. 2015; Koh and Ghazoul 2008) and challenge biofuels' overall emissions balance (Laborde and Valin 2012; Timilsina and Mevel 2012). Yet despite the relationship between FFSR and biofuels, evaluations of the impact of reforms have so far neglected to consider their effect on land use, including through biofuels. Earlier results on the net emissions reductions of FFSR (Antimiani et al. 2023; Arzaghi and Arzaghi 2023; Chepeliev and Mensbrugghe 2020), therefore, provided a skewed overall assessment of their benefits by disregarding their impact on the biofuels value chain.

Different modeling approaches have been used to capture the effects of biofuel consumption and production (Panichelli and Gnansounou 2015). Agent-based models have successfully depicted individual farmers' responses to local biofuel policies (Scheffran and BenDor 2009) while Computable General Equilibrium (CGE) models captured indirect effects through trade (Laborde and Valin 2012). Coupling approaches have combined the strengths of different practices (Panichelli and Gnansounou 2015). Britz and Hertel (2011) linked a Computable General Equilibrium (CGE) with a Partial Equilibrium (PE) model to depict bilateral trade and regional land-use changes from biodiesel policies at the NUTS2 level in the EU. However, concerned with the direct impact of biofuel policies only, none of these studies considered the interaction between biofuels and other climate policies.

Bauer et al. (2020) and Merfort et al. (2023) instead coupled a general equilibrium model with a land optimization model and considered the link between biofuels and carbon prices. Through a soft link approach, they captured the impact of a uniform carbon price on emissions from biofuel deployment and the impact of alternative land protection policies. Still, they did not consider the interaction between biofuels and FFSR, which, even when implemented globally, do not trigger a uniform pricing effect. Earlier coupling studies, including their own, also either treated the world market for traded goods as completely integrated with zero transport costs, focused on a single region, or did not fully integrate biophysical conditions for crop allocation.

In this study, we couple the biophysical crop growth model PROMET with the Computable General Equilibrium (CGE) model DART-BIO to capture the feedback between biophysical and socio-economic drivers of land use while considering bilateral trade and general equilibrium effects in the economy (Zabel et al. 2019). This iterative linking approach was previously used to measure future biomass potential (Mauser et al. 2015), trade-offs between alternative farming practices, land expansion, biodiversity, and food security (Delzeit et al. 2017; Zabel et al. 2019; Schneider et al. 2024). In this study, it is used to simulate the global effects of oil subsidy reforms on the economy, land use, and GHG emissions from fossil fuels, land use, and land cover change, while considering their interaction with existing biofuel mandates.

The environmental impact of fossil fuel subsidy reform is evaluated, taking into account its interactions with biofuel policies, effects on land use and trade, and general equilibrium effects. To track the different mechanisms affecting the result of the reforms and dissociate its impact from ongoing biofuel mandates, the following questions are explored; (1) what is the impact of existing biofuels mandates on energy and agricultural sectors, land use, and GHG emissions, (2) accounting for biofuel mandates, how would FFSR impact these sectors and the environment, (3) what are the mechanism driving the changes, and (4) how does the impact of the reforms on land use affect its emissions balance. The contribution is twofold: with an evaluation of the reforms' environmental benefits that account for land spillover effects and a broader understanding of the relationship between climate policies and land use dynamics.

Simulations show that oil subsidy reforms result in modest land use and cover changes at the aggregate level, at least compared to biofuel mandates, but that their impact is subject to important spatial variations. Regions' harvested area of energy crops expands or decreases depending on the relative size of their oil subsidies, the existence and design of domestic bioenergy policies, and income and trade effects. Despite cropland expansion not being found to reverse the net emissions balance of the global reform for an extended period, land use and cover changes may have an important impact on the benefits of the reforms locally. An important detail given the variation of the economic cost of land use for carbon storage and biodiversity conservation at a fine resolution scale (Naidoo and Ricketts 2006). Complementary policies will therefore be required to account for the spillover effects of the policies on land use.

The result of the article is structured as follows. Section 2 presents the methodology, the scenarios, and the model design. Section 3 analyzes the impact of land expansion, biofuel mandate, and oil subsidy reform. Section 4 discusses the results and compares them to the existing literature. Section 5 outlines the conclusions of this analysis.

2. Method

The Computable General Equilibrium (CGE) DART-BIO (Delzeit et al. 2021) model is coupled with the biophysical crop growth model PROMET (Jägermeyr et al. 2021; Müller et al. 2021; Zabel et al. 2021; Müller et al. 2024) in a well-established modelling framework to combine environmental conditions and simulated crop yields with socio-economic drivers for land-use change and regional economic conditions (Schneider et al. 2024, Zabel et al. 2021, Delzeit et al. 2018). DART-BIO captures the interaction between supply and demand factors, including income effects in the economy. PROMET simulates bio-physical crop growth and agricultural yields globally for future climate conditions around 2030 (2016-2045) under SSP 585, independently from current land use and assuming current crop management practices. Within the integrative land-use change model iLANCE (integrative land-allocation sequencer), crops are spatially allocated to land by maximizing profits, considering the spatial distribution of simulated yields from PROMET and the marginal profitability of crops from DART-BIO within predefined regions (Schneider et al. 2024; Mauser et al. 2015).

2.1 DART-BIO

The DART-BIO model is a global recursive dynamic CGE model. It simulates the world economy from 2011 to 2030 in a sequence of single-period static equilibria connected via labor growth and capital accumulation. The model is calibrated to the GTAP9 database (Aguiar et al. 2016). It includes 51 sectors (listed in the appendix), several of which were split from the initial GTAP database using the SplitCom software and a combination of data on production, consumption, and trade from the Food and Agriculture Organization (FAOSTAT) and F.O.Licht (F.O.Licht 2015), see Delzeit et al. (2021) for details on the model and overall splitting approach. The 18 model's regions, depicted in Table 1 and mapped spatially in the appendix, are adapted from Cheperliev et al. (2018) and aggregated based on countries' energy trade balance and geographical location. The approach is combined with the interest in biofuels, and larger bioenergy producers are singled out (e.g. Brazil, Malaysia, and Indonesia). In the Walrasian tradition, each region is modeled as a competitive economy with flexible prices and market-clearing conditions.

Table 1: Regions in DART-BIO

Europe and Central Asia		**North America**	
EU27	European Union	NA	United States & Canada
REU	Switzerland, Norway, Iceland, Liechtenstein	**Central and South America**	
NEC	Energy producers in Europe & Central Asia	BRA	Brazil
XEC	Rest of Europe & Central Asia	NLC	Energy producers in Latin America
Asia		XLC	Rest of Latin America & Caribbean
CHN	China, Hong Kong	**Middle East and Africa**	
IND	India	NMN	Energy producers in MENA
MAI	Malaysia & Indonesia	XMN	Rest of MENA
XEA	Rest of East Asia	SSA	Sub-Saharan Africa
XSA	Rest of South Asia	**Oceania**	
SEA	Rest of South East Asia	NA	United States & Canada

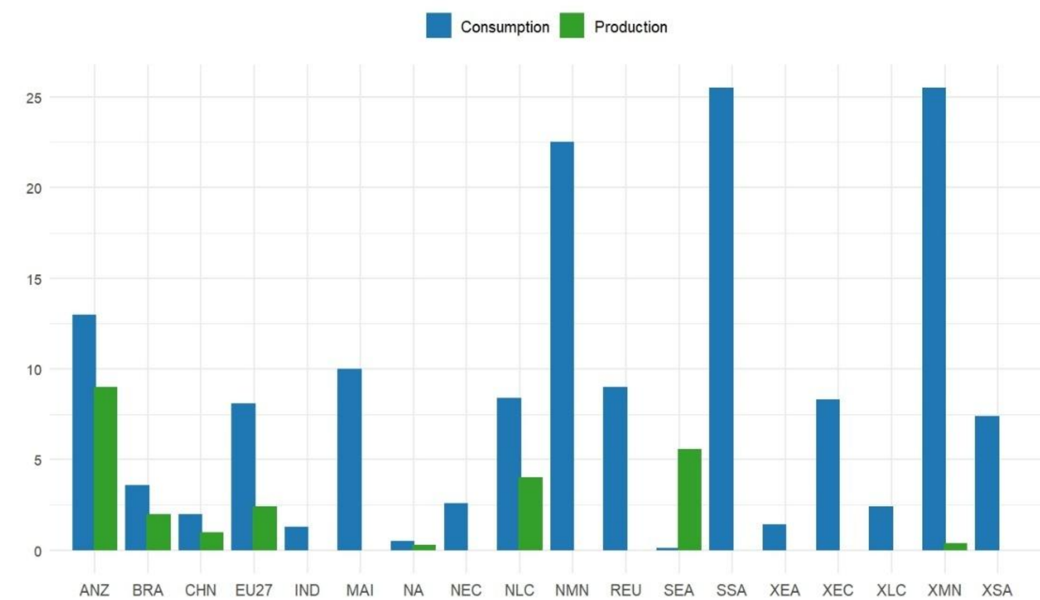
Following the regional agent approach, a single agent simultaneously represents utility-maximizing consumers, profit-maximizing producers, and the regional government. Consumption is modeled using a Linear Expenditure System (LES) allowing for non-unitary income elasticities through a fixed subsistence consumption category with no substitution possibilities. It is combined with a surplus also called supernumerary consumption where the additional income is spent and exhibits positive elasticities between the different commodities. Energy and food commodities enter both consumption types. Motor diesel, motor gasoline, bioethanol, biodiesel, and oil specifically are nested within the supernumerary consumption with an elasticity of substitution between 2 and 3 depending on the region.

Production is modeled following a similar approach where primary inputs and intermediate commodities are nested within a Constant Elasticities of Substitution (CES) function. The general structure combines capital and labor with an energy bundle, itself produced with its own specific nest and elasticities. The resulting composite is joined with the land factor, itself made up of 18 Agroecological Zones (AEZs) defined over six different lengths of growing period and three climatic zones (Lee et al. 2005). Different commodities, however, rely on alternative nest structures that may include additional components. The non-electricity energy input for example integrates natural resources like coal, crude oil, and natural gas with the factor and intermediate composites. Biofuels, in contrast, incorporate various feedstocks within their intermediate nest, allowing for a greater degree of substitution than other commodities in the model.

A transformation function governs land mobility across uses, a common approach in the CGE literature concerned with land-use change and biofuel policies (see for example Laborde and Valin 2012; Taheripour and Tyner 2013). Land is first allocated between agricultural use and managed forest. Land for agriculture is then allocated between pasture and crops. Finally, cropland is allocated between rice, palm, sugar cane/beet, and annual crops (wheat, maize, rapeseed, soybeans, other grains, other oilseeds, and other annual crops). At each level, the elasticity of transformation increases, reflecting that land is more mobile between different crops than between forestry and agriculture. Cropland is then allocated among specific categories: rice, palm, sugarcane/beet, and annual crops, which include wheat, maize, rapeseed, soybeans, other grains, other oilseeds, and various other annual crops. For a detailed review of this approach, see Calzadilla et al. (2017).

As standard in the literature, fossil fuel subsidies are integrated into the model as negative tax rates (Cheperliev et al. 2018; Argueyrolles et al. 2025; Fouré et al. 2023). Two types of subsidies are considered, consumption and production subsidies in the oil sector, historically one of the largest recipients of fossil fuel subsidies (OECD 2024). The ad-valorem subsidy rates to be phased out are constructed using 2021 estimates from the IEA Fossil Fuel Consumption Subsidy Database and the OECD Inventory of Support (IEA 2023; OECD 2023). While rarely overlapping, the smallest of the two estimates is used when figures for the same regions are available for both databases. Again, as is conventional in the literature (e.g. Cheperliev et al. 2018), figures reported in values were divided by the simulated consumption and production of the model to derive ad-valorem rates.

Figure 1: Oil ad-valorem subsidies in the study regions, in percent



As shown in Figure 1, consumption subsidies are substantial and primarily concentrated in Africa, the Middle East, and Asia, where they can reach up to 26%. However, they are also present in several other regions, with estimated levels around 7%. To ensure a robust baseline and accurate subsidy rates, the model crude oil and electricity sector was calibrated to replicate 2021 regional production shares and cumulative production growth between 2011 and 2030 reported by the BP Statistical Review of World Energy 2022 and the JRC (Wojtowicz et al. 2021). Further details on the calibration of the baseline can be found in section 2.4 on the model simulations.

2.2 Crop modeling

Crop yields are simulated with the biophysical land surface process model PROMET (Mauser et al. 2015; Hank et al. 2015). PROMET uses first-order physical and physiological principles to determine net primary production and respiration based on approaches from Farquhar et al. (1980) and Ball et al. (1987), combined with a phenology and a two-layer canopy architecture component of Yin et al. (2005). It considers the interdependency of net primary production and phenological development, leaf temperature, water availability, and environmental conditions, including meteorology, Carbon dioxide (CO_2) concentration, as well as water and temperature stress. PROMET has been used in global (Mauser et al. 2015; Jägermeyr et al. 2020; Jägermeyr et al. 2021; Zabel et al. 2021; Schneider et al. 2022b) and regional studies (Degife et al. 2019, 2021). It takes part in the Global Gridded Crop Model Initiative (GGCMI) (Franke et al. 2020a; Franke et al. 2020b; Franke et al. 2021; Minoli et al. 2019; Molina Bacca et al. 2023; Müller et al. 2021; Müller et al. 2024; Orlov et al. 2024) within the Agricultural Model Intercomparison and Improvement Project (AgMIP), which is connected to the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP).

PROMET simulates crop growth on around 170,000 representative samples at an hourly time step for each year of the 30-year time period around the economic target year 2030, considering climate change under SSP585 as median over the five bias-corrected CMIP6 climate models ('GFDL-ESM4', 'IPSL-CM6A-LR', 'MPI-ESM1-2-HR', 'MRI-ESM2-0', 'UKESM1-0-LL') from ISIMIP (Lange et al. 2022). Potential yields are simulated for 18 agricultural crops, which we consider globally important regarding their cultivation area and economic relevance, as they represent around 67% of the global harvested area and 73% of the global production volume according to FAOSTAT (average 1981-2010). For the simulation of potential yields, we assume an optimized crop management considering nutrient supply, and no harvest losses, for example, due to pests and diseases. The yields are simulated for irrigated and rainfed conditions separately, assuming full irrigation and no water stress under irrigation.

2.3 iLANCE

iLANCE is an integrative land-use model based on an established coupling approach between the biophysical crop growth model PROMET and the Computable General Equilibrium (CGE) model DART-BIO, which has previously been used in other interdisciplinary studies (Delzeit et al. 2019; Delzeit et al. 2016; Mauser et al. 2015; Schneider et al. 2022a; Zabel et al. 2019). It allows for integratively simulating crop allocation and land-use change on current cropland on the basis of biophysical and socio-economic drivers globally at 0.5° spatial resolution. It has recently been extended by an expansion module to investigate the spatial allocation of profit-driven cropland expansion (Schneider et al. 2024).

iLANCE uses the yield data of the PROMET model and combines irrigated and rainfed yields based on spatial data on current irrigation patterns (Meier et al. 2018). The yields are aggregated to 30-year averages to (1) avoid bias from selecting a single-year yield, caused by annual variabilities and (2) refer to yields that represent a wider timespan in which land-use decisions are made. In our scenarios, we assume no additional agricultural intensification. Therefore, we applied a bias adjustment based on statistical yields at the Agro-Economic Sub-region (AES) level to adjust the simulated potential yields to the current statistical intensification level while conserving yield changes induced by climate change. For the expansion scenario, we assume that expansion areas are cultivated at the same agricultural intensification level as regional current cropland. In a final step, the yields of the 18 crops simulated with PROMET are aggregated to the 10 crop categories considered in DART-BIO to be consistent with the representation of crops in the economic model, which is necessary for the coupling within iLANCE.

In iLANCE, the simulated crop yields from PROMET and the marginal profit functions for each crop category and each AES from DART-BIO, describing the relative marginal profits to land, are used to allocate crops to maximize regional profits. We use the crop-specific marginal profit functions in iLANCE to rank all locations (pixels) in a specific AES according to their profitability when allocating an additional unit of cropland within the AES. Generally, the attainable marginal profit is highest for the first cultivated hectare of a crop category and decreases the more cropland is allocated until we assume that it approaches zero when the area to be allocated within an AES is reached. The profit share per crop category on a pixel determines the crop-specific area share on the respective pixel accordingly. iLANCE considers current land-use constraints, referring to data on areas that are potentially cultivable and potentially available for cropland use and information on the current cropland extent (Schneider et al. 2022a).

2.4 GHG emissions

We consider three sources of emissions: Fossil fuels, land use, and land cover change.

Fossil fuel CO_2 emissions data can be accessed through the primary GTAP database. This data encompasses the consumption of energy goods by firms, households, and governments (Aguiar et al., 2016). In the context of climate policy analysis, DART-BIO applies an emission price for CO2 where fossil fuel-based energy production occurs. Details on policy implementation will be outlined in the next section.

Land-use emissions are included in an additional dataset for non-CO2 emissions in the GTAP-9 database, covering methane, nitrous oxide, and a category of fluorinated gases (Irfanoglu et al., 2016). The GTAP database captures emissions from four sources: household consumption, intermediate input usage by industries (such as the use of synthetic fertilizers in agriculture), the inherent roles within industries (including manure management and enteric fermentation), and industry output (like burning crop residues) (Irfanoglu et al., 2016). Thus, to ensure consistent accounting of non-CO_2 emissions, DART-BIO incorporates an emission price for these emissions on output production across all sectors, on land as an input factor, and for private consumption. The implementation of GHG prices is designed to prevent double-counting.

As previously stated, production activities in DART-BIO are modeled with CES production functions. In the base year of 2011, GHG prices are introduced as an input with a substitution elasticity of zero, suggesting a fixed relationship between production and a specific quantity of GHGs. In later years, through the model's dynamics, GHG emissions are determined by multiplying this coefficient with production levels in each scenario.

Land cover change emissions that result from agricultural expansion are calculated from the identified expansion areas, as a result of the iLANCE simulations. Therefore, we use a dataset on the global distribution of primary and secondary vegetation (Zabel 2024). It combines Hilda+ landuse/cover data by Winkler et al. (2020) and the global dataset on human influence by Riggio et al. (2020). The carbon emissions result from the delta between the carbon storage (Hansis et al. 2015) of the converted primary, secondary vegetation, or pasture and the carbon storage of cropland on the expanded area. Thereby, the loss of carbon stored in the aboveground biomass and the loss of soil carbon are considered in dependence of the affected plant functional type (PFT) (Hansis et al. 2015).

2.4 Scenarios/simulations

Three scenarios are simulated to evaluate the effect of FFSRs on land use and how these impact the reform's emissions balance. A baseline where current trends are replicated and two policy scenarios.

In the baseline (BS), the model's regional GDP and CO_2 emissions growth were calibrated using labor and energy productivity to match 2030 projections from the OECD and the World Energy Outlook (OECD

2019; IAE 2018). Labor supply evolving based on regional workforce and population dynamics consistent with the GDP calibration targets taken from OECD data (OECD 2019). Other key assumptions shaping the baseline include policy measures, such as commodity tax rates, sourced from the GTAP database (Aguiar et al., 2016). In line with the Agricultural Outlook 2023-2032, we implement a cropland expansion of 3.6%. This is done by determining the most profitable expansion areas (see also Schneider et al. 2024) and crop yields under climate change (see section 2.2). The resulting marginal profit functions to land and harvested areas per crop category are used to determine the most profitable cropland expansion area under baseline conditions in iLANCE.

In the biofuel policy scenario (BP), biofuel mandate targets are regionally calibrated to ensure they are reached by the end of the simulation. The targets are taken from OECD projections and expressed as a percentage of total transport fuel consumption (OECD/FAO, 2021). In the EU, consumption is capped, and palm-based biodiesel is phased out based on the rules outlined in the Renewable Energy Directive (RED). Like Heimann et al. (2023) and Philippidis et al. (2018), the EU region is assumed to reach the 7% limit on 1st generation biofuels to fulfill its overall share of renewables in total transport fuel consumption. Also here, the resulting (and different compared to the baseline scenario) marginal profit functions and harvested areas of the crop categories are used to spatially determine the cropland expansion areas. The biofuel policy scenario (BP) is compared to the baseline (BS) in the rest of this paper to establish the impact of current policies in the transport sector.

In a second policy scenario (BP_FFSR), oil consumption and production subsidies are linearly phased out globally starting in 2025. Following the standard procedure in the literature, this is modeled as an increase in output and sales taxes, which aggregate taxes and subsidies. Biofuel mandates are calibrated in this scenario as well, so that the second policy scenario includes both biofuel mandates and subsidy reforms. In other words, the phase-out of oil subsidies occurs globally while existing biofuel mandates are accounted for. The BP_FFSR scenario is compared to the BP scenario in the rest of this paper to isolate the impact of the fossil fuel subsidy reforms rather than the reference with no policies. For all scenarios, a 3.6% cropland expansion is determined. An overview of the specific scenario assumptions is provided in Table 2.

Table 2: List of scenarios

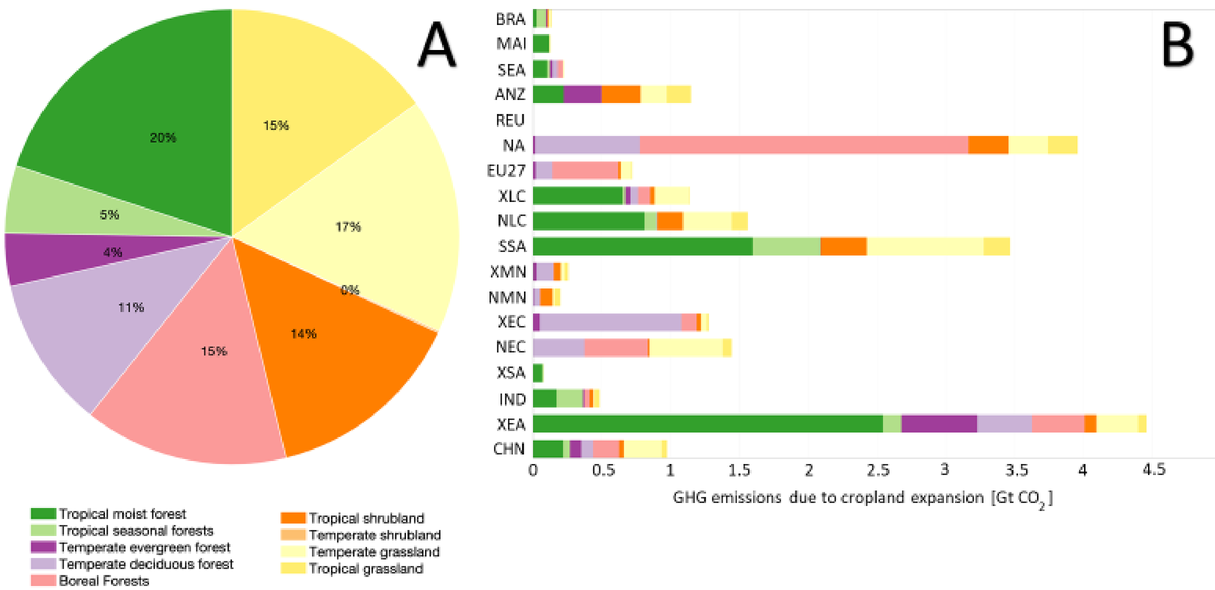
Scenario	Cropland expansion	Biofuel Policies	Oil Subsidy Reform
Baseline (BS)	3.6%	No	No
Biofuel Policies (BP)	3.6%	Yes, global	No
BP and FFSR (BP_FFSR)	3.6%	Yes, global	Yes, global

3. Results

3.1 Baseline land expansion and land cover change emissions

The projected 3.6% cropland expansion is found to correspond to a 537,600 km^2 increase in global harvested area, with the most profitable expansion areas located in a range of ecosystems and regions. The expansion is concentrated in Sub-Sahara Africa (SSA), North America (NA), and the rest of East Asia regions (XEA), which together account for 51% of the total increase in cropland. Other regions, such as Australia and New Zealand (ANZ) or Energy producers in Latin America (NLC), experience more moderate growth around 40,000 km^2 each, while some, including the rest of Southeast Asia (XSA), show relatively small changes. As per Table 2, tropical moist forests see the highest rate of conversion to cropland, while Boreal forests, tropical shrublands, temperate grasslands, and tropical grasslands each show a relatively even share of change, ranging between 14% and 17%. This matches results in Schneider et al. (2024) where expansion reaches 515,000 km^2 and takes place in comparable cover types.

Figure 2: Land cover change emissions generated by converting the areas into cropland



Notes: **A**, Shares of the different cover types (primary, secondary, pasture) where global expansion takes place. **B** Regional distribution of the increase in km2 and generated emissions in absolute terms (Gt CO_2).

The expansion of current cropland by 3.6% generates 21.8 Gt CO_2eq emissions globally from changes in the soil carbon and the carbon stored in the above-ground biomass. Spatially, the distribution of emissions broadly matches the changes in harvested area. Yet, variations are observed between regions reflecting differences in the ecosystems converted. For example, while the cropland expansion in Sub-Saharan Africa (SSA) is higher than the rest of East Asia (XEA), emissions in the region increase only 78% as much. North America (NA), in turn, shows a comparable change in land use but a noticeably lower increase in emissions than both regions. This reflects the differences in carbon densities both in the soil carbon and the above-ground biomass of the converted ecosystems in the regions (Table 2, panel B). For the same reason, tropical regions such as Malaysia and Indonesia (MAI) and the Rest of South Asia (XSA), for example, result in few additional emissions as less land is converted, but have a high contribution to emissions per km^2 converted.

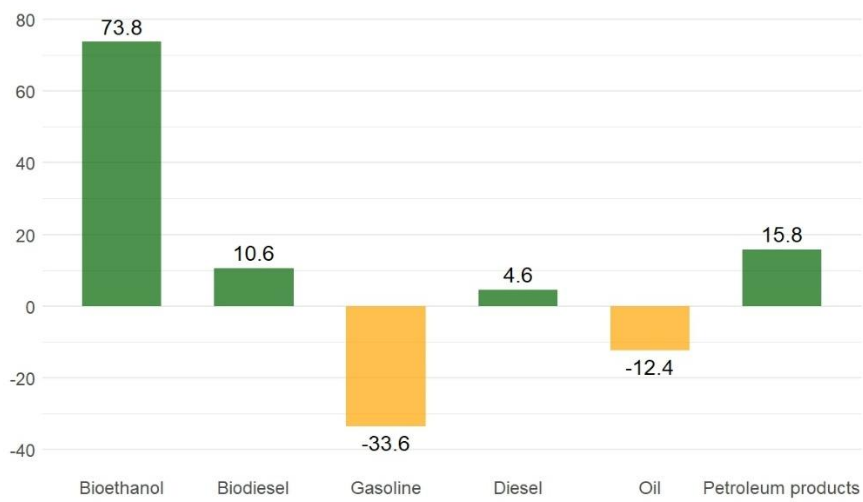
3.2 Biofuel policies scenario (BP)

Before evaluating the impact of FFSR, we compare the impact of the biofuel policy scenario (BP) to the baseline. Doing this, the impact of biofuels mandates on energy and agricultural sectors, land use, and GHG emissions is evaluated. It allows in the next section to isolate the mechanism by which FFSR impacts land use through their interaction with biofuels policies in the next section and to compare the impact of the two policies.

Energy markets

Biofuel mandates are simulated to result in a substitution both between and within fossil and bio-based fuels in the transport sector. Following their implementation, biofuel consumption in 2030 is simulated to expand by 84$bn at benchmark prices while the combined gasoline and diesel consumption drops by 29$bn (Figure 3). This leads to a 3-percentage point increase in the share of biofuels in the world transport fuel market. This is largely driven by a rise in bioethanol use, particularly in regions such as North America (NA) and Brazil (BRA), where mandates are relatively high, and consumption growth of $36 billion and $24 billion, respectively. Malaysia and Indonesia (MAI), instead, account for 70% of the increase in biodiesel consumption.

Figure 3: Impact of biofuel mandates on global energy commodity consumption in 2030, in $bn at Benchmark Price



Through their impact on the transport fuel markets, biofuel mandates impact other energy commodities via intermediate commodities. This is especially the case for oil, which on average makes up between 62% and 73% of diesel, gasoline, and other petroleum products cost share. As per Figure 3, biofuel mandates reduce oil demand by approximately $12 billion in 2030 at the benchmark price. This puts downward pressure on the world price of oil which falls by about 1.9%. The production cost of petroleum products thereby declines, and its world price is simulated to drop by 1.8% by 2030 which triggers an expansion in consumption of about 16$ bn.

Agricultural markets

In addition to the backward and forward linkages in the energy sector, biofuel mandates impact agricultural markets through their effect on biofuel feedstock demand. Maize and sugar cane/beet, especially, are found to experience a production/consumption increase in 2030 at benchmark prices of 24 $bn and 16 $ bn respectively (see appendix). Despite a larger increase in maize, its world price rises by 1%, whereas the price of sugar beet and cane grows by 22%. This reflects the larger share of sales sold to the bioethanol industry and the shared land price for annual crops. It is also the case for palm and palm-oil-based biodiesel, whose world price, mostly driven by Malaysia and Indonesia, experiences a 26% increase while the quantity of palm consumed in 2030 rises by 2.5 $bn.

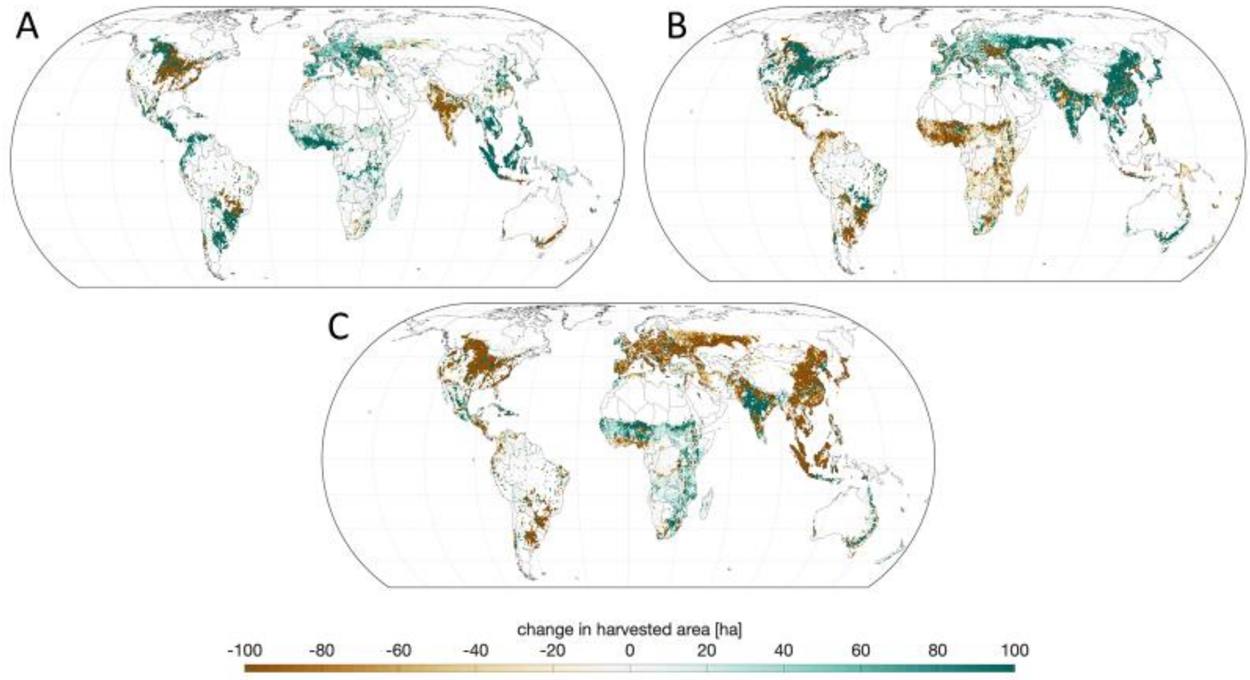
The increase in demand for land to produce bioenergy crops triggers a rise in the world price of all agricultural commodities. And except for rapeseed, used to produce additional biodiesel in the EU and North America, biofuel mandates led to a decline in the global demand for other agricultural commodities. Soy global demand, for example, drops by 5.3 $bn as its world price rises by 4.8% from growing land rent across regions. Variations are observed across regions and commodities. In the EU, for instance, wheat consumption increases by approximately $1.25 billion, with the share of wheat-based bioethanol in total bioethanol consumption rising by 3%. Energy producers in Latin America (NLC) lower their consumption of maize in favor of sugar cane and beet-based bioethanol, whose cost share in the region's bioethanol production rises by 5%.

Land use change

Regional land use and cover shifts as crops are reallocated based on the new marginal profitability in the agricultural markets triggered by the biofuel mandates. The global harvested area for non-biofuel crops accordingly declines in favor of biofuel feedstock crops. In North America, the mandate leads to 64450 additional km^2 dedicated to bioethanol feedstocks and an 11% rise in cropland prices. Figure 4 shows that this mainly occurs in and around the Corn Belt, aligning with the region's high maize share in bioethanol production. To a lesser extent, a similar change is observed in China, where cropland price rises by 2%, and the harvested area of other crops contracts in favor of bioethanol feedstock, especially maize.

In Brazil, the harvested area of crops used in bioethanol production expands by 7120 km^2, mostly in the South of the country, but as we have seen earlier, rather than maize, this is the result of an increase in sugar beet and cane production. In India, too, the harvested area of sugar beet and cane expands by about 2770 km^2, and cropland's price rises by 3%, while in Oceania (i.e., Australia), the harvested area of bioethanol crops grows from an expansion in wheat of 2560 km^2.

Figure 4: Biofuel mandates' impact on harvested area



Notes: Depicts the absolute different harvested area between the Biofuel Policy scenario (BP) and the baseline (BS) per pixel, with a spatial resolution of 0.5 degree (approx. 50 km at the equator). Panel A shows the change in the harvested area of crops used in biodiesel production (i.e. rapeseed, soy, other oil seeds, and palm) Panel B the change in crops used for bioethanol production (i.e. maize, wheat, sugar cane and beet, and other cereal grains), and panel C, the change in all other crops.

In the EU, the harvested area of bioethanol feedstocks is also found to increase and replace non-biofuel crops. The price of cropland rises by about 5% in the EU. The region is, however, also found to expand its harvest area of crops used for biodiesel production so that the overall harvested area for biofuel crops grows by 6270 km^2. Ukraine, a major grain producer, unlike the rest of Europe, substitutes bioethanol with biodiesel feed on cropland rather than other agricultural commodities. However, the change in biodiesel feeds is most clearly observed in Malaysia and Indonesia (MAI), where the harvest area of palm expands by 4230 km^2. Countries in the Gulf of Guinea are also found to expand the harvested area of palm. In contrast to MAI, where non-biofuel crops are replaced, they mainly replace bioethanol crops.

<u>Fossil fuel and land use emissions</u>

The impact of the biofuel mandates on fossil fuel and land use emissions emitted by the different regions flows from the changes in consumption and production patterns. Biofuel mandates lower global emissions by 124.5 Mt CO_2eq in 2030, equal to a 0.22% annual decrease once fully established. In comparison, according to the results of the Baseline Scenario on the most profitable expansion path and assuming that the increase in harvested area for bioenergy crops in each region occurs entirely outside of existing cropland, it would take 18.9 years for the mandate to begin reducing net emissions, starting from the point of full implementation in 2030. North America and Brazil contribute the most to the reduction, with emissions falling by 54 Mt CO_2eq (0.8%) and 34.4 Mt CO_2eq (2.8%), respectively. Notably, 88% of the total decline stems from reduced CO_2 emissions, largely due to decreased gasoline consumption in the two regions.

In addition to the leakage across products from the lower demand for oil, several regions have also been found to experience a rise in total fossil fuel and land use emissions. The EU and Sub-Saharan Africa (SSA), especially, are simulated to increase emissions by 14 Mt CO_2eq and 9.7 Mt CO_2eq, respectively. In the EU where most of the increase is the result of CO_2 emissions, an increase in the share of gasoline, diesel, and petroleum entering the service sector is found to be responsible. The region thereby reallocates its fossil fuels away from the transport sector to other uses. In SSA, a similar mechanism is observed, but for both CO_2 and non-CO_2 emissions. Considering all regions in which emissions rise, a geographical leakage of 25% is simulated.

3.3 Oil subsidy reform scenario (BP_FFSR)

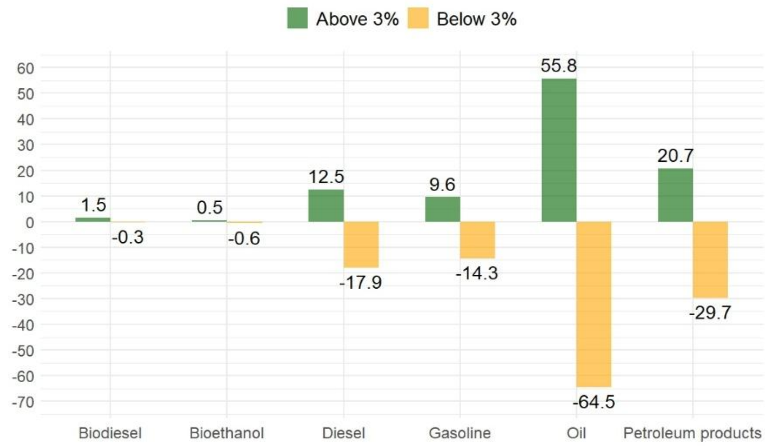
In order to evaluate the impact of oil subsidy reforms given existing biofuel mandates, we now compare the biofuel policy scenario (BP) to the scenario including both biofuel policies and FFSR (BP_FFSR). The FFSRs share similar substitution and competitive effects compared to the biofuel policies, but have different impacts.

Energy markets

Subsidy reforms lead to an 8.6 $bn drop in the 2030 global consumption of oil at the benchmark price. Rather than a decrease in demand for the intermediate commodity, this is found to be the impact of raising prices. The global fall is the combined impact of a fall/rise in consumption in regions with relatively high/low consumption subsidies. The cutoff for the direction of the effect lies at 3% consumption subsidies.

Consumption falls from the rising prices in regions with relatively high subsidies, while it rises in the rest of the world as the import price there falls from the decline in overall demand on the world market. Considering each group individually, regions with consumption subsidies above 3% are found to lower oil consumption by about 64.5 $bn in total, and the rest of the world to increase consumption by 55.8 $bn (Figure 5). As oil prices rise, the cost of producing petroleum products, including gasoline and diesel, increases, leading to higher prices and reduced consumption. The effects of relative subsidy sizes in the oil sector extend to these markets, causing consumption patterns to diverge. In regions where subsidies exceed 3%, consumption of these commodities declines by $62 billion, while in the rest of the world, it grows by $43 billion.

Figure 5: Impact of oil subsidy reform on global energy commodity consumption in 2030, in $bn at Benchmark Price



Following the subsidy reforms, biofuels become more competitive in regions phasing out large subsidies, like in the Middle East and Africa, where their price relative to the fossil-based alternatives falls by as much as 7%. This triggers an increase in biodiesel consumption in the rest of the MENA region (XMN) of 1.8 $bn. Instead, countries whose consumption of fossil fuel drops and require fewer biofuels to reach their target may lower their consumption of bioethanol and biodiesel. This is the case of the EU, where bioethanol and biodiesel consumption drops by 0.27 $bn and 0.33 $bn, respectively following a fall of 3.5 $bn and 5.9 $bn in gasoline and diesel consumption. Globally, consumption as a consequence rises relatively little due to the biofuel mandates' design and the influence of trade between regions with subsidies of different sizes.

Agriculture markets

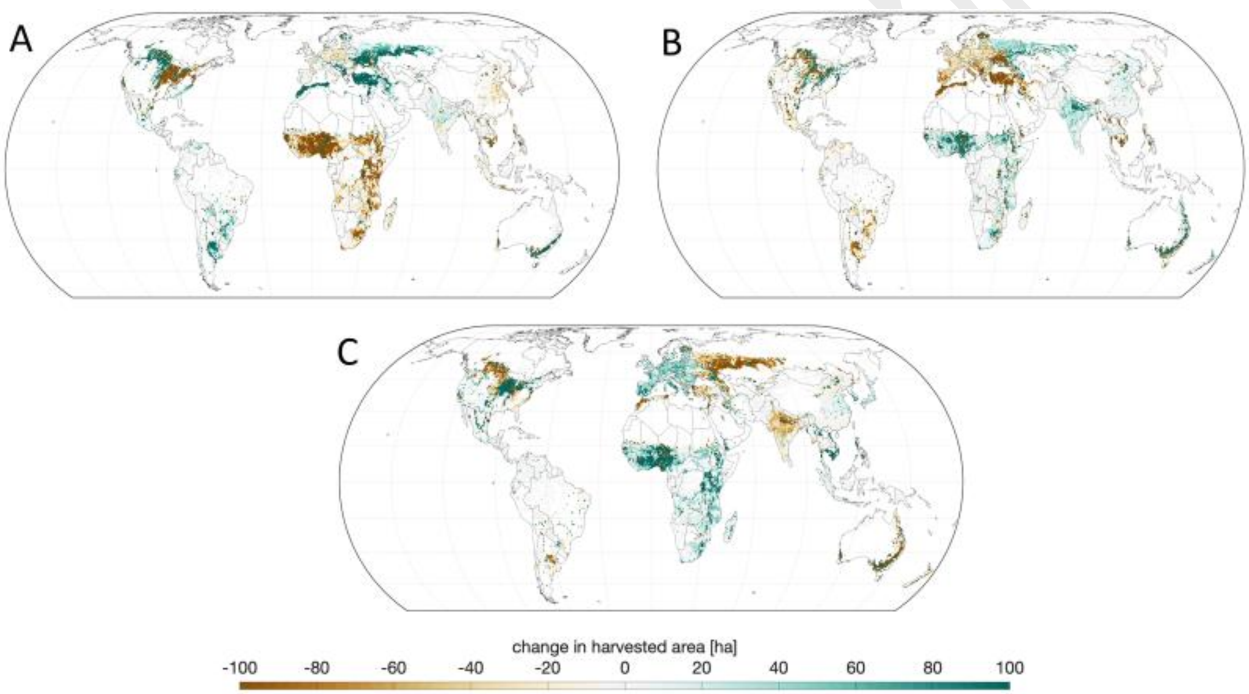
Following the oil subsidy reforms, the global price of agricultural commodities generally increases alongside cropland prices in most regions. However, these changes are relatively modest compared to the increase triggered by the biofuel mandates, remaining below 1% across regions for both cropland and commodity world prices. Still, the growing biodiesel consumption in XMN from the change in transport fuel’s relative prices leads the region to expand its consumption and production of oilseeds. In North America, where oil subsidies are relatively low, maize consumption and price rise by about 0.1 $bn and 0.7% respectively as bioethanol consumption grows. The EU, whose biofuel feedstock demand drops, lowers its oilseeds and grain production and consumption. The region's growing production and consumption of food commodities (non-biofuel feed), however, suggests a substitution of cropland use. Brazil, like the EU, sees its biofuel level target fall from the lower fossil fuel consumption, and as a consequence, lowers its sugar beet and cane demand, and the price of the commodity in the region drops by about 0.4%.

Changes in consumer incomes, driven by regions benefiting or suffering from cheaper/more expensive oil, are also found to influence agricultural markets in other regions. In India, for example, higher consumer incomes lead to increased consumption of all agricultural commodities, both biofuel-related and otherwise, along with a 0.5% to 1.4% rise in agricultural commodity prices and a 0.7% increase in cropland prices. Part of this growing demand is met through increased imports from regions experiencing a decline in income due to the phase-out of relatively high domestic subsidies. For instance, in sub-Saharan Africa and energy-producing countries in MEAN (NMN), food consumption declines while exports to India rise.

Land use/cover & crop allocation

Globally, the increase in biodiesel consumption from the FFSR translates into a 2360 km^2 expansion in the harvested area of its feedstocks. This is the combined impact of an increase/decrease in demand for different biodiesel feed crops. For example, the harvested area of other oil seeds expands by 3740 km^2 while the one of rapeseed contracts by 2850 km^2. This matches the regional changes in agricultural markets, with regions like XMN increasing oilseed consumption to meet its growing biodiesel demand while North America substitutes away from rapeseed in favor of bioethanol feeds like maize. As visible in Figure 6, XMN's growing oilseed harvested area is concentrated in Turkey, Morocco, Algeria, and Tunisia, where simultaneously the bioethanol feed harvested area, especially wheat, falls.

Figure 6: Subsidy reforms' impact on harvested area



Notes: Depicts the absolute different harvested area between the Oil Subsidy scenario (BP_FFSR) and the Biofuel Policy scenario (BP) per pixel, with a spatial resolution of 0.5 degree (approx. 50 km at the equator). Panel A shows the change in the harvested area of crops used in biodiesel production (i.e. rapeseed, soy, other oil seeds, and palm) Panel B the change in crops used for bioethanol production (i.e. maize, wheat, sugar cane and beet, and other cereal grains), and panel C, the change in all other crops.

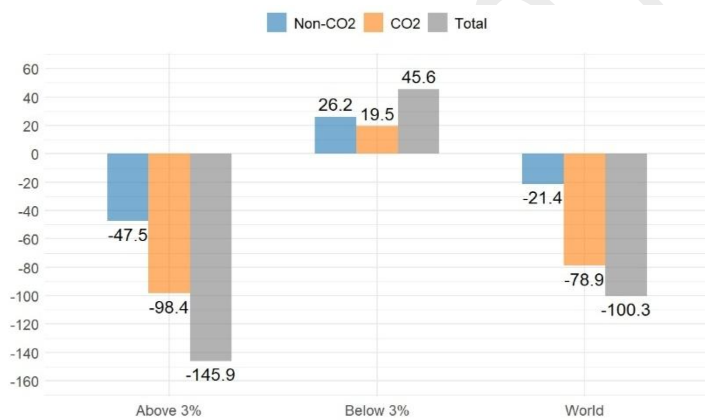
Trade also plays an important role in the reforms' impact on land use. XMN, for example, increases its import of wheat from energy producers in the rest of Europe and Central Asia (NEC), where the harvested area of the crop expands by 4950 km^2. As per Figure 6, this mainly occurs in Russia and Kazakhstan, where the harvested area of bioethanol feed grows while the harvested area of non-bioenergy crops falls. In the European Union and the rest of the EU, the harvested area of non-bioenergy crops expands by 1290 km^2 as consumption shifts away from biofuels and the harvested area of bioethanol and biodiesel feed crops falls. The growing harvested area of food crops in the region is used to meet the growing domestic demand as well as the increase in demand from regions like India, where the harvested area of non-bioenergy crops grows by a modest 130 km^2, but imports rise.

Fossil fuel and land use emissions

Regions with relatively large oil subsidies decrease their energy consumption following the reforms, resulting in reductions in their overall fossil fuel and land use emissions by 0.4% or 145.9 Mt CO_2eq following the subsidy reforms. This is, however, partially offset by the rest of the world increasing emissions by 0.22% or 45.6 Mt CO_2eq. Despite a 31% leakage rate, global fossil fuel and land use emissions thereby fall by 0.18% or 100 Mt CO_2eq in 2030. Comparing this to the change in biofuel feed crops harvested area in each region, assuming this one fully takes place outside existing cropland, the drop in global emissions corresponds to 53% of the emission release from cropland expansion. In other words, it would take 2 years for the fully established policy net emission balance to turn negative.

In regions with relatively high subsidies, energy producers in the Middle East and North Africa (NMN) contribute to a 56 Mt CO_2eq reduction, while other African countries and the EU account for approximately 43% of the remaining 145.9 Mt CO_2eq decline. The change in the Middle East and North Africa, as well as in the EU, is mostly the result of a decrease in CO_2 emissions from oil and oil-based products. The two regions' CO_2 emissions from natural gas increasing as they substitute away from oil products. In the Sub-Saharan region, on the other hand, a fall in non-CO_2 emissions from factors used in the service sector is responsible for most of the decrease in overall emissions. The relatively low drop in CO_2 emissions in the region is due to an increase in coal emissions which suggests a different substitution path to NMN and the EU.

Figure 7: Impact of oil subsidy reforms on 2030 GHG emissions, Mt CO_2eq



North America, India, and the rest of South East Asia (SEA) are found to be responsible for 81% of the increase in emissions in regions with relatively small subsidies. In NA and SEA, changes in CO_2 emissions from cheaper oil and an increasing consumption of fossil-based transport fuels contribute the most to the increase in overall emissions. In India, however, CO_2 emissions decrease, but a rise in non-CO_2 emissions outweighs this decline, resulting in a net increase in overall emissions. The region shifting away from coal in electricity generation, which drives the CO_2 decline. Rising non-CO_2 emissions from overall consumption growth and higher output and input emissions in the service sector more than outweigh the drop in CO_2 emissions, so that overall GHG increase in the region. To a lesser extent, the same effect is observed in China, which, like India, lowers CO_2 emissions from lower coal use but increases non-CO_2 emissions so that overall GHG emissions in the country grow.

4. Discussion

Oil subsidy reforms' impacts on relative prices are found to enhance the competitiveness of biofuels in regions where subsidies are relatively high. This is consistent with Argueyrolles et al. (2025) results for gasoline and diesel subsidy reforms, which were found to lower the government's support needed to reach biofuel targets. A comparable price mechanism drives Bauer et al. (2020)'s conclusion that CO_2 mitigation efforts can increase biofuel deployment. Rather than competitiveness, we find that changes in consumption or deployment are dependent on how biofuel mandates are specified in our simulations. Biofuel consumption, for example, drops in regions where fossil fuel consumption and biofuel targets fall. A parallel can be drawn with Daioglou et al. (2020), who showed that more stringent climate policies may not translate into greater bioenergy trade as final energy demand drops. Rather than through lower carbon budgets, we find this to be a function of bioenergy policies themselves.

At the aggregate level, the additional impact of oil subsidy reforms on land use and food prices is comparatively lower than the initial effect of biofuel mandates. Despite similar global annual emissions reduction when assuming identical cropland expansion rates, oil subsidy reforms and biofuel mandates thus have different net emission balances at times. A fraction of the simulated increase in bioenergy crop production from biofuel mandates, if taking place in natural ecosystems, would be enough to turn the emissions balance of the policy positive for an extended period. This matches Timilsina and Mevel (2012), who found that biofuel mandates would cause a net release of GHG emissions if forests and pastures were used to meet the new demand for land they induce. Given substitution possibilities on cropland, as is simulated here for non-bioenergy crops, in the long run, biofuel mandates net emission balance would still likely prove negative. Aligned with our results, Wise et al. (2014), who consider global biofuel policies and a comparable oil replacement rate of 4%-8% estimate the policies to start lower emissions after 2050.

The global oil subsidy reforms instead are simulated to take 2 years for their annual emission reduction once fully established to offset the expansion of biofuel feeds in natural ecosystems, again assuming no substitution within non-bioenergy crops in existing cropland. Comparison is difficult since previous studies on fossil fuel subsidy reforms did not discuss the impact of the policy on land use. Instead, when considering carbon pricing, Summers et al. (2021) find its impact on land use to be modest but geographically dispersed. Similarly, we simulate cropland reallocation to be spatially variable and the global change in land use to blur the more complex shifting patterns at the local level. An important detail based on the result of Naidoo and Ricketts (2006) who emphasize that the economic benefit and cost of land use for carbon storage and biodiversity conservation are variable even at fine resolution.

As for bioenergy policies, the impact of oil subsidy reforms on land uses can be indirect and occur removed from the place where they are implemented. This is the case of energy producers in Europe and Central Asia who, increase their wheat harvested area in response to changes in biofuel consumption abroad. Delzeit and Britz (2013) highlighted this point in their analysis of Germany's biogas policy, noting that its benefits depend on fluctuations in global agricultural market prices and quantities. While they focused on consumer prices and GHG emissions, Tudge et al. (2024) instead showed that land clearing for biofuel crops reduces local biodiversity. Given the results from Schneider et al. (2024) that only 17% of the most profitable expansion areas are currently protected, oil subsidy reforms may be subject to leakages between environmental outcomes (i.e. emission saving vs biodiversity loss). This extends Balmford et al. (2025) work, who explore the leakages of natural conservation programs on biodiversity, to the possibility of energy policy resulting in biodiversity leakage too.

Abstracting from emissions from land cover change, phasing out global oil subsidies is simulated to result in a 0.18% decrease in global GHG emissions. In comparison, the IPCC (2022) reports that a global FFSR lowers CO^2 emissions by 1% to 4%. However, this figure refers to reform on all fossil fuels, and although other energy commodities like coal can have relatively small subsidies, they can be subject to important externalities (Black et al. 2023). The lower impact of the reform may also be linked to the leakage rate simulated at 31%. A figure comparatively higher than Chepeliev and Mensbrugghe (2020) and Burniaux and Chateau (2014), who for example, reported rates of 0.4% and 12%, respectively. Differences in the reform's scope, but also variations in data sources may explain the discrepancies in figures. Regardless, like for them, the impact of the reform on emissions is concentrated in regions with relatively high subsidies. This supports Jewell et al. (2018) findings that while the annual decline in global emissions remains modest, there are potentially significant shifts in higher-income oil-exporting countries.

5. Conclusion

Unlike a uniform pricing mechanism like carbon taxes, fossil fuel subsidies are decoupled from emissions and vary across regions and fuels. Even if implemented globally, an oil subsidy reform would result in important leakages across space and commodities, undermining its effectiveness in lowering emissions. Global emissions would nevertheless still fall, and renewable energies would become more competitive in the region where subsidies are phased out. By promoting renewable alternatives with larger land requirements, such as biofuels, the reform can lead to land use and cover changes that reduce its net emissions savings due to increased demand for cropland in the agricultural sector. The impact of reforms on land use, however, is not simulated to be large enough to offset their emissions balance in the long run.

Biofuel mandates, which more directly affect agricultural markets, are found to cause relatively greater land use change. The resulting land cover change emissions can lead to a net increase in greenhouse gas emissions for several years following their implementation. Like biofuel policies, the FFSRs' impact on land use varies geographically. Not only do energy policies interact with each other (i.e. biofuel, FFSR) across regions, but the localized costs of land use changes add complexity to assessing spillover effects when evaluating regulations. An evidence-based impact assessment of FFSR must therefore combine economic and environmental analysis with region-specific data to capture these dynamics effectively. Such an assessment will be key in optimizing the benefits of reforms and designing complementary policies to address their unintended consequences.

Governments can leverage existing land-use policies and draw from existing biofuel policies to hedge against the risks of FFSR-induced land use and cover changes. Regions subject to an important increase in bioenergy crops could consider implementing a ban on the use of biofuels with a high risk of causing land-use change in high-carbon stock areas, like the one stipulated by the EU Renewable Energy Directive sustainability criteria. Alternatively, they could complement FFSR with land-use-specific policies and more directly target areas at risk. Given the identification of hotspots of potential future conflicts

(Zabel et al. 2019) zoning policies could prove effective and support other conservation or protection policies (Verdade et al. 2015).

The successful design of complementary land use policies will require the evaluation of local spillover effects from domestic and foreign policies, bridging local to global scales. This represents a challenge for assessments whose resolution across space needs to account for mechanisms and impacts at different scales. The present study, through its linking procedure, highlighted the benefit of combining models to mitigate this challenge. Still, it failed to capture the local environmental costs associated with different land use, especially in regard to biodiversity loss. Exploring further modeling linking strategies to capture this effect is seen as a promising area of research to improve the evaluation of FFSR.

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Appendix

Table 3: Sectors in DART-BIO

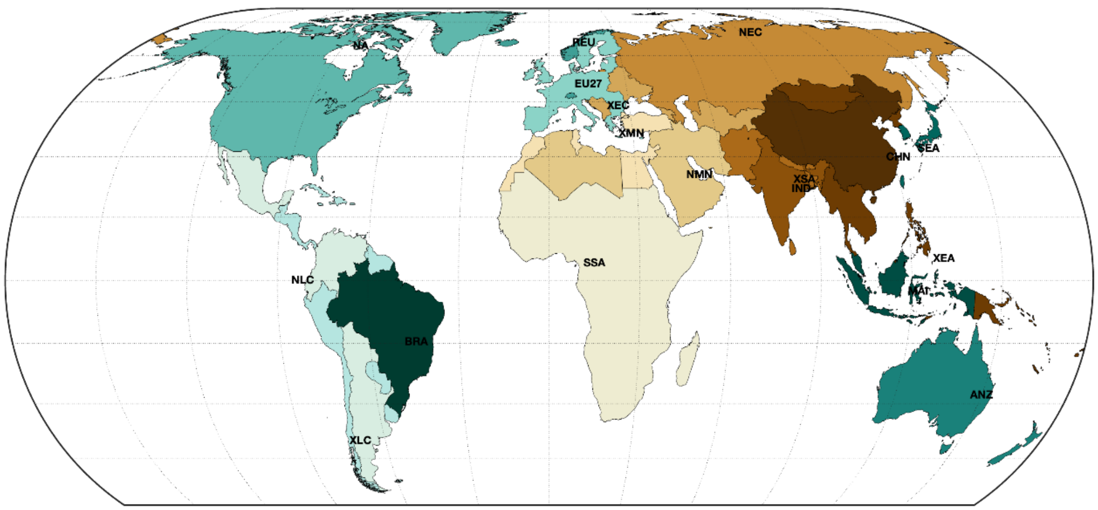
Agricultural related products (29)	
Crops	
PDR	Paddy rice
WHT	Wheat
MZE	Maize
GRON	Other cereal grains
PLM	Oil palm fruit
RSD	Rapeseed
SOY	Soybean
OSDN	Other oil seeds
C_B	Sugar cane and sugar beet
AGR	Rest of crops
STR	Agricultural residues
Processed animal products	
VOLN	Other vegetable oils
SGR	Sugar
FOD	Rest of food
PLMoil	Palm oil
RSDoil	Rapeseed oil
SOYoil	Soybean oil
OSDNoil	Oil from other oil seeds
SOYmeal	Soybean meal
OSDNmeal	Meal from other oil seeds
PLMmeal	Palm meal
RSDmeal	Rapeseed meal
DDGSw	DDGS from wheat
DDGSm	DDGS from maize
DDGSg	DDGS from other cereal grains
UCO	Used cooking oil
Meat and dairy products	
OLSV	Outdoor livestock and related animal products (cattle and other grazing animals, raw milk and wool)
ILVS	Indoor livestock (swine, poultry and other animal products from indoor livestock)
PCM	Processed animal products

Energy products (14)	
COL	Coal
CRU	Oil
GAS	Gas
MGAS	Motor gasoline
MDIE	Motor diesel
OIL	Petroleum and coal products
ELY	Electricity
ETHW	Bioethanol from wheat
ETHM	Bioethanol from maize
ETHG	Bioethanol from other grains
ETHS	Bioethanol from sugar cane
ETHC	Cellulosic Bioethanol from agricultural residues
Biofuels	
BETH	Bioethanol
BDIE	Biodiesel from all other oilseeds
BDIE_PLM	Biodiesel from palm oil
UCOME	Biodiesel from used cooking oil

Non-energy products (4)	
CRPN	Other chemical rubber plastic products
ETS	Paper, minerals and metals
OTH	Other goods and services
SERV	Services

Forest and forest products (2)	
FRS	Forestry
FRI	Forest related industry

Figure 8: Region mapping of the 18 economic study regions



Notes: Region mapping of the 18 economic study regions: ANZ (Australia & New Zealand), BRA (Brazil), CHN (China), EU27 (European Union), IND (India), MAI (Malaysia & Indonesia), NA (United States & Canada), NEC (Energy producers in Europe & Central Asia), NLC (Energy producers in Latin America), NMN (Energy producers in MENA), REU (Switzerland, Norway, Iceland, Liechtenstein), SEA (Rest of South East Asia), SSA (Sub-Saharan Africa), XEA (Rest of East Asia), XEC (Rest of Europe & Central Asia), XLC (Rest of Latin America & Caribbean), XMN (Rest of MENA), XSA (Rest of South Asia).

Figure 9: Regional land expansion generated by converting the areas into cropland under the baseline, in km^2

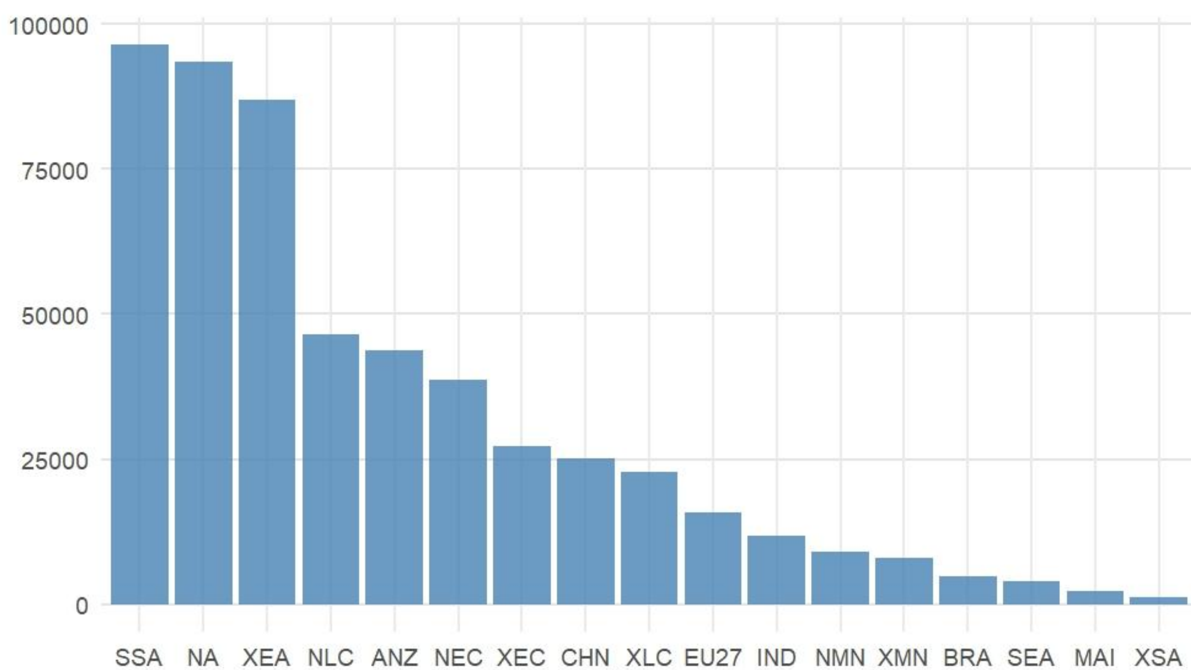


Table 4: Impact of biofuel mandates on agricultural commodity consumption ($bn) and world prices (%) in 2030

	Biofuel mandates	
	Quantity ($bn)	World Price (%)
Paddy rice	-1.6	0.6
Wheat	-0.4	1.0
Maize	24.2	1.1
other cereal grains	-1.7	1.9
Palm	2.5	26.4
Rapeseed	0.4	2.0
Soy	-5.3	4.8
other oil seeds	-0.1	1.6
Sugar cane and beet	15.5	22.5
Rest of agriculture	-9.9	2.1
Outdoor livestock	-2.4	0.5
Rest of food	-36.7	1.2