Interactions between U.S. Vehicle Electrification, Climate Change, and Global Agricultural Markets

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Abstract

Future agricultural production in the United States (U.S.) and elsewhere is influenced by climate change and the proliferation of battery electric vehicles (BEV). The influence of the latter on U.S. farming is more pronounced due to the large share of U.S. maize currently being used for biofuels. Global commodity price increases triggered by declining yields due to climate change can be dampened by reduced biofuel use due to an accelerated increase of BEV sales. A higher market share of BEVs reduces the demand for maize ethanol which by itself reduces commodity prices but this decline in prices is dampened by the reduction of crop supply due to climate change. Using a global agricultural trade model, this analysis quantifies the effects of large-scale U.S. vehicle fleet electrification until 2050 under different Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCP). The results show that a 100% market share of BEVs by 2050 leads to a smaller commodity price increase in the presence of climate change compared to no climate change and baseline market shares. The 2050 price increase for maize under SSP2 (middle-of-the-road SSP) and enhanced CO_2-fertilization is 9.4%-35.8% (depending on the RCP) under the baseline electrification and -2.8%-21.9% under 100% BEV sales share by 2050. Price effects on rice, soybeans, and wheat are similar in direction but smaller in magnitude. Lower commodity price increases in the 100% BEV sales scenario also reduce cropland requirements with area changes ranging from -9.8 to -0.3 million hectares (ha) in SSP2 (with enhanced CO_2-fertilization) compared to -4.9-4.6 million ha in the baseline electrification scenarios. The accelerated market share of BEVs also (1) lowers the decrease in caloric intake for maize, rice, and wheat which has important food security implications in the presence of climate change and (2) changes trade relationships. Policy implications arise from the added effects on land-use change and food security of more BEVs besides the direct emissions reduction from reducing vehicles with internal combustion engines. Although, implications arise for farmers' welfare with the reduction in biofuel demand.

Keywords: land-use change; crop yield; international trade; representative concentration pathway; shared socioeconomic pathway; road transportation decarbonization

JEL Codes: F17, F18, Q15, Q17, Q18, Q54

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1 Introduction

At least two large developments are impacting United States (U.S.) and global agriculture in the long-run. First, climate change is negatively affecting crop yields in large crop-producing countries (Costinot et al., 2016; Debnath et al., 2019; Dellink et al., 2019; Iizumi et al., 2017; Zhao et al., 2017; Schauberger et al., 2017; Schleussner et al., 2018; Huffman et al., 2018; Arora et al., 2020). This leads to changes in the comparative advantage in crop production across nations with well-studied trade implications (Popp et al., 2017; Dumortier et al., 2021a). The second development is the proliferation of battery electric vehicles (BEV) in the U.S. and elsewhere (Debnath et al., 2019; Dumortier et al., 2021b). Currently, U.S. gasoline is blended at a rate of 10% with maize ethanol (E10) whose production uses over a third of U.S. maize.[1] Because maize ethanol is at the so-called blend-wall (i.e., the maximum possible amount of ethanol that can be blended with gasoline), a direct link between gasoline and ethanol consumption exists. Hence, any decline in gasoline consumption, either through electrification or any other policy or technological development reducing gasoline use, translates into a decrease in ethanol and maize demand. Although vehicles of model year 2001 and newer can be fueled with 15% ethanol (E15), the U.S. Energy Information Administration (EIA) projects that the penetration of E15 is limited until 2050 due to market and regulatory constraints.[2] Given the decarbonization of the road transportation sector, demand for E10 and/or E15 is ultimately going to decline in the U.S. because of its linkage to declining gasoline demand over the next decades (EIA, 2021b). Combined with changing crop yields due to climate change, alterations for U.S. and global agriculture in terms of commodity prices and production, land allocation, and trade can be expected. The purpose of this article is to shed light on the interaction between road transportation decarbonization in the U.S., yield impacts of climate change, and agricultural markets at the global level. The analysis focuses on ethanol and road transport electrification in the U.S. as opposed to biofuel reduction in other countries because of (1) its importance regarding food prices, trade, and land-use change and (2) different biofuel policy approaches and potential in Brazil and the European Union (EU). The U.S. focus also allows to isolate the effect on crop prices, land-use, and trade from potential policies to accelerate BEV deployment beyond the current baseline.

U.S. biofuel policy impacts agricultural markets (at least in the short-run) through higher food prices, changes in trade, and land-use change (Elobeid and Tokgoz, 2008; Fabiosa et al., 2010;

[1] See USDA U.S. Bioenergy Statistics "Corn supply, disappearance, and share of total corn used for ethanol" at `https://www.ers.usda.gov/data-products/us-bioenergy-statistics/`.

[2] Assumptions to the Annual Energy Outlook 2021: Liquid Fuels Market Module available at `https://www.eia.gov/outlooks/aeo/assumptions/`.

Condon et al., 2015; Hochman and Zilberman, 2018; Khanna et al., 2021; Wu and Langpap, 2015). An increase in ethanol production diverts maize away from food, feed, and exports. This results theoretically in a price increase for maize and other crops because of competition for land. The increase in commodity prices in the years 2007 and 2008 — in which maize prices in the U.S. increased by at least 35%[3] — is attributed to a variety of factors which are directly and indirectly linked to biofuel production. First, a sharp increase in oil price led to the substitution of ethanol for gasoline. Second, policy changes and implementations around the same time increased the demand for maize ethanol and exacerbated the impact on commodity prices. For example, the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 established blending mandates and granted tax credits for ethanol producers and blenders. Wu and Langpap (2015) find that the combined effect of the biofuel mandates and subsidies implemented under the 2007 Energy Independence and Security Act resulted in 25% to 40% higher corn prices as well as gasoline prices that were lower by 5% to 10%. In addition, methyl tert-butyl ether (MTBE), which raises the octane number in gasoline, was banned in the U.S. because it as associated with negative health and environmental effects (Solomon et al., 2007). Crop production was unable to adjust in the short-run which led to the crop price increase not only in the U.S. but globally (Hochman and Zilberman, 2018; Khanna et al., 2021). Reviewing two decades of U.S. biofuel, Khanna et al. (2021) conclude that the effect of biofuels on global commodity prices is important in the short-run and leads to moderate increases in the long-run due to changes in productivity and cropping patterns. The changes in trade extend beyond agricultural markets and into oil markets as well. Conducting a meta-analysis, Hochman and Zilberman (2018) find that the biofuel mandate in the U.S. reduces oil imports and thus, reducing the U.S. trade deficit. Hill et al. (2016) find that the substitution of ethanol for gasoline and the resulting decrease in gasoline demand leads to a global rebound of oil consumption because of cheaper prices. Although comparable, the economic effects from a decrease in biofuels through decarbonization efforts in the U.S. vehicle market as assessed in this analysis are different (and not simply a reversal) due to the climate change effects on yields.

One aspect of U.S. biofuel policy which has received particular attention since the work by Searchinger et al. (2008) and Fargione et al. (2008) is global land-use and associated biomass and soil carbon loss. The aforementioned higher commodity prices leads farmers to increase crop production by expanding area. The land expansion not only occurs in the U.S. but also in other countries due to global agricultural markets being linked by trade (Fabiosa et al., 2010). The cropland expansion into native vegetation increases the life-cycle emissions from maize ethanol. Recent research has shown that Searchinger et al. (2008) overestimate the magnitude of the effect but not

[3]USDA Feed Grains Database at `https://www.ers.usda.gov/data-products/feed-grains-database/`.

the direction (Hertel et al., 2010; Dumortier et al., 2011; Carriquiry et al., 2020). Furthermore, a study by Timilsina and Mevel (2013) concludes that the time frame for meeting biofuel targets and the type of additional land used for biofuel expansion matter when analyzing the impacts of biofuels on greenhouse gas (GHG) emissions. While GHG emissions are shown to increase in the short to medium term due to biofuel expansion, GHG emissions are estimated to decrease in the longer term with the carbon payback period depending on whether additional land comes from pasture or forest. Consequently, the analysis presented in this paper includes the effects on land-use change because the potential reduction of biofuels through more electric vehicles does not occur in isolation but in combination with climate change which potentially offsets the reduction crop land.

Brazil and the European Union (EU) as the largest producers of biofuels behind the U.S. differ in their policies regarding future road transportation and their overall future potential of biofuels. Brazil produces two types of ethanol: Hydrous ethanol is used in flex-fuel vehicles and E100 vehicles. Anhydrous ethanol is blended with gasoline at a rate of 20%-25% (known as gasoline C). In 2003, Brazil has introduced flex-fuel vehicles to the market which can be operated using a wide range (up to 100%) of ethanol blends. Gasoline without any ethanol is not sold in Brazil anymore. Through a variety of policies, the majority of passenger and light commercial vehicles registered in Brazil are flex fuel vehicles with a 2019 market share of 93.9% and 50.7%, respectively (ICCT, 2015; ANFAVEA, 2020). Projections until 2050 suggest that electric and hybrid vehicles will represent 15% and 85% of the light-duty vehicle registrations, respectively. (EPE, 2016). Given the overall importance of sugarcane ethanol for Brazilian road transportation, major policy incentives for electric vehicles are unlikely. In the context of this analysis, it is also not probable that the U.S. or the EU would be pursuing a road transportation strategy similar to Brazil, i.e., large scale introduction of flex-fuel vehicles. With regard to the EU, there are two aspects which make the future evolution of biofuels different compared to the United States. First, the blending limit is much lower and was raised from 4.1% to 7.0% in December 2018 (EU, 2018). Second, the major biofuel in the EU is biodiesel. As mentioned in Khanna et al. (2021), there are more applications for biodiesel such as in shipping and heavy trucking which may result in sustained biofuel use in the EU.

It is a priori not clear how strongly prices will react due to yield changes from climate change and the electrification of the U.S vehicle fleet. With an increasing atmospheric carbon concentration and the resulting changes in climate, maize yields in the U.S. are expected to decline. There is a wide range of estimates for the maize yield decline by 2050 depending on the warming scenario considered. For the period 2031-2055, Crane-Droesch (2018) finds that maize yields decline by approximately 30% in a climate change scenario assuming a very high carbon concentration. Miao

et al. (2016) estimates that U.S. maize production could decline in the medium-run (average 2041-2060) by up to 27.5%. That estimate is based on the same high carbon concentration scenario as in Crane-Droesch (2018). A recent analysis by Makowski et al. (2020) suggest that maize has low positive effects of increased CO_2 compared to other crops and limited adaption possibilities. Glob-ally, similar trends in crop productivity are observed (Schmitz et al., 2014; Schleussner et al., 2018). Taking the situation in the U.S. in isolation, a simple demand and supply model would suggest a decrease in quantity and either an increase or decrease in the price given the decline in crop supply (due to climate change) and demand (due to lower ethanol demand). To analyze the interactions between climate change, vehicle fleet decarbonization, and various macroeconomic environments, a U.S. transportation model is coupled with a global agricultural trade model as well as global yield estimates under various climate change scenarios (including no climate change) to assess the effects on crop prices, production, land use, and trade. The hypothesis is that an accelerated vehicle fleet decarbonization in the U.S. as the largest biofuel producing and consuming country can ease the pressure on global agriculture given increasing population and climate change. The contribution of the paper is to inform policy and decision makers about the economic and environ-mental effects of pushing for more electric vehicles on the road. This analysis shows that there are global effects of lower crop prices and higher caloric intake but also lower cropland use. Although not explicitly modeled in this paper, the lower use of cropland results in fewer carbon emissions contributing to the slow-down of climate change. Lower crop yields and prices will have negative welfare effects for farmers in the U.S. and elsewhere.

2 Materials and Methods

The analysis is based on four components: (1) Shared Socioeconomic Pathways (SSP), (2) commodity yields under climate change, (3) U.S. transportation model, and (4) agricultural trade model (Figure 1). All components except the transportation model have been developed and/or used in previous research (Nelson et al., 2014; Iizumi et al., 2017; Dumortier et al., 2021a). Thus, the focus of this section is on the detailed development of the transportation model.[4] The other components are described to better understand the overall framework presented in this paper and the reader is referred to previous research for more details. The SSPs described in the next section are exogenous and influence the remaining three components.

[4]The calculations and data associated with the transportation model are available in the Supplemental Information.

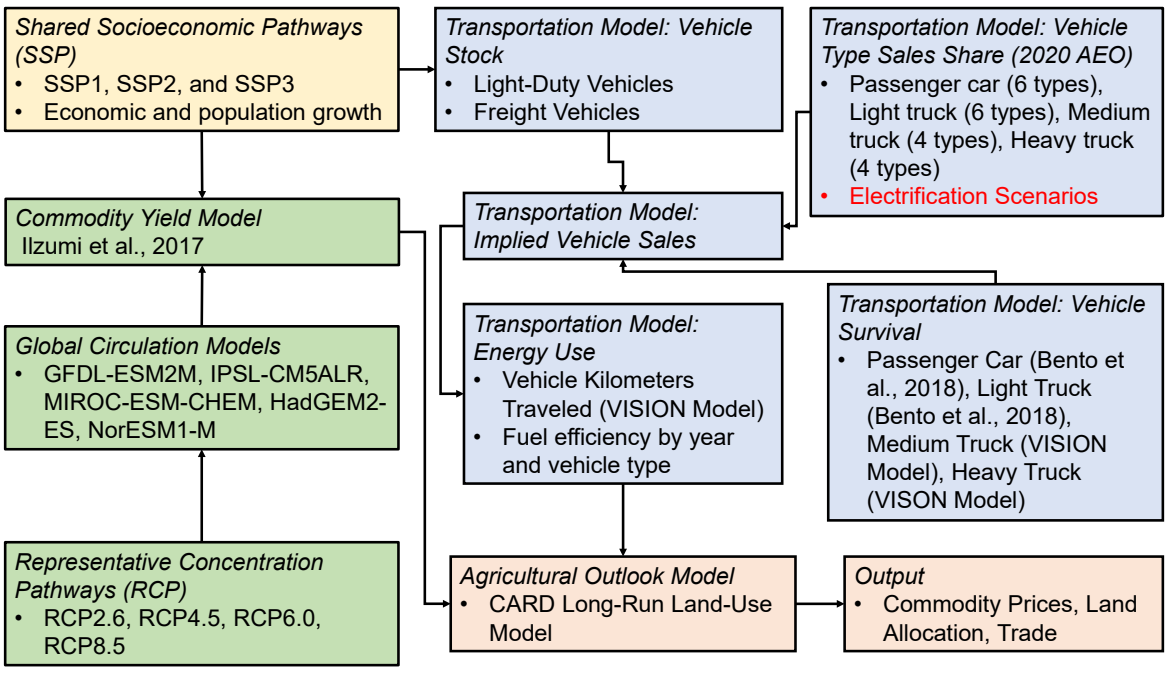

Figure 1. Overview of the four model components: (1) SSPs, (2) commodity yield model depending on Global Circulation Models (GCM) and RCPs, (3) Transportation Model, and (4) Agricultural Outlook Model. The electrification scenarios are implemented via different sales shares.

2.1 Shared Socioeconomic Pathways

Main drivers of transportation demand and agricultural markets are economic and population growth. Households or individuals receive utility from either vehicle kilometers traveled (VKT) or the stock of vehicles, which depend on income among other variables (Greenspan and Cohen, 1999; Bento et al., 2009). The same is valid for food demand. The importance of economic and population growth are not limited to agriculture and transportation but extend to other sectors such as electricity and industry. Since the modeling of climate change and associated policies involves projections into the future, the use of standardized economic growth and population pathways — which is what the SSPs are — allows to compare the findings across studies.

SSPs were developed for the Intergovernmental Panel on Climate Change (IPCC) and are composed of quantitative and qualitative storylines (O'Neill et al., 2014). The purpose of the SSPs is to standardize — to the degree possible — the underlying economic and social assumptions to make climate change projections comparable across models. The three main quantitative components are (1) population growth, (2) economic growth, and (3) urbanization rates. The qualitative components include restrictions on land-use and regulation, international trade openness, productivity

growth in agriculture (e.g., crop yields, livestock technology), and the environmental impact of food consumption (e.g., changing diets away from livestock products) (Popp et al., 2017). Other qualitative markers could include education attainment, effectiveness of institutions, type and direction of technological progress not related to agriculture, etc. (O'Neill et al., 2014). Economic and population growth are the two quantitative components used in this analysis because those are main vehicle and commodity demand drivers.[5] The assessed scenario of a more rapid electric vehicle deployment is also consist with a qualitative component focusing on technological progress. The section below on commodity yields under climate change also outlines how the SSPs influence the management and technological progress in the crop yield model by Iizumi et al. (2017).

The three SSPs used in this analysis are SSP1 ("Sustainability"), SSP2 ("Middle of the road"), and SSP3 ("Regional Rivalery") (Popp et al., 2017; van Meijl et al., 2018). SSP1 is characterized by favorable conditions concerning mitigation and adaptation strategies. Economic growth is high and population growth in developing countries is low. At the opposite end of SSP1 is SSP3 with low economic and generally medium to high population growth. The high population growth in SSP3 is observed in low income countries with medium growth in other countries. As the name "Middle of the Road" suggests for SSP2, economic and population growth are medium (van Meijl et al., 2018). The SSP data is available in five-year intervals, which requires to interpolate the years in between using a constant annual growth rate. In addition, the monetary values in the agricultural trade model used in this analysis are in real 2010 terms whereas the SSPs use 2005 as the base year. Thus, the economic and population trajectories used are consistent with the SSPs in terms of growth rates.

2.2 Commodity Yields under Climate Change

The yield projections under climate change which are fed into the agricultural trade model are taken from Iizumi et al. (2017). The use of the (exogenous) yield data in the agricultural outlook model is described in detail in Dumortier et al. (2021a) and the purpose of this section is to out-line the relevant aspects of the data. The commodity yield model in Iizumi et al. (2017) uses five Global Circulation Models (GCM), i.e., GFDL-ESM2M, IPSL-CM5ALR, MIROC-ESM-CHEM, HadGEM2-ES, and NorESM1-M, to evaluate the effects of four Representative Concentration Pathways on precipitation and temperature. The four RCPs are RCP2.6, RCP4.5, RCP6.0, and RCP8.5 and correspond to the radiative forming in W m^{-1} i.e., RCP6.0 assumes 6 W m^{-1}. Besides

[5]The population levels and economic growth trajectories used in this analysis are available from the SSP Database Version 2.0 located at `https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10`. For GDP, there is more than one trajectory and the one used in this analysis is IIASA GDP. For population, IIASA-WiC POP is used.

the climate influences, the crop yield model also includes nitrogen application rates, knowledge stock of agricultural technologies and its impact agricultural management, and irrigation intensity. The nitrogen application rates as well as the knowledge stock of agricultural technologies are a function of Gross Domestic Product (GDP) and thus, the SSPs influence yield growth besides precipitation and temperature. Thus, the yields used in this analysis indirectly (through GDP growth) include some of the more qualitative components of the SSPs related to technological development. Iizumi et al. (2017) also provide yield data for each SSP under the assumption of no climate change. In addition, yield data with and without enhanced CO_2-fertilization are presented. Enhanced CO_2-fertilization from increased atmospheric concentration of CO_2 results in stronger yield growth for some but not all crops. That is, maize as a C_4 crop has a lower responsiveness as compared to C_3 crops such as soybeans, rice, and wheat (Hertel and Lobell, 2014).

Although each RCP and SSP combination is theoretically possible, some combinations are more likely than others. For example, the storyline of SSP1 which postulates low mitigation and adaptation challenges is more consistent with RCP2.6 or RCP4.5 than RCP8.5. O'Neill et al. (2020) indicates that RCP8.5 is unlikely for any of the three SSPs considered in this analysis. RCP8.5 is consistent with so-called SSP5 which assumes fossil-fueled development. Similarly, SSP3 is not consistent with low warming, i.e., RCP2.6. Thus, RCP8.5 and the combination SSP3/RCP2.6 are not considered are excluded from this analysis.

2.3 Transportation Model

To determine the effects of U.S. vehicle electrification on ethanol demand and agricultural markets, plausible pathways of BEV market shares and resulting sales and stock dynamics are required. Vehicle stock, sales, scrappage value, fuel economy, and vehicle kilometers traveled are all com-ponents that determine the energy use in the road transportation sector. The age distribution of the vehicle stock is important for two reasons: First, vehicles of different ages have different fuel economies and second, older vehicles are not driven as much as newer vehicles. A total of 20 vehi-cle types are modelled, which are sometimes aggregated into groups for parametrization purposes depending on the data availability (Table 1). This section lays out the transportation model and ethanol consumption calculations that are fed into the agricultural trade model.

The two large vehicle groups representing passenger and freight transport are light-duty vehicles (LDV) and freight trucks, respectively. Those groups are also the basis for modelling the vehicle stock. The travel demand literature models either demand for (1) vehicle kilometers traveled (VKT) or (2) vehicle stock as opposed to vehicle sales (Bento et al., 2009). From an economic perspective, households and firms demand the service stemming from vehicles, i.e., travel, and not

	Survival			Vehicle Kilometers Traveled		
	Parameter Source	γ_1	γ_2	θ_0	θ_1	First Year
Light-duty vehicle						
Passenger car	Bento et al. (2018)	7.734	0.163	10.050	-0.034	22391
Light truck	Bento et al. (2018)	7.435	0.137	10.165	-0.040	24964
Freight truck: Medium	VISION Model	5.898	0.088			
Gasoline				10.522	-0.057	35074
Diesel				11.074	-0.088	59078
E85				10.622	-0.057	38757
AFV				10.903	-0.089	49771
Freight truck: Heavy	VISION Model	5.548	0.092			
Single-unit Diesel				10.684	-0.069	40776
Single-unit AFV				10.656	-0.121	37625
Combination Diesel				12.231	-0.125	181140
Combination AFV				11.349	-0.121	75250

Table 1. Parameters for the survival function and vehicle kilometers traveled (VKT). Note that $\theta_2 = \theta_1/100$ to ensure that vehicle miles traveled are decreasing with age over 50 years. Passenger cars and light trucks in the light-duty vehicle category are further subdivided by fuel into six types: Gasoline, Diesel, E85, BEV, Hybrid, and Plug-in hybrid.

	Light-duty Vehicles (R^2 = 0.995)		Freight Trucks (R^2 = 0.957)	
	Coefficients	Standard Error	Coefficients	Standard Error
$\ln(pcs_{i,t-1})$	0.880^{***}	(0.026)	0.936^{***}	(0.067)
$\ln(pcgdp_t)$	0.235^{***}	(0.063)	0.503^{*}	(0.296)
$\ln(pcgdp_{t-1})$	-0.211^{***}	(0.063)	-0.438	(0.303)
Constant	-0.291^{**}	(0.138)	-0.909	(0.657)

Table 2. Stock estimation results for the year 1971 to 2018 (48 observations) for light-duty vehicles and freight trucks. Note: *p<0.1; **p<0.05; ***p<0.01.

from purchasing the vehicles themselves. In this analysis, the per-capita vehicle stock is modeled as a function of GDP. Specifically, the following functional form is assumed:

$$\ln(pcs_{i,t}) = \beta_0 + \beta_1 \cdot \ln(pcs_{i,t-1}) + \beta_2 \cdot \ln(pcgdp_t) + \beta_3 \cdot \ln(pcgdp_{t-1}),\ i \in \{\text{LDV, Freight Trucks}\} \quad (1)$$

where $pcs_{i,t}$ and $pcgdp_t$ represents the per-capita vehicle stock of type i and the per-capita GDP in time t, respectively. Although the transportation sector is an important part of the economy and data on the motor vehicle stock is available from various sources, differences in stock estimates, especially for light-duty vehicles, exist. Light-duty vehicle stock data from four sources are used in this analysis: U.S. Energy Information Administration (EIA), U.S. Federal Highway Administration (FHWA), VISION Model, and IHS Automotive.[6] There are two reasons for the discrepancy in estimates. First, there is a difference between *industry* (such as used by IHS Automotive) and *regulatory* (such as used by EIA) classification. Second, FHWA changed the definition of light trucks in 2009 which moved some vehicles from the light truck to the passenger car category. This results in large discrepancies of up to 25 million vehicles (close to 10% of the total LDV stock) between passenger cars and light trucks across the sources. This does not affect the estimation of Equation 1 because the total LDV stock used but may affect subsequent analysis when passenger vehicle and light trucks are divided into groups. To estimate Equation 1 and overcome the issue of varying vehicle stocks, the ensemble mean for LDVs is calculated across the four sources.[7] The estimation results for Equation 1 are reported in Table 2. Given the estimates in Table 2, the vehicle stock over the period 2019 to 2050 is projected based on the economic growth and population data from the SSPs. The 1971 to 2018 historic projections from the IHS Automotive as reported in ORNL (2021) are combined with the previously calculated projections to obtain the vehicle stock from 1971 to 2050.

Detailed vehicle sales data by vehicle and fuel type is neither readily accessible nor available for a sufficiently long time period. Because the electrification scenarios are implemented on the market share of new vehicles sold, the vehicle sales corresponding to the above stock estimates must be calculated. Vehicle scrappage or vehicle survival rates must be used to obtain vehicle sales corresponding to the vehicle stock. Vehicle scrappage rates determine how many vehicles of a particular vintage a scrapped each year, i.e., how many vehicles survive from one year to the next. Vehicle survival rates are assumed to be constant over the projection period despite

[6]The data from the FHWA and IHS Automotive are reported in ORNL (2021). The VISION Model is published by the Argonne National Laboratory Transportation Systems Assessment Group and is available at `https://www.anl.gov/es/vision-model`. The VISION Model is updated annualy and is based on the Annual Energy Outlook published by the EIA.

[7]Data from the EIA is only available for the years 2012 to 2018.

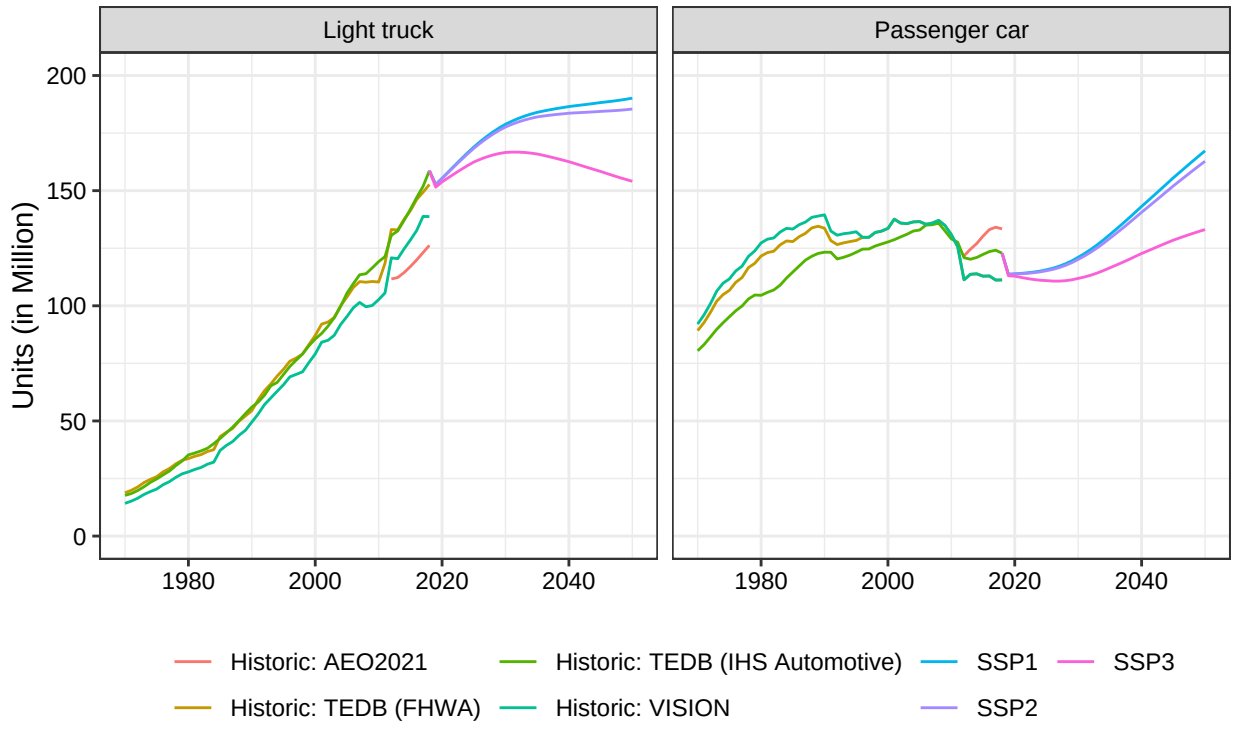

Figure 2. Historic LDV stock from EIA (2021b), ORNL (2021), and the VISION Model as well as projected stock based on the SSPs.

there being evidence that those rates change over time due to technological progress increasing the vehicle quality (Bento et al., 2018). Vehicle survival rates in this study are taken from Bento et al. (2018) for passenger cars and light trucks and from the VISION Model for medium and heavy trucks. The vehicle survival function is assumed to be of the following form (Gompertz function):

$$v_{m,t} = 1 - \exp\left[-\gamma_1 \cdot \exp(-\gamma_2 \cdot (t - m))\right] \tag{2}$$

where $v_{m,t}$ represents the surviving vehicle share of model year m in time t. The age of the vehicle is presented by $t - m$. The Gompertz functional form has been used in previous analysis to model vehicle scrappage. The values of γ_1 and γ_2 are reported in Table 1. The yearly scrappage rates provided by the VISION Model and Bento et al. (2018) are fitted to Equation 2 by minimizing the mean squared error. Given the calculated sales of passenger cars as well as light-, medium-, and heavy trucks to match the stock of light-duty vehicles and freight trucks, the stock projections are re-calculated. The differences between the original stock calculations and the new values (based on sales) are small. The historic and projected LDV stock is divided into passenger cars and light

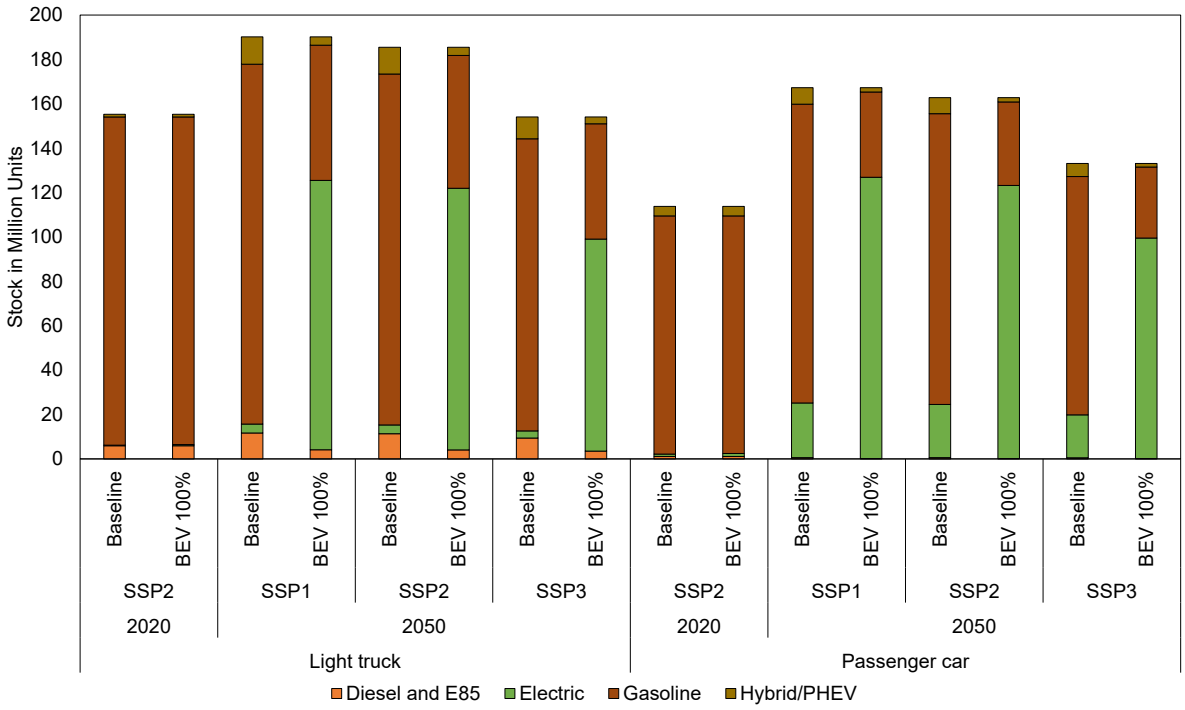

Figure 3. Light-duty vehicle stock and share in 2020 and 2050 under the baseline and the Electric LDV Sales Share of 100% by 2050.

trucks (Figure 2).

The core part of the transportation model as it relates to agriculture is the modeling of the market share of BEVs. The baseline market share for the various vehicle types outlined in Table 1 (including the various fuel types for passenger cars and light trucks) is the 2020 Annual Energy Outlook (AEO) from the U.S. Energy Information Administration (EIA) (EIA, 2021a). Each year, the EIA projects U.S. energy consumption and supply over the next decades including the vehicle stock and sales. For the 100% electrification scenario in 2050, the BEV market sales share is linearly increased to 100%. Due to the longevity of vehicles, the 100% market sales share does not translate into 100% BEV stock in 2050. The difference in stock for the scenarios are displayed in Figure 3.

Given the sales of the 20 vehicle types and the scrappage rates, the stock and age distribution in each year can be calculated. To calculate the energy consumption, the vehicle miles traveled and resulting fuel use (based on fuel efficiency) must be calculated. The fuel efficiency is taken from the VISION Model for the various vehicle types. The VISION Model also provides vehicle kilometers traveled for the various vehicle types and by age. In general, vehicle usage declines

with age and the function form used in this analysis is specified as $\ln(vkt) = \theta_0 + \theta_1 \cdot age + \theta_2 \cdot age^2$ with the parameter values for θ_0, θ_1, and θ_2 specified in Table 1.[8] Similar to the scrappage rate, the annual values provided for the VKT are fitted to the functional form by minimizing the mean squared error. Given the sales, age distribution, VKT, and fuel efficiency, the fuel consumption (gasoline, diesel, and ethanol) of the U.S. vehicle stock can be calculated. Under the baseline electrification, U.S. ethanol consumption decreases between 2020 and 2050 by 10.2%, 12.8%, and 28.7% in SSP1, SSP2, and SSP3, respectively. The decrease amounts to 35.1%, 35.7%, and 38.8% in SSP1, SSP2, and SSP3, respectively in the electrification scenarios.

2.4 Agricultural Trade Model

The global agricultural trade model used for the analysis is the Center for Agricultural and Rural Development Long-Run Land-Use Model (CARD LRLU Model) (Dumortier et al., 2021a). It is a partial-equilibrium model which equates global demand and supply for major commodity markets in 22 regions.[9] There is a single international trade market, i.e., the model does not include bi-lateral trade between individual countries, which must clear in equilibrium. That is, the market equilibrium is reached by a time series of global commodity prices that eliminates excess demand and supply in all markets and all countries. The qualitative SSP story lines include trade restrictions but those are not implemented in the current analysis because the CARD LRLU consists of a single international trade market. The CARD LRLU Model projects land-use, crop consumption and production, and trade (i.e., imports and exports) until 2050. For the current analysis, the model uses the maize, rice, soybeans, and wheat components which are the commodities covered by the climate change yield data in Iizumi et al. (2017). A previous version of the agricultural trade model has been used to assess policies and agricultural market dynamics in the short-run (10-15 years). This time horizon was sufficient to evaluate biofuel policies (Fabiosa et al., 2010; Dumortier et al., 2011; Carriquiry et al., 2020), carbon taxes (Dumortier et al., 2012; Dumortier and Elobeid, 2021), and biochar deployment (Dumortier et al., 2020) but is inadequate to capture the long-term dynamics associated with climate change. In addition, the transportation dynamics as analyzed in this paper are also beyond a 10- or 15-year cycle due to the longevity of vehicles.

The domestic demand sectors for each country and crop combination are (1) feed, (2) food, seed, and industrial, and (3) biofuels (if applicable). Per-capita food demand is a function of

[8] 2009 NHTS Average Annual Vehicle Miles of Travel Per Vehicle (self-reported) by Vehicle Age and Type: https://nhts.ornl.gov/tables09/fatcat/2009/avmtvs_VEHAGE_VEHTYPE.html.

[9] The countries/regions modeled are Argentina, Australia, Brazil, Canada, Chile, China, Egypt, the European Union, India, Indonesia, Japan, Malaysia, Mexico, New Zealand, Nigeria, Peru, Russia, South Africa, Ukraine, the U.S., Vietnam, and the aggregate rest of the world (ROW) region. ROW is required to close the model.

the prices of crops used as substitutes, GDP, and GDP-squared. The squared term is included to restrict per-capita food demand to increase indefinitely. Whereas the crop prices are endogenous to the model, GDP and population are exogenous and consistent with the SSP scenarios as outlined in the previous section. The key demand component for this assessment is the maize ethanol demand from the transportation model, which reflects various levels of vehicle fleet electrification.

Crop production is a function of yields and allocated area. Iizumi et al. (2017) provide the yield projections for three SSPs, four RCPs, and five GCMs. There are also "no climate change" yield projections which assume historic climate conditions. The five GCMs are also averaged to obtain an ensemble mean to eliminate the reliance on a particular GCM (Auffhammer et al., 2013). The results section uses the ensemble mean but reports the upper and lower bounds of the five GCMs as well. As described in Dumortier et al. (2021a), a rolling mean of yields is calculated using ±4 years because the production for some crops take place in overlapping years which affects how the annual yields in Iizumi et al. (2017) are calculated. The crop area allocation is based on the linear method proposed by Holt (1999) and is a function of crop net returns, i.e., area allocation to an individual crop does not only depend on the crops own return but also of the return to other crops. For example, if the returns to maize production are decreasing due to lower demand for biofuels, then the maize area declines and the area allocated to other crops increases because the returns to other crops increases relative to maize.

The SSPs impact the CARD LRLU Model in two ways: First, there is a direct and indirect effect on crop demand. Economic and population growth determine directly the demand from crops. The indirect effects occurs via a transportation model. The SSPs affect transportation demand and hence, the size of the vehicle stock and maize ethanol demand. Second, the SSPs affect the technology use in agriculture in the yield projections by Iizumi et al. (2017). Higher economic growth affects yields through the nitrogen application rate, the knowledge stock of agricultural technologies, improved technologies and management systems, and irrigation intensity (assuming constant irrigation area).

3 Results

The presentation of the results focuses on economic, environmental, and food security aspects. Commodity prices and trade are of importance to consumers, producers, and policy makers whereas land allocation is pertinent because of its potential expansion/contraction into carbon-sensitive na-tive vegetation. Per-capita food consumption and commodity prices are related and a key concerns regarding the effects of climate change on agriculture. Some additional results are found in the

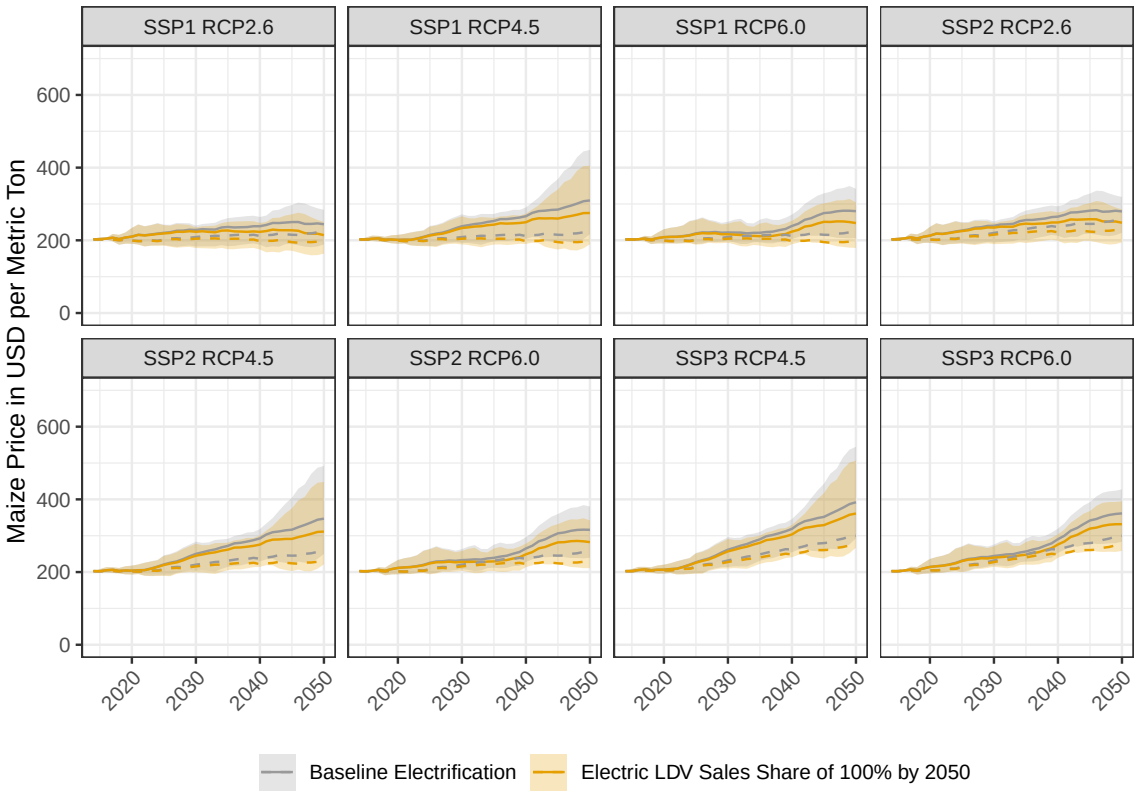

Figure 4. Evolution of maize price over the projection period by SSP, RCP and electrification scenario. "Baseline" and "Electric LDV Sales Share of 100% by 2050" represent the 2020 AEO and the full electrification sales shares, respectively. The solid line represents the results using the mean yield across the GCMs whereas the shaded area represents the minimum and maximum associated with the individual GCMs. The dashed line represents the evolution of prices in the absence of climate change. The time series presented includes enhanced CO_2 fertilization. The results without enhanced CO_2 fertilization as well as for rice, soybeans, and wheat are included in the Supplemental Information.

Supplemental Information associated with this paper.

3.1 Commodity Prices

In general, the supply side effect of higher radiative forcing on yields and the demand side effect of low economic and high population growth as for example observed in SSP3 result in stronger price increases over the projection horizon (Figure 4). In addition, the low economic growth also negatively affects yields in which is an additional supply shock leading to higher prices. Given the implementation of the electrification scenario in the U.S. with its high biofuel consumption blended with gasoline, maize prices are affected stronger than the prices of other crops (Figure

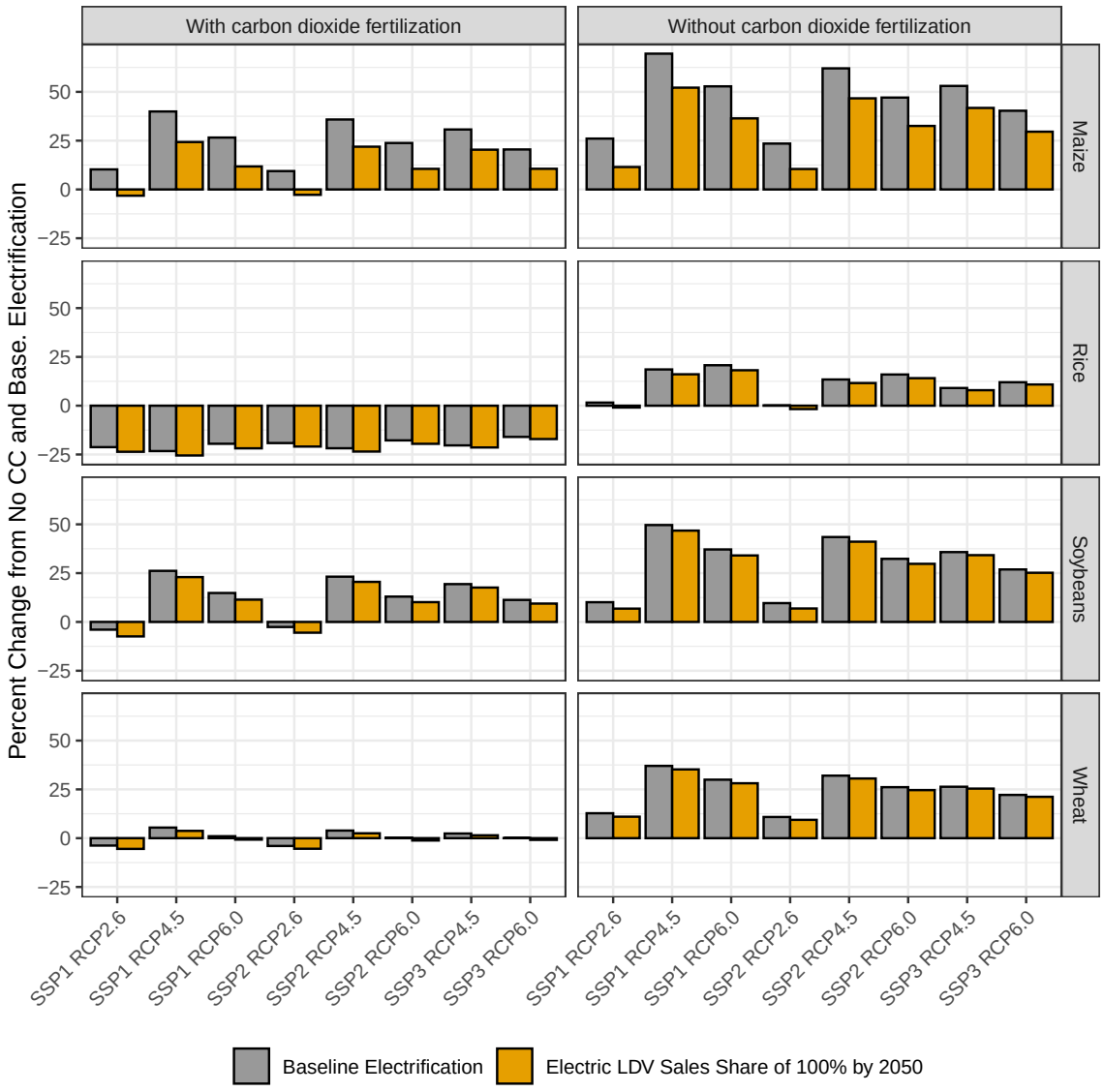

Figure 5. Price change of maize, rice, soybeans, and wheat compared to the no climate change scenario and baseline BEV vehicle in 2050.

4 and Supplemental Information). For the case of maize and SSP1, prices are stable over the projection period in the absence of climate change. For SSP2 and SSP3, an increase in commodity prices is observed even in the absence of climate change. Similar trends are observed for rice and soybeans independent of the presence of CO_2 fertilization. Wheat is the exception which displays an increase in prices over the projection period with and without climate change. Figure 4 also illustrates that U.S. vehicle fleet electrification reduces the global price increase for maize. In

SSP1 RCP2.6 and SSP2 RCP2.6, the price level under electrification is lower than under neither climate change and nor electrification.

The main argument of the paper is that prices increases due to yield declines from climate change are dampened by a higher share of electric vehicles. The results indicate that the magnitude of the effect depends on CO_2 fertilization, radiative forcing, and macroeconomic framework remembering that high GDP results in a larger vehicle stock and more vehicle sales in the base-line and the electrification scenarios (Figure 5). Compared to no climate change and baseline electrification, maize commodity prices increase in the middle-of-the-road SSP2 (assuming CO_2 fertilization) by 9.4%, 35.8%, and 23.8% in RCP2.6, RCP4.5, and RCP6.0, respectively.[10] In the electrification scenario, the price changes are -2.8%, 21.2%, and 10.6% in RCP2.6, RCP4.5, and RCP6.0, respectively. Note that assuming no CO_2-fertilization, the prices changes are significantly more pronounced ranging (depending on the RCP) from 23.5% to 62.0% in the baseline and 10.5%-46.7% in the electrification scenario. For other crops, similar trends are observed (Figure 5). As noted in Iizumi et al. (2017) and Dumortier et al. (2021a), rice is very responsive to CO_2 fertilization which results in the price decline in 2050. Also, the largest decline in commodity prices is observed in SSP1 which is characterized by high GDP growth and thus, a higher travel demand. This leads to the number of BEVs in the electrification scenario being larger and leading to the bigger decline. The commodity prices are lowest in the SSP1 scenario already which is caused by the lower population growth compared to the SSP2 and SSP3 pathways.

Price changes for rice, soybeans, and wheat are smaller in the electrification scenario than for maize. The decrease in soybean prices is expected to be higher than for the other commodities due to its crop rotation with maize in the U.S. Midwest. Since the relative price of maize declines compared to soybeans, farmers have the incentive to increase the soybean area. The price of other commodities declines in the electrification scenarios because of the lower maize demand which triggers crop area being allocated to other crops.

3.2 Trade

The reduction of maize demand from the U.S. biofuel sector has substantial consequences on U.S. exports. U.S. maize exports are between 44.7 and 59.6 million metric tons higher in the 100% electrification scenario than the baseline. This range of additional exports from vehicle electrification should be compared to the average of 49.0 million metric tons of U.S. maize exports

[10]The higher increase in prices in the RCP4.5 scenario compared to the RCP6.0 is associated with the differential yield trajectories by country. That is, some large maize producers such as Argentina, the EU, Mexico, the United States, the Ukraine, and ROW are producing more in RCP6.0 than RCP4.5.

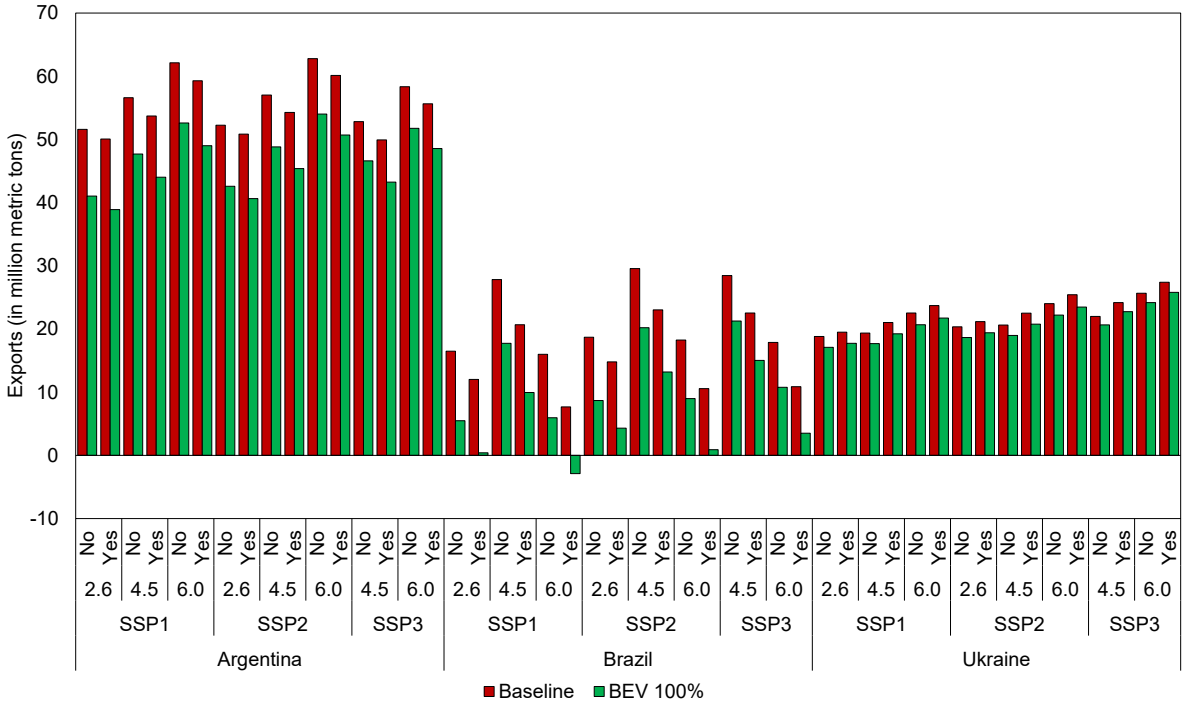

Figure 6. 2050 maize exports for major exporters besides the United States. The presence and absence of CO_2 fertilization is indicated with *Yes* and *No*, respectively.

over the years 2011-2020.[11] U.S. maize yields are decreasing under climate change limiting its export ability under the baseline BEV market share whereas the electrification does not result in lower U.S. maize production but an increase in exports. Because U.S. maize production does not decrease by the amount of the reduction in ethanol demand but is sold abroad, the U.S. exports of soybeans and wheat are only slightly affected. That is, soybean and wheat exports increase by 0.5%-0.9% and 0.4%-0.6%, respectively between the baseline and the electrification scenario across all SSPs and RCPs.

The change in the U.S. maize exports under the electrification scenario affects other maize exporters in the sense that those countries see a decrease in their exports. Argentina's maize exports decrease by 11.3%-22.3% with the higher decrease occurring in the SSP1 and RCP2.6 cases. A similar pattern of a higher percentage decrease in SSP1 is also observed for other large maize

[11] U.S. maize exports reach low levels under climate change and baseline vehicle electrification which leads to very large percentage increases between the baseline and the electrification scenario which is the reason why absolute values are reported. For example, under SSP2 RCP6.0 (with CO_2-fertilization), the exports increase from 15.7 to 72.4 which represents a 4.5-fold increase.

exporters such as Brazil and the Ukraine. There are large variations in Brazilian exports across the scenarios, though (Figure 6).

For Brazilian soybeans, an increase in exports is only observed for SSP1 RCP2.6 under the electrification scenario and exports decrease in all other RCP/SSP combinations. Although the changes are small and range from -1.0% to 1.7%. Because soybeans in Brazil are planted on potentially sensitive land (i.e., rich in soil and biomass carbon or on previously forested land), this can have implications regarding GHG emissions from land-use.

3.3 Land Allocation

Land-use change with U.S. biofuel policy has received substantial attention due to its effect on GHG emissions. Although GHG emissions are not explicitly modeled in this analysis, the changes in land-use resulting from electrification can serve as a discussion starting point. Because less U.S. maize is used for biofuels in the electrification scenario and due to the trade changes discussed in the previous section, less cropland is needed in the electrification scenario although there are major differences due to CO_2-fertilization and macroeconomic environment (Figure 7). Except for SSP1 RCP4.5, less cropland is needed compared to no climate change and baseline electrification in the presence of CO_2-fertilization and vehicle electrification across all RCPs. The largest cropland savings occur under SSP1 RCP2.6 and SSP2 RCP2.6 which are scenarios characterized by high economic growth and low population growth. In addition, RCP2.6 is also at the lower end of climate change scenarios. In both cases, the land area spared from cultivation almost doubles from approximately 5 million hectares to 10 million hectares. Across the individual GCMs, there are variations, though. For SSP1 RCP2.6, the range of crop area spared from cultivation ranges from 1.8 to 13 million ha in the baseline and 7.0 to 18.4 million ha in the electrification scenario.

The effects on crop area are very different if no CO_2-fertilization is considered in the yield estimates. For all SSPs, RCPs, and the electrification scenario, crop area increases compared to no climate change and the baseline electrification (Figure 7). Note that the crop area difference in Figure 7 is relative to the no climate change and baseline electrification scenario for each SSP. The area used in SSP1 as opposed to SSP3 is 711.4 and 746.4 million ha, i.e., more area is used in SSP3 than SSP1. This leads to the large expansion observed in Figure 7 under SSP1 because it is already starting at a lower level.

There are also differences in the distribution of land-use changes across countries. To illustrate this point, the crop area changes by crop and scenario are depicted in Figures 8 and 9. The change in maize demand is compensated by an increase in U.S. maize exports to other countries. This leads in a decrease in the demand for maize from other countries including Brazil. Maize and

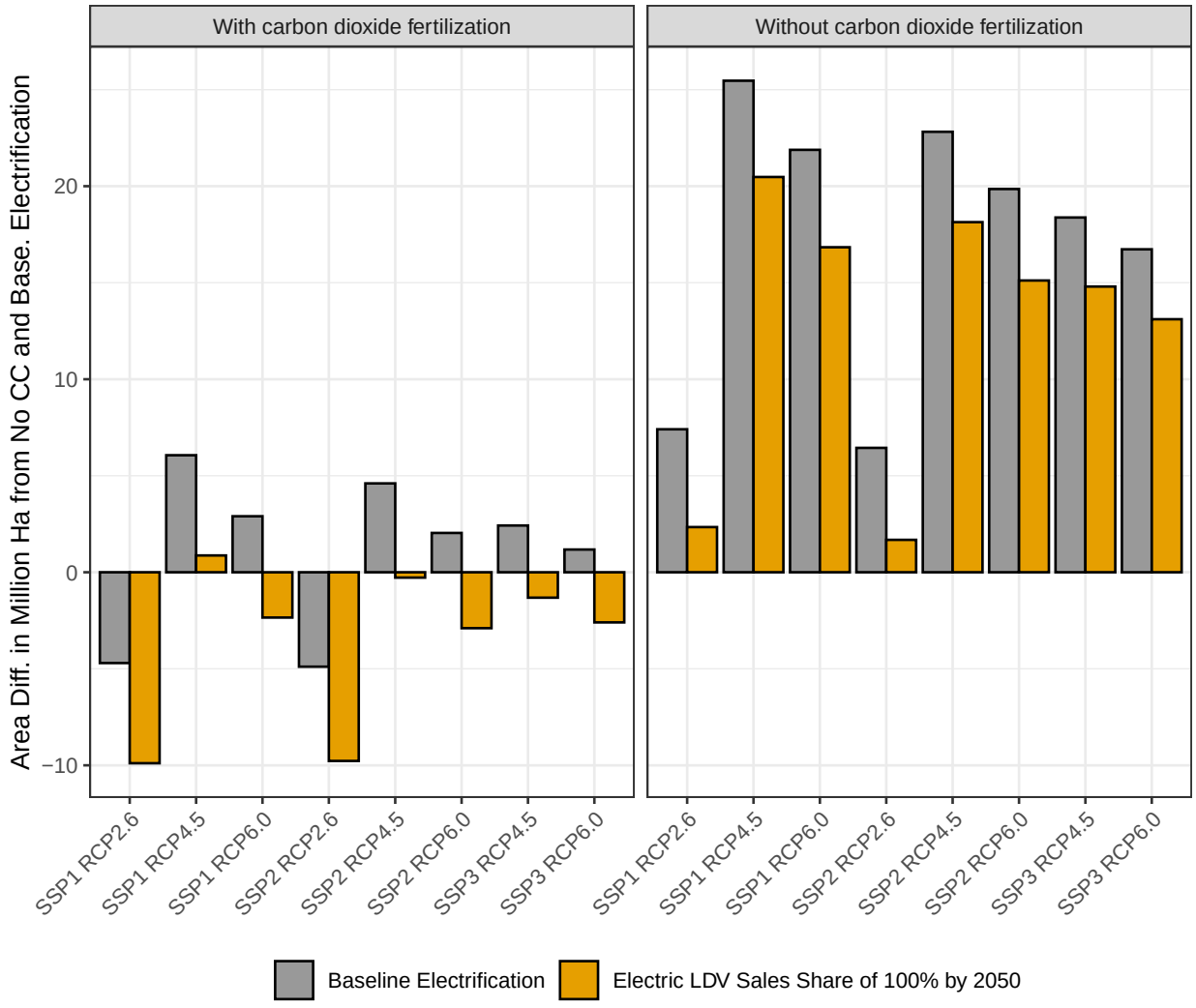

Figure 7. Difference in global area between the baseline and the electrification scenario by 2050.

soybeans are grown in the same regions in Brazil and thus, the area for soybeans increase because they get relatively more expensive compared to maize. Beyond the scope of this paper are the GHG emissions but the question arises if there is a one-to-one substitution in area between maize and soybeans in Brazil with no crop area increase in the Legal Amazon or if there are other effects (positive or negative) with respect to deforestation. Our results suggest an overall decrease in the Brazilian crop area from additional electric vehicles in the United States.

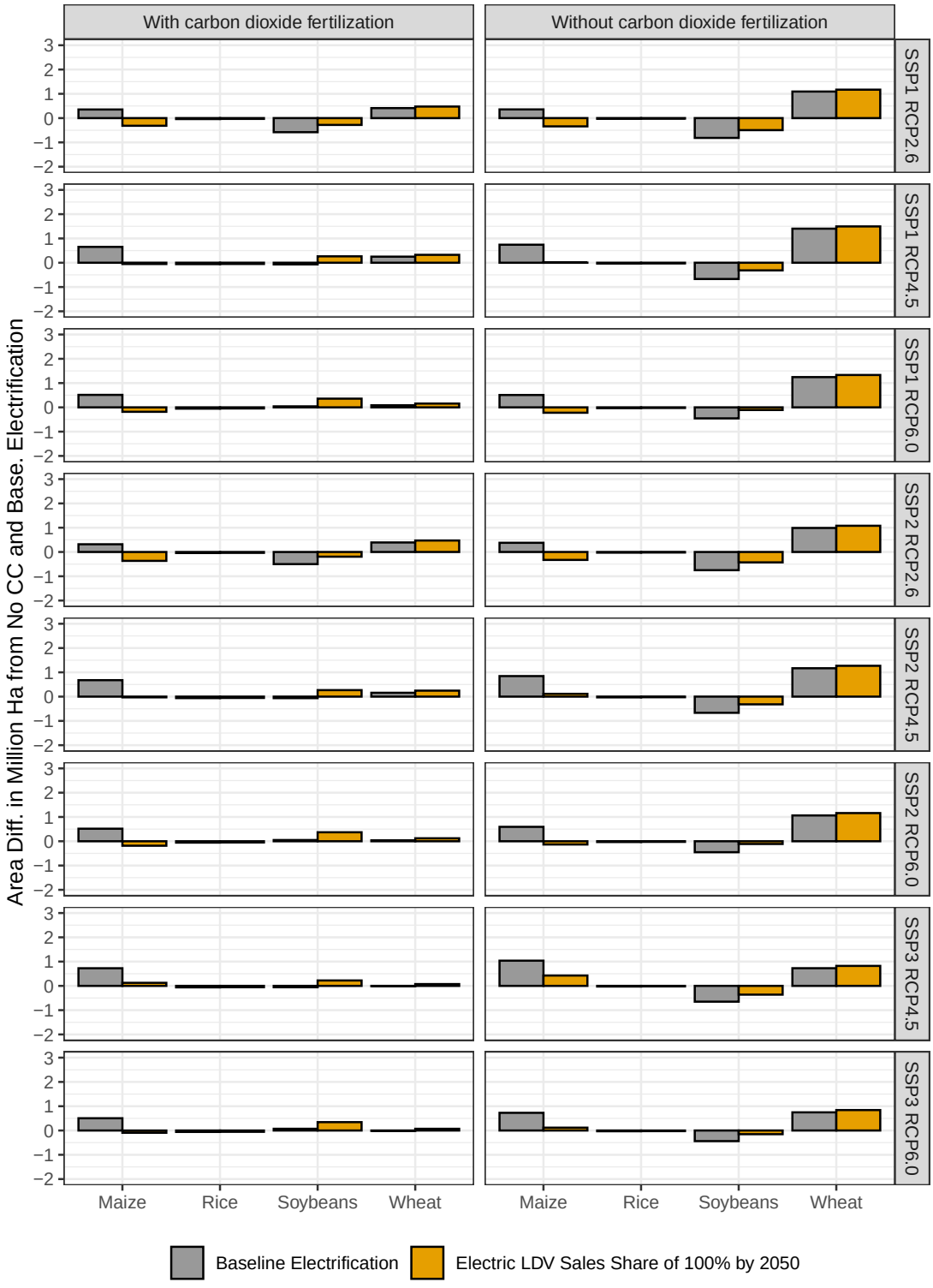

Figure 8. Difference in U.S. area between the baseline and the electrification scenario by 2050.

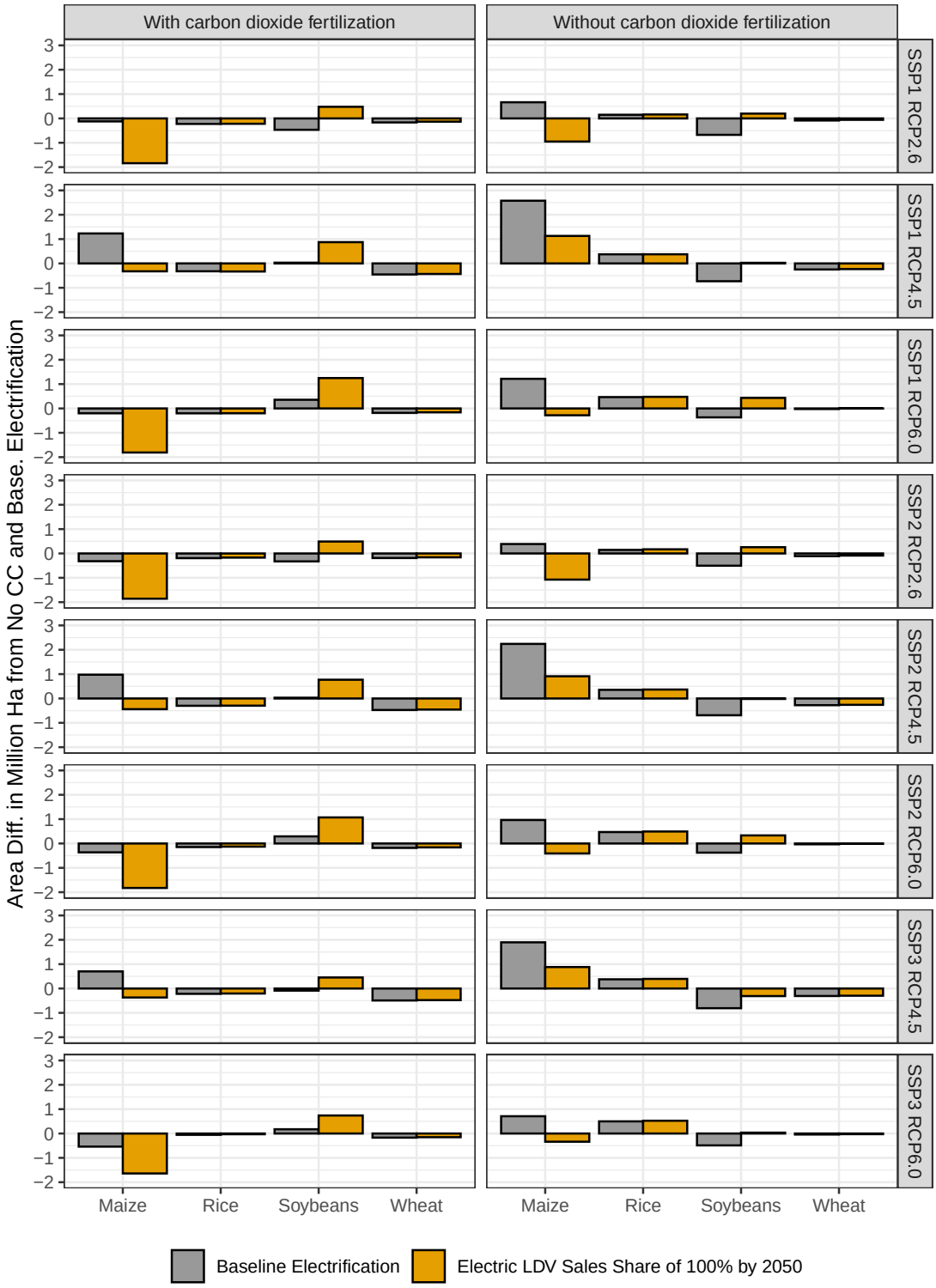

Figure 9. Difference in Brazilian area between the baseline and the electrification scenario by 2050.

3.4 Food Security

One among many major concerns associated with climate change is the effect on food security. Declining crop yields reduce available food (on a given unit of land) and increase food prices (Figure 5). Tables 3 summarizes the effects on per-capita food consumption across the scenarios and regions covered in the CARD LRLU Model.[12] The decrease in food consumption from the three food crops is lessened by accelerated sales of electric vehicles in the United States. The food consumption issue is of course more complex than analyzed in this paper because other protein sources are not included in this analysis.

4 Conclusion

There is little doubt that major changes are coming to U.S. and global agriculture in the future that are directly or indirectly linked to climate change. Directly in the sense that changes in temperature and precipitation patterns (and the resulting increase in heat and water stress likelihood) will affect crop yields and indirectly through policies and technological changes to prevent those losses in agricultural productivity. Among other objectives, biofuel development in the U.S. has been advanced under the premise of reducing GHG emissions from road transportation. The achievement of this objective is still debated given the consequences on land-use and the possible rebound effect from lower oil prices due to large-scale ethanol use in the United States. An unambiguous consequence of U.S. biofuel development is the high share of maize production used for ethanol and the exposure of American farmers to the risk of declining biofuel demand in the future. In this paper, the effects on international agricultural markets from a decline in biofuel demand due to vehicle fleet electrification are outlined. The decrease in U.S. maize demand is not simply a reversal from the increase seen in the early 2000s but is no affected by changing crop yields due to climate change as well. Although the accelerated decarbonization of the vehicle sector is presented as a scenario in this paper, vehicle fleet electrification is almost inevitable and will happen sooner or later. The decline in maize as a feedstock for ethanol is likely given the absence of any alternative uses such as aviation fuels.

From an consumer and environmental perspective, there are two important takeaways from this analysis. First, lower commodity prices will result in higher caloric intake than under the absence of vehicle fleet electrification. The lower commodity prices and absence of ethanol demand also

[12] The aggregate the various crops, an energy content (in kilo joule per 100 grams) of 1527, 1506, and 1368 is used for maize, rice, and wheat respectively. Values are available at USDA's FoodData Central Database under `https://fdc.nal.usda.gov/index.html`.

	SSP2 RCP2.6		SSP2 RCP4.5		SSP2 RCP6.0		SSP3 RCP4.5		SSP3 RCP6.0	
	Baseline	BEV 100%	Baseline	BEV 100%	Baseline	BEV 100%	Baseline	BEV 100%	Baseline	BEV 100%
Argentina	-0.5%	0.4%	-3.9%	-2.8%	-2.2%	-1.2%	-4.3%	-3.3%	-2.6%	-1.6%
Australia	0.3%	0.8%	-2.7%	-2.2%	-1.2%	-0.7%	-3.1%	-2.6%	-1.6%	-1.1%
Brazil	0.4%	1.1%	-1.4%	-0.6%	-0.6%	0.1%	-1.2%	-0.6%	-0.5%	0.1%
Canada	-1.3%	0.7%	-7.5%	-5.2%	-4.5%	-2.3%	-8.6%	-6.3%	-5.3%	-3.2%
Chile	-1.1%	0.3%	-7.0%	-5.5%	-4.0%	-2.5%	-8.3%	-6.8%	-5.0%	-3.5%
China	0.8%	1.2%	-0.2%	0.3%	0.1%	0.6%	0.1%	0.5%	0.3%	0.8%
Egypt	0.6%	1.1%	-1.4%	-0.8%	-0.5%	0.0%	-1.3%	-0.8%	-0.5%	0.0%
European Union	-0.3%	0.5%	-3.9%	-3.0%	-2.1%	-1.2%	-4.5%	-3.6%	-2.6%	-1.7%
India	1.6%	2.0%	0.6%	1.1%	0.9%	1.3%	1.2%	1.6%	1.2%	1.6%
Indonesia	2.5%	3.0%	2.7%	3.1%	2.2%	2.6%	3.8%	4.2%	3.0%	3.4%
Japan	0.5%	1.6%	-1.9%	-0.6%	-0.9%	0.3%	-1.6%	-0.5%	-0.8%	0.3%
Malaysia	2.6%	3.0%	2.4%	2.8%	2.1%	2.5%	3.5%	3.9%	2.9%	3.3%
Mexico	-3.5%	0.5%	-12.7%	-8.1%	-8.5%	-4.1%	-14.2%	-9.8%	-9.5%	-5.3%
New Zealand	0.4%	1.0%	-3.1%	-2.5%	-1.3%	-0.7%	-3.4%	-2.8%	-1.7%	-1.1%
Nigeria	-0.7%	1.0%	-4.5%	-2.5%	-2.9%	-0.9%	-5.2%	-3.1%	-3.3%	-1.3%
Peru	1.9%	2.7%	-0.2%	0.6%	0.5%	1.4%	0.5%	1.3%	1.0%	1.9%
Rest of World	0.5%	0.9%	-0.4%	0.0%	0.0%	0.3%	-0.2%	0.1%	0.1%	0.4%
Russia	0.1%	0.7%	-3.8%	-3.2%	-1.8%	-1.2%	-4.3%	-3.7%	-2.3%	-1.7%
South Africa	-1.5%	0.8%	-6.7%	-4.1%	-4.3%	-1.8%	-7.3%	-4.9%	-4.8%	-2.4%
Ukraine	-0.2%	1.4%	-8.8%	-7.1%	-4.4%	-2.7%	-10.5%	-8.9%	-5.8%	-4.1%
United States	-1.7%	0.4%	-6.7%	-4.3%	-4.4%	-2.1%	-7.1%	-5.0%	-4.7%	-2.6%
Vietnam	1.3%	1.5%	1.7%	1.9%	1.3%	1.5%	2.2%	2.4%	1.7%	1.8%

Table 3. Change in per-capita food consumption compared to the no climate change and baseline electrification scenario on a caloric basis for maize, rice, and wheat (with CO_2-fertilization). Due to the similarity of SSP1 and SSP2, the change in SSP1 is not reported.

results in lower cropland use which likely protects native vegetation. Although not explicitly modeled in this paper, the lower cropland use likely results in fewer carbon emissions and protection of biodiverity. In addition, maize is very fertilizer intensive and a switch to other crops can also reduce leaching and run-off as well as nitrous oxide emissions from crop management.

Although the present analysis is limited to four major commodities, the effects on crop prices and cropland likely extend to other crops as well meaning that the results presented, especially for cropland, are a lower bound. Although it is possible that the lower crop prices result in increased livestock because of lower input prices. This would result in the expansion of pasture and increased agricultural cropland use. Additional limitations of the analysis are the absence of bilateral trade relationships which would be of particular importance in SSP3 with the storyline of trade restrictions.

There are multiple needs for future research. First, explicit models of future vehicle stock pathways for major car markets such as Brazil, China, the EU, and India need to be incorporated. As mentioned before, Brazil is pursuing a different transportation strategy based on hybrid vehicles using sugercane ethanol. Depending on road transportation policies in other countries, U.S. ethanol may be exported to countries which are lacking domestic resources for the production of biofuels. feedstock. Second, future uses in sectors different from road transportation need to be assessed. For example, there is interest in using biofuels for the aviation sector. The potential barriers and opportunities of aviation biofuels are not addressed in this analysis.

Integrated Assessment Models are necessary to determine which policies and technology pathways are effective and efficient at staying within the remaining carbon budget that limits global warming to a set temperature increase above pre-industrial levels. Given the goal of net-zero by 2050, decisions need to be made soon in order to achieve the goal especially with regard to sectors such as transportation. The vehicle stock changes slowly over decades even if policies are enacted today. A 100% market share of sales in 2050 does not translate into only electric vehicles on the road. This analysis shows that accelerated electric vehicle deployment has positive consequences in terms of limiting commodity price increases due to declining yields. The results are increased food security, potentially less cropland expansion into native vegetation, and lower carbon emissions from land-use change and — assuming renewable energy as the feedstock for electric vehicles — road transportation.

References

ANFAVEA (2020). Anuário da Indústria Automobilística Brasileira 2020. Yearbook, Associação Nacional dos Fabricantes de Veículos Automotores, São Paulo, Brazil.

Arora, G., Feng, H., Anderson, C. J., and Hennessy, D. A. (2020). Evidence of climate change impacts on crop comparative advantage and land use. *Agricultural Economics*, 51(2):221–236. 10.1111/agec.12551.

Auffhammer, M., Hsiang, S. M., Schlenker, W., and Sobel, A. (2013). Using weather data and climate model output in economic analyses of climate change. *Review of Environmental Eco-nomics and Policy*, 7(2):181–198. 10.1093/reep/ret016.

Bento, A., Roth, K., and Zuo, Y. (2018). Vehicle lifetime and scrappage behavior: Trends in the U.S. used car market. *Energy Journal*, 39(1):159–183. DOI: 10.5547/01956574.39.1.aben. Bento, A. M., Goulder, L. H., Jacobsen, M. R., and von Haefen, R. H. (2009). Distributional and efficiency impacts of increase US gasoline taxes. *American Economic Review*, 99(3):667–699. DOI: 10.1257/aer.99.3.667.

Carriquiry, M., Elobeid, A., Dumortier, J., and Goodrich, R. (2020). Incorporating sub-national Brazilian agricultural production and land-use into U.S. biofuel policy evaluation. *Applied Eco-nomic Perspectives and Policy*, 42(3):497–523. 10.1093/aepp/ppy033.

Condon, N., Klemick, H., and Wolverton, A. (2015). Impacts of ethanol policy on corn prices: A review and meta-analysis of recent evidence. *Food Policy*, 51:63–73. DOI: 10.1016/j.foodpol.2014.12.007.

Costinot, A., Donaldson, D., and Smith, C. (2016). Evolving comparative advantage and the impact of climate change in agricultural markets: Evidence from 1.7 million fields around the world. *Journal of Political Economy*, 124(1):205–248. 10.1086/684719.

Crane-Droesch, A. (2018). Machine learning methods for crop yield prediction and climate change impact assessment in agriculture. *Environmental Research Letters*, 13(114003):1–12. 10.1088/1748-9326/aae159.

Debnath, D., Khanna, M., Rajagopal, D., and Zilberman, D. (2019). The future of biofuels in an electrifying global transportation sector: Imperative, prospects and challenges. *Applied Eco-nomic Perspectives and Policy*, 41(4):563–582. DOI: 10.1093/aepp/ppz023.

Dellink, R., Lanzi, E., and Chateau, J. (2019). The Sectoral and Regional Economic Consequences of Climate Change to 2060. *Environmental and Resource Economics*, 72:309–363. Dumortier, J., Carriquiry, M., and Elobeid, A. (2021a). Impact of climate change on global agricultural markets under different Shared Socioeconomic Pathways. *Agricultural Economics (forthcoming)*. DOI: 10.1111/agec.126600.

Dumortier, J., Carriquiry, M., and Elobeid, A. (2021b). Where does all the biofuel go? Fuel efficiency gains and its effects on global agricultural production. *Energy Policy*, 148(A):111090. 10.1016/j.enpol.2020.111909.

Dumortier, J., Dokoohaki, H., Elobeid, A., J.Hayes, D., Laird, D., and Miguez, F. E. (2020). Global land-use and carbon emission implications from biochar application to cropland in the United States. *Journal of Cleaner Production*, 258(120684):1–10. 10.1016/j.jclepro.2020.120684.

Dumortier, J. and Elobeid, A. (2021). Effects of a carbon tax in the United States on agricultural markets and carbon emissions from land-use change. *Land Use Policy*, 103(105320):1–16. DOI:

10.1016/j.landusepol.2021.105320.

Dumortier, J., Hayes, D. J., Carriquiry, M., Dong, F., Du, X., Elobeid, A., ..., and Tokgoz, S. (2011). Sensitivity of carbon emission estimates from indirect land-use change. *Applied Eco-nomic Perspectives and Policy*, 33(3):428–448. 10.1093/aepp/ppr015.

Dumortier, J., Hayes, D. J., Carriquiry, M., Dong, F., Du, X., Elobeid, A., Fabiosa, J. F., Martin, P. A., and Mulik, K. (2012). The effects of potential changes in United States beef production on global grazing systems and greenhouse gas emissions. *Environmental Research Letters*, 7(2):024023. 10.1088/1748-9326/7/2/024023.

EIA (2021a). Annual Energy Outlook 2020. Technical report, U.S. Energy Information Administration.

EIA (2021b). Annual Energy Outlook 2021. Technical report, U.S. Energy Information Administration.

Elobeid, A. and Tokgoz, S. (2008). Removing Distortions in the U.S. Ethanol Market: What Does It Imply for the United States and Brazil? *American Journal of Agricultural Economics*, 90(4):918–932. 10.1111/j.1467-8276.2008.01158.x.

EPE (2016). Demanda de energia 2050. Nota Técnica DEA 13/15, Ministério de Minas e Energia.

EU (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. Official Journal of the European Union last accessed September 24th, 2021.

Fabiosa, J. F., Beghin, J. C., Dong, F., Elobeid, A., Tokgoz, S., and Yu, T.-H. (2010). Land allocation effects of the global ethanol surge: Predictions from the international fapri model. *Land Economics*, 86(4):687–706. 10.3368/le.86.4.687.

Fargione, J., Hill, J., Tilman, D., Polasky, S., and Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. *Science*, 319(5867):1235–1238.

Greenspan, A. and Cohen, D. (1999). Motor vehicle stocks, scrappage, and sales. *Review of Economics and Statistics*, 81(3):369–383. DOI: 10.1162/003465399558300.

Hertel, T. W., Burke, M. B., and Lobell, D. B. (2010). The poverty implications of climate-induced crop yield changes by 2030. *Global Environmental Change*, 20:577–585. 10.1016/j.gloenvcha.2010.07.001.

Hertel, T. W. and Lobell, D. B. (2014). Agricultural adaptation to climate change in rich and poor countries: Current modeling practice and potential for empirical contributions. *Energy Economics*, 46:562–575. 10.1016/j.eneco.2014.04.014.

Hill, J., Tajibaeva, L., and Polasky, S. (2016). Climate consequences of low-carbon fuels: The United States Renewable Fuel Standard. *Energy Policy*, 97:351–353. DOI: 10.1016/j.enpol.2016.07.035.

Hochman, G. and Zilberman, D. (2018). Corn ethanol and U.S. biofuel policy 10 years later: A quantitative assessment. *American Journal of Agricultural Economics*, 100(2):570–584. DOI: 10.1093/ajae/aax105.

Holt, M. T. (1999). A linear approximate acreage allocation model. *Journal of Agricultural and Resource Economics*, 24(2):1–15.

Huffman, W. E., Jin, Y., and Xu, Z. (2018). The economic impacts of technology and climate change: New evidence from U.S. corn yields. *Agricultural Economics*, 49(4):463–479.

10.1111/agec.12429.

ICCT (2015). Brazil passenger vehicle market statistics: International comparative assessment of technology adoption and energy consumption. White paper, The International Council on Clean Energy Transportation.

Iizumi, T., Furuya, J., Shen, Z., Kim, W., Okada, M., Fujimori, S., . . . , and Nishimori, M. (2017). Responses of crop yield growth to global temperature and socioeconomic changes. *Scientific Reports*, 7:7800. 10.1038/s41598-017-08214-4.

Khanna, M., Rajagopal, D., and Zilberman, D. (2021). Lessons Learned from US Experience with Biofuels: Comparing the Hype with the Evidence. *Review of Environmental Economics and Policy*, 15(1):67–86. DOI: 10.1086/713026.

Makowski, D., Marajo-Petitzon, E., Durand, J.-L., and Ben-Ari, T. (2020). Quantitative synthesis of temperature, co_2, rainfall, and adaptation effects on global crop yields. *European Journal of Agronomy*, 115(126041). DOI: 10.1016/j.eja.2020.126041.

Miao, R., Khanna, M., and Huang, H. (2016). Responsiveness of crop yield and acreage to prices and climate. *American Journal of Agricultural Economics*, 98(1):191–211. 10.1093/ajae/aav025.

Nelson, G. C., Valin, H., Sands, R. D., Havlík, P., Ahammad, H., Deryng, D., . . . , and Willenbockel, D. (2014). Climate change effects on agriculture: Economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences*, 111(9):3274–3279. 10.1073/pnas.1222465110.

O'Neill, B. C., Carter, T. R., Ebi, K., Harrison, P. A., Kemp-Benedict, E., Kok, K., Kriegler, E., Preston, B. L., Riahi, K., Sillmann, J., van Ruijven, B. J., van Vuuren, D., Carlisle, D., Conde, C., Fuglestvedt, J., Green, C., Hasegawa, T., Leininger, J., Monteith, S., and Pichs-Madruga, R. (2020). Achievements and needs for the climate change scenario framework. *Nature Climate Change*, 10:1074–1084. DOI: 10.1038/s41558-020-00952-0.

O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., . . . , and van Vuuren, D. P. (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change*, 12(3):387–400. 10.1007/s10584-013-0905-2.

ORNL (2021). *Transportation Energy Data Book*. Oak Ridge National Laboratory, 39th edition.

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., . . . , and van Vuuren, D. P. (2017). Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, 42:331–345. 10.1016/j.gloenvcha.2016.10.002.

Schauberger, B., Archontoulis, S., Arneth, A., Balkovic, J., Ciais, P., Deryng, D., . . . , and Frieler, K. (2017). Consistent negative response of US crops to high temperatures in observations and crop models. *Nature Communications*, 8(13931):1–9. 10.1038/ncomms13931.

Schleussner, C.-F., Deryng, D., Müller, C., Elliott, J., Saeed, F., Folberth, C., . . . , and Rogelj, J. (2018). Crop productivity changes in 1.5 °c and 2 °c worlds under climate sensitivity uncertainty. *Environmental Research Letters*, 13:064007. 10.1088/1748-9326/aab63b.

Schmitz, C., van Meijl, H., Kyle, P., Nelson, G. C., Fujimori, S., Gurgel, A., . . . , and Valin, H. (2014). Land-use change trajectories up to 2050: Insights from a global agro-economic model comparison. *Agricultural Economics*, 45(1):69–84. 10.1111/agec.12090.

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S.,

Hayes, D., and Yu, T.-H. (2008). Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science*, 319(5867):1238–1240. Solomon, B. D., Barnes, J. R., and Halvorsen, K. E. (2007). Grain and cellulosic ethanol: History, economics, and energy policy. *Biomass and Bioenergy*, 31(6):416–425. DOI: 10.1016/j.biombioe.2007.01.023.

Timilsina, G. and Mevel, S. (2013). Biofuels and climate change mitigation: A CGE analysis incorporating land-use change. *Environmental and Resource Economics*, 55(1):1–19. DOI: 10.1007/s10640-012-9609-8.

van Meijl, H., Havlik, P., Lotze-Campen, H., Stehfest, E., Witzke, P., Dominguez, I. P., . . . , and van Zeist, W.-J. (2018). Comparing impacts of climate change and mitigation on global agriculture by 2050. *Environmental Research Letters*, 13(064021):1–19. 10.1088/1748-9326/aabdc4.

Wu, J. and Langpap, C. (2015). The Price and Welfare Effects of Biofuel Mandates and Subsidies. *Environmental and Resource Economics*, 62(1):35–57. DOI: 10.1007/s10640-014-9814-9. Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., . . . , and Asseng, S. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences*, 114(35):9326–9331. 10.1073/pnas.1701762114.