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Assessing the impact of closing global commodity yield gaps on food production and land-use change emissions from biofuels

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Abstract

The greenhouse gas emissions (GHG) associated with corn ethanol have received considerable attention over the last decade. Higher commodity prices from additional U.S. ethanol demand leads to land-use change in the U.S. and globally potentially leading to significant GHG emissions. Some research argues that higher commodity prices also result in yield increases above the trend. This yield increase is due to farmers changing management practices to increase returns. This paper sheds some light on the yield trends that are observed around the world and the possibility to increase yields above trend. This paper uses a global agricultural outlook model and GIS data to quantify the potential increase in global commodity yields.

Note that this paper is an early draft of a book chapter in “Biofuels, Bioenergy, and Food Security: Technology, Institutions, and Policies” (Elsevier).

1 Introduction

Over the last decade, there has been significant discussion about the economic and environmental consequences of corn ethanol production. Numerous studies have analyzed the effects on land-use change (Searchinger et al., 2008; Hertel et al., 2010; Dumortier et al., 2011), commodity prices (Zilberman et al., 2013; Condon et al., 2015), and international trade (Elobeid and Tokgoz, 2008; Keeney and Hertel, 2009). The reason is the rapid increase in ethanol production and consumption prior to 2010 and the leveling off in the last years. According to the U.S. Department of Agriculture (USDA), 32.1% of the total corn supply in the 2016/17 marketing year was used for corn ethanol. This increased use of corn as a feedstock for ethanol has implications on commodity prices and land-use allocation. There has been a one-time significant re-allocation of land in 2007 between corn and soybeans which is explained by expectations associated with the increase in corn prices in that time period. Since higher prices are not only observed by farmers in the U.S. but also globally, concerns about carbon release from land-use change is a significant part of the policy debate surrounding ethanol.

The effects on land-use change are of particular importance because in order to qualify as a renewable fuel, corn ethanol must achieve a reduction in life-cycle greenhouse gas emissions (GHG) by at least 20% compared to gasoline under the Energy Independence and Security Act (EISA) of 2007. Initial life-cycle analysis (LCA) by Searchinger et al. (2008) and Fargione et al. (2008) have shown that corn ethanol could potential increase GHG emissions compared to gasoline if indirect land-use change, i.e., farmers in different parts of the world increase crop acreage because of higher commodity prices, is taken into account. Subsequent research revises those initial estimates downward because market mediating effects and price-induced yield increases can reduce those adverse land-use change effects (Hertel et al., 2010; Dumortier et al., 2011). Wang et al. (2012) calculates the LCA emissions of five ethanol feedstocks, i.e., corn, sugarcane, corn stover, switchgrass, and miscanthus using the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. Their results indicate that the lowest GHG savings (19%-48%) compared to gasoline are achieved with corn ethanol. A report by the USDA finds that emissions from corn ethanol are about 43% lower compared to gasoline based on the recent performance of ethanol plants and the farm sector (USDA, 2017).

Dumortier et al. (2011) show that land-use change emissions are very sensitive to the assumptions with respect to crop yields. Small changes in yields can have large effects in terms of land-use change emissions because of the high carbon content in biomass and soil especially in countries with tropical forests such as Brazil and Indonesia. Price-induced yield increases above the trend yield are possible due to higher commodity prices, i.e., farmers find it profitable to change agricultural practices to increase yields on their cropland beyond what would have happened in the absence of higher prices. The argument of price-induced yield changes is difficult to measure and some research rejects this hypothesis (Roberts and Schlenker, 2009).

Related to the increase in yields is the question concerning the yield on newly converted cropland. The paper by Hertel et al. (2010) is based on the Global Trade Analysis Project (GTAP) and assumed that the yield on newly converted land is two-thirds compared to existing cropland. Taheripour et al. (2012) recently re-assessed this assumption by using a global GIS data set that allows to specify location-specific yields on new cropland. The authors show that new cropland requirements decrease by 25% compared to the original two-third assumption.

Besides the questions whether price-induced yield increase is possible and how much yield is achievable on newly converted cropland, we are interested in how far farmers are currently from the yield frontier. Mueller et al. (2012) report that significant increases (45% to 70%) in production can be achieved for most crops by completely closing the yield gap. Producing on the yield frontier my be difficult to achieve and Foley et al. (2011) find that bringing yields within 95% of their potential yield for 16 crops could increase food production by 58% and bringing them up to 75% would result in an increase in production by 28%.

In this paper, we are interested in the yield growth that could potentially occur if countries move closer to the production frontier due to additional research or changing land management practices. Closing the yield gap for major crops globally would reduce the land requirements in case of a increase in biofuel production and thus, would result in lower life-cycle GHG emissions. In general, LCA calculations are conducted by comparing a baseline to a scenario in which there is a higher consumption/production of ethanol. Closing the yield gap would affect both, the baseline and the scenario even in the absence of price-induced yield increases. The second relevant question is whether that yield increase occurs in regions that are carbon rich. Countries moving closer to their yield frontier in carbon rich areas would be more advantageous in terms of avoided GHG emissions than for countries that are in a region with low soil and carbon biomass.

Many countries with large yield gaps have inadequate technological and economical resources (Grassini et al., 2013). Figures 1 and 2 show the yield gap data for sugarcane and corn, respectively. In addition to taking into account the potential yield gap that exists for major crops, the modeling strategy for yield growth is also important because small changes can result in large differences in terms of area. Using a fixed growth rates of yields assumes that yields are increasing exponentially. Grassini et al. (2013) find that a linear trend (with declining growth rates over time) is more than adequate to describe the future yield for 36 countries and regions for corn, rice, and wheat production. In addition, yield growth will at some point plateau, i.e., level off, due to the physical limitations imposed by soil and climate conditions. Grassini et al. (2013) concludes that "estimates of future crop production and land use must consider both historical yield trends and biophysical yield ceilings to improve forecasting capability." Grassini et al. (2013) are concerned about the possibility of yield plateaus for some major crops and countries such as rice in China or wheat in India and Northwest Europe.

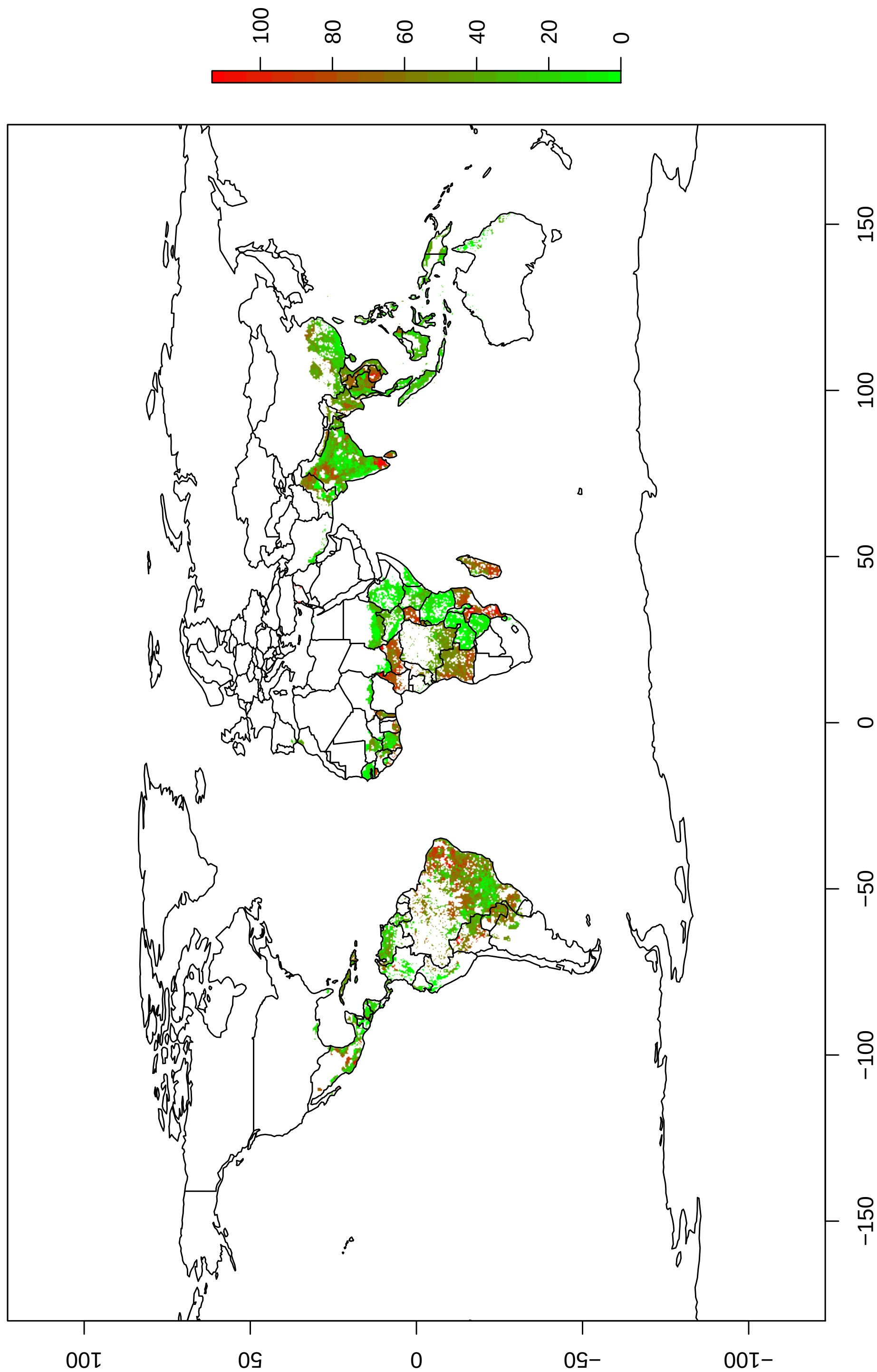

Figure 1: Yield Gap for Sugarcane (Foley et al., 2011)

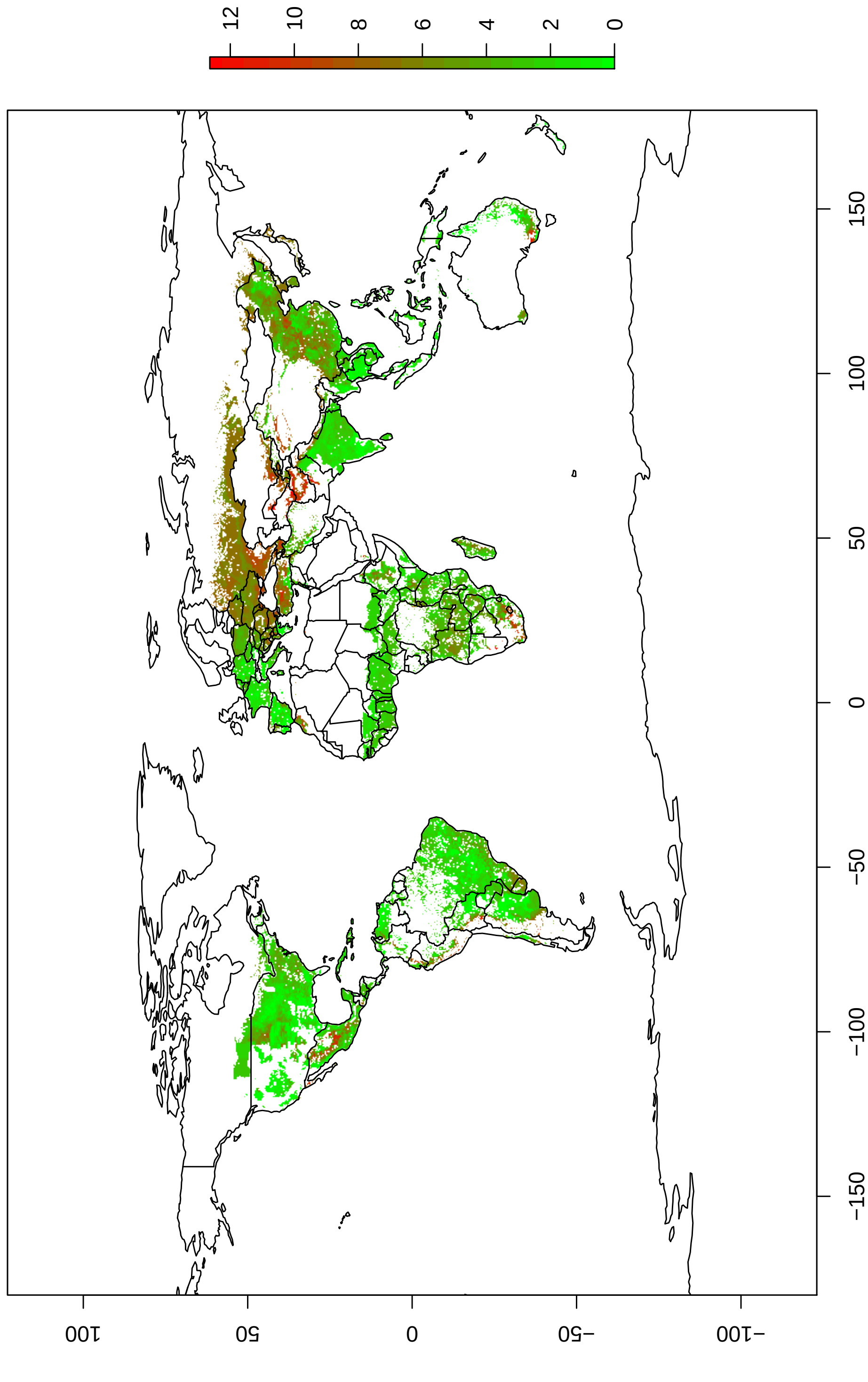

Figure 2: Yield Gap for Corn (Foley et al., 2011)

Based on the fact that yield gaps exist and the importance of crop yields on evaluating the environmental performance of biofuels, this paper addresses three issues. First, we identify the yield gaps for the crops and countries/regions covered in an global agricultural outlook model. The model has been used to assess LCA emissions from corn ethanol and includes price-induced yield increases. In second step, we compare the yield gaps identified to the yield changes calculated by the model. We expect the largest percentage increases to occur in countries that are furtherest away from the yield frontier. And lastly, we compare the yield gaps and the price-induced yield changes to the biomass content that would exist in the natural vegetation. If the yield gap is large in areas with a high biomass content in potential natural vegetation, then a policy focus may be warranted in those areas to reduce GHG emissions from a increase in biofuel production.

2 Modeling Framework and Data

We are combining to groups of data sets. First, we use data from the CARD/FAPRI Model to compare a baseline and a scenario. The baseline assumes status-quo policies and macroeconomic conditions. The scenario assumes that ethanol production in the United States is increasing by 15%. The model includes price-induced yield growth. This data is the combined in a second step with information on yield gaps, land allocation, and carbon storage.

2.1 CARD/FAPRI Model

The CARD/FAPRI Model[1] is a global partial-equilibrium model that forecasts agricultural production over the next 10 to 15 years. It covers 15 major crops and livestock categories for a total of 58 countries and regions. Smaller countries are grouped into regions, e.g., other Asia, to achieve global coverage. The CARD/FAPRI Model was initially designed as a trade model able to predict the effects of policies on international agricultural trade. In recent years, the model has been used to predict land-use change to assess the effects of U.S. biofuel policy. For our analysis, 2021/22 represents the final year of the predictions coinciding with the long-run equilibrium. That is, in 2021/22, all economic actors in the model make zero economic profit. The input to the model are policy parameters and macroeconomic projections such as economic growth and oil prices. The CARD/FAPRI Model then looks based on the input parameters such as yield, demand, and available area for the commodity prices that clear the world market for all commodities.

[1]Center for Agricultural and Rural Development (CARD) and Food and Agricultural Policy Research Institute (FAPRI)

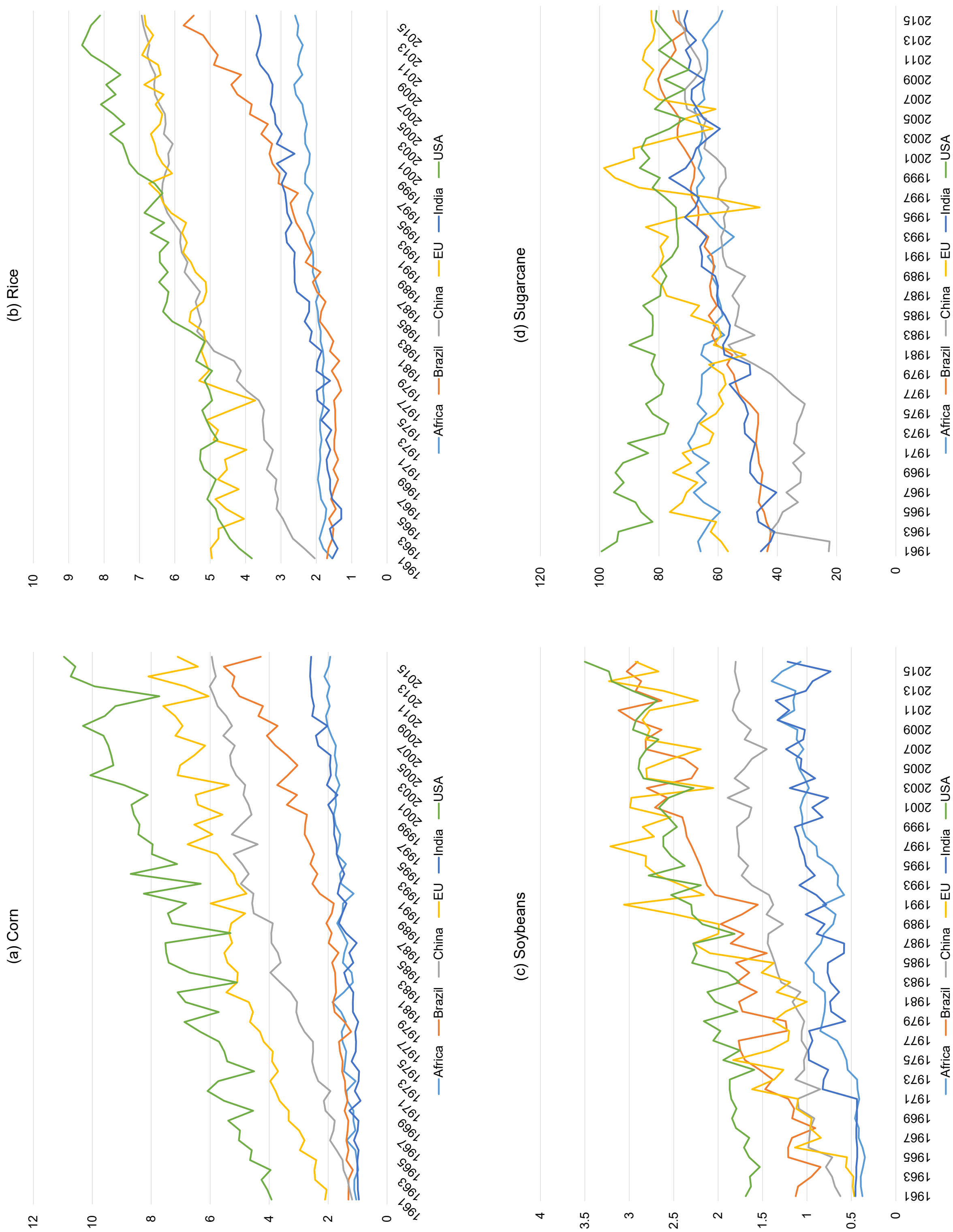

Figure 3: FAO yield data in metric tons per hectare for select commodities.

Note that the model is non-spatial in the sense that only world trade is calculated and not the trade flows between two countries. The output of the model is area, production, and consumption for the covered crop commodities as well as production and consumption for livestock.

Over the last decade, the model underwent significant updates to better incorporate land-use change triggered by biofuel policy. The land-use output of the model was first used Searchinger et al. (2008) to assess GHG emissions from corn ethanol. Subsequently, the CARD/FAPRI Model was extended to include a GHG model (Dumortier et al., 2011, 2012) as well as a subnational Brazil model (Dumortier et al., 2012). The GHG model quantifies the emissions from land-use change as well as from agricultural production (livestock and crop management). The subnational Brazil model was developed to better capture the dynamics of Brazilian agriculture at the regional level because expansion of cropland or pasture into the Amazon biome has important implications for global GHG emissions. The Brazil model also includes the pasture area based on cattle herd as output. A detailed description of the entire CARD/FAPRI Model and its components are available in Dumortier et al. (2011), Dumortier et al. (2012), and Elobeid et al. (2012).

2.2 Spatial Information on Agricultural Production and Carbon Content

To assess our research questions, we complement the aforementioned CARD/FAPRI Model output from a 15% increase in ethanol production by three spatial datasets containing information about the (1) carbon storage in natural vegetation, (2) yield gap by crop and country, and (3) spatial distribution of crops in terms of area. We have standardized all spatial datasets to a resolution of 0.5 degrees for each grid cell.

West et al. (2010) quantify the carbon trade-off between global crop production and natural vegetation. They calculate the ratio of change in carbon stock to crop yield. For example, in the subtropics, the average annual crop yield is 3.3 tons (t) ha^{-1} year^{-1} and the average change in carbon stock from land conversion is 68.3 t C year^{-1}. If compared to the tropics where the average annual crop yield is only 1.7 tons (t) ha^{-1} year^{-1} and but the average change in carbon stock from land conversion is 120.3 t C year^{-1}, allocating cropland in the subtropics is more beneficial in terms of carbon emissions than in the tropics. Part of their assessment is a global map with the potential carbon content in natural vegetation. The authors combine a map of natural vegetation with the Intergovernmental Panel on Climate Change (IPCC) Tier 1 method on carbon content. The resulting map contains the carbon content in potential natural vegetation at the global level. The data set allows us to determine the cost of the yield gap for a particular crop and country with respect to carbon.

The key aspect of our analysis is the gap that exists between the observed yield and the potential yield. According to Foley et al. (2011), yield gaps result in different yields in areas that have the same growing conditions but different agricultural management practices. Foley et al. (2011) present a global data set which calculates the potential yield given current farming practices and technologies and compares those yields with the observed yield.[2] Their analysis is based on work by Licker et al. (2010) who determines the "climatic potential yield" for 18 major crops to the current yields. The analysis by Licker et al. (2010) is based on crops and yields in similar climatic regions. Foley et al. (2011) categorize the factors limiting yields in two categories, i.e., nutrient limited and water limited. Both authors, Licker et al. (2010) and Foley et al. (2011), point out that closing the yield gap using conventional management practices such as irrigation and fertilizer may result in different environmental problems than the carbon release from requiring more land for the same amount of production. Their data set is for the year 2000 and we calculate the yield gap the ratio of current yield to potential yield. This implicitly assumes that the potential yield is increasing over time as well and that the gap remained constant over time.

The final spatial data set contains information about the spatial distribution of crops at the global level Monfreda et al. (2008). The dataset is compiled using national and subnational data sources and remote sensing information of cropland. The data reports the area harvested, yield, and production for the year 2000. The same dataset has also been used by Dumortier et al. (2012) to determine the effects of a potential expansion of global beef production. For our analysis, we assume that the fraction of land allocated to a particular crop in a grid cell is constant (compared to the overall crop production in a country).

3 Results

As aforementioned, the CARD/FAPRI Model was used to generate a baseline until 2021/22 to incorporates status-quo agricultural policies and macroeconomic forecasts. The model was then used to simulate a scenario that results in a 15% increase in ethanol production in the United States. In lifecycle emission analysis, the difference in land-use and GHG emissions between the baseline and the scenario is attributed to the additional production in ethanol.

The 15% increase in ethanol production in the U.S. results in a total expansion of global crop area by 1.2 million hectares representing an increase of 0.25% compared to the baseline. The largest relative increases

[2]The crops covered in the dataset by Foley et al. (2011) are barley, maize, palm oil, rapeseed, rice, rye, sorghum, soybeans, sugar beet, sugarcane, sunflower, and wheat. Their data set does not include oats, cotton, and groundnuts/peanuts which are covered in the CARD/FAPRI Model.

can be observed in Mexico (0.76%), Brazil (0.52%), and the United States (0.44%). The increase in area in all other countries is 0.07%. The largest absolute increase occurs in the U.S. with an additional 399,176 ha followed by Russia (157,921 ha), Mexico (80,436 ha), Brazil (316,026 ha without the subnational model and 41,209 ha with the subnational model), and Indonesia (38,456 ha). All other countries combined increase their crop area by 208,536 ha. In addition, the scenario results in an increase in U.S. prices for barley, corn, wheat, and soybeans by 2.4%. 3.4%, 1.5%, and 5.3%, respectively. Global prices for corn, soybeans, and wheat increase by 3.6%, 1.1%, and 1.3%, respectively. The total increase in ethanol production from the baseline to the scenario is 10.82 billion liters in the United States.

For sugar, i.e., sugar beets and sugar cane, the largest increases are observed in the U.S. (sugar beet and sugar cane), "Other Asia" (sugar beet and sugar cane), and "Other Oceania" (sugar cane only). Brazil as the largest producer of sugar cane increase yields only by 0.1%. In the category of grains, the most pronounced increases in yields occur for corn and soybeans because global prices increase the most for those commodities in the scenario. Note that significant gains are made in "Other Africa" and "India" for both corn and wheat as well as for oilseeds. In some cases, we observe a yield decrease compared to the baseline because we have a decrease in price. For grains, we see a significant increase in the regions "Other Africa" (especially corn and wheat) and "Other Asia" as well as in Russia (barley) and Mexico (corn). For oilseeds, the CARD/FAPRI Model predicts a significant increase in the yield of soybeans in "Other Africa."

The two main aspects of this paper are the existing yield gaps and the carbon content of natural vegetation in countries that exhibit a yield gap. Our results show that corn and soybeans in the U.S. as well as sugar beet in the European Union and soybeans in Brazil are all above 80% of their potential yield. Rice in India occupies the largest area for any crop/country combination and it only achieves 60% of its potential yield. Note that China is close to 80% for rice.

Indirect land-use change is a large component of lifecycle emissions from biofuels (USDA, 2017). Increasing yields in regions that have a high carbon content would reduce the land requirements in case of an increase in crop area due to biofuel policy. This is true even in the absence of price-induced yield improvements. Countries that have a high carbon content, a large yield gap, and are major producers would be of concern in terms of GHG emissions. For barley, Africa, Asia, Russia, and the Ukraine are below 50% of their attainable yield but the carbon content in areas where barley is cultivated is generally small. A similar conclusion can be drawn for sorghum. Mexico, China, and countries in Africa plant large areas of corn in regions with a high biomass carbon content and a large yield gap. Policy interventions or technical assistance in those areas to close the yield gap would be beneficial in reducing GHG emissions from agriculture in general.

4 Conclusion

Over the last decade, there has been a large amount of research regarding the life-cycle emissions of corn ethanol and how those emissions are mitigated by a price-induced increase in yield. The price-induced increase in yield assumes that due to higher commodity prices, farmers are able to change management practices to achieve an above-trend increase in yields. Previous research assumes a constant elasticity of yield with respect to price, i.e., a percentage increase in price results in an increase in yields. Environmental science and agronomy research shows that there is a global variation in terms of countries being close to their yield potential. This yield potential is determined by the land and soil type as well as by the technological possibilities. Not all countries are close to their yield potential – especially low income countries – and there is the potential to increase the yield in those countries given the price-induced yield increase. Other countries such as as the United States, Brazil, and the European Union are already close to their yield potential for certain crops and thus, it may be more difficult for those countries to increase the yield above the trend yield.

Note that the current analysis does not attempt to make the argument that the only possibility to increase yields above the trend is the production of ethanol since it could potential yield to in increase in yields due to prices.

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