Biofuels and the Water-Energy Nexus: Perspectives for the United States

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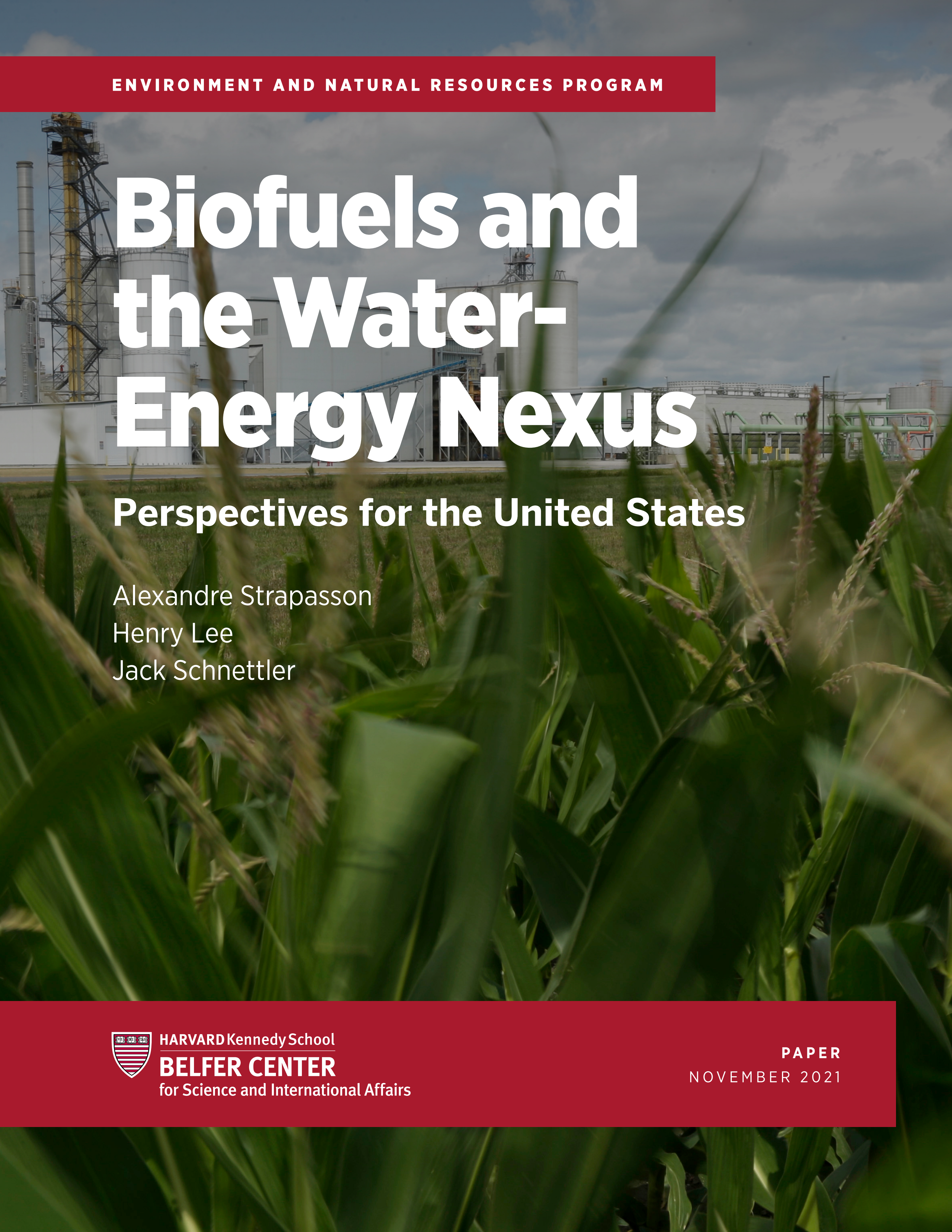

ENVIRONMENT AND NATURAL RESOURCES PROGRAM

Biofuels and the Water-Energy Nexus

Perspectives for the United States

Alexandre Strapasson
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HARVARD Kennedy School
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for Science and International Affairs

PAPER
NOVEMBER 2021

Environment and Natural Resources Program
Belfer Center for Science and International Affairs
Harvard Kennedy School
79 JFK Street
Cambridge, MA 02138

www.belfercenter.org/ENRP

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About the Authors

Alexandre Strapasson is a Belfer Center Fellow in Agriculture and Energy Policy at Harvard Kennedy School. He is also an Honorary Research Fellow at Imperial College London and a Visiting Lecturer at IFP School in France. Prior to these experiences, Alexandre was Director and Head of Department of Bioenergy at the Brazil's Ministry of Agriculture, and a UNDP Consultant in Energy and Climate, participating in the UNFCCC negotiations. He is an Agricultural Engineer, holding a M.S. in Energy from the University of Sao Paulo (USP) and a Ph.D. from Imperial College, with a Postdoc in Sustainability Science from Harvard.

Henry Lee is the Jassim M. Jaidah Family Director of the Environment and Natural Resources Program within the Belfer Center for Science and International Affairs at the Harvard Kennedy School; Faculty Co-Chair of the HKS Arctic Initiative and Decarbonization in China research endeavors; and a Senior Lecturer in Public Policy. He has served on numerous state, federal, and private advisory boards concerning energy and the environment.

Jack Schnettler is a J.D. Candidate at Georgetown University Law Center. Until recently, he was a Belfer Center Research Assistant at Harvard Kennedy School. Jack's experience includes working in the U.S. Senate for Senators Tina Smith and Al Franken as a legislative staffer for energy, environment, and agriculture issues. He also worked as a Fellow for the Office of the Governor of North Carolina, assisting the Governor's energy and environmental advisor with the implementation of the state's executive order on climate change. He holds a B.A. in History and International Relations from Colgate University, and a Master of Public Policy from Harvard.

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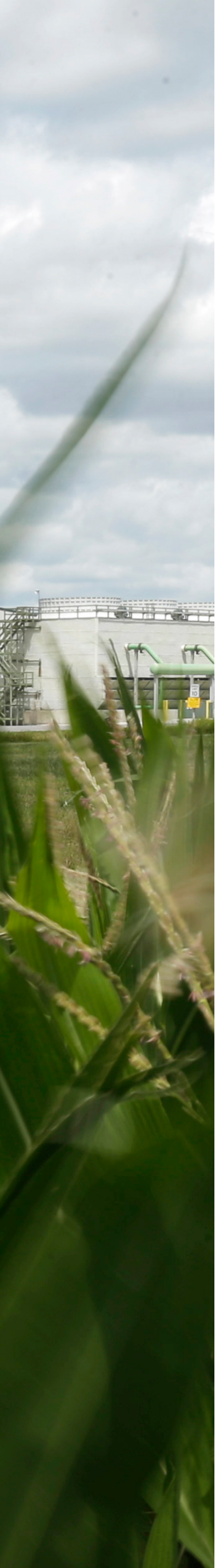

Highlights

- To date, biofuel production in the United States has not been limited by water availability.
- Some simulations show that it is possible to expand corn-based ethanol nationwide over the next ten years without using additional water and land resources. Conventional ethanol production could reach approximately 19 billion gallons in the 2030-31 crop year, representing a 28% increase from current levels, based on yield growth on existing acreage and without changing the annual corn exports and internal stocks.
- Doubling current ethanol production in ten years without an acreage expansion, achieving about 32 billion gallons in 2030-31, would require the reallocation of corn from other uses. Otherwise, an increase in existing corn area might be required, which could exacerbate water scarcity in some areas, if precautionary measures are not addressed.
- Policies and regulations should establish clear incentives to reduce agricultural water withdrawals in water stressed areas in favor of rain-fed crops. To the extent possible, they should also account for changing climatic conditions.
- Future policies should support sustainable water management and develop markets for advanced biofuels, aiming to minimize both irrigation and carbon intensity.

1. **Overview**

Both biofuels and thermoelectricity generation have a significant water footprint associated with their production cycles.[1] As electricity and biofuels gain a larger share of the transportation fuel market, the cumulative impact on water resources must be considered.[2] As shown in Figure 1, agriculture and thermo-electric power represent the largest share of water withdrawal in the United States.[3] As the country strives to transition away from fossil fueled facilities by 2035, agriculture will become the dominant share. In terms of the consumptive water use in the United States, agriculture represents the largest share, accounting for approximately 80% of the total use nationwide according to the U.S. Department of Agriculture (USDA).[4]

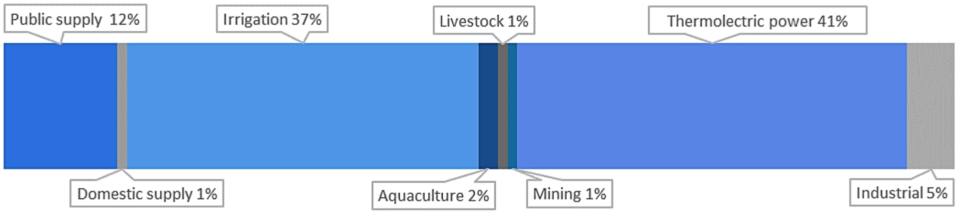

Figure 1. Total water withdrawals in the United States. per category (2015 base year). Note: total water withdrawal = 322,000 million gallons per day. Domestic supply refers to self-supplied water at residences, whereas public supply refers to both public and private water suppliers, aiming at several purposes, including domestic deliveries. Source: prepared by the authors, with data from USGS (2017).[3]

This paper focuses on liquid biofuels, especially corn-based ethanol, and the energy-water nexus. It examines the implications of potential land area expansion for increased biofuel production and on water supply availability. Given the potential expansion of the use of irrigation in crop production for biofuels, the associated water footprint can be challenging in some areas, depending on the assumptions and trends considered in the projections. On average, biofuels are among the most water-intensive energy products. Producing a gallon of conventional gasoline requires 3 to 7 gallons of water, whereas a gallon of corn ethanol requires from 11 gallons up to 160 gallons of water[5] in extreme situations. Thus, these impacts vary according to the production system and region. Biorefineries represent only a small share of this total, consuming approximately three gallons of water per gallon of denatured ethanol produced on average,[5] mainly for washing, cooling, and fermentation processes. The total water footprint is particularly high when full irrigation is used. On the other hand, only about 15% of corn is currently irrigated nationwide,[4] given that most states located in the corn-belt zone have sufficient rainfall to meet production targets without irrigation. Besides, only a fraction of this irrigated land is associated with ethanol production. Most biorefineries are not located in these areas, due to risks of building ethanol plants in fringe areas with water scarcity. Will it be possible to meet any increase in future ethanol demand through higher crop yields[*] on existing land, which in most cases will not require any irrigation or additional water use?

Corn is considered a food-and-fuel crop. This is because ethanol is produced from the starch content[†], which accounts for approximately 72% of the kernel,[7] while the remaining parts (e.g. proteins, digestible fibers, vegetable oil, minerals, and vitamins) are driven to food and feed markets, especially the Distiller's Dried Grains with Solubles (DDGS)[‡] and corn oil, as well as the yeasts used in the fermentation process[§]. While starch is relatively abundant in the global market, DDGS has been often traded at similar prices to corn per ton, but with a higher concentration of protein and other nutrients. Therefore, these nutrients usually come at a "discount" for livestock farmers, without jeopardizing world's food security. Other similar examples of integrated systems can be commonly observed in different biofuel production chains. Rather than food versus fuel, what has been observed in biofuels production worldwide is a food AND fuel case, i.e. a synergy between both.[8, 9, 10] What determines if a plant is a food or a fuel crop usually depends on its post-harvest destination, rather than the crop itself. Ultimately, to avoid major impacts on the

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[*] Crop yield is defined as the production quantity of crop harvested per unit of land area, also known as agricultural productivity. It can be measured in bushels per acre, tons per hectare, among other units. A bushel is a unit of volume, whereas a ton is unit of mass (1 metric ton = 1,000 kg). One U.S. bushel of shelled corn with about 15.5% moisture is equivalent to 56.0 lb (or 25.4 kg). Regarding land area, 1 hectare (or 10,000 m^2) = 2.471 U.S. acres.

[†] Approximately 94% of the ethanol produced in the United States is derived from corn starch, being the remaining share from feedstocks such as sorghum, waste sugars, and cellulosic biomass.[6]

[‡] DDGS are largely used as a protein-rich nutrient source for animal feed, supplying several markets, from livestock production (meat, milk and eggs) to aquaculture and pet food.

[§] Distillers' dried yeasts are a by-product of ethanol production. They have a high protein value and palatability and can be used as supplements in animal feed.

food market, farmers should strive to produce biofuels from efficient and cost-competitive crops, because the larger the biofuel production per unit area, the lower the direct and indirect impacts on land use.[11] In addition, it is worth noting that annual crops are usually cultivated in rotation cycles, i.e. other crops are produced in the same area in the same year. An example is the corn-soy rotation, which is adopted by many farms. Biofuels can also be a co-product of other crops (e.g. biodiesel from soybean)* or derived from grasses (e.g. switchgrass) and plant residues (e.g. corn stover, straws, forest residues) which are sources of lignocellulosic material for second-generation ethanol. Moreover, part of the biomass production (e.g. straw, leaves, bagasse) can be used for power generation. The food versus fuel debate[12] must be understood in this broad context, often requiring the use of Integrated Assessment Models (IAMs) and Life-cycle Assessments (LCA).[13]

As climate change and existing agricultural production strain water resources across the United States, governments and industry need to consider the nexus between biofuel expansion and water sustainability. This is not only a domestic issue, but an international concern,[14] given that there is a water footprint associated with the production cycle of any agriculture and energy product. For example, the United States is a large exporter of several agricultural commodities (e.g. soybean and corn), while also participating in the international ethanol trade (e.g. with imports and exports to and from Brazil, among other nations); therefore, the United States has also been exporting and importing water worldwide, either directly via water content products or indirectly via the water footprint associated with their respective production cycles.

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* Soybean-based biodiesel is produced from the transesterification of its vegetable oil, which is one of the co-products of a broad soybean market. The oil content in the soy grain represents approximately 20% of its total mass, the other part is the soy meal, which is a protein-rich nutrient widely used as a source of animal feed, representing the main product of the soybean market worldwide.

This paper provides an overview on the main impacts of biofuels production on water resources within the United States, with an emphasis on the corn-based ethanol market and the agricultural stage. The following issues are examined:

- the relationship between biofuel production and water availability;
- trends and policy options for future biofuel production and the tradeoffs for water scarcity;
- technological changes in transportation fleet, with consequential effects on biofuels demand and water resources;
- considerations for policy makers who seek to reduce the future impact of biofuels on water sustainability.

2. Biofuels and Water Availability

2.1. Biofuel Production in the United States

Biofuel production in the United States has increased substantially since the passage of the 2007 Energy Independence and Security Act (EISA)[*]. This law required the U.S. Environmental Protection Agency (EPA) to revise the existing Renewable Fuel Standard (RFS) program to increase the volume of renewable fuel to be "blended into transportation fuel from 9 billion gallons per year in 2008 to 36 billion gallons per year by 2022". Of the 36 billion gallons in 2022, 21 billion gallons are required to be advanced biofuels which emit at least 50% less greenhouse gases (GHGs) than gasoline or diesel and are produced from biomass other than corn kernels. Corn ethanol would represent 15 billion gallons per year in 2015[†]. The goals of the EISA were to improve energy security by incentivizing domestic energy production, to promote second generation transportation fuels with lower GHG footprints, and to support rural agricultural economies. The revised statutory provisions require increased volumes of cellulosic biofuel, biomass-based diesel, advanced biofuel, and total renewable fuel in transportation fuel. EPA requires annual quotas of biofuels, unless it establishes lower volume requirements using specified waiver authorities.[16] Ethanol has been largely used in the United States as a gasoline oxygenate in blending ratios up to 10% (i.e. less than or equal to E10), avoiding the use of MTBE[‡], which can be very detrimental to water bodies and human health. More recently, the EPA authorized the year-round use of blends with 15% ethanol (E15).[18] Some states have fuel blends at E15, E20, and E30. Ethanol is also available in higher

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[*] The two main driving forces around the passage of this Act were to increase national energy security, by reducing international fossil fuel dependency, particularly on Mideast oil, and to support the agricultural sector, especially corn growers. Energy security was, for example, the main message of President George W. Bush's speech in the Washington International Renewable Energy Conference (WIREC) in 2008. The Act was initially conceived as an environmental bill, but part of the environmental community was still reluctant to fully support it. Over the years, it became a major environmental policy to reduce greenhouse gas emissions.

[†] This is just a reference amount required by the RFS. Currently, grain-based ethanol industry can produce about 17.5 billion gallons of ethanol per year at full production.[15]

[‡] Prior to ethanol, MTBE (methyl tertiary-butyl ether) was used as a fuel additive. It has a high water solubility and persistence in the environment. It is highly contaminant when released into aquifers and has potential carcinogenic effects[17] on humans as well.

blending ratios in some gas stations nationwide, e.g. E85, which is used by flexible-fuel vehicles (FFVs).

Since passage of the EISA, biofuel production has more than doubled. From 2007 to 2019, ethanol production, largely based on corn feedstock, grew from 6.8 billion gallons to 15.8 billion gallons.[19] Biodiesel production, based on soy feedstock, grew from 490 million gallons to 1.7 billion gallons.[20] Market constraints have started to slow biofuel expansion, especially due to reduced prices of ethanol and DDGS, as well as policy setbacks regarding the implementation of the RFS.[21] In 2019, production levels of corn-based ethanol dropped by 300 million gallons compared to 2018,[6] and biodiesel was reduced by 133 million gallons in the same period.[20] Despite the goal of the 2007 EISA to increase production of next generation biofuels, production of advanced biofuels has never come close to reaching the statutory targets, due to a variety of technical and cost challenges, primarily the high capital costs of new production facilities.[22, 23] Due to these problems, the EPA has consistently been forced to grant waivers from the statutory targets. The U.S. biofuel sector, therefore, remains dependent on traditional corn ethanol and soy-based biodiesel, and it is these traditional fuels that drive the industry's aggregate water impact.

At the same time, the GHG footprint for ethanol production gradually reduced in the past decades, whereas ethanol production efficiency has also increased in the same period. Some preliminary estimates in the 2000s suggested high carbon footprints, but several modeling uncertainties have recently been clarified. In 2016, EPA made new emissions factors available.[24] In 2021, an comprehensive study[25] assessed several papers using life-cycle assessment approaches and obtained an average footprint of 51.4 $gCO_2e.MJ^{-1}$ (varying from 37.6 to 65.1 $gCO_2e.MJ^{-1}$), which represents on average a 46% reduction compared to neat gasoline (about 96 $gCO_2e.MJ^{-1}$). Based on this footprint variation, the GHG reduction could range from 32% to 61%. The average footprint may reduce even further in the coming decades, for example, by using biomass (e.g. wood chips and pellets, agricultural residues) rather than natural gas as an energy input in the biorefinery processes. The main component of the GHG footprint is the ethanol production, accounting for 58% of the total emissions, followed by net farming emissions (including co-products credits) with 26%, land use change with about 7%, and other sources.[25] In general, the higher the overall efficiency in terms of energy use and carbon emissions, the lower the water impact per volume of ethanol produced.

2.2. **Potential Impacts on Water Resources**

It is not the cropland size or growing corn *per se* that affects water consumption, but where it is grown. For example, some regions have considerable water resources; hence, the moderate use for biofuels production is unlikely to jeopardize water supplies. In water stressed areas, however, a measurable expansion of corn ethanol could potentially aggravate water availability.[26] Therefore, the use of water either for irrigation or industrial process does not necessarily represent a major environmental impact. These impacts depend on a case-by-case assessment. Moreover, the use of water for corn may vary regardless of changes in ethanol production, as discussed later in this paper.

The impacts on water quantity of biofuel production vary significantly by the type of feedstock and regional rainfall (green water) and irrigation requirements (blue water)[*]. A county level assessment[27] of ethanol from corn grain, stover, and wheat straw showed wide variances in blue water consumption with a national average of 31, 132, and 139 liters of water per liter of biofuel[†], with a standard deviation of 133, 323, and 297 liters of water to liter of biofuel, respectively. The variances reflect the fact that feedstocks grown in areas with rain-fed agriculture demand far less blue water than feedstocks grown in areas where irrigation is widespread. This range in water consumption intensity makes biofuels' water impact significantly different across the 29 corn and soy producing states.[28] A comparative study[29] on water footprint for biofuels found that the water requirements for corn ethanol could equal 50 gallons of water per mile driven[‡], if the feedstock were grown on irrigated land in Nebraska, and

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[*] "Blue water" volume represents the amount of ground or surface water used for irrigation, whereas "green water" refers to rainfall that is taken up and used by the plant.

[†] Water used for growing corn is the same whether using the grain and/or the stover for producing ethanol, given that they are parts of a same plant. However, the proportion of water use per amount of ethanol produced according to these different parts are different. This is because, on average, the amount of ethanol obtained from a ton of grain is higher than from a ton of stover.

[‡] For this simulation, it was assumed by the referenced study[29] that a car can run approximately 16 miles per gallon of ethanol and that the ethanol was produced using irrigated corn. It was also assumed that producing irrigated corn in Nebraska requires about 800 gallons of water per gallon of ethanol obtained.

that this number could decrease by more than half (to 23 gallons of water per mile) for corn grown in Iowa. This study concluded that to minimize water demands associated with higher corn ethanol production, any expanded corn production should be concentrated in areas requiring none or little irrigation.

The need for irrigation depends on local characteristics, such as rainfall patterns, soil water retention capacity, air temperature, wind speed, humidity, solar radiation, crop variety, soil cover (e.g. straws, if any), and management practices. These characteristics are affected by different evapotranspiration rates*. Thus, while some states do not require irrigation, others do need it to remain competitive, since irrigation can substantially increase crop yields. In Nebraska, for example, there are approximately eight million acres of row crops using irrigation (out of 16 million acres in total), around 70% with center pivot sprinkler systems and 30% with furrow irrigation. Irrigated corn alone accounts for 5.6 million acres, i.e., about 70% of the total irrigated area in Nebraska.[30]

The amount of water required by a crop varies according to the plant's phenological stage. In the case of corn, the main stages can be visually identified through the number of days required for emergence (VE), 4 leaf (V4), 8 leaf (V8), 12 leaf (V12), early tassel (R1), silking (R2), blister kernel (R3), beginning dent (R4.7), full dent (R5.5), and maturity (R6)†. Figure 2 illustrates the approximate daily water quantity‡ (bell curve trendline) required in each stage of corn production, as well as the cumulative water use (S curve trendline)§. In most corn production sites nationwide this quantity can be fully obtained from rainfall alone. Therefore, irrigation is only required to supplement water amounts in soil when precipitation is not sufficient to maintain the desirable soil moisture according to each plant's phenological stage. This is particularly critical during dry spells, which partially explain why irrigation is more common in regions such

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[*] Evapotranspiration (ET) is comprised of plant transpiration and soil water evaporation combined from a certain land area.

[†] The number of days that the plant takes in each growing stage depends on the lifecycle of the specific crop variety, e.g. very-short, short, medium, and long-term crops, among other variables, such as the photoperiod.

[‡] The volume of water in 1 inch (2.54 cm) depth per unit of area is equal to 0.62 gal/ft^2 (or 25.4 L/m^2), which is equivalent to 3630 ft^3/ac (or 254 m^3/ha). Conversion factor: 1 US gallon = 3.785 liters.

[§] The water use rate curve is the derivative of the cumulative use curve per unit time.

as Pacific, Mountain, West South Central and West North Central than in East South Central, East North Central, South Atlantic, and New England.[31] Therefore, while some farmers use irrigation either only in critical periods of water deficit or throughout the crop season, the majority do not use any type of irrigation at all.

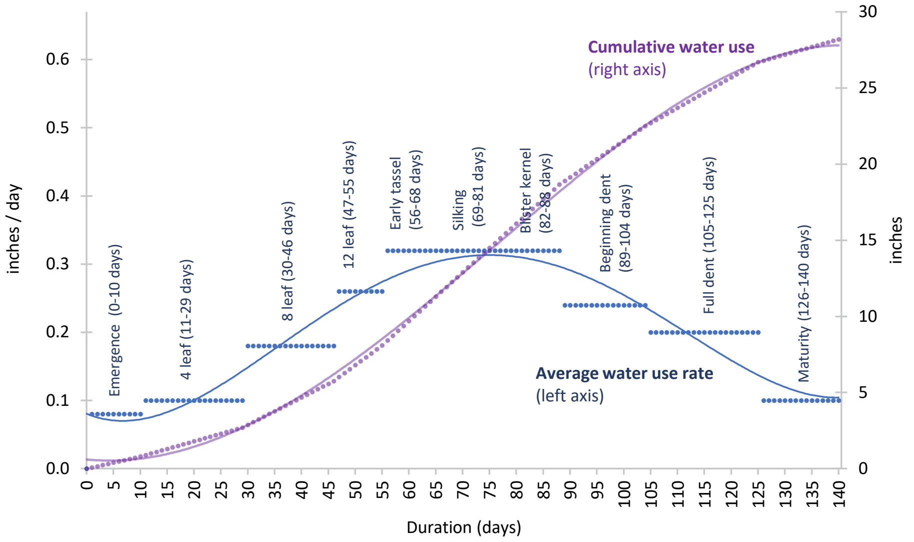

Figure 2. Daily and cumulative water required for corn production by growth stage for a long-term hybrid crop variety in South Central Nebraska. Source: prepared by the authors, based on data from the Clay Center.[30]

Plants can effectively express their yield potential when the required amount of water is available to them (among other inputs, such as nutrients and solar radiation), according to each phenological stage, and edaphoclimatic (soil and climate) condition. All growing stages are vulnerable to water stress, but during tasseling and silking each day of water stress can reduce the final crop yield more severely, especially when combined with windy and hot days with low relative humidity, which leads to higher evapotranspiration rates.[32] Therefore, a greater variability in weather associated with rising global temperatures can have direct impacts on crop yields. Areas with sandy soils with low amounts of organic matter, for instance, are even more sensitive, because of their reduced water holding capacity. In fact, not only a lack of sufficient water supply can affect crop yields, but also a surplus. An excess of water can, for example, damage the root system and increase the leaching of soil nutrients, especially nitrogen. Persistent and heavy rainfall can cause flooding and soil saturation, as sometimes observed in corn fields in North Carolina during the planting season[33]. Moreover, very heavy rainfall can cause soil compaction, particularly when the soil is mostly exposed, as well as physical damage to the crops.

Second generation feedstocks such as cellulosic biomass from annual or perennial crops, e.g. switchgrass and short rotation coppice, usually require less irrigation and offer a less water intensive option for biofuel production.[34] However, as already noted, the potential for these alternative biofuels has not been fully realized. Technical challenges and high capital costs have constrained the development of these products and annual production is limited.[23] Besides, some alternative crops involve tradeoffs in their water footprint. Miscanthus has been found to be more productive in generating biomass than switchgrass, but its higher water demand might be challenging to be produced in water stressed areas.[35] While cellulosic feedstocks have reduced blue water needs (i.e. the need for supplementary water via irrigation, compared to conventional biofuel crops) and can reduce nitrate run-off, some cellulosic feedstocks consume more water during the growing process through evapotranspiration and can reduce sub-surface water flows and streamflow in nearby surface waters.[36] During low flow periods or drought, these reductions can have negative impacts on aquatic and riparian ecosystems. Thus, cellulosic feedstocks, even if they did become more economically competitive, may involve tradeoffs in water impacts in some regions.[37]

The processing water requirements for a typical corn ethanol refinery are about 2-10 liters of water (*Lw*) per liter of ethanol (*Le*)[29], which in some situations can be relatively small compared to irrigation requirements. However, water used in biofuel production is often withdrawn from point sources and can have localized impacts on water quantity, especially in communities reliant on groundwater aquifers for local water supplies. However, biofuel producers have made significant progress in reducing water use in the processing stage.[*]

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[*] A recent study by ANL study[38] showed that the water use efficiency for biofuel production has substantially increased. This includes water recycling in several production stages within the biorefinery. Successful examples are also observed in other biofuel producing nations,[39, 40] including integrated systems with algae-based biofuel.[41] Moreover, the water use can vary according to the technology type. About 91% of all corn ethanol facilities use dry milling processes, whereas only 9% use wet milling[6]. The main difference between these two technologies is the way that the grain is initially treated, before being directed to the subsequent industrial processes. This can impact the final yield of the several co-products obtained from corn. Wet milling is more capital intensive, but it is more efficient to extract the different components of corn kernel.

In addition to the potential effects of corn ethanol production on the availability of water quantity, impacts on water quality may also occur, if sustainable management practices are not addressed. Some examples are the sedimentation of surface waters from soil depletion and erosion, and the eutrophication of water bodies from fertilizer and nutrient runoff. However, it was not the focus of this paper to assess the impacts of biofuels on water pollution, which have already been addressed by several studies,[42, 43, 44, 45, 46] including both the agricultural and industrial stages, and potential effects on the availability of freshwater for other purposes.

2.3. **Feedstock Crop Expansion and Land Use Change**

To demonstrate a causal connection between biofuel expansion and water scarcity, it is important to consider the question between the associated acreages of crops driven to energy production (as their main destination) and crops driven to ordinary markets (e.g. food and feed). Corn or soybean farmers, for example, simply grow crops based on profit margins, regardless of their final destination in the industrial markets. Crops are not specifically grown "for food", "for feed", or "for biofuels". In fact, most corn and soybean production are used for feed. Therefore, these crops are not specialty crops aimed primarily at food, such as tomato, onions, or sweet corn. In the case of corn-based ethanol and its associated land use, the production can be expanded by 1) increasing crop yields, 2) redirecting corn currently allocated to other purposes, including exports, and/or 3) expanding total acreage, in equivalent area to rebalance the corn market. The second and third alternatives may (or may not) have significant direct and indirect Land Use Change (dLUC[*] and iLUC[†]) impacts either within the United States or abroad, with different effects on water use.

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[*] A dLUC "occurs when crops for biofuel production are planted on land that has not previously been used for that purpose; for example, the conversion of forest into an energy crop plantation for biofuel production. The effects of dLUC can be directly observed and measured as the effects are localised to a specific plantation" (p. 84)[11, 47]

[†] An iLUC "occurs when, as a result of the switching of agricultural land to biofuel crops, a compensating land use change occurs elsewhere to maintain the previous level of agricultural production. These effects are typically the unintended consequence of land use decisions elsewhere and, given that the effects are not limited by geographical boundaries (e.g., the complex dynamics of food commodities worldwide), often are not directly observable or measurable" (p. 84)[11, 47]

Land use dynamics associated with biofuels is a multifaceted issue, subject to several uncertainties, including economic, social, and ecological effects. This section focuses on its relationships with potential water impacts, as a brief context to the subsequent discussions on biofuel expansion scenarios. It was not the objective here to provide a detailed assessment on land use change and its effects on energy balance and carbon dynamics, which have been addressed by several studies.[8, 10, 11, 48, 49, 50, 51] Improvements in existing LUC models over the past decades have contributed to better understand the potential risks and benefits associated with biofuels and land use change, as opposed to early research that often overstated the magnitude of these impacts.[52] Land cover data, for example, are normally obtained from remote sensing, which may not clearly differentiate some land use patterns, including difficulties in assessing land uses which simultaneously occur on similar land areas (e.g. crop-livestock integration, co-cropping, agroforestry systems).[53] Apart from the uncertainties involved in this debate, corn has been mostly produced in the traditional corn-belt zones with suitable hydrological conditions so far.

Furthermore, since the green revolution[*], corn yields have grown linearly on average in the United States.[55, 56] Hence, a larger food and biofuel demand does not necessarily require a larger area to meet such demand. This conclusion depends on the magnitude of crop yield growth potentials and the possibility of producing more crops per year on same land area, a.k.a. multiple cropping[†]. The technical capacity for multiple cropping has been reached in several regions, but there are still areas available for expansion not only within the United States.[57] but also in several other nations (mainly in tropical zones).[58] A double cropping of corn, for example, can nearly double the amount of ethanol produced per area unit in a given year, although this potential is subject to climactic constraints in higher latitudes. In the future, if crop yield growths are not sufficient to meet biofuel production targets, then the impact of biofuels on water supplies may be affected by the amount of additional land that will be

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[*] The “green revolution” occurred with the growing use of agricultural technologies in the 1950s and 1960s, such as hybridized seeds, the use of chemical fertilizers, pesticides, and mechanization, resulting in larger crop yields. The green revolution was led by the American Agronomist Normand Borlaug based on experiments in Mexico and spread worldwide in subsequent years.[54]

[†] The production of multiple crops a year in a same land surface represents how intensively a certain area has been used, for example, from no cropping to single cropping, double cropping and triple cropping. This intensity can be measured through the so-called Multiple Cropping Index (MCI), which may vary according to temperature and rainfall constraints, as well as the agricultural development of the assessed region.

brought into cultivation, as well as the potential requirement for additional irrigation, particularly if crops expand into areas that are normally subject to droughts. On the other hand, biofuel production has not been constrained by water availability to date.

A study[59] carried out using official historical data estimated that crop yield gains alone would not be sufficient to avoid a net gross expansion of land use to meet the demand of biofuel production; however, while also considering the additional amount of DDGS available for the livestock market, this expansion was avoided. The DDGS is a key issue, which is often neglected in the biofuels debate, including in water use assessments. The interplay between land and the energy-water nexus must also look at the biofuel co-products and other consequential benefits, such as economic development and job creation, through a systems perspective. Ethanol production has supported the livestock sector with additional amount of DDGS obtained from the biorefineries, while also helping farmers to sustain corn prices at a competitive level to maintain their activities, stimulating the agricultural sector in the United States and abroad.[*] In addition, biorefineries can promote rural development and induce more job creation than gasoline production.[†] There are currently 198 fuel ethanol plants nationwide,[15] while an average plant involves about US$ 200 million of direct investments. Thus, ethanol production has contributed not only to decarbonize the transportation sector and reduce fossil fuel dependance, but also to revitalize rural America. On the other hand, it is equally important to have precautionary measures to avoid unintended effects on land use.

The U.S. Congress originally designed the EISA to prevent crop expansion into previously untilled land, while also stimulating the expansion of advanced biofuels. If previously uncropped land is cleared for the purpose of growing row crops, the carbon reduction benefits of biofuels is largely diminished, because the land conversion releases carbon stocks

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[*] Corn is one of the largest agricultural commodities globally. It has been traded in several stock markets, mostly in U.S. dollars. Considering that the United States is the top corn producer, followed by China, Brazil, Argentina, Ukraine and India, changes in corn exports and use in the United States can influence international corn prices.

[†] According to the Renewable Fuels Association (RFA),[60] ethanol and its co-products represented a US$ 23 billion market in 2020, involving about 62,180 direct jobs and 242,600 indirect and induced jobs, while also contributing with US$ 34.7 billion to the U.S. GDP and US$ 18.6 billion in household income.

from previously untilled soil.[61, 62] This type of land use change would require several years of cumulative net GHG reduction obtained from gasoline substitution to offset the carbon released from the original land cover, including carbon released from both the soil and above ground vegetation.[11] In order to prevent this unintended consequence, the EISA specifically required that all lands eligible for feedstock production must have been "cleared or cultivated" prior to 2007.[63]

Initial proposals to enforce this requirement envisioned that biofuel refineries would track the source of feedstock sent to their facilities. However, in 2010, the EPA adopted a domestic "aggregate compliance" approach, which determined that as long as the total number of agricultural acres in the United States did not increase, the requirement of the statute would be met.[64] The EPA established a baseline number of acres of U.S. agricultural land in 2007 (the year the EISA was enacted) and determined that as long as this number was not exceeded, it was unlikely that new land would be devoted to crop production. The baseline number was set at 402 million acres. This approach relieved biofuel producers of any tracking or record keeping requirements. The EPA subsequently found that total agricultural land had decreased to 392 million acres in 2011 and 384 million acres in 2012. The Agency also concluded that, the aggregate compliance measure having been satisfied, it was unlikely the biofuel mandate would cause additional land conversion or related environmental concerns.

However, some independent studies[65, 66] disagreed, indicating that while total agricultural acres were reduced in some categories, corn and soy acres (for all purposes, i.e. not necessarily associated with biofuels) were expanding and often into previously untilled or water sensitive lands. In its 2018 Triennial Report on Biofuels and the Environment, the EPA reviewed the increasing evidence of feedstock crop expansion and concluded that "synthesizing all these major national efforts, there is a consistent signal emerging that demonstrates an increase in actively managed cropland by roughly 4 to 7.8 million acres" (p. 37)[43] from about 2007 to 2012, apart from the decrease in total agricultural land. Part of this increase in corn and soy production, more specifically, may have been the result of farmers removing land used for different agricultural purposes (e.g. grasslands) and putting it into a corn/soy rotation, so the total agricultural acreage may not have changed, but there was still an effective expansion of cropped acres*. The EPA found that the increase in corn and soy production is coming "mostly from lands that were formerly in grassland for 20 or more years and are now being used for corn, soy, and wheat. These trends are likely occurring throughout the country but especially in the Northern Plains, the western margin of the corn belt, and with infilling of the central corn belt" (p. 38).[43] The USDOE[45] also found that corn acreage expansion partially occurred by shifting areas used for hay production and livestock grazing, among other land uses.

While an increase of four to almost eight million cropped acres is small compared to the nearly 400 million total agricultural acres in the United States, Lark et. al.[65] found that 50% of this expansion has occurred on marginal lands and an additional 15% on lands deemed unsuitable for agriculture. By marginal lands,[67] the authors meant lands having significant limitations to cultivation uses as defined by the USDA's Natural Resource Conservation Service (NRCS).[68] In addition, another study[66] found that nearly 4.2 million acres of arable non-cropland were converted to crops within 100 miles of biorefinery locations, including 3.6 million acres of converted grassland. This expansion was coincident with a higher expansion of biofuel production, but several other variables must also be considered, such as broader changes in the international corn and soy markets. Some studies[69, 70] pointed out the high uncertainties associated with land use change assessments, showing that the uncertainty in estimates can be greater than the point estimates of land use dynamics. Therefore, policy makers must be aware of these issues and that changes in the techniques and caveats used to perform these assessments can provide very different results.

Currently, corn ethanol production is facing new challenges, particularly the growing electrification of passenger vehicles and, hence, future projections on land use may not necessarily represent past trends. In contrast, ethanol demand in several other nations in Asia (especially

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[*] These studies[43, 65] reflect mainly short term, point comparisons, and longer term trends and inter-annual variability are equally important.

India[71, 72]), Africa, and Latin America may keep increasing[*], with potential imports from large producing countries, chiefly the United States and Brazil, to complement their local productions when necessary, depending on price and profit margins. As a climate change mitigation fuel, ethanol (and other biofuel types) could play a major role in several nations to help them achieve their carbon reduction targets under the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC), as long as it is sustainably produced.[73]

Corn yield rates increased in recent decades and these rates tend to be sufficient to meet the future demand for both biomass and food. However, for scenarios of high ethanol demand, this may not be the case[74]. If ethanol demand increases, farmers will initially meet this demand by either diverting part of its total internal production currently aimed at other purposes (food and feed market) or by gradually reducing corn exports. In practice, farmers will simply respond to better prices, regardless of the final destination of their feedstocks.

The U.S. Department of Energy's Billion Ton Report,[75] which analyzed the potential to produce a billion ton of biomass per year necessary to achieve a goal of replacing 30% of the nation's 2005 petroleum consumption with biofuels, concluded that a combination of expanded traditional feedstocks and next generation feedstocks (i.e. other lignocellulosic biomass) will be necessary. A study[76] carried out by researchers from the Argonne National Laboratory similarly assumes expanded acres of both corn and soy, and new acres of cellulosic feedstocks, such as switchgrass and miscanthus. The impact on water scarcity will vary depending on the location of these expansions. Therefore, the additional water demand may not be from corn crops, but from other crops, such as cellulosic feedstocks, as they become more competitive.

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[*] The electrification of light-duty vehicles in most developing countries may take much longer than in developed nations like the United States, for several reasons, such as high costs for infrastructure development, lack of sufficient electricity supply and grid integration, longer vehicle lifetime, and different scrappage rates.

2.4. **Climate Change Impacts on Water Availability**

In the previous sections, we assessed historical data and trends at national level since the beginning of the biofuel expansion in the 2000s, showing that water is not likely to be a major constraint on biofuel production in a foreseeable future, unless demand for ethanol increases dramatically, forcing production onto marginal lands. However, this finding assumes that climate does not substantively shift[*], which may not be the case.

Recent research has demonstrated that climate change and population growth are likely to present serious challenges to water availability in some regions of the United States, including the central and southern Great Plains, the Southwest, California, and some areas in the South and the Midwest. An assessment by the U.S. Forest Service,[77] conducted as part of the Resources Planning Act (RPA), compared future water supply versus estimated water demand in different water-dependent sectors, particularly industry and agriculture, in 204 watersheds. While climate change is likely to bring increasing precipitation in some regions of the contiguous 48 states, other areas are expected to receive less rainfall. In some areas, increasing temperatures will lower streamflow due to evaporation, counterbalancing the positive effect of increasing precipitation. Further, climate change is expected to increase hydrologic extremes leading to more intense and prolonged droughts in some areas.[77] Water conservation efforts have led to decreases in per-capita use rates, these efforts are likely to continue and become more technically sophisticated. However, by themselves, they will be insufficient to avoid impending water shortages in some regions due to the combined effects of climate change and population growth. The same study[77] found that, by 2074, nearly half of 204 U.S. watersheds will face potential water shortages, impacting agricultural production. Irrigated agriculture accounts for around 75% of the annual consumption of water from many of these basins. Similarly, Brown et al.[78] suggest that water withdrawals in the United States may significantly change by 2060, based on assumptions related to population growth, temperature increases, and increases in evapotranspiration rates.[79]

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[*] Climate change is here understood as the result of human-driven GHG emissions as opposed to natural climate variability, which can also influence water stress. An example of natural variability is the La Niña phenomenon, which can exacerbate droughts in the U.S. Southwest. Both effects, the natural and anthropogenic-induced climate variability, are intrinsically interconnected in the global atmospheric system.

The EPA[80] notes that a higher CO_2 concentration in the atmosphere may have a positive effect on crop yields, given that it may increase average photosynthetic efficiency of plants. However, the agency also notes that several other impacts may counteract this potential benefit, such as a higher incidence of extreme temperatures, precipitations, and droughts, as well as the occurrence of pests and weeds. As already shown in Figure 2, it is not only a lack of sufficient water quantity that can damage crop productivity, but also an excess of precipitation. According to the U.S. Global Change Research Program,[79] dry spells are expected to increase in length in several states. Higher temperatures increase the atmospheric capacity to retain water, which can also lead to more rain in some regions. Another study[81] projects that, specifically for the U.S. Great Plains, temperature increases would be beneficial for corn yields, although detrimental for soybean and sorghum yields, whereas the precipitation trends would be beneficial to all three crops. The same study also recommends the use of additional irrigation as an adaptation strategy for mitigating climate change impacts. Other studies[82, 83] suggest significant future water stress. Given the many uncertainties involved in all these forecasts, water risk management will become more important for farmers.

2.5. **Impact of Future Biofuel Production on Water Stress**

Currently, there is overlap in U.S. agriculture between corn and soy production* and some areas of water stress, particularly in Nebraska, Kansas, Western Oklahoma, Northern Texas, and the Lower Mississippi River Basin. This phenomenon can be observed by comparing current corn and soybean production sites [84] (Figure 3) with water availability assessments made by Argonne National Laboratory (ANL)[85] using their Water Analysis Tool for Energy Resources model (WATER 4.0)[86] together with changes in soil moisture shown by Dorigo et al.[87] Corn has been produced in about 32 states, while a water deficit (water stress index > 0.12) has been identified in 20 states,[85] i.e. in 62.5% of the corn producing states in total. However, such water stress is not necessarily influenced by the corn production and is not homogenously distributed within each state. All U.S. States have some level of irrigation used for crops in general;[31] however, as fore-mentioned, most corn is currently grown without irrigation (about 85%)† and only 35% of the total corn production is used for ethanol.[88] Besides, potential increases in ethanol production

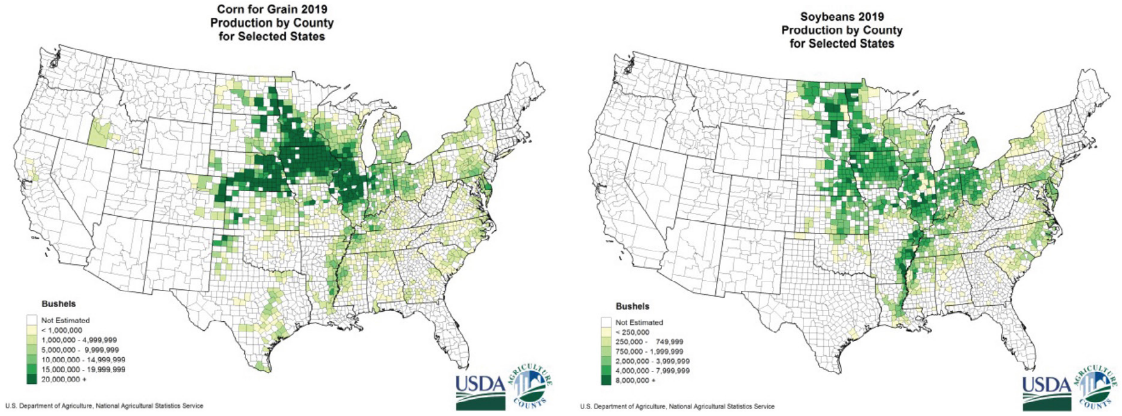

Figure 3. Corn (left map) and soybean (right map) production by county in the United States. Source: USDA (2020).[84]

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* Crop and soy have a valuable synergy as rotational crops, given that corn is a *Gramineae*, whereas soy is a *Leguminosae*, among other interesting aspects for integration, including the possibility of using no-tillage system, and similar logistics as global commodities. Another advantage is that leguminous plants can fix nitrogen in soils due to a symbiosis in their root system with *Rhizobium* bacteria.

† Maps with disaggregated data at county level on the water footprint for corn production are available in Wu (2019).[86] Additional mapping representations on water stress are also available in Georgakakos et al. (2014).[79]

may be based on crop yield gains, rather than land use changes. For scenarios of high ethanol demand, in which crop yield gains alone may not be sufficient to meet the market, the primary question for government officials is whether future expansion of biofuel production will increase the areas of water stress and create conflicts with competing water users.

The existing fuel ethanol plants are located not only in the corn belt zone, but also in several other states, as shown in Figure 4 and Table 1, given that corn grains can be easily stored and transported. In total, there are 24 states with ethanol plants. Thus, the impacts on water use from biorefineries may not follow the same spatial distribution as corn production sites, although most biorefineries are located in the corn belt. In contrast, as previously mentioned, biorefineries represent just a small fraction of total water consumption.

Table 1. Existing fuel ethanol plants by state in 2021. Source: prepared by the authors, based on data obtained from USEIA online figure[15], as of Jan 1, 2021.

State	No. of ethanol plants	Annual capacity (Mgal.y^{-1})
Arizona	1	55
California	5	228
Colorado	3	140
Connecticut	1	33
Idaho	1	60
Illinois	12	1,740
Indiana	14	1,293
Iowa	42	4,667
Kansas	13	603
Kentucky	2	53
Michigan	5	389
Minnesota	19	1,405
Missouri	6	315
Nebraska	25	2,288
New York	2	162
North Carolina	1	51
North Dakota	5	527
Ohio	7	743
Oregon	1	40
Pennsylvania	1	128
South Dakota	16	1,425
Tennessee	3	236
Texas	4	405
Wisconsin	9	587
Total	198	17,573

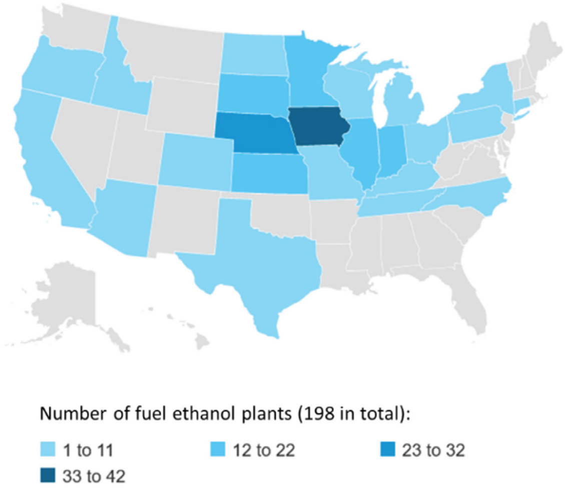

Figure 4. Distribution of existing fuel ethanol plants by state in 2021. Source: adapted from USEIA[15], as of Jan 1, 2021.

Recently, a study by Xu et al.[76] from Argonne National Laboratory assessed consumptive irrigation requirements for proposed large-scale bioenergy feedstock production. They found that these requirements would affect blue water resources available to non-bioenergy sectors (i.e. for other activities, such as conventional agriculture, and industrial use) under several scenarios.

They concluded that careful planning is still needed in certain regions. Their modeling assessments showed that the water demands for bioenergy feedstock production could significantly reduce renewable groundwater resources available to non-bioenergy sectors in the Northern and Southern Plains. In two scenarios of their modelling simulations, including projections of the DOE 2016 U.S. Billion-Ton Report,[75, 89] the fraction of renewable groundwater resources available to non-bioenergy sectors would be zero in about 88 to 99 counties.[*] Most of these counties are located in western Kansas, eastern Colorado, northern Texas, and southern Nebraska.[76] This result suggests that, while groundwater use due to the production of bioenergy feedstock is less of a concern in water-rich states of the Midwest, careful planning is needed to address potential competition between bioenergy and non-bioenergy sectors in the 110–125 counties identified as water-stressed. Another study[28] suggested that increasing fuel blends from E10 to E20 in a near future would require a crop expansion and increase irrigation demands in some areas.[28]

The EPA agreed with the Argonne report and found that, in specific regions, water scarcity concerns may constrain biofuels feedstock expansion. The EPA's 2018 Triennial Report on Biofuels and the Environment noted that future groundwater consumption for biofuel production will likely come from areas including Nebraska that are "already impacted by over-pumping due to their high blue water footprint for corn production" (p. 77)[43]. Pressure on the Ogallala Aquifer has made Nebraska one of the states with the largest water withdrawals for irrigation, and usage of the aquifer has continued to increase, in part due to biofuels feedstock demand.[90]

Despite the critical analyses shown in these studies,[28, 43, 76] regarding corn-based ethanol more specifically, electric vehicles (EVs) are likely to substantially affect the ethanol fuel market in the coming years. Therefore, we believe that any expansion of corn ethanol will come primarily from crop yield gains, although we recognize that there is a possibility that alternative ethanol markets may emerge.

In summary, Section 2 and its respective subsections showed that the energy-water nexus involves several interconnected issues, such as land

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[*] If the climate changes, the number of counties facing water availability problems may increase.

use change, regional edaphoclimatic conditions, fuel-food-feed market integrations, agricultural management practices, regulatory policies, climate change effects, and the emergence of new technologies. Based on the assessed literature and databases, no clear evidence was found that biofuels impact on water scarcity at the national level, apart from some regional concerns. Regarding a possible biofuel expansion in the future, the impacts will depend on the features of the projected scenario.

3. Policy Perspectives and Discussion

3.1. Current Context and Future Trends

The current RFS standards, enacted in 2007, only extend until 2022, after which EPA has discretion to adjust these standards.[91, 92, 93] The impending 2022 date may lead policy makers to consider changes. Some policy makers have already pushed to build on the RFS by transitioning to a Low Carbon Fuel Standard (LCFS), similar to California's approach.[94]

At the same time, the use of electric and hybrid vehicles in the United States is growing, especially for light-duty vehicles in states and cities with robust incentive policies.[95, 96] In 2010, for example, the total U.S. light vehicle fleet was approximately 250 million vehicles, with just a small share of hybrid cars and almost no electric vehicles.[97] Currently, conventional vehicles still represent the dominant share of sales, but hybrid cars have become more common. EVs took longer than hybrids to became commercially viable but demand is expected to grow in the coming years. By 2030, some experts[97] estimate that the total U.S. fleet of light vehicles will be about 340 million vehicles, of which around 230 million will still be conventional vehicles; however, the majority of the new car sales will be electric. Moreover, tighter efficiency standards for conventional vehicles will reduce gasoline demand still further. If these predictions are correct, gasoline sales in the coming decades will be significantly lower and therefore ethanol sales to this market will be lower (*ceteris paribus*). In the case of hybrid cars (battery + liquid fuel), biofuels will remain an option, either in small blending ratios with gasoline or in higher concentrations for use in flex-fuel hybrid vehicles. However, under most of these scenarios, ethanol will have its market affected.

If biofuel demand is to increase, new markets will need to emerge, such as fuels for aviation,[98] trains and heavy trucks, ships, bioplastics (e.g. green polyethylene), ethanol-based hydrogen fuel cells,[*] hybrid vehicles (ethanol and battery),[99] power generation in peaking electricity thermopower plants,[100, 101] alongside the development of new feedstocks and biorefinery technologies which require less water. For heavy transportation, biodiesel, Hydrotreated Vegetable Oil (HVO), and biokerosene,[†] including from pyrolysis oil, may remain attractive options, given that combustion engines are likely to remain the dominant technology for heavy trucks in the coming years, with a longer transition towards alternative modes of power.[103, 104] It is possible to use ethanol directly in diesel-cycle engines such as in heavy trucks and buses, although this has been observed only in niche markets, such as the ethanol-powered buses made by Scania that have been in operation in Stockholm for many years, as well as in several pilots[105] conducted in the United States and Brazil.[‡] Another use under investigation is the conversion of wet ethanol into fungible hydrocarbon fuel blendstocks (a.k.a. Consolidated Alcohol Dehydration and Oligomerization - CADO)[106] via catalytic processes, through which

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[*] There is a technology under development through which ethanol is used as a source of hydrogen for fuel cells in EVs, including light and heavy-duty vehicles. It consists of an embarked system (Solid Oxide Fuel Cell - SOFC) through which the vehicle has no need to be plugged in to be recharged. This system could take the advantage of the already existing ethanol pump stations and avoid using electricity from the grid, which may not be carbon free in its generation process. The State University of Campinas and companies such as Nissan and Volkswagen, for example, have been working on this type of technology. The main challenges to be overcome are its high production cost, and weight and size of the ethanol reformer.

[†] The aviation sector may also explore some different types of biofuels (a.k.a. bio-jet fuels), such as synthetic paraffinic kerosene (SPK) from Fischer-Tropsch process, alcohol-to-jet (ATJ), among other technological routes.[102]

[‡] One of the main challenges of using ethanol in diesel cycle is the need of manufacturing a dedicated ethanol-powered engine, in contrast to FFVs, given that ethanol and diesel require substantially different compression rates. In addition, ethanol must be refueled more often (for a same tank size), because it has a lower energy density than diesel. To use ethanol, the engine may require using a specific additive as well. Therefore, this strategy demands investments in logistics and infrastructure to supply both ethanol and the additive regularly even in distant locations for heavy trucks. It also demands policy regulations and the interest of automakers in producing this type of vehicles, with potential impacts on both selling and reselling prices, and warranty. The main advantage is to use a fuel that: 1) is derived from higher efficient crops such as corn and sugarcane (compared to biodiesel from soy and rapeseed oil); 2) is available in a liquid form at standard conditions (compared to hydrogen and natural gas); and 3) has a significant energy content per mass unit and is rapid to refuel (as opposed to conventional batteries).

the new fuel could be used in aviation in small blends with jet fuel for example.*

3.2. **Water Use and Biofuel Policy Assessment**

Pathways that allow biofuels expansion, aligned with environmental conservation requirements, may allow the corn-based ethanol ceiling to be increased from the 2015 reference of 15 billion gallons a year (as established by the 2007 EISA). To address this hypothesis, we reviewed several studies, based on models such as the Biofuel Environmental Policy Analysis Model (BEPAM) and the CropWatR model (process-based crop-water modeling).[36] We also used some original alternative projection exercises (Section 3.3) in order to assess alternative policy strategies. We should emphasize that our review of these studies should not be read as an endorsement of their findings, since we have not conducted independent analysis of our own.

What if the United States retains the RFS?

If the current policy system were maintained, what is the likely impact on water resources?

To consider this question, a study conducted by Teter et al.[36] compared two U.S. policy options for biofuels support, a mandate scenario and a proposed clean fuel intensity standard (CFS), to a hypothetical "no biofuels support" policy. The study compared the land use changes induced by the two policies "by coupling a biophysical model with an economic model to simulate the economically viable mix of crops, land uses, and crop management choices" (p. 1)[36] under each scenario. For the "mandate" scenario, the study used a volumetric mandate scenario that simulated a stylized version of the Renewable Fuels Standard by setting quantity targets for different types of biofuels. This scenario was modeled with a target of 150 billion ethanol equivalent liters of biofuel at the end of the modeling period (2030) with an upper limit of 56 billion liters of corn ethanol

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[*] Several other technologies are also under deployment, such as the production of sugarcane diesel-farnesane by Amyris and sugarcane "biodiesel" by LS9,[107] as well as the use of ethanol together with supercapacitors in hybrid engines (diesel cycle + electric), among other technologies.

(aligned with the Annual Energy Outlook's forecasts), although these targets are unlikely without major technological breakthroughs.

While both biofuel policies incentivized more biofuels than in the counterfactual (no policy support) scenario, they differed in the mix of corn ethanol and advanced biofuels from miscanthus and switchgrass, with more corn ethanol in the mandate scenario.

National irrigated acreage increased 0.7% in the mandate scenario and decreased 3.8% in the CFS scenario. However, both scenarios showed the demand for irrigated water increase by 10-25% in the Western Corn Belt (namely Kansas and Nebraska). This specific regional increase is due to an overall expansion in corn and soy acreage under the mandate scenario, and a displacement of corn and soy from existing 'good' cropland to marginal lands in favor of advanced biofuel feedstocks. This analysis indicates that the current RFS mandate is likely to lead to increased production of corn feedstock, including a small increase in land used for corn production (by 2% under the mandate scenario, and by 6% under the CFS scenario).[36] Thus, according to this specific study, some additional impact on already stressed U.S. water resources would occur and some irrigated row crops may partially expand into more arid regions of the Great Plains. This includes areas in Kansas, Nebraska, Oklahoma, the Texas' panhandle, and North and South Dakota.

What if the United States reforms the RFS?

Under this pathway, the RFS mandate would be maintained but reformed with increased tracking of land use change and water quantity impacts. As discussed, the original EISA envisioned that EPA would ensure the increased biofuel incentives in the RFS did not result in unintended land use changes or the conversion of land to row crops. There is now evidence that EPA's "aggregate compliance" approach has been unsuccessful. However, a petition to force EPA to reject the aggregate compliance approach and enforce the no land use change from the original EISA target was not successful either.[108]

One possible policy solution could include a requirement that biofuel feedstocks meet water sustainability criteria. Under this scenario, EPA together with other responsible governmental bodies would propose water sustainability guidelines for biofuel feedstocks, using zoning schemes and Geographic Information System (GIS) tools. This scenario is challenging to implement, as already observed in past difficulties to track land use change and water use, as well as the legal limitations for the federal government to become involved in water affairs at the local level. The regulation of water resources is primarily a state-level responsibility in the United States. Therefore, corn producing states should develop strategies for water conservation in the context of biofuel production.

What if we move to sustainable biofuel standards or guidelines?

This pathway assumes an expansion of biofuels will be linked to standardization programs for the sustainable use of water resources. To date, no such standards exist specifically for biofuels production at the national level. Given that land use and water resources are under the jurisdiction of states, the federal government could provide "guidelines" instead of "standards". The level of interest by state governments in sustainable biofuel standards, including water use, may vary state by state. While some states may oppose any expansion of crops on water stressed areas, others may not see this as a major issue.

Currently, there are several standards aimed at carbon mitigation that could serve as a reference for promoting water conservation. This could be done by including (or further improving) water use guidance in existing standards for carbon mitigation. For example, a growing number of policy makers are expressing interest in building on the RFS by moving toward a low carbon fuel standard (LCFS) for transportation.[94] A LCFS is currently in place in California. It assesses fuels based on a life-cycle carbon intensity benchmark (emissions per unit of energy output) that declines over time. "The life-cycle assessment considers the direct greenhouse emissions associated with producing, transporting, and using the fuel and indirect emissions associated with changes in land use for some biofuels. Fuels with a carbon intensity below the benchmark generate credits, while fuels with a carbon intensity above the benchmark generate deficits" (p. 101)[94].

This idea has also been advanced by a broad coalition of agricultural, environmental, and energy stakeholders in the Midwest, which have proposed a Midwest Clean Fuel Standard for the region.[109] On the other hand, programs such as the LCFS may be expensive, if measured on a per unit of carbon reduced basis. Some studies,[110, 111] for example, show that the implementation of LCFS can affect the production cost of ethanol due to compliance costs, among other unintended consequences, with potential impacts on price at the consumer level as well.

The study by Teter et al.[36] also compared the water impact of a hypothetical LCFS to a hypothetical mandate (RFS) scenario. The model indicated that the LCFS resulted in more cellulosic feedstocks (miscanthus and switchgrass) and that net irrigation requirements decreased by 3.8% in the LCFS standard scenario. Another assessment[112] similarly found that stacking low carbon policies on the RFS leads to a reduction of first-generation biofuels and an increase in cellulosic feedstocks. However, even in the LCFS scenario, irrigation increases were needed in Kansas and Nebraska. Thus, in designing a LCFS policy option, it will still be necessary to ensure the program avoids increasing water demand in water stressed regions.

Standardization programs at state level could be associated with agroecological zoning schemes[113] to avoid the expansion of biofuel feedstocks in water stressed areas. These programs could also learn from sustainable criteria and indicators proposed by other initiatives, such as the Global Bioenergy Partnership (GBEP).[114]

Is there any role for agricultural incentives in the energy-water nexus?

Total government payments to U.S. farmers varied in the past two decades, from as high as US$ 33.7 billion in 2000 to as low as US$ 10.7 billion in 2014, whereas in 2019 it reached US$ 22.6 billion, representing about 20% share of total net farm income (US$ 111 billion in profits).[115] These values are for all crops and exclude crop insurance payments. The large variability occurs not only between different years but also within specific program payments. This variation has a significant influence on cropland and planting decisions, with potential direct and indirect effects on water management. Corn and soybean receive the largest subsidies. The U.S. has several agricultural subsidy schemes,[116] which often result in complex crossed interactions. Changes in Farm Bill funding and programs (e.g. Conservation Reserve Program - CRP[*]) can influence total national cropland over time. For instance, the CRP enrollment (cumulative at the end of each fiscal year) peaked at 36.7 million acres in 2007 and has decreased since then, reaching 21.9 million acres in 2020, as shown by the USDA.[117] Some farmers argue that, if they are not paid to set aside their lands, they will need to increase production in order to pay for it. In the case of corn ethanol, this could be compensated, at least partially, by processing the surplus grain being produced, rather than expanding land area. Most subsidies (e.g. price floors, support payments, insurance) are based on acreage. They may indirectly affect biofuels projections, too, with associated water impacts. Nowadays, there is no agricultural incentive specifically related to ethanol production for U.S. corn growers, apart from the biofuel consumption mandates, i.e. these are not "biofuel subsidies".

Future land use change for biofuel production can be indirectly influenced by the variation of agricultural subsidies. A single subsidy program (out of many others), when it was incorporated in the GTAP (Global Trade Analysis Project) model,[†] was found to modify results for acreage estimates associated with biofuel policies at significant levels, as shown by Taheripour and Tyner.[118] These authors also stated that "… ignoring the reduction of agricultural output subsidies due to higher coarse grain prices induced by biofuels demand leads to very misleading geographical distribution of land use changes" (p. 631).[118] Although changes in agricultural subsidies can affect land use dynamics, their effects on water use for biofuels were not clearly identified in much of the literature.

Therefore, no clear linkage was found between the associated impacts of agricultural incentives and the energy-water nexus for biofuels production. Direct farm subsidies for biofuels are not expected to be implemented at national level. However, future incentives for crops in general could be used to reduce agricultural water withdrawals in critical zones. In the case

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[*] One of the largest U.S. soil conservation programs is the Conservation Reserve Program (CRP), which allows farmers to enroll marginal land into the program and receive annual payments for keeping the land planted with grass or other species that ensure environmental benefits rather than row crops.

[†] See more on the GTAP model at: https://www.gtap.agecon.purdue.edu/models/current.asp

of corn and soybean, this could indirectly reduce the biofuels' average water footprint.

3.3. **Assessing Corn Ethanol Production Pathways by 2030**

Total cropland in the United States increased about 7% in the last two decades and this increase is not historically linked with ethanol production.* The farmer's decision to where and how much land will be allocated for a certain crop depends on several aspects, including prior year returns, federal subsidies, CRP programs, crop rotation plans, market trends, among other factors. The USDA regularly updates its projections on land use change and crop productions for the subsequent 10 years. Based on assumptions from these projections, this section assesses how changes in corn acreage and industrial destinations may affect ethanol production (and water use) by 2030. Longer term scenarios may follow different pathways, due to future technological advances.

One of the uncertainties involved in these hypothetical scenarios is that they do not include potential impacts of climate change on corn production, given that there is no climate modeling involved in these simulations. Instead, they assume that decadal weather patterns will be about the same ten years from now. However, this may not be the case as the impacts of climate change may affect rainfall patterns and summer temperatures in several regions. As previously noted, these impacts are likely to be larger in long term projections, with considerable implications to the energy-water nexus.

What if we follow USDA forecasts for corn production for the next 10 years?

By following the USDA decadal agricultural projections for corn,[88] this scenario forecasts a minor increase in the allocation of corn to ethanol

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* As demonstrated by Keith Kline (personal contact) from the Oak Ridge National Laboratory (ORNL), using USDA data.[119] Kline and his colleagues have also shown that the impacts of U.S. corn ethanol on international corn prices as well as on corn availability and net corn exports might be overestimated, given that ethanol was not found to be a relevant driver of these changes.[120]

production. Therefore, this pathway may indirectly simulate a situation in which ethanol policies would be maintained but no longer strengthened.

As shown in Figure 5, the current land associated with planted and harvested corn in the United States are expected to decrease, respectively from 91 and 82.5 million acres in 2020/2021 crop year to 89 and 81.5 million acres in 2030/2031. At the same time, total corn production would keep increasing linearly, from 14.7 billion bushels in 2020/2021 to 16.2 billion bushels in 2030/2031. In the same period, crop yields will increase from 178.4 to 198.5 bushels per acre. All projections show linear trends in this figure.

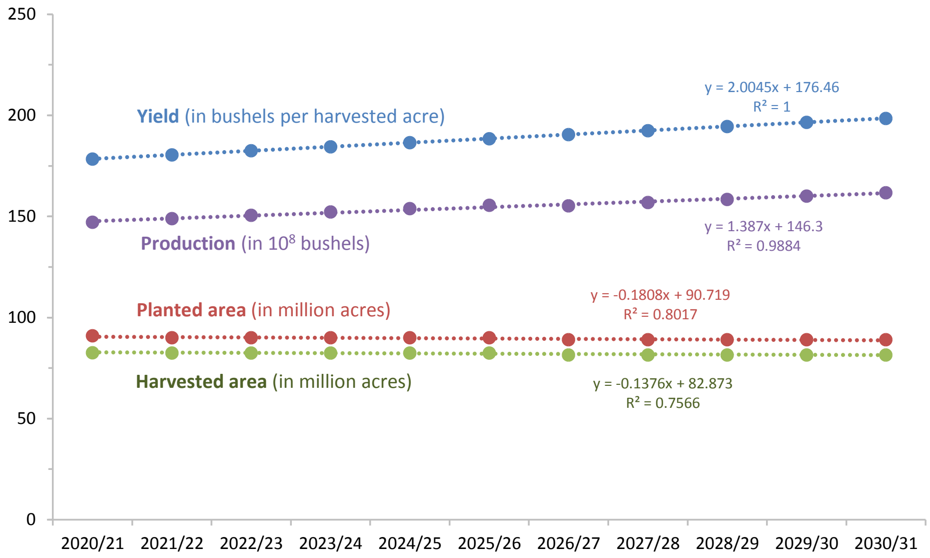

Figure 5. Official projections for corn area, production, and yield in the United States, per crop year. Source: prepared by the authors, based on USDA projections released in Jan 2021.[88]

The USDA is not forecasting a net expansion of corn acres at the national level. In addition to market trends, this inertia may be partially associated with the fact that most corn farmers have already become highly specialized in producing this same crop over the years, if not over generations. Farmers have made significant investments in dedicated machinery and know-how. Moreover, most of them have been traditionally connected to several associated local businesses (e.g. technical assistance services, agricultural and equipment shops, logistics, storage facilities (silos) and biorefineries). Thus, under these projections, concerns about a substantial expansion of acreage for corn into lands that are water stressed do not occur.

Apart from the minor variations in total corn acreage, will there be any change in the amount of corn grains allocated for ethanol production? To answer to this question, it is important to analyze the USDA forecasts for different corn uses, as shown in Figure 6. The use for "feed and residual", for example, is expected to increase in the next 10 years, from 5,775 million bushels in 2020/21 to 6,850 million bushels in 2030/31. USDA also forecasted an increase in total exports of corn from 2,325 to 2,775 million bushels in the same period. These increases in both domestic and external markets follow projected growth in livestock production, not only in the U.S. but globally, to meet the growing per capita meat and milk consumption. In this context, the use of corn for ethanol and byproducts is projected to remain nearly the same, varying only from 5,050 to 5,150 million bushels (resulting in approximately 14.9 to 15.2 billion gallons of ethanol) in the same period, whereas the share of corn used for ethanol production (versus all other uses) will decrease from around 35% to 32%, respectively.

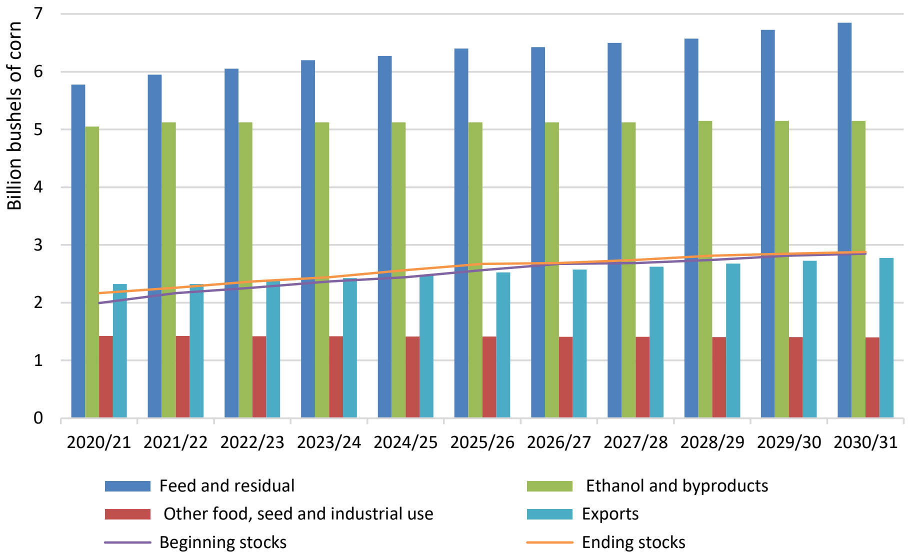

Figure 6. Official projections for corn use (column graphs) and socks (line graphs) in the United States, per crop year. Source: prepared by the authors, based on USDA projections released in Jan 2021.[88]

This pathway, therefore, indirectly illustrates the impact on the corn sector from a gradual policy shift towards fleet electrification, along with minor increases in ethanol blending ratios with gasoline and use of E85 in some states, although these aspects were not clearly identified in the USDA projections.[85] At the biorefinery level, however, the total production of ethanol may increase over time due to gains in efficiency and technological innovation. This includes a potential expansion in advanced fuels and the possibility of using other types of crops for cellulosic ethanol (e.g. switchgrass, miscanthus, short rotation coppice). On the other hand, if the expansion of EVs occurs more rapidly than expected[97] and other ethanol markets do not emerge in the coming years, then the total ethanol demand may gradually reduce by 2030 and beyond. In this case, the United States could either decrease its domestic production accordingly or export more ethanol to counterbalance this loss, especially if the commoditization of ethanol evolves in the international market.

The USDA projections are cited as an example of one forecast. These projections imply that the current *status quo* of corn to ethanol will be maintained in the next 10 years. Although the USDA did not address water issues particularly in these forecasts, based on past trends and the assessed literature, this pathway is not expected to exacerbate water stress. Water withdrawals for crops peaked in the 1980s and have decreased more recently,[31] due to cost impacts and the

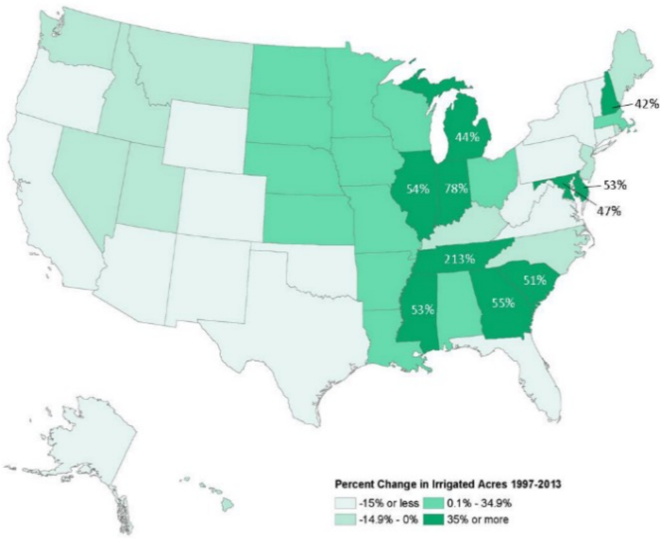

Figure 7. Percent changes in irrigated areas for all croplands in the U.S. from 1997 to 2013. Source: Congressional Research Service.[31]

salinization of soils,* whereas from 1997 to 2013 a significant increase in water withdrawal is observed in most states located in the corn belt (Figure 7). At the national level, from 1964 to 2017, corn irrigation peaked in 2007, reaching approximately 13.2 million acres out of 86.5 million acres of harvested corn for grains in total (i.e. 15.3%), whereas in 2017 the irrigated area reduced to 12.4 million acres out of 82.7 million acres in total (i.e. 15.0%).[4, 121] Nonetheless, climate change creates an uncertainty to the extent of irrigation in the future. Regardless, the use of more efficient irrigation technologies and best management practices (BMP) results in a more efficient use of water resources.

What if we increase corn ethanol production in the next 10 years, only via crop yield gains and without changing the current levels of corn acreage, exports, and internal stocks?

Under the USDA projections assessed in the previous pathway, corn-based ethanol production may not vary significantly over the next 10 years. However, several other scenarios could occur, for example, one in which ethanol use increases faster than the gasoline consumption declines, due to future changes in blending ratios, new climate policies (e.g. carbon taxes, mandatory targets), and the emergence of new ethanol markets and technologies, which were not clearly addressed in these USDA projections. Such an increase could more than offset the reduction in gasoline sales due to the penetration of electric vehicles. Would it be possible to meet this new demand without a net expansion of land area, while also avoiding ramping up corn exports?

To answer to this question, we present an alternative illustrative projection. As shown in Figure 8, if both corn exports and the beginning and ending stocks remained at the same current level, with all other trends ("feed and residual", and "other food, seed and industrial use") being equal to those previously shown in Figure 6, then the production of "ethanol and byproducts" could significantly increase, without an acreage expansion. However, this increase in ethanol supply would depend on an equivalent

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* Soil salinization occurs when a high-salinity groundwater is repeatedly used (without pretreatment) for irrigation on a same area, leading to soil degradation. While water is subject to evapotranspiration, the salt accumulates in the soil, affecting crop production to a certain level that this type of irrigation must be interrupted.

increase in demand within the U.S. market and/or through higher biofuel exports, rather than exporting more corn. In this simulation, corn exports are kept stable at around 2,325 million bushels and the internal stocks at around 1,995 million bushels (dashed line). The assumptions used in this projection (total corn production, yield, and area) would remain the same as originally forecasted by the USDA and already described in Figure 5.

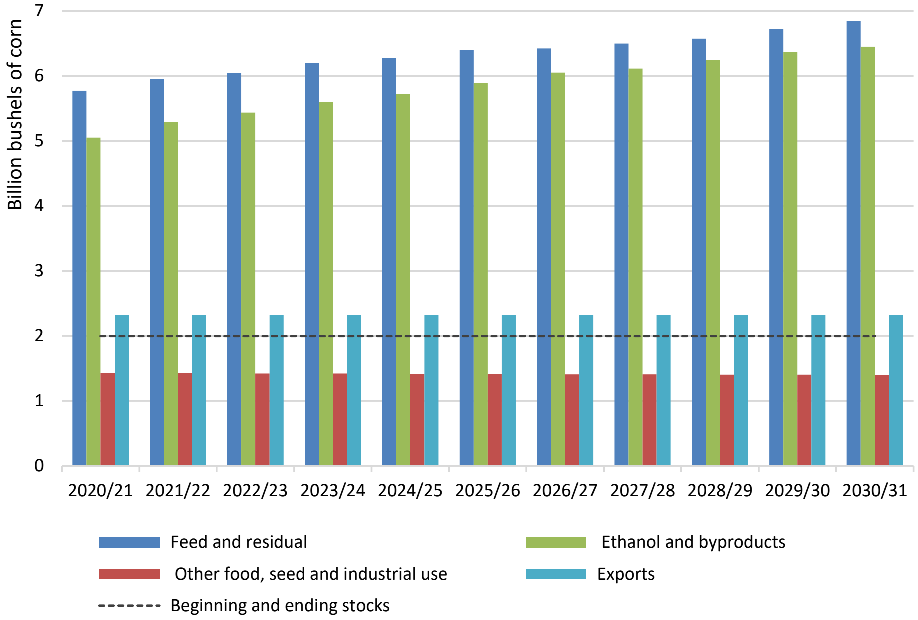

Figure 8. Ambitious corn to ethanol simulation, with adapted projections for corn use (column graphs) and socks (dashed line) in the U.S., per crop year. Source: prepared by the authors, adjusted from USDA projections released in Jan 2021.[88]

As a result, the use of corn to ethanol in the United States would increase from 5,050 to 6,452 million bushels from 2020/21 to 2030/31 crop year, i.e. a 28% increase in the next 10 years. The share of corn to ethanol out of the total use of corn would increase from 35% to 40% in the same period. Assuming (hypothetically) that the biorefinery efficiency will remain approximately the same,[*] how much ethanol would be produced in 10 years? The answer is that it would increase from 14.9 to 19.0 billion gallons (a 28% increase) from 2020/21 to 2030/31, i.e. an additional 4.1 billion gallons in 10 years. With productivity gains in biorefineries, these figures could be even higher.

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[*] On average a bushel of corn produces 2.95 gallons of ethanol, as in 2018/2019.

Moreover, this ethanol production increase would allow an additional volume of DDGS, among other co-products, which could increase the competitivity of livestock production in the United States. Thus, more meat* could be exported rather than coarse grains. On the other hand, this would potentially impact the food and feed markets of other nations, which may increase their domestic production of corn. An indirect Land Use Change (iLUC)[123, 124] outside the United States could also be associated with this pathway. At the same time, the food-water-energy balance could be improved via collaborative innovations between nations such as the United States, Brazil, China, and India, through which the need for disciplinary silos† could be more efficiently managed.[125] Similar coupled dynamics can be observed in the case of biodiesel, such as land use change interactions between the European Union (as a consumer market) and soybean producing countries such as the Argentina, Brazil, China, and the United States.[126] In short, more effective collaborations between countries will lead to greater innovation in how biofuel production uses water.

This simulation has several uncertainties, such as, i) second generation ethanol may also increase, driving up the total ethanol production; ii) the use of irrigation in corn fields may increase (or decrease) in the next 10 years, as already discussed in Figure 7, regardless of its final destination (e.g. feed, food, ethanol production, stocks, and/or exports); and iii) the impacts on corn price dynamics may have indirect effects on the ethanol market.

What if the United States doubles corn ethanol production in 10 years?

Based on the assumptions used from the USDA trends for corn production and yield gains, it would be necessary to either reduce the current levels of corn exports and/or the use of corn for food and feed, while also keeping the current level of stocks. Otherwise, it would be necessary to change the

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* Climate change mitigation advocates argue, however, that we should be reducing our per capita meat consumption globally.[8, 122]

† Disciplinary silos of grains work as a storage system to ensure sustainable food supply at national level, while also reducing the risks of abrupt price variations, as observed in the 2007-2008 global food price crisis.

projected harvest acreage of corn, which is expected to slightly decrease in the next 10 years.

By gradually reducing the U.S. exports of corn to zero in the next 10 years, an additional 2,235 million bushels of corn could be used internally. Based on the yield reference already adopted (i.e. 2.95 gallons of ethanol per bushel of corn), this would result in 6.6 billion gallons of ethanol, on top of the 4.1 billion gallons projected in previous pathway, i.e. 10.7 billion gallons in total. However, in order to double current ethanol production (15.8 billion gallons as for the 2018/19 crop year), i.e. to achieve around 32 billion gallons by 2030 (without the use of new technologies), 5.1 billion additional gallons would be required on top of the 10.7 billion gallons obtained by gradually reducing corn exports until 2030/31. Assuming the same USDA projections for land use to grow corn, as already shown in Figure 5, this scenario would require a reduction equivalent to approximately 1,729 million bushels of corn used for "feed and residual". The results of this simulation to double corn ethanol in the next 10 years are shown in Figure 9.

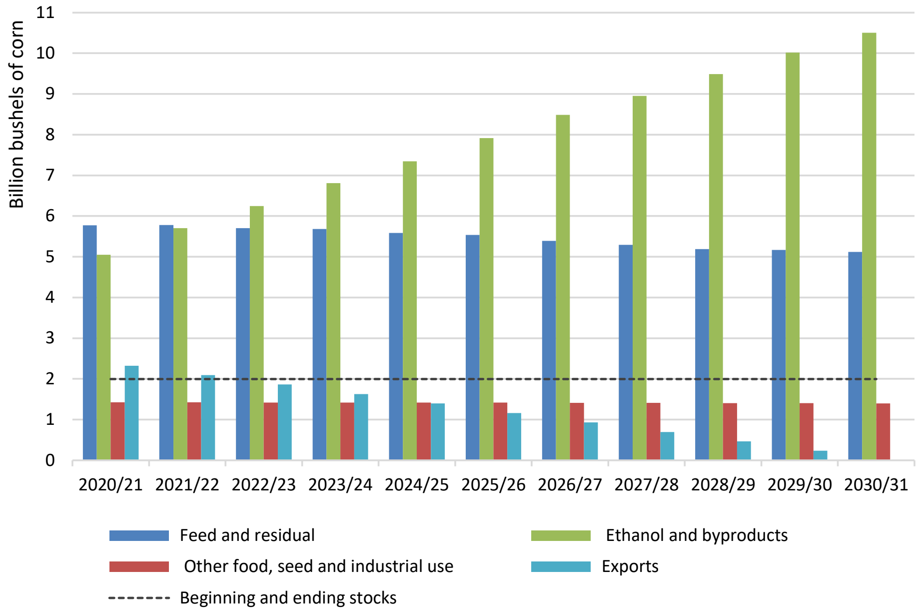

Figure 9. Very ambitious corn to ethanol simulation, with adapted projections for corn use (column graphs) and socks (dashed line) in the United States, per crop year. Source: prepared by the authors, adjusted from USDA projections released in Jan 2021.[88]

Compared to the previous simulations, this scenario would affect both the domestic and international corn markets. While the domestic supply of DDGS would increase, the potential iLUC effect abroad could become more critical, including impacts on water and GHG emissions. These dynamics may also affect the market of other corn products, such as starch, gluten feed, gluten meal, and corn oil, as well as the international food prices, given the importance of the United States in the world food market. Moreover, corn ethanol is an energy source reliant on rainfall and agriculture and, therefore, this high expansion should be well spatially distributed and integrated with other energy sources to reduce risks associated with climate change. However, this scenario would depend on a major and rapid increase in ethanol demand and, currently, there is no evidence that this is likely to occur. Besides, the existing biorefinery capacity would have to increase accordingly, including the need for new industrial plants.

4. Final Considerations for Policy Makers

This paper demonstrated that there are sufficient water supplies to support existing production of corn-based biofuels. It also shows that, if the demand of biofuels increases in the next ten years, it is likely to be met by crop yield gains and produced in areas that, in most cases, do not require irrigation. This means that no significant change in water availability associated with biofuels production is expected to occur in most scenarios. For high ethanol expansion scenarios, production growth may require a partial reallocation of corn grains to different markets. Nonetheless, the chances that the demand for biofuels for gasoline will substantially increase is limited due to projected growth in the penetration of EVs, although in the short term, higher ethanol blending ratios with gasoline (e.g. >10%) and hybrid flex fuel engines could help sustain the current market. Increase in ethanol demand is likely to come from other sectors, such as aviation, ethanol-to-hydrogen, and biochemicals. Increased demand could temporarily come from higher ethanol exports, particularly to nations that will remain reliant on combustion engines for longer periods.

Other types of biofuels, such as biodiesel, HVO, and biokerosene, are expected to follow different trends, because of their strategic roles in decarbonizing heavy transportation. Similarly, solid biomass and biogas have several different applications, such as heating and power, and are likely to expand in the coming decades, including Bioenergy with Carbon Capture and Storage (BECCS),[127, 128] which may become a key technology if the world is to obtain negative emissions.

While markets may change, biofuels will continue to play an important role in reducing GHG emissions and in most of these scenarios, the water impacts of corn ethanol production will represent a minor risk. All policy options to meet or increase the energy goals for biofuels must balance the potential benefits against possible negative impacts on water resources. The following suggestions would reduce the residual problems of biofuel production and water availability.

i) Adjust biofuel incentives so they vary geographically, favoring rain-fed feedstock, and limiting expansion into water stressed areas.

- Policies and regulations should establish clear incentives to reduce agricultural water withdrawals in critical zones in favor of rain-fed crops. Climate change may also affect rain distribution in some corn producing regions. Thus, future policies should be periodically updated to reflect new climate patterns. Corn ethanol policy strategies either at state or national level, such as a reformed RFS and sustainable biofuel standards or guidelines, should discourage feedstock production in water stressed regions. This could be determined through zoning schemes.
- Adjustments to the USDA's robust subsidy programs for corn and soy could assist in accomplishing this recommendation. Policymakers should consider reforming the Farm Bill's 'commodity programs', so they better account for the externality of water drawdown in specific regions. These programs offer price protections for corn and soy beyond typical crop insurance policies.

ii) Increase efforts to develop markets for advanced biofuels from more low-carbon, non-food feedstocks.

- Most current projections, which argue that biofuel production can significantly expand without a negative impact on water resources, assume a dramatically increased use of cellulosic feedstock. However, current technologies have not successfully commercialized cellulosic fuels at large scale yet. If biofuel production is to significantly expand without negative impacts on water resources, incentives for innovation and investment in cellulosic and other advanced biofuels, which have reduced water impacts, should be included in any new biofuel policy or program.

Finally, the energy-water nexus should be addressed as a systemic issue, which requires a spatial perspective and systemic solutions, by integrating different renewable energy sources and technologies. Producing biofuels domestically is equivalent to developing an oil field, but with the advantage of reducing GHG emissions, generating income and jobs in rural and urban areas, and avoiding international conflicts related to energy access. Biofuels are readily available and viable to be produce in most nations. Thus, they should be part of any major climate change mitigation strategy, especially for the transport sector. On the other hand, increasing ethanol production requires supporting policies. As the largest biofuel producer globally, the United States could take advantage of its position and encourage other nations to produce biofuels sustainably, reducing risks associated with fuel supply and water stress from climate variability.

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