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2019 Nebraska Water Productivity Report

Mesfin M. Mekonnen

Christopher Michael Usher Neale

Chittaranjan Ray

Galen E. Erickson

Adam Liska

See next page for additional authors

Authors

Mesfin M. Mekonnen, Christopher Michael Usher Neale, Chittaranjan Ray, Galen E. Erickson, Adam Liska, Haishun Yang, Thiago L. Romanelli, and Arjen Y. Hoekstra

2019 Nebraska Water Productivity Report

Water for Food
DAUGHERTY GLOBAL INSTITUTE
at the University of Nebraska

A farmer examines her cornfield.

Robert B. Daugherty Water for Food Global Institute

The University of Nebraska founded the Robert B. Daugherty Water for Food Institute (DWFI) in 2010 to address the global challenge of achieving food security with less stress on water resources through improved water management in agricultural and food systems. The institute is committed to ensuring a water- and food-secure world while maintaining the use of water for other vital human and environmental needs.

The institute's approach is to extend the University of Nebraska's expertise through strong partnerships with other universities and public and private sector organizations. DWFI develops research, education, and engagement programs in a focused effort to increase food security while ensuring the sustainability of water resources and agricultural systems. The institute works locally and internationally, bridging the water and agriculture communities and worlds of small- and large-holder farmers to deliver innovative solutions to this complex global challenge.

See the DWFI website for more information at waterforfood.nebraska.edu and stay informed through the institute's Facebook page at facebook.com/waterforfoodinstitute, and on Twitter @water4food.

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Lead Authors

Mesfin Mekonnen, Ph.D.
Research Assistant Professor
Daugherty Water for Food Global Institute

Christopher Neale, Ph.D.
Director of Research
Daugherty Water for Food Global Institute

Chittaranjan Ray, Ph.D.
Director
Nebraska Water Center

Contributing Authors

Galen Erickson, Ph.D.
Professor, Ruminant Nutrition
University of Nebraska–Lincoln
DWFI Faculty Fellow

Adam Liska, Ph.D.
Associate Professor, Departments of Biological Systems Engineering and Agronomy & Horticulture
University of Nebraska–Lincoln
DWFI Faculty Fellow

Haishun Yang, Ph.D.
Associate Professor, Department of Agronomy & Horticulture
University of Nebraska–Lincoln

Thiago Romanelli, Ph.D.
Professor, Department of Biosystems Engineering
University of São Paulo

Arjen Hoekstra, Ph.D.
Professor, Water Management
University of Twente, the Netherlands

List of Acronyms

DGS	Distillers' Grains
DM	Dry Matter
DWFI	Robert B. Daugherty Water for Food Global Institute
ET	Evapotranspiration
FCR	Feed Conversion Ratio
GHG	Greenhouse Gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
NRD	Natural Resources District
NU	University of Nebraska
NWPR	Nebraska Water Productivity Report
SNR-UNL	School of Natural Resources, University of Nebraska–Lincoln
UNL	University of Nebraska–Lincoln
WF	Water Footprint
WP	Water Productivity

Summary

A soybean field at sunrise.

Summary

Nebraska's agricultural production is diverse and vast, ranking the state fourth in total value of agricultural products in the U.S. The state is a national leader in terms of agricultural production: it is the third largest producer of corn and second largest in cattle production. Nebraska is also the second largest producer of ethanol and distillers' grains. The production and use of these three commodities are highly interlinked. Corn is a major input in livestock feed and the ethanol industry. Ethanol plants then produce distillers' grains as a co-product that is also used as livestock feed, thus forming what the Nebraska Corn Board refers to as "Nebraska's Golden Triangle." The main objective of the current report is to assess the water productivity of crops and livestock products, and the water, energy and carbon footprint of ethanol produced from corn. The findings show that:

- The observed shift to more efficient irrigation systems (eg. changing from gravity to center pivot systems) and setting regulatory limits on pumping for irrigation has helped to reduce the field level irrigation application depth in three Natural Resources Districts (NRDs): Central Platte, Lower Niobrara, and Tri-Basin. The irrigation application rate in the three NRDs studied has dropped on average 20% for cornfields and 8% for soybean fields between 2004 and 2013.

- The yield and modeled water productivity (WP) of both irrigated and rainfed corn decreases from eastern to western Nebraska. The drop in irrigated corn yield in western Nebraska is due to a shorter growth season in the west compared to eastern part of the state due to altitude

- The modeled water productivity of the two major crops, corn and soybeans, has increased over the years. Between 1990 and 2014, the average WP of corn and soybeans has increased 1.7 and 1.8 times, respectively. These increases closely follow the increase in the crop yields in Nebraska.

- There are WP gaps for corn and soybeans that, if targeted investments and improvements are feasible, will help reduce pressure on water resources.

- Livestock production (swine and cattle, and eggs) has increased considerably between 1960 and 2016. The increase in livestock production has been accompanied by an increase in animal feed demand. The rate of feed demand has risen more slowly than the rate of increased production, due to increases in livestock productivity.

- From 1960 to 2016, the WP of livestock products (beef, pork, chicken meat, turkey meat, milk, and eggs) increased considerably, from 1.8 times for beef to 5.1 times for milk.

- Setting benchmarks, estimating the WP gaps, and identifying the critical factors affecting WP are potential future areas of research and investment to enhance the WP of livestock products.

- Bioethanol from Nebraska's corn produces roughly two times more energy output for every unit of fossil fuel input and reduces greenhouse gas (GHG) emission by 53% relative to gasoline.

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Land irrigated with water from the Ogallala Aquifer.

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Introduction

Farmland in the Nebraska Sandhills.

1. Introduction

The purpose of the current Nebraska Water Productivity Report (NWPR) is to assess the water productivity of crop and livestock production, as well as the water, energy and carbon footprint of ethanol. The report is divided into seven sections. This introduction is followed by a section that describes the study area. The third section presents different definitions of WP and the methods and data source used. The fourth section presents comparison of four WP indicators. The fifth section presents the WP of selected crops in Nebraska at NRD level. The sixth section presents the WP of major livestock products at Nebraska state level and U.S. federal level. The seventh section presents the comparison of water, energy, and carbon footprint of ethanol production from Nebraskan corn and Brazilian sugarcane. These results are followed by a general discussion. The detailed content of sections 4-7 (WP indicators, the WP of crops, WP of livestock products, and the water, energy, and carbon footprints of ethanol) are, or will be, submitted to scientific journals and made available once published.

Nebraska is the third largest producer of corn after Iowa and Illinois, the second largest producer of cattle, and the second largest producer of ethanol in the country. The production and use of these three commodities are highly interlinked. Corn is a major input in livestock feed and the ethanol industry. Ethanol plants then produce distillers' grains as a by-product that is also used as livestock feed, thus forming what the Nebraska Corn Board refers to as "Nebraska's Golden Triangle" (Figure 1). By addressing the WP of corn and livestock production, and the environmental footprint of ethanol, this report hopes to provide information that will be useful to increase the sustainable use of water with positive impacts on the social, economic, and environmental well-being of the state.

This current Nebraska Water Productivity Report (NWPR) is intended to be the foundation for future Water Productivity Reports published by the Robert B. Daugherty Water for Food Global Institute (DWFI) at the University of Nebraska. Future editions will update the existing statistics and trends and include additional crops and analysis scenarios.

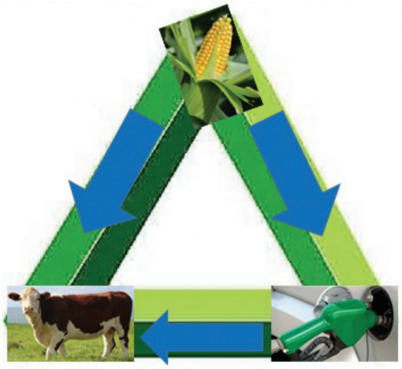


Figure 1. Nebraska's Golden Triangle.

2. Nebraska Agriculture

Study Area

Nebraska has 93 counties and 23 NRDs. The two major crops produced in the state are corn and soybeans, accounting for 49% and 27% of the total harvested cropped area of the state, respectively (USDA, 2017). The other crops with large harvested areas are hay/haylage and winter wheat, contributing 14% and 6% to the total harvested area of the state, respectively. According to Sharma and Irmak (2012), Nebraska can be classified into four zones based on climatic, soil, and topographic characteristics (Figure 2C). The western (Zone 1) and west central (Zone 2) parts of the state are characterized by a semi-arid climate, lower precipitation and soils with lower agronomic potential. Zone 3 is characterized by moderate precipitation and by flat topography. The eastern part of the state, which is characterized by relatively high annual precipitation, very productive soils and generally higher agronomic productivity, is classified as Zone 4.

Irrigation in Nebraska

Irrigation plays a vital role in Nebraska's agriculture, where in 2017, 65% of the corn and 55% of the soybean production came from irrigated agriculture (USDA-NASS, 2014). With an irrigated area of 3.4 million hectares, Nebraska ranks the first in the nation in terms of total irrigated cropped area (USDA-NASS, 2014). Between 1959 and 2012, Nebraska's irrigated area quadrupled from 0.8 to 3.4 million hectares, moving ahead of Texas and California, which have experienced a 21% decline and only 6% increase in the irrigated area, respectively. On the other hand, the total applied irrigation water between 1978 and 2012 shows an increase of only 14%, from 8.7 to 9.95 km^3. Although Nebraska has the largest irrigated area, its total applied irrigation water is close to one-third of that of California due to a lower irrigation application depth (m^3/ha) (Figure 3). In Nebraska, 89% of irrigated areas use the more efficient sprinkler system, while in California, sprinkler and drip systems account for only 22% and gravity systems for 78% of the irrigated area. In addition, California grows crops over multiple seasons and a significant area of tree crops that require irrigation year-round.

A tractor sprays a soybean field.

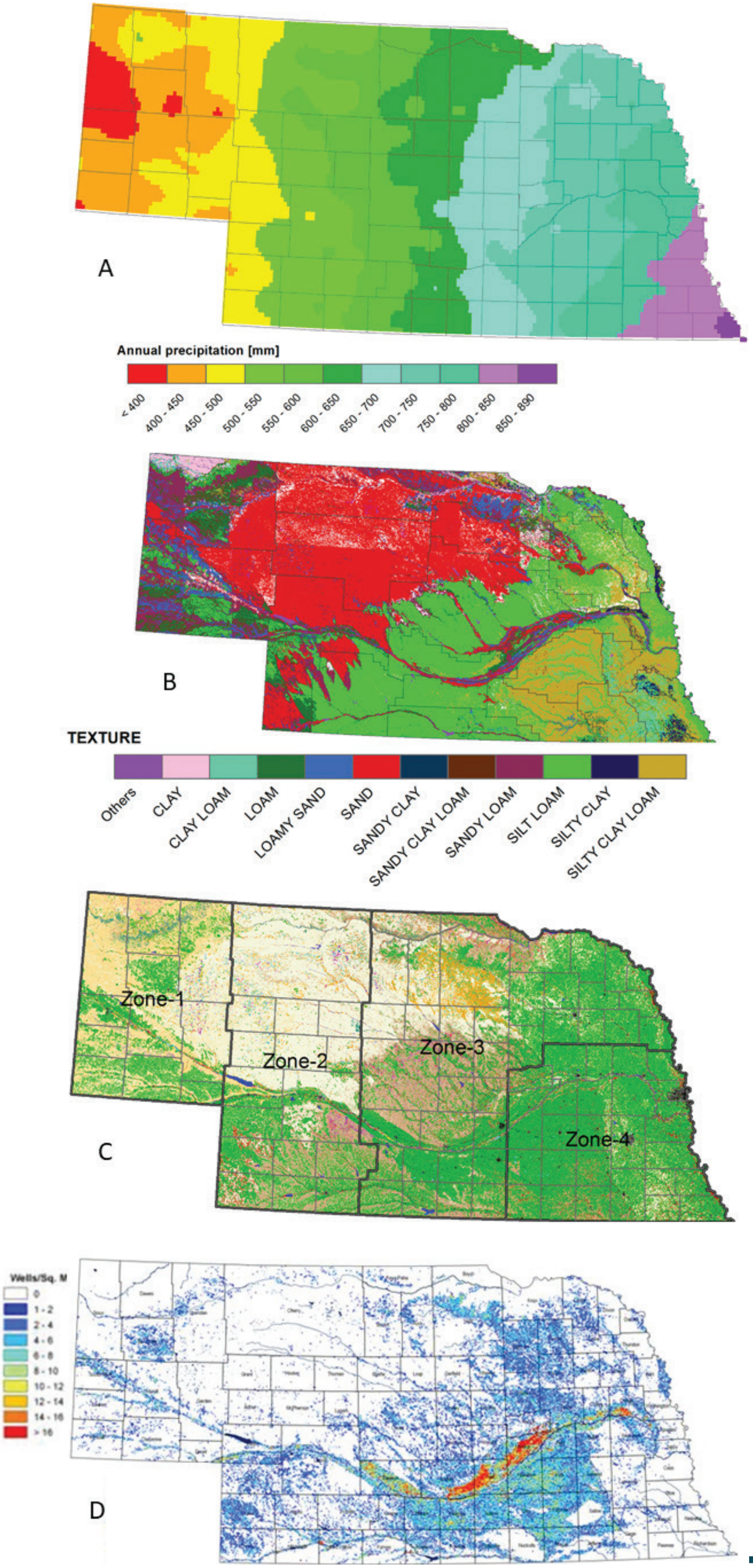


Figure 2. Variation in the annual long-term average annual precipitation (A) and soil texture (B) across the state, classification of the state in four zones (C), and density of irrigation wells (D). Data source: long term average annual precipitation (1981-2010) from Daly et al. (2008); soil texture from Soil Survey Staff (2017); and Land cover map from SNR-UNL UNL (2005); Zones from Sharma and Irmak (2012); Irrigation wells density from UNL-SNR (2007).

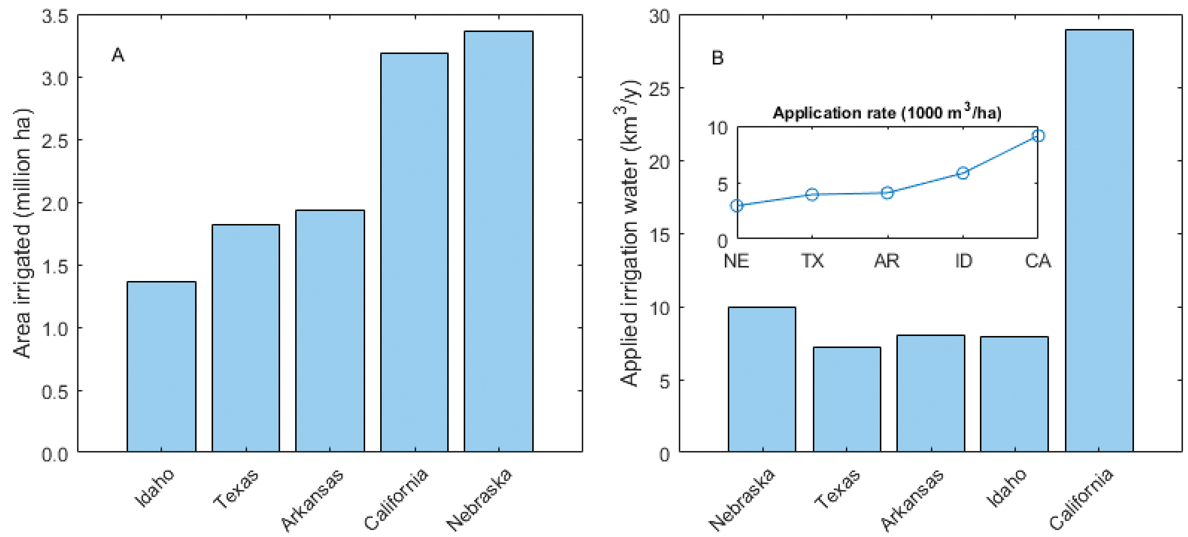


Figure 3. Irrigated area (A), applied irrigation (B), and irrigation application rate per unit of irrigated area (insert figure in B) for the top 5 states in 2012. Data source: USDA-NASS (2014).

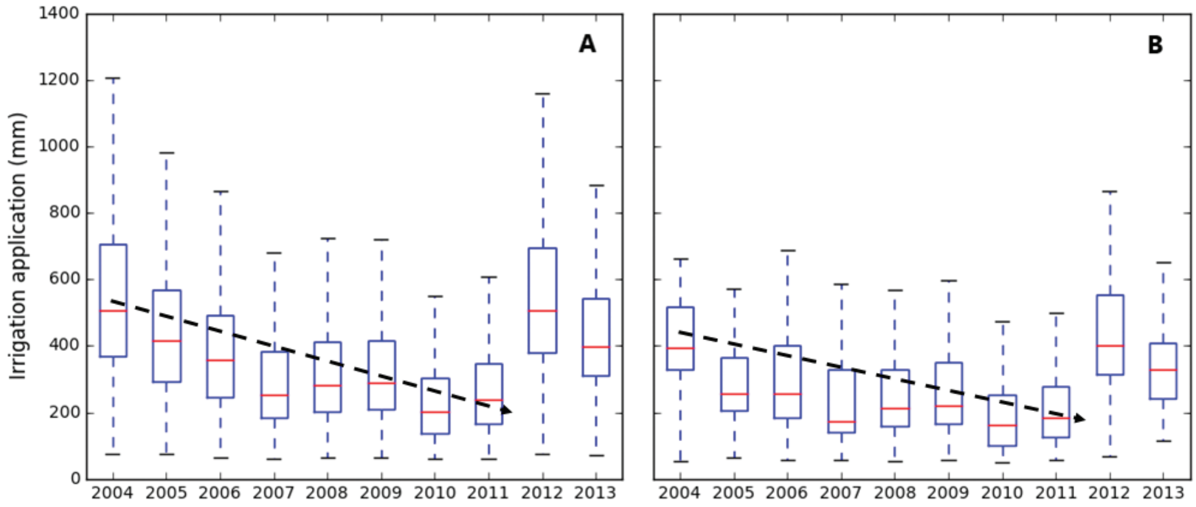


Figure 4. Annual variation in the applied irrigation for (A) corn and (B) soybean in the Central Plate, Lower-Niobrara, and Tri-Basin NRDs. Thick dashed black arrow shows overall decline in irrigation application from 2004 to 2011.

Irrigation application in farmers' fields in three Natural Resources Districts

DWFI used 10 years (2004-2013) of data on applied irrigation depths collected from 2,248 farmers' fields by three NRDs (Central Plate, Lower Niobrara, and Tri-Basin) to assess irrigation management practices in corn and soybean production. Field-level applied irrigation has dropped on average by 110 mm (by 20%) from 2004 to 2013 for corn and 39 mm (by 8%) for soybeans in the three NRDs. While there are still a large number of farms with surface irrigation (837 out of 2,248 in 2013), more farms have replaced gravity/furrow surface irrigation with center pivot sprinkler irrigation. Between 2004 and 2013, the number of center pivots used for irrigation in the three NRDs has more than doubled (from 358 in 2004 to 720 in 2013). The shift from gravity to sprinkler irrigation systems has helped reduce the applied irrigation depth in corn and soybean fields (Figure 4). Applied irrigation depth shows large variation within the same year, with large numbers of farms applying beyond the average application level. The observed variation can only partly be explained by differences in soil type among farms within the three NRDs and differences in the irrigation systems.

On-farm adoption of improved irrigation technology and water management will help to conserve water. Replacing less efficient gravity systems with drip, center pivot or sprinkler irrigation will help to reduce groundwater drawdown by reducing the amount of groundwater that is pumped. Reducing the applied irrigation is also beneficial to farmers in the form of reduced on-farm energy cost for pumping and reduced fertilizer and chemical leaching. Therefore, farmers need to be supported to adopt advanced irrigation technologies, more precise soil moisture management, and data-driven irrigation scheduling combined with accurate weather forecasts in order to reduce irrigation application beyond optimal amounts.

However, it is important to note that improved irrigation efficiency is not directly related to actual water saving or improvement in the WP as documented in a recent Food and Agriculture Organization of the United Nations (FAO) report and other review documents (Grafton et al., 2018; Perry, 2007) and also in earlier works from the International Water Management Institute (IWMI) (Keller and Keller, 1995; Seckler et al., 2003). Center pivot systems (unlike drip or sub-surface drip systems) reduce the applied irrigation depth, but not necessarily the actual consumptive water use. In some cases, actual crop evapotranspiration (ET) with a sprinkler system is larger than with gravity systems. Therefore, there is a need to monitor that water conservation doesn't lead to further expansions of irrigated area, thus increasing total water application rather than reducing it (Grafton et al., 2018). Measures that reduce both the applied irrigation depth and water consumption, such as deficit irrigation and no-till farming, need to be encouraged.

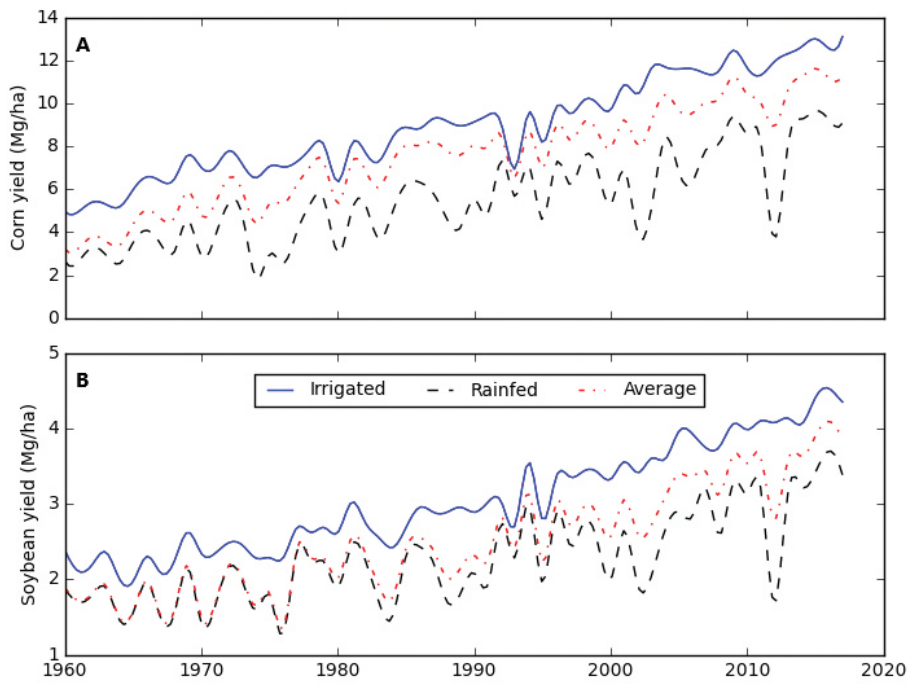


Figure 5. State-level irrigated, rainfed, and average grain yield for corn (A) and soybeans (B) from 1990 to 2014 in Nebraska. Data source: USDA (2017).

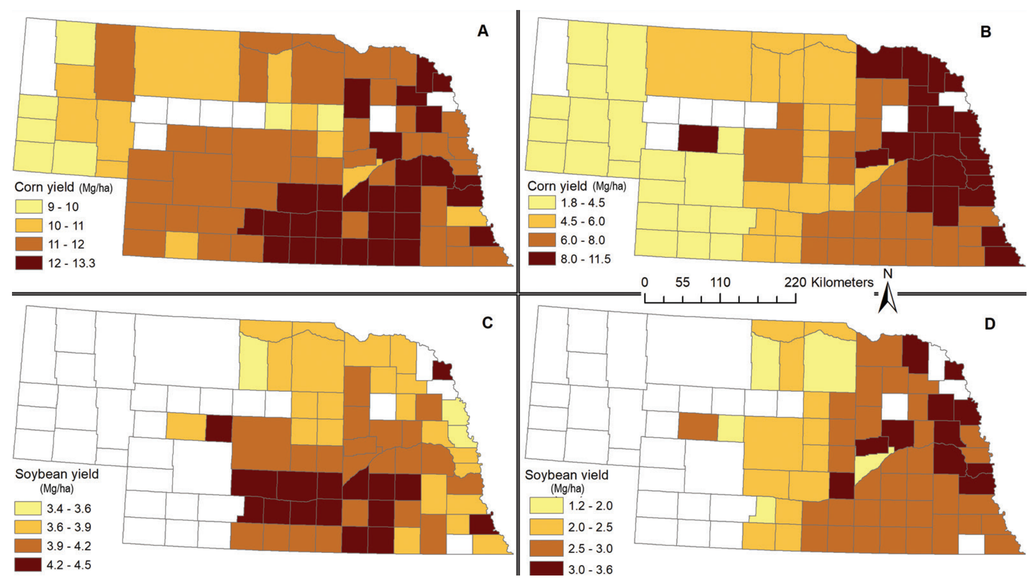


Figure 6. Average county level yield of irrigated (A) and rainfed (B) corn, irrigated (C) and rainfed (D) soybean averaged over 2010-2014. Data source: USDA (2017).

Temporal and spatial variation of grain yield

Although there are inter-annual variations due to climate variability (both drought and very wet years), both irrigated and rainfed grain yields show increasing trends in Nebraska between 1960 and 2017 (Figure 5). Rainfed corn yield saw the largest growth, increasing 3.4 times, compared to the irrigated yield that increased 2.6 times between 1960 and 2017. These improvements were achieved through enhanced crop genetics, development of high-producing hybrid varieties and improvements in the management of soil, nutrients, and water. Given that the rainfed corn yield in 2017 was only 69% of the irrigated corn yield, there is still room to further improve the rainfed corn yield with a combination of agronomic measures including supplementary irrigation. In the case of soybeans, both the irrigated and rainfed yields increased 1.8 times between 1960 and 2017. There were major declines in rainfed corn and soybean yields in some years caused by unfavorable climatic conditions, such as drought and very wet conditions/flooding.

The spatial variation in grain yield of the two major crops, corn and soybeans, is shown in Figure 6. Grain yield for irrigated and rainfed agriculture generally declines as we move from the eastern part of the state, where the annual precipitation is relatively high and soils are of higher agronomic productivity, to the west central and western parts of the state that are characterized by semi-arid climate with less precipitation and soils with the lowest relative agronomic potential. The south-central part of the state is highly productive with larger yields of corn and soybeans under irrigation.

Corn harvest on an early summer morning.

3. Water productivity concepts and definition

To tackle the increasing pressure on worldwide freshwater resources, increasing emphasis is placed on increasing water use efficiency in the agricultural sector (Falkenmark et al., 2009; Gleick, 1998; Passioura, 2006; Postel, 2000; Rockström, 2003; Wallace and Gregory, 2002). The various terms and definitions used to express the efficiency of water use are often creating confusion between planners and policymakers (Jensen, 2007; Perry, 2007). The term "irrigation efficiency" is frequently used to express the efficiency of water use by crops. It is a dimensionless ratio of the irrigation water effectively used or consumed by the crops to the irrigation water applied. Over the years, various proposals have been made to improve the definition of water use efficiency (Hansen, 1960; Jensen, 1967; Jensen, 2007; Perry, 2007; Wolters, 1992). While a helpful indicator to understand how much irrigation water actually benefits the crop, irrigation efficiency does not clearly show the full benefits of the irrigation water used. Viets (1962, 1966) was the first to define "water use efficiency" (WUE) as the ratio of crop production to actual amount of water consumed through evapotranspiration by the crop. Turner (1986) and Howell (2001) later used the same terminology. However, the term WUE is used interchangeably with irrigation efficiency and water productivity, generating confusion (Djaman and Irmak, 2012; Irmak, 2015; Irmak and Sharma, 2015; Perry, 2007; Sharma et al., 2016). Efficiency also refers to a ratio or a percent obtained by dividing output by input, both of which have the same unit. Therefore, due to its distinct connotations, the term efficiency is discovered to be less suitable and less helpful (Kijne et al., 2003). Molden (1997) introduced the term "water productivity" (WP) in order to prevent confusion. Water productivity is defined as ratio of total output, expressed either physical or economic units, to the amount of water applied or consumed (Bessembinder et al., 2005; Kijne et al., 2003; Molden et al., 2003). Water is consumed through evapotranspiration from cropped fields, or embodied into a product, or flows to unusable sinks, or gets highly polluted making it unsuitable for further use (Hoekstra et al., 2011; Molden et al., 2003; Molden and Sakthivadivel, 1999). Water productivity analysis can be applied to crops, livestock, fisheries, or a combination of these (Molden et al., 2003). The definition and the procedures followed in WP analysis differ depending on the scales: crops, fields, farms, irrigation systems, and basins. Accounting for differences in scale helps to explain the issue of "which crop and which drop" (Molden et al., 2003). An alternative to water productivity (output per unit of water used) is the inverse ratio, i.e. amount of water used per unit of output, commonly referred to as ”virtual water content" (Hoekstra and Hung, 2005) or "water footprint" (Mekonnen and Hoekstra, 2011).

Crop water productivity indicators

Water productivity is defined as ratio of crop output to water applied or consumed. Here we will consider different water productivity indices, based on various choices for measuring water use and crop output. First, a distinction is made between total water productivity, whereby total water input in the form of rainwater and irrigation water and total crop output are considered; and irrigation water productivity, whereby only irrigation water and the additional crop production as a result of irrigation is considered. In both cases, water use is measured either in terms of field water input or water consumption (i.e. evapotranspiration). Table 1 shows the definitions of the four water productivity indicators.

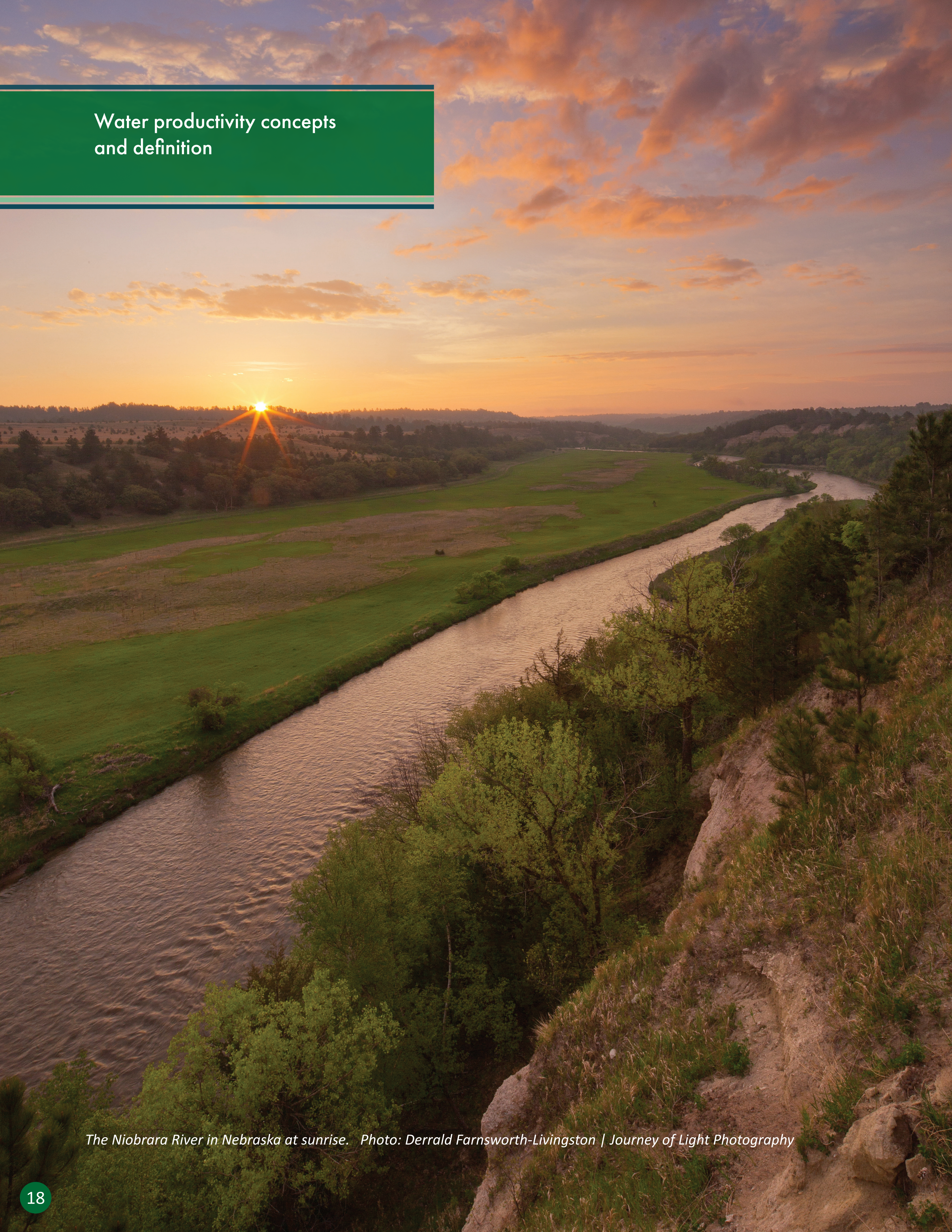
The first WP indicator is "total available water productivity" ($WP_{t,a}$) and refers to the total crop yield divided by the total water input. The latter is taken as the amount of soil water during planting, in-season rainfall, and irrigation applied (Grassini et al., 2015; Grassini et al., 2011). This indicator takes the water supply viewpoint, which differs from actual water consumption perspective. Here, water consumption refers to the water that is lost from the catchment through evapotranspiration, for the short term at least. Therefore, the second indicator we consider is the "total consumed water productivity" ($WP_{t,c}$), which is defined as the ratio of total crop yield to total water consumed. Total water consumed refers to total evapotranspiration from the cropped field during the growing period. This indicator has the advantage that it places the focus on the water that we want to conserve (Viets, 1962, 1966). It makes it possible to compare the water productivity of different crops, or even different products , such as the water consumed to produce a metric ton of sugar from sugar beets versus the water consumed to produce a metric ton of steel from a steel mill (Viets, 1962).

The specific contribution of the applied or consumed irrigation water (Howell, 2001; Sharma et al., 2016) is demonstrated by considering two additional indicators: applied irrigation water productivity ($WP_{i,a}$) and consumed irrigation water productivity ($WP_{i,c}$). The former refers to the extra yield gain resulting from irrigation divided by the irrigation water applied; the latter refers to the extra yield gain because of the applied irrigation divided by the irrigation water consumed. The latter is calculated as the difference between ET under rainfed crop production and the ET under irrigated crop production. These indicators can be used to evaluate different irrigation strategies (e.g. full or deficit irrigation) and quantify the additional crop production due to the use of irrigation water (Djaman and Irmak, 2012).

	Total water productivity		Irrigation water productivity	
	Total available water productivity	Total consumed water productivity	Applied irrigation water productivity	Consumed irrigation water productivity
Equation	$WP_{t,a} = \frac{Y}{S_0+P+I}$	$WP_{t,c} = \frac{Y}{ET}$	$WP_{i,a} = \frac{Y_i - Y_r}{I}$	$WP_{i,c} = \frac{Y_i - Y_r}{ET_i - ET_r}$
Numerator	Yield (Y)	Yield (Y)	Difference between irrigated yield (Y_i) and rainfed yield (Y_r)	Difference between irrigated yield (Y_i) and rainfed yield (Y_r)
Denominator	The sum of initial soil water content (S_0),the amount of rainfall (P), and irrigation (I) per hectare during the crop growing season	Evapotranspiration (ET) during the crop growing period	Volume of applied irrigation water per hectare over the growing period (I)	Difference between ET under irrigation (ET_i) and ET under rainfed conditions (ET_r) during the crop growing period

Table 1. The four water productivity definitions as applied in this study.

Water productivity concepts and definition



The Niobrara River in Nebraska at sunrise. Photo: Derrald Farnsworth-Livingston | Journey of Light Photography

Water productivity of livestock products

Livestock water productivity is defined as the ratio of benefit generated from livestock products and services to the total green and blue water consumed (Peden et al., 2003; Peden et al., 2007). A number of earlier efforts have presented livestock water productivity accounting for the full net benefits generated from livestock products and services including meat, milk, hides, traction power, manure, risk spreading, as means of storing wealth, and cultural value (Descheemaeker et al., 2010; Haileslassie et al., 2009; Peden et al., 2009). However, in the case of Nebraska, the benefits derived from livestock are mainly meat, milk, and eggs.

In the current report, DWFI defines the water productivity of an animal product as the ratio of the product output (meat, milk, or eggs) per animal to the water footprint (green plus blue water consumption) over the lifetime of the animal. The water footprint (WF) of a live animal is estimated as the sum of the WF of the feed, the WF related to drinking water consumed, and the WF related to service water consumed (Mekonnen and Hoekstra, 2012). The latter refers to the water used to clean the farmyard, wash the animal and carry out other services necessary to maintain the environment. There are earlier publications that focused on the water productivity of the final livestock products (Van Breugel et al., 2010) or the water footprint of the livestock products as an alternative to water productivity, which is measured as output over volume of water used (Beckett and Oltjen, 1993; Chapagain and Hoekstra, 2003; Mekonnen and Hoekstra, 2012; Pimentel et al., 1997).

DWFI considered six products (beef, milk, swine meat, chicken meat, eggs, and turkey meat) from six farm animal categories (beef cattle, dairy cattle, swine, broiler chickens, layer chickens, and turkeys). The WF includes both a green and blue component (Hoekstra et al., 2011). The volume of surface and groundwater consumed (evaporated) as a result of the production of a feed crops refers to blue WF and the rainwater consumed refers to the green WF.

The water, energy, and carbon footprint of ethanol

The WF of ethanol from corn and sugarcane is the sum of the water used in crop production, production of different inputs and machinery production. The green and blue WF related to corn and sugarcane production were calculated based on the crop water use (m^3/ha) data from Mekonnen and Hoekstra (2011), and the 2016 corn and sugarcane yields from USDA (2017) and FAO (2017), respectively.

To estimate the energy and carbon footprint of bioethanol from corn in Nebraska and sugarcane in Brazil, DWFI used the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model developed by Argonne National Laboratory. The energy footprint of bioethanol is the sum of the direct and indirect fossil fuel energy input in crop production and in the production of ethanol at the processing plant.

An ear of corn ready for harvest.

4. Comparison of four crop water productivity indicators

Total available and total consumed water productivity

In the drier, western portion of Nebraska (Zone 1 and 2), total available water productivity is relatively high compared to the wetter portion of the state (Zones 3 and 4). The $WP_{t,a}$ of corn in Zones 1 and 2 first increases up to a certain amount of applied irrigation (~90mm), then decreases with additional irrigation (Figure 7A). In Zone 1, the amount of precipitation is low so an additional reduction in the applied irrigation amount below 90mm will impact crop yield resulting in a sharp fall in the WP. For soybeans, the $WP_{t,a}$ was largest under rainfed conditions (zero applied irrigation), and any additional increase in the irrigation amount will reduce the $WP_{t,a}$ (Figure 7B). On the other hand, total consumed water productivity at a certain irrigation level is greater in the eastern portion of the state (Zones 3 and 4) where there is sufficient precipitation, so water is not a limiting factor in determining the yield level (Figure 8). In the western portion of the state, where precipitation is not sufficient to satisfy the crop water requirements, additional increases in irrigation will have a larger impact on raising crop yield (see Figure 8). While in Zones 1 and 2, $WP_{t,c}$ increases with additional irrigation application, is reduced in Zone 3 for corn (Figure 7C) and Zones 3 and 4 for soybeans (Figure 7D). This underlines that irrigation water is more important for the dryer western portions of state than to the wetter eastern portion.

Based on the two water productivity indicators ($WP_{t,a}$ and $WP_{t,c}$), DWFI makes two observations. The first is that with $WP_{t,a}$, wetter regions have smaller WP simply because of higher precipitation compared to the drier western portion of the state. This indicator therefore doesn't assess whether or not the available water has been used productively. The second is that additional reduction in the applied irrigation depth until certain thresholds are reached, will enhance $WP_{t,a}$ in all areas but reduce $WP_{t,c}$ in dry areas (Zones 1 and 2). In the wetter regions (Zones 3 and 4), both indicators have a comparable trend – WP rises with further decreases in the irrigation water. However, $WP_{t,a}$ will decrease

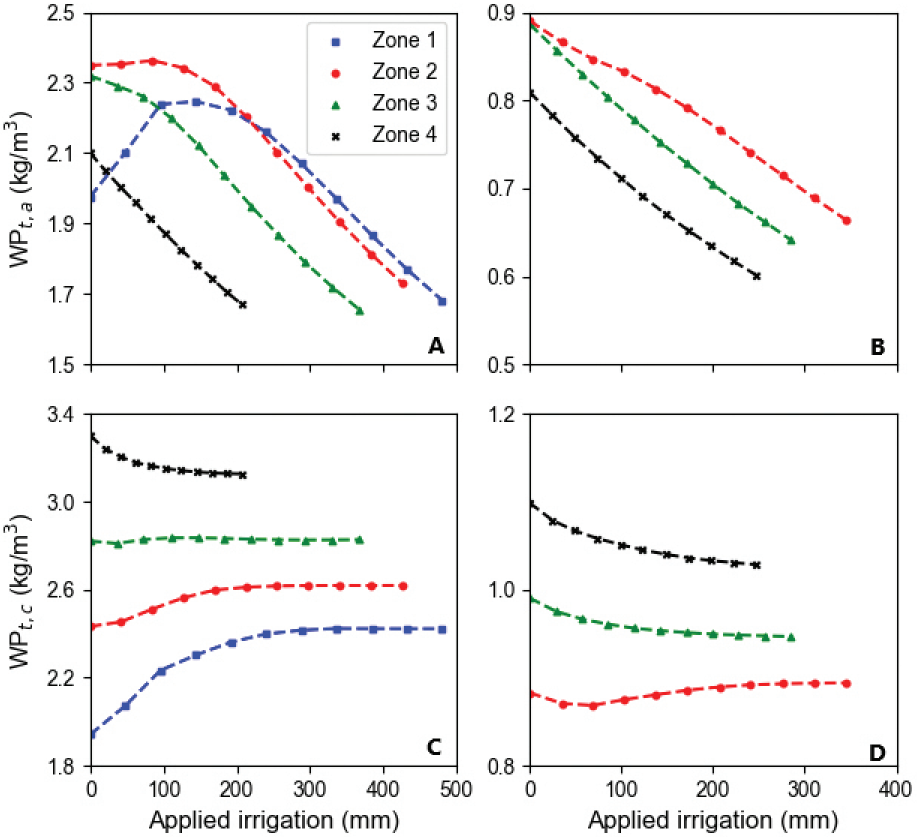


Figure 7. Total available water productivity (WP$_{t,a}$) for corn (A) and soybean (B), and total consumed water productivity (WP$_{t,c}$) for corn (C) and soybeans (D) as a function of applied irrigation in different zones. Data is for 2011, which is a normal precipitation year.

in the driest region (Zone 1) with further reduction in irrigation water below 89 mm. The rise in WP$_{t,a}$ with deficit irrigation in dry regions hides the difference in irrigation water's marginal contribution in increasing crop yield and WP under varying agro-climate conditions.

Because water availability in the drier western portion of the state is a limiting factor for crop yield, the curve slopes for Zones 1 and 2 in Figure 8 are very steep compared to those for Zones 3 and 4, showing a comparatively big increase in crop yield per unit of applied irrigation water. In the eastern part of the state (Zones 3 and 4) where rainfall is relatively high, the yield is already high at a lower irrigation rate, and as a result, increasing the irrigation amount further will not lead to significant increases in yield. The figure also demonstrates the difference in crop yield between irrigated and non-irrigated fields. The increase in crop yield with further increases in irrigation, particularly in Zone 4, is very marginal. The rainfed yield in this area is already very high, even closer to the irrigated yield level in some instances. Therefore, the increase in crop yield per unit of irrigation water added is minimal. On the other hand, in the western portion of the state (Zones 1 and 2) where rainfall is very low, the crop yield from rainfed fields is very low. In these zones, the marginal water productivity of irrigation is higher with comparatively higher yield increases over the corresponding rainfed yield.

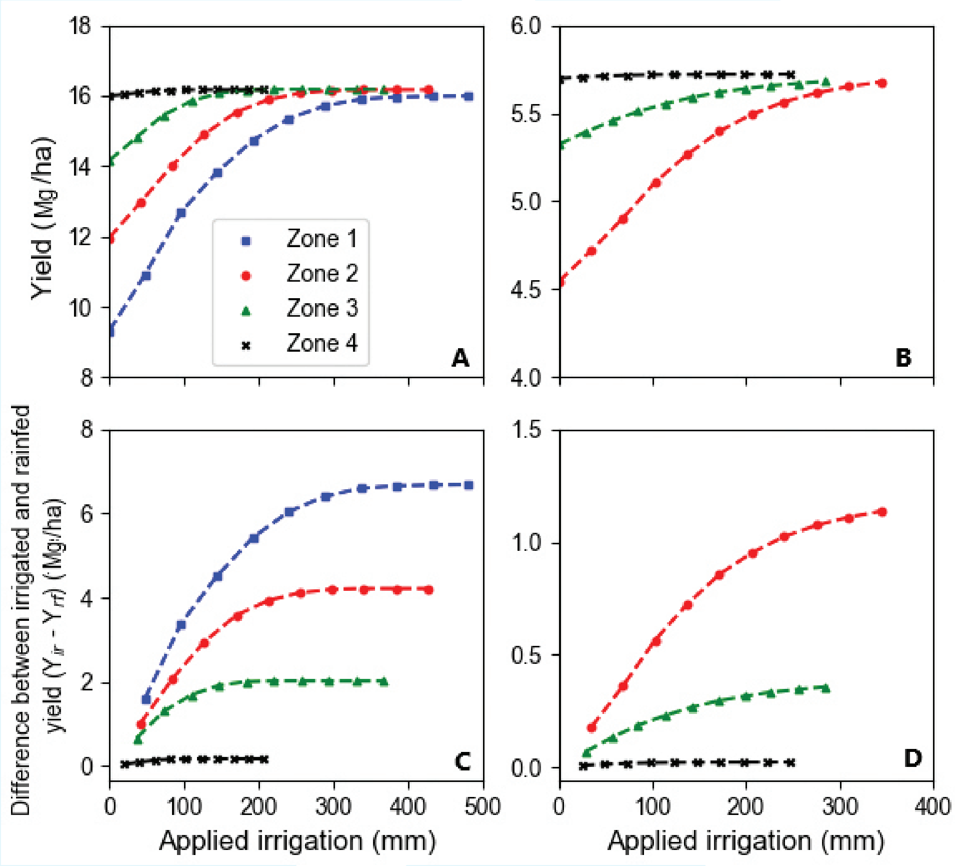


Figure 8. Relationship between yield and yield gain vs. applied irrigation amount for corn (A and C) and for soybeans (B and D) in the different agro-climate zones. Data for 2011 (average precipitation year).

Applied and consumed irrigation water productivity

Total consumed water productivity is better compared to total available water productivity because it puts the focus on the water that we want to conserve. However, it doesn't explicitly show the contribution of irrigation in raising WP. In comparison, applied and consumed irrigation WP measure the impact of irrigation on raising production compared to the non-irrigated condition.

Applied irrigation water productivity measures the marginal contribution of the irrigation water in increasing the yield under irrigation compared to non-irrigated conditions. Applied irrigation WP ($WP_{i,a}$) and consumed irrigation WP ($WP_{i,c}$) for Zones 1 and 2 are higher than that of Zone 3 and 4 (Figure 9), showing that irrigation is important in boosting yield and WP in the western portion of the state. From the figure we also notice that while $WP_{i,a}$ is dropping rapidly with additional irrigation, $WP_{i,c}$ is increasing and then leveling out. In the wetter region (Zone 4) where the crop yield differences between irrigated and rainfed fields are very small, $WP_{i,a}$ and $WP_{i,c}$ are comparatively small compared to the other zones.

Table 2 presents a summary of the strength and weakness of the four WP indicators. There are both advantages and disadvantages in each indicator that make it suitable for some purposes, but less suitable for others. Therefore, a single or a combination of the four indicators can be applied based on the intended purpose of the WP indicator.

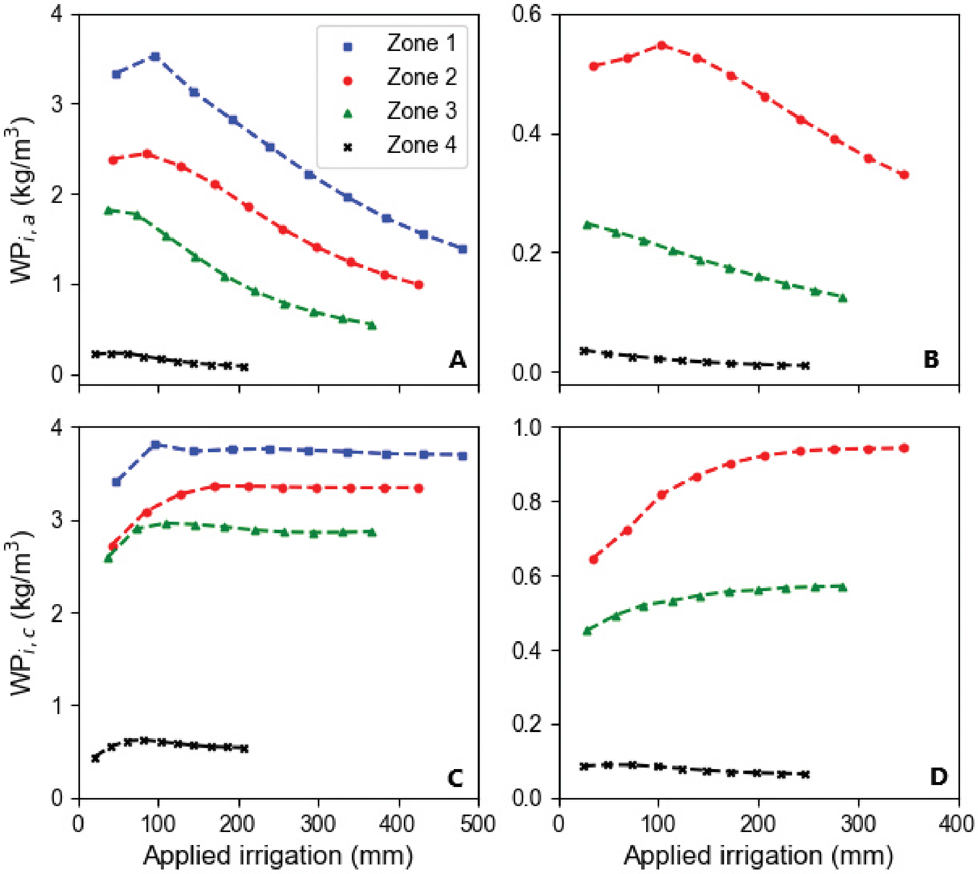


Figure 9. Applied irrigation water productivity ($WP_{i,a}$) for corn (A) and for soybeans (B), and consumed irrigation water productivity ($WP_{i,c}$) for corn (C) and soybeans (D) versus applied irrigation water in the different agro-climate zones. Data is for 2011, which is an average precipitation year.

Comparison of four crop water productivity indicators

The scenic Platte River south of Overton, Nebraska. Photo: Craig Chandler | University Communications

WP Indicator	Strength	Weakness
Total available water productivity ($WP_{t,a}$) (kg/m^3)	• The denominator term (total water supply) is simple to derive from available weather information • Easy to assess performance improvement such as increase in crop yield, decrease in irrigation application rate.	• In wetter years and regions $WP_{t,a}$ is smaller than dry years and regions. The WP values were low simply because of relatively high rainfall during these wet periods and in these wet regions. This has nothing to do with how efficiently the available water was used. Thus, under extreme condition of wet or dry periods and regions, it may provide inaccurate information. • May be misleading as it usually indicates that it is more productive to reduce the volume of irrigation under all climatic conditions. • Achieve highest WP at lower yield level, which may not be economically acceptable level of yield. • Fails to show the contribution of irrigation in raising WP explicitly.
Total consumed water productivity ($WP_{t,c}$) (kg/m^3)	• It demonstrates how a unit of consumed water (rain and irrigation) has been used productively and emphasizes the water that we want to conserve. • The peak of the WP coincides with acceptable yield levels.	• It could be hard and less precise to estimate ET. • It doesn't explicitly show the contribution of irrigation in increasing WP. • It doesn't show reduction in rate of irrigation application and other field level management that may not directly decrease ET or boost yield.
Applied irrigation water productivity ($WP_{i,a}$)	• It is simple to drive the denominator term (total applied irrigation) from available information. • Provides useful information on the impact of irrigation on raising production compared to the rainfed condition. • Simple to assess decrease in irrigation application rate.	• May be misleading as it usually indicates that it is more productive to reduce the volume of irrigation applied under all climatic conditions. • The maximum WP is attained at lower yield level, which may not be economically acceptable level of yield. • Focuses on irrigation water only, leaving out green water (rain water stored in root zone of the crop), which is the main source of water for crop production.
Consumed irrigation water productivity ($WP_{i,c}$)	• It demonstrates how a unit of consumed irrigation water has been used productively and emphasizes the water that we want to conserve. • The peak of the WP coincides with acceptable yield levels. • Provides useful information on the impact of irrigation on raising production compared to the rainfed condition.	• It could be hard and less precise to estimate ET. • Focuses on irrigation water only, leaving out green water (rain water stored in root zone of the crop), which is the main source of water for crop production.

Table 2. Strength and weakness of the four water productivity indicators.

Water productivity of corn and soybeans in Nebraska: temporal and spatial dimension

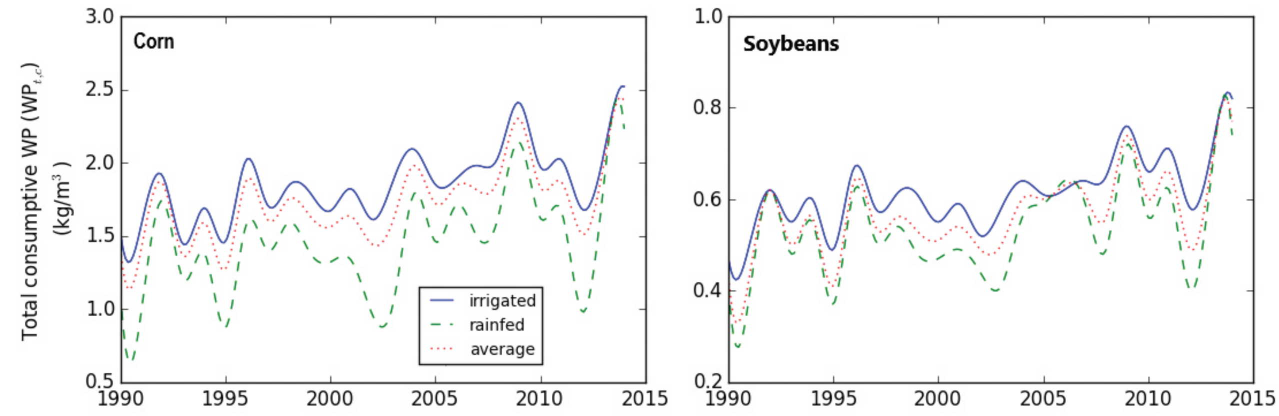


Figure 10. The WP of irrigated and rainfed corn and soybeans in Nebraska. The WP was calculated as the ratio of yield data from USDA (2017) and seasonal evapotranspiration from AquaCrop.

		Corn					Soybeans				
		Zone 1	Zone 2	Zone 3	Zone 4	State wide	Zone 1	Zone 2	Zone 3	Zone 4	State wide
Yield (Mg/ha)*	Rainfed	3.29	4.84	7.96	8.20	7.56		2.38	2.81	2.88	2.83
	Irrigated	9.88	11.46	11.86	11.98	11.73		4.39	4.10	4.14	4.14
Water Productivity (kg/m³)	Rainfed	0.94	1.03	1.72	1.69	1.63		0.45	0.59	0.59	0.59
	Irrigated	1.69	1.78	2.05	2.15	2.03		0.77	0.68	0.71	0.70

Table 3. Variation in the irrigated and rainfed yield and WP for corn and soybeans in the four agro-climatic zones and statewide. Averaged over the period 2010-2014.

*Yield data are averaged from county level USDA data.

5. Water productivity of corn and soybeans in Nebraska: temporal and spatial dimension

The results in this section are based on the modeling of yield, seasonal ET and irrigation water requirement using FAO's AquaCrop model (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009). AquaCrop is a crop growth model that simulates the daily soil water balance and biomass growth. Cumulative aboveground biomass is estimated by multiplying normalized water productivity by the ratio of crop transpiration to reference evapotranspiration (Steduto et al., 2009). In this section, we will use the total consumed water productivity indicator, as it emphasizes the water we want to conserve and provides valuable information on how the consumed water was used productively.

Temporal variation in crop water productivity based on crop modeling

Figure 10 shows that the WP of corn and soybeans improved significantly in both irrigated and rainfed lands between 1990 and 2014. The temporal variation in WP strongly matched the variation in the crop yield of the corresponding crops, demonstrating that crop WP is highly correlated with crop yield. Over the study period, the WP of irrigated and rainfed corn improved by 65% and 98%, respectively. The average corn WP improved from 1.41 kg/m^3 to 2.42 kg/m^3, primarily due to rises in corn yield over the years. Improved high yielding hybrid varieties with excellent water stress tolerance, increased planting densities, improved fertilizer use, soil management, and weed control have contributed to increasing crop yields. Similarly, irrigated and rainfed soybeans WP improved by 72% and 79%, respectively.

Spatial variation in crop water productivity

A summary of the irrigated and rainfed yield and WP of corn and soybeans per zone is provided in Table 3. Compared to the rainfed condition, the irrigated yields and WPs are larger for both crops in all zones. The yield and WP of both irrigated and rainfed corn decreases from eastern (Zone 4) to western (Zone 1) Nebraska. The lower irrigated yield of both crops in the western portion of the state is mainly due to the shorter growing season in the west. The reduction in yield and WP from east to west is more pronounced for rainfed corn. The lower rainfed yield and WP in the western part of the state (Zone 1 and 2) is primarily due to the higher evaporative demand combined with the lower amounts of precipitation compared to the eastern and central portions of the state (see the precipitation map in Figure 2). In addition, the soil in western Nebraska is weathered sandstone that has a lower water holding capacity compared to central and eastern part of the state. For soybeans, the spatial variation in the WP is not clear. For irrigated soybeans, Zone-2 has relatively larger WP.

Figure 11 shows the spatial variation in the WP for corn and soybeans. The climate gradient from east to west is reflected on the WP, which falls from east to west Nebraska, especially for the rainfed corn and soybean crops. The spatial variation in WP can be explained in part by variation in climate and soil across the state. In the east the crops are mostly rainfed because there is enough rainfall for viable crop production. In the west where rainfall is smaller, irrigation is required for optimum crop growth. Under sufficient irrigation, plants will not experience water stress and as a result will have higher yield and WP. In the northeastern part of the state (Lower Elkhorn, Lewis & Clark, and Papio-Missouri River NRDs), the WP of rainfed crops, particularly for corn, is relatively large because of the higher rainfed yield (see Figure 6) in this region. The relatively large WP of the rainfed fields in Upper Loup NRD is not due to higher yields rather because of relatively low actual evapotranspiration over the growing season that is generally lower than the potential evapotranspiration due to the lower precipitation in the region.

Water productivity of corn and soybeans in Nebraska: temporal and spatial dimension

Benchmark values for the WP of corn and soybean

The relationship between corn and soybean yield and ET during the growing season is shown in Figure 12. Each point represents actual crop yield and modeled ET for a particular county and year between 2010 and 2014. This period includes years with normal rainfall and a year with severe drought (2012). For both corn and soybeans, the variation in yield is larger in the rainfed than irrigated fields. The rainfed yield for corn varies between 0.7 and 12.0 Mg ha^{-1} and for soybeans between 0.4 and 3.9 Mg ha^{-1}. This is due to variation in the evaporative demand and rainfall over the state in different years. There is large state-wide variation in the WP of both crops due to differences in climate, soil and water management, planting date, and duration of the growing period. The slopes shown in Figure 12 represent the top 20th percentile of crop production for each crop with the largest WPs (benchmark values), differentiating between agro-climate zones and between irrigated and rainfed fields. The WP benchmark value of irrigated corn gradually rises from west to east of Nebraska. The benchmark is larger for irrigated than for rainfed corn. The WP benchmark of rainfed corn in Zone 1 is significantly lower than in the other zones, owing to very low precipitation. Soybeans WP benchmarks varies very little across the three zones and between irrigated and rainfed fields. The WP

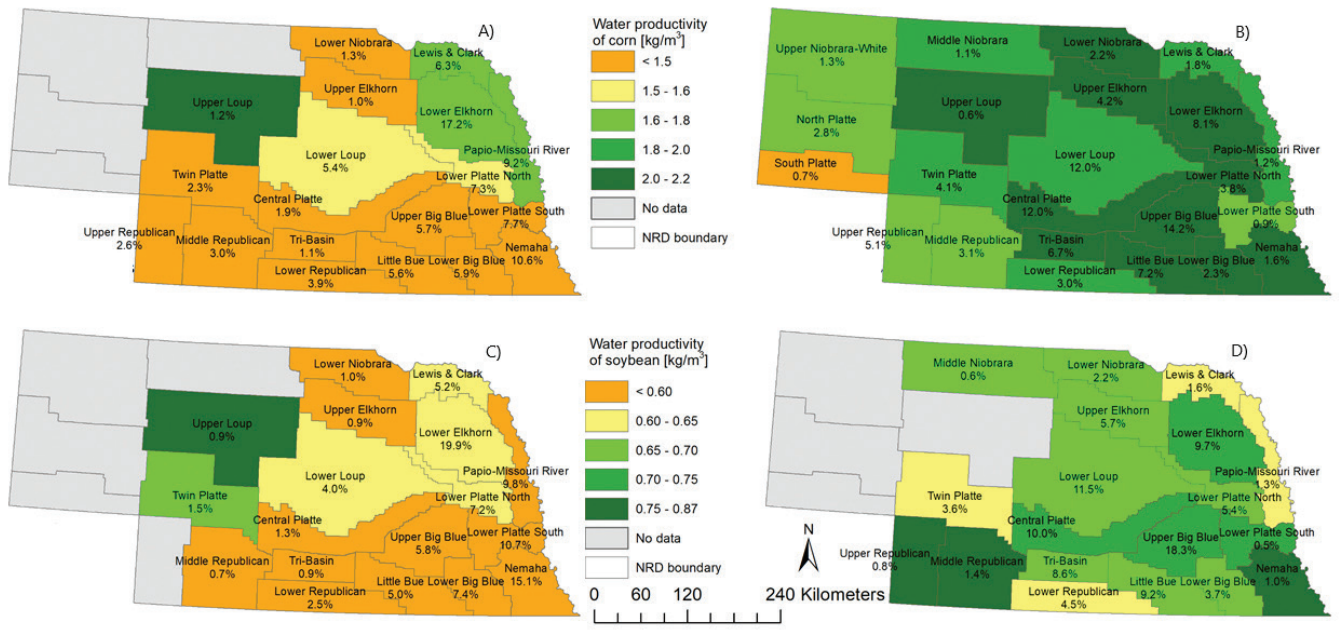


Figure 11. The WP for rainfed (A) and irrigated (B) corn, the WP of rainfed (C) and irrigated (D) soybeans at NRD level. The WP at NRD was derived as production-weighted average of the grid data. The percentages show each NRD's contribution to the total rainfed and irrigated crop production of the state. NRDs with contribution below 0.5% are shown as no data. The values represent average of 2010-2014.

benchmark of irrigated and rainfed soybeans is larger in Zone 2 than in Zones 3 and 4. For irrigated soybeans, larger WP benchmark in Zone 2 is due to a relatively larger yields in Zone 2 than in Zones 3 and 4. The larger WP benchmark for Zone 2 for rainfed soybeans is due to comparatively lower actual seasonal ET, which is usually smaller than the potential ET due to lower rainfall in Zone 2 thank in Zones 3 and 4.

The first step toward decreasing the water footprint of crop production is to set WP benchmarks per agro-climate zone. The observed wide variation in county level WP shows the presence of non-climate factors affecting the WP. Thus, factors that affect yield and WP in different areas across the state need to be identified and WP benchmarks defined taking into account state-wide variations in climate and soil properties.

The actual WP and WP gap for corn and soybeans are shown in Figure 13. The WP gap was calculated by subtracting the 20th percentile benchmark value (Figure 12) from the actual WP. For both irrigated corn and soybeans the WP gaps are due to other limiting factors besides water. The actual WP can be limited by factors such as pests, soil properties, cold stress, frost, and management practices.

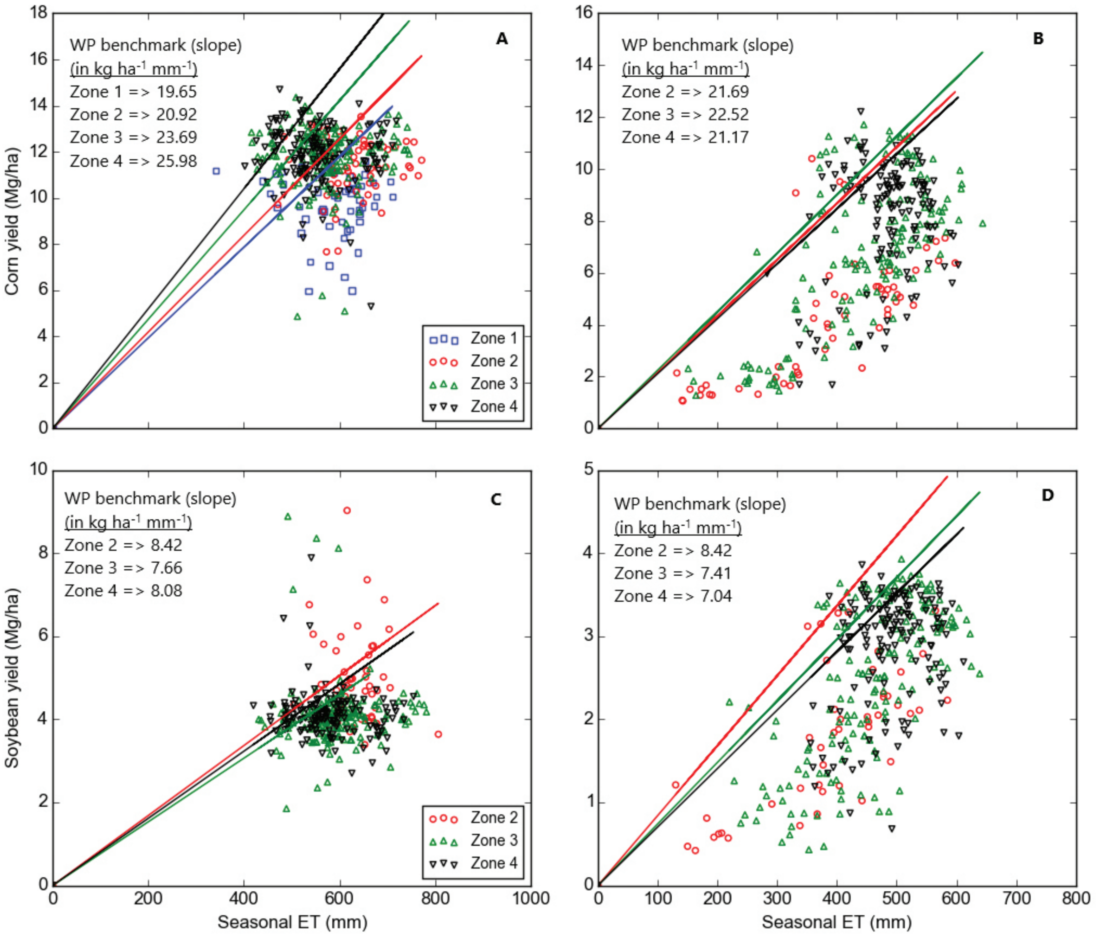


Figure 12. Relationship between county specific crop yield and seasonal ET for irrigated corn (A) and rainfed corn (B), and for irrigated soybeans (C) and rainfed soybeans (D) in Nebraska. Each data point represents the combination of yield and ET in a specific county and year from 2010 to 2014. Each colored cloud represent one climate zone. The WP benchmark of each climate zone is displayed as a line in the ET-Y graph and written in each figure's top left corner. Soybeans and rainfed corn are less common in Zone 1.

Water productivity of corn and soybeans in Nebraska: temporal and spatial dimension

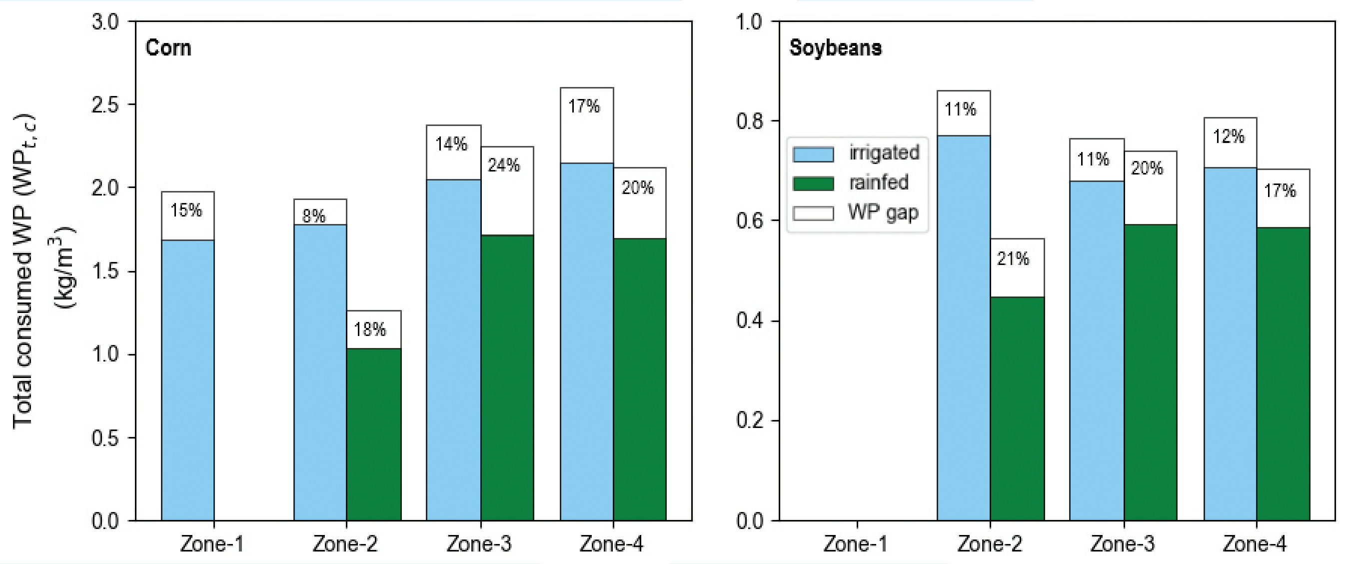
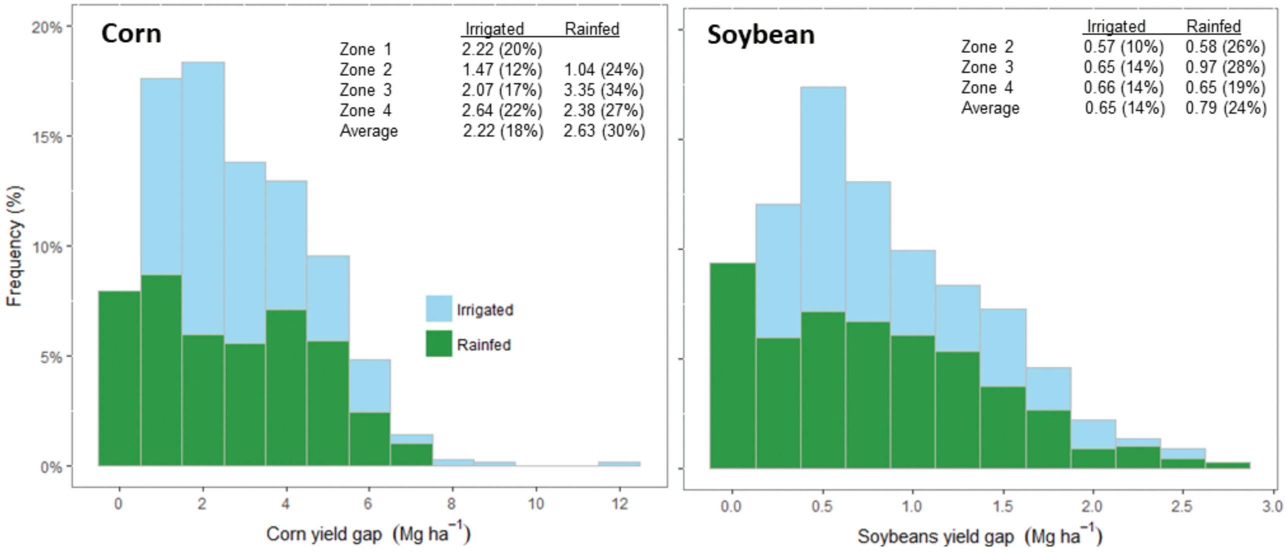


Figure 13. Actual WP and the WP gap for irrigated and rainfed corn and soybean across Nebraska's four zones. The shaded part shows the actual WP and the portion in white shows the WP gap. The WP gap expressed as a percentage of the potential WP is also shown. Soybeans and rainfed corn are less common in Zone 1. The data are averaged over the period 2010-2014.

Yield increases when closing the WP gaps

Reducing a WP gap means either increasing yield at a given ET or decreasing ET at a given yield. Significant yield increases can be accomplished by reducing gaps in WP. This can lead to important water savings if the increase in yields is accompanied by decrease in total harvested areas. The WP benchmark per crop per climate zone was used to evaluate the yield gap, which is calculated by subtracting the observed county level corn and soybeans yields from the estimated potential yields. Figure 14 displays yield gaps for irrigated and rainfed corn and soybeans. The two crop yield gaps differs extensively owing to state-wide variability in climate, soil properties and crop cultivars. The yield gap varies from 1.04 to 2.4 Mg ha^{-1} for rainfed corn and from 1.5 to 2.6 Mg ha^{-1} for irrigated corn. The yield gap for soybeans ranges from 0.58 to 0.97 Mg ha^{-1} for rainfed areas and from 0.57 to 0.66 Mg ha^{-1} for irrigated areas. The average corn yield gap in Nebraska for irrigated and rainfed areas was 2.2 Mg ha^{-1} and 2.6 Mg ha^{-1}, respectively. The average yield gap for soybeans was 0.65 Mg ha^{-1} and 0.79 Mg ha^{-1} for irrigated and rainfed areas, respectively. Closing the WP gap will help to close the yield gap, making it possible to produce the same quantity of crop with less water, thereby decreasing the pressure on the groundwater resources of the state. Optimal soil, fertilizer, and water management will be required to close the water and yield gaps. The production of corn and soybeans in the state can be increased by as much as 21% and 19%, respectively if the actual WP levels in both rainfed and irrigated agriculture are raised to benchmark levels in each climate zone.

These findings demonstrate that WP can still be improved in the production of corn and soybeans; yields can be further improved by closing the gaps in WP without increasing the stress on the water resources. If total production levels of corn and soybeans are kept constant by increasing yields and decreasing cropped area, the overall water consumption of crop production in the state can be efficiently decreased.



	Irrigated	Rainfed
Zone 1	2.22 (20%)	
Zone 2	1.47 (12%)	1.04 (24%)
Zone 3	2.07 (17%)	3.35 (34%)
Zone 4	2.64 (22%)	2.38 (27%)
Average	2.22 (18%)	2.63 (30%)

	Irrigated	Rainfed
Zone 2	0.57 (10%)	0.58 (26%)
Zone 3	0.65 (14%)	0.97 (28%)
Zone 4	0.66 (14%)	0.65 (19%)
Average	0.65 (14%)	0.79 (24%)

Figure 14. Frequency distribution of yield gaps for corn and soybean across Nebraska's four zones. The yield gaps were calculated as a difference between the WP benchmarks and actual yield. The average yield gaps (2010-2014) for irrigated and rainfed areas are shown in absolute terms (Mg ha-1) and as percentage of the potential yield per climate zone.

Water productivity of corn and soybeans in Nebraska: temporal and spatial dimension

Newly-planted corn growing in a field.

Water productivity can be raised by either producing more crop per hectare with the same ET level, or reducing ET per hectare while producing the same amount of crop (or a combination of both). Better crop cultivars and nutrient and pest management can help to increase crop production per hectare, while interventions such as mulching, deficit irrigation and precision irrigation can help to reduce ET. Soil mulching can decrease unproductive soil evaporation without influencing crop yield, thereby increasing WP. Deficit irrigation can boost WP by decreasing net irrigation application and evapotranspiration during less sensitive portions of the growing seasons, potentially at the expense of some yield, but with a percentage of yield loss significantly lower than the percentage of water savings. Precision irrigation allows for different irrigation application rates across the fields according to local irrigation requirements, thereby reducing overall water use.

Increasing water productivity is one factor among others, such as farmers' income, sustainable use of groundwater and streams, and reduced level of water pollution from excessive nutrient use, indicating successful water and agricultural management. All of these factors need to be taken into account in order to understand potential trade-offs (Giordano et al., 2017).

6. The water productivity of livestock products in Nebraska

The livestock sector is an important source of protein, as well as a producer of income and livelihood. It also often has negative impacts on the environment in the form of GHG emissions, water pollution and depletion, and land degradation (Bouwman et al., 2013; Capper, 2011; Deutsch et al., 2010; Mekonnen and Hoekstra, 2012; Pelletier and Tyedmers, 2010; Steinfeld et al., 2006). However, there are some promising trends observed that may reduce environmental externalities. These changes include the increase in livestock productivity and the corresponding decline the amount of feed consumed per unit of output produced and the shift to monogastric animals (poultry and swine) that are relatively more efficient in converting feed to animal products compared to ruminants.

In the U.S., Nebraska is first in commercial red meat production and second in total cattle inventory (USDA, 2017). In 2016, the total value of the livestock sector (including poultry) in Nebraska was $12.2 billion, which was equivalent to 54% of the total economic value of the state's agricultural sector (USDA-ERS, 2017).

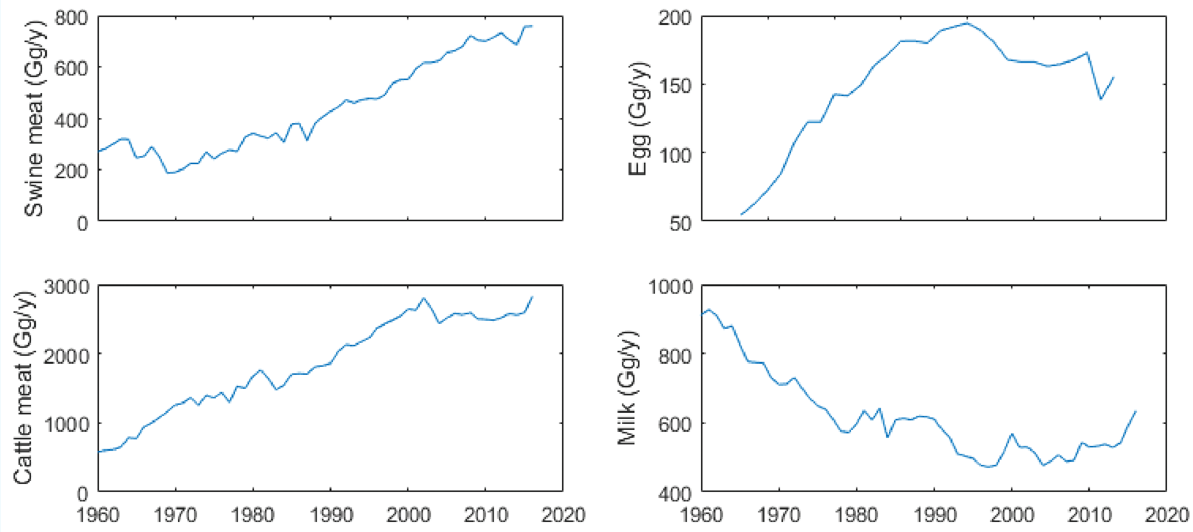


Figure 15. Trends in livestock products output in Nebraska from 1990 to 2016. Data from USDA (2017).

Given its importance to the state's economy and its impacts on the water resources, there are surprisingly few studies on the water productivity of the different livestock products. This report tries to fill this gap by estimating the WP of different livestock products. Here DWFI looked at the full animal production cycle: breeding animals, young animals, growing replacement animals, growing market animals and finished market animals for multiple animal categories. Detail on the method and result for the U.S. are available in a separate published article (Mekonnen et al., 2019).

Trends in livestock production and productivity

Between 1960 and 2016, livestock products output (carcasses of swine and cattle, and eggs) has increased considerably, as shown in Figure 15. The largest increase was observed in cattle meat production, which increased 4.9 times from 1990 to 2016. The second largest increase was for swine meat production, which increased 2.8 times during the same period. Egg production initially increased 1.8 times from 1988 to 2005 then started to decline, with a net increase of 80% between 1988 and 2016. Milk production, on the other hand, showed a 30% drop between 1960 and 2016.

While the production of total animal products has almost quadrupled, the associated animal feed requirement has increased by only 2.5 times from 1960 to 2016. The relatively smaller increase in total feed requirement compared to the increase in animal production was mainly due to the increase in the livestock productivity (Figure 16) and improvement in the nutritive value of feeds. Cattle meat and pork production per head of animal increased by 46% and 42% between 1960 and 2016, respectively. Milk production per dairy cow increased by 380% from 1960 to 2016. Egg production per layer chicken has also increased by 18% between 1988 and 2016, with a slight decline in 2016.

The feed conversion ratio (FCR), which is the ratio of amount of dry matter (DM) consumed to amount of animal product output (meat, milk, egg), has decreased for all livestock (blue line in Figure 16). Dairy cows had the largest drop in the FCR, with a decline of 68% between 1960 and 2016. In the same period, the FCR decreased by 30% and 20% for swine and beef cattle, respectively. For layer chickens, the decrease in the FCR was 12% from 1988 to 2016. Fewer animals were needed to produce relatively large quantity of livestock products. For instance, in 2016, 38% fewer dairy cows produced 4% more milk than in 1990 (USDA, 2017).

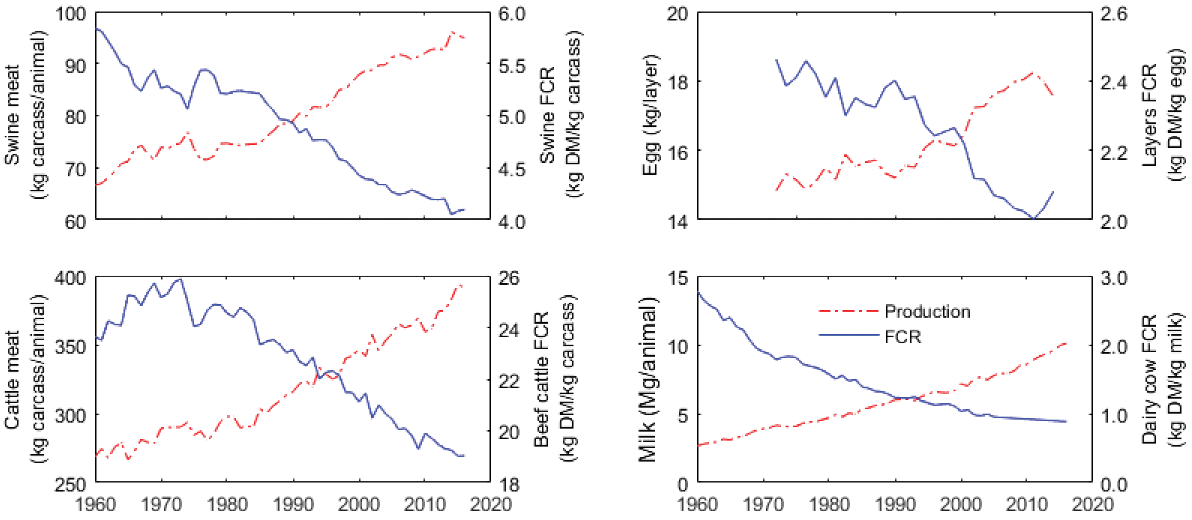
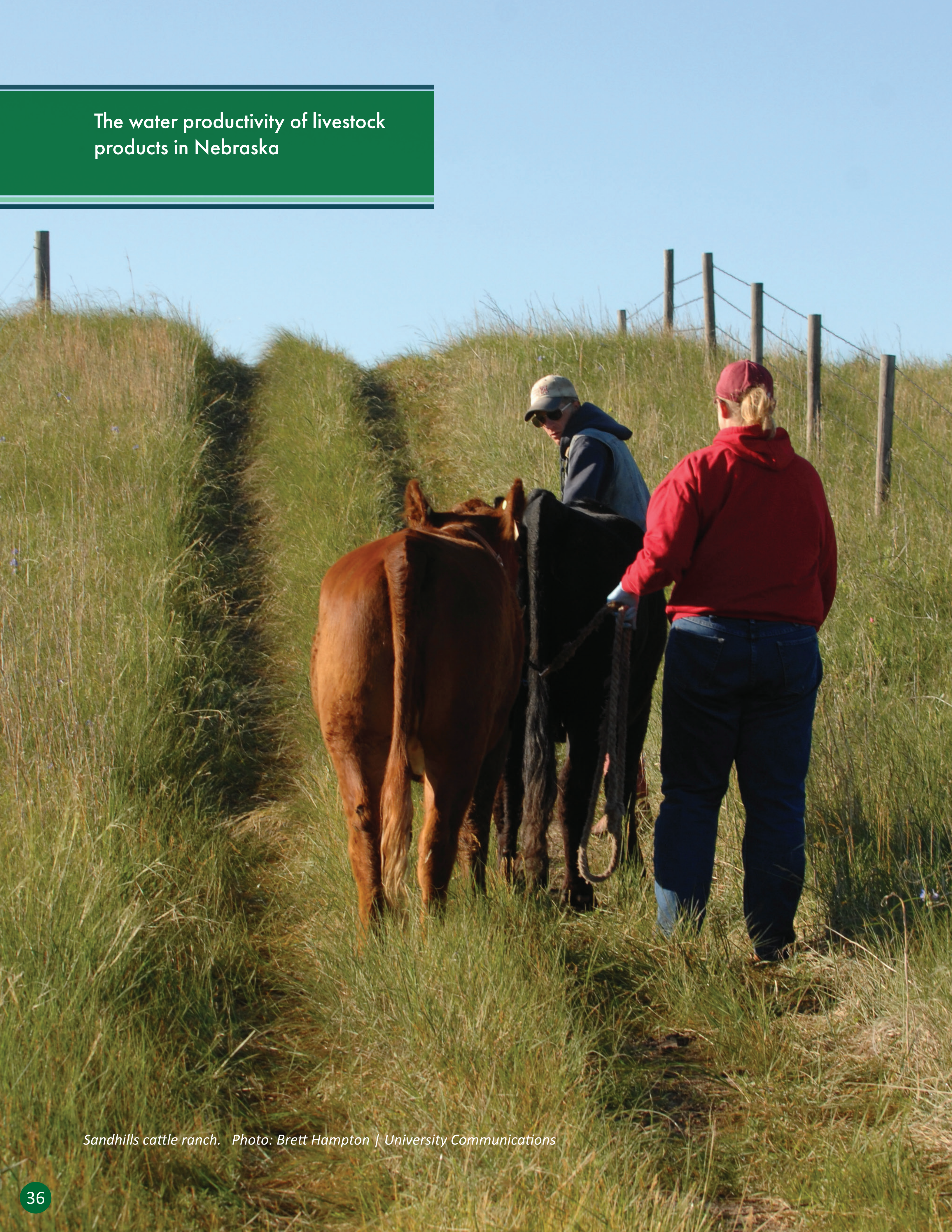


Figure 16. Animal products output per animal and FCR for swine, beef cattle, layer chickens, and dairy cows in Nebraska from 1960 to 2016. Animal products output per animal data from USDA (2017).

The water productivity of livestock products in Nebraska



Sandhills cattle ranch. Photo: Brett Hampton | University Communications

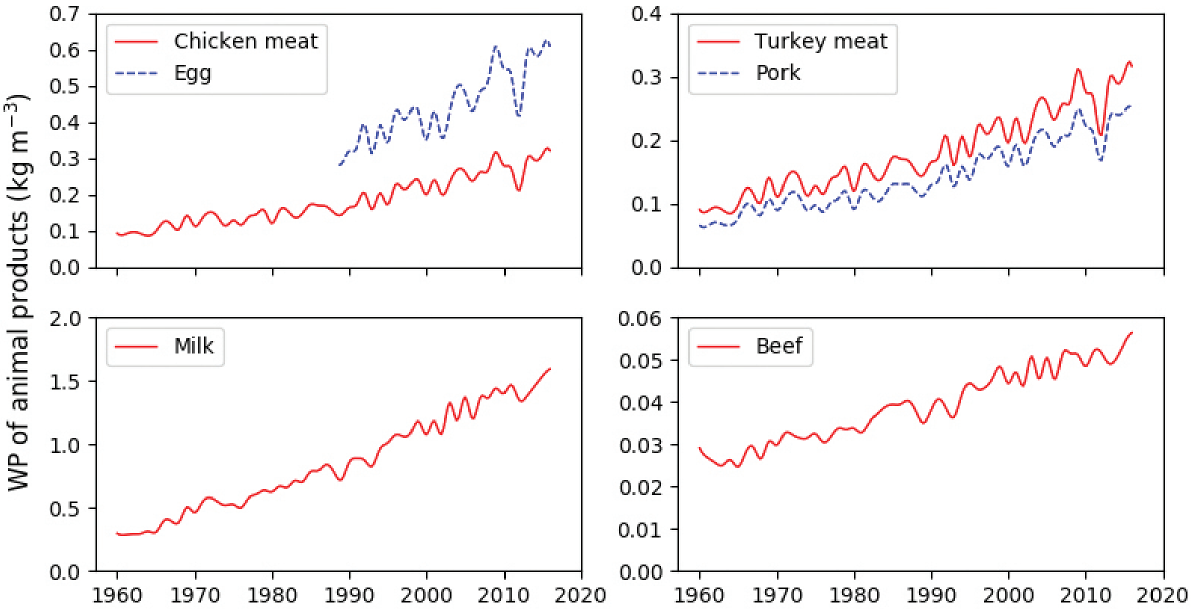


Figure 17. Changes in the WP of livestock products for Nebraska. Egg production data is available from 1988 onwards.

Improvements in the water productivity of livestock products

From 1960 to 2016, the WP of all livestock products in Nebraska increased significantly (Figure 17). The largest increase was for dairy milk, which rose 5.1 times, followed by pork, which rose 3.8 times from 1960 to 2016. During the same period, poultry products (chicken and turkey meat) and beef WP increased 3.5 times and 1.8 times, respectively. The increase in the WP is due primarily to an increase in livestock productivity (output per head) as shown in Figure 16, a decrease in FCR, and an increase in feed crop yields that resulted in a decrease in the average feed WF. The fluctuations in WP of the livestock products around the growing trend lines are due primarily to inter-annual rainfall variations. The declines in WP occur during dry years when feed crop yields fall due to shortage of rainfall. The biggest decrease in WP occurred in 2012, which was a major drought year (Scientific American, 2013). The drought has particularly affected rainfed feedstuffs, causing a relatively large decrease in the WP. Also impacted were irrigated feeds, but the effect of droughts was minimized due to the use of irrigation water.

While, there are encouraging improvements in the WP of livestock products, the question is whether these improvements will continue. Another pertinent question is what benchmark should be used to assess the progress in the WF of livestock. Unlike the efforts to benchmark the WP or WF of crops (Chukalla et al., 2017; Edreira et al., 2018; Mekonnen and Hoekstra, 2014), there are none for livestock products. Setting benchmarks, estimating the WP gaps, and identifying the critical factors affecting consumptive water use are potential future areas of research.

Difference in the water productivity of livestock products

Figure 18 (A) shows the WP in kg/m^3 of the six livestock products in Nebraska. The WP of livestock products depend mainly on the feed conversion ratio and the composition of feed the animal consume. The average WP of the different livestock products ranges from 0.05 kg/m^3 for beef to 1.46 kg/m^3 for milk.

To account for differences in the nutritional value of animal products, we normalized the WP values in terms of the protein and energy content of the final livestock

The water productivity of livestock products in Nebraska

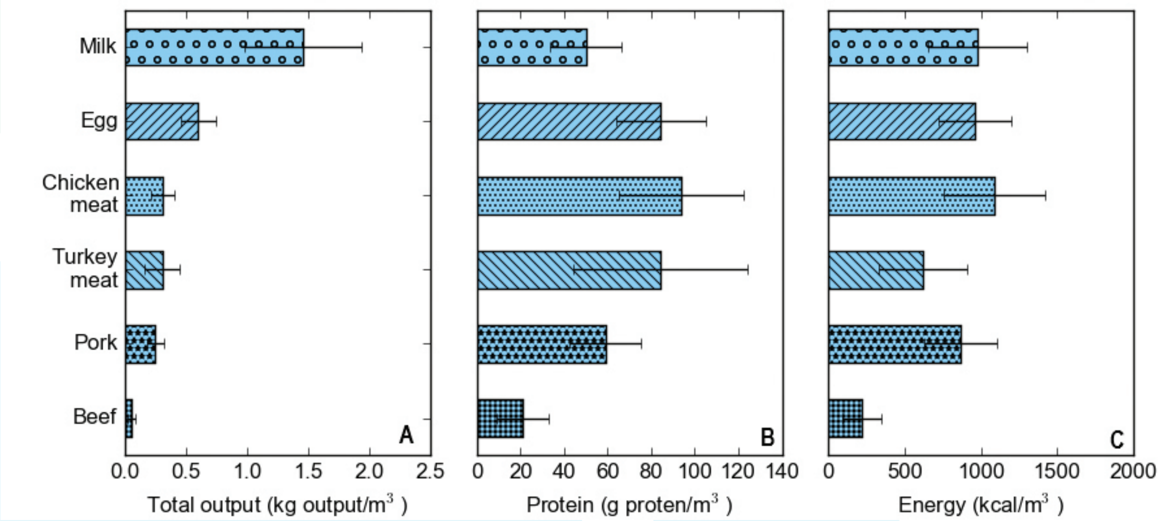


Figure 18. Water productivity of the livestock products in terms of product weight (A), protein content (B), and energy content (C) of the animal product per cubic meter of water consumed, in Nebraska. The values are averaged over 2014-2016. Variability is shown through the standard deviation (±1SD) around the mean.

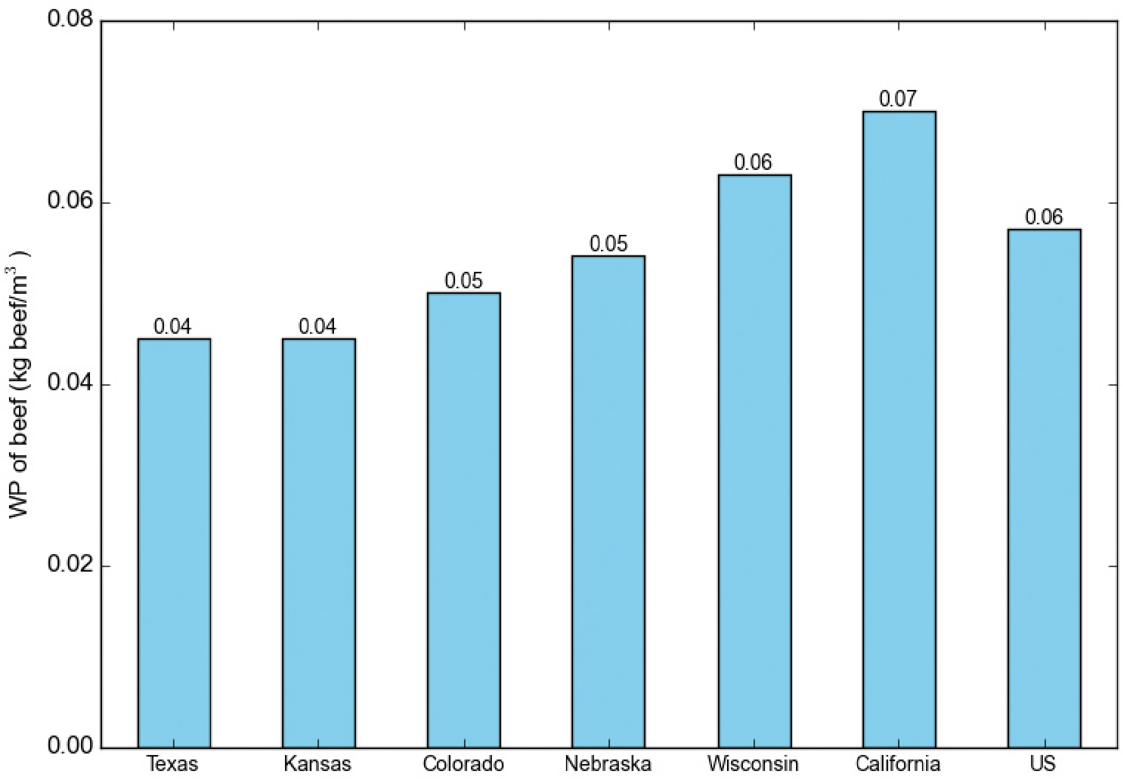


Figure 19. Water productivity of beef for Nebraska, U.S. average and other five major beef producing states, averaged over the period 2014-2016.

products. Comparing WP across animal products on the basis of the nutritional content (protein or energy) per cubic meter of water consumed instead of on the basis of the product weight obtained per cubic meter of water consumed provides a different perspective (Figure 18 B and C). When we evaluate the energy content of the final product (Figure 18C), milk and chicken meat have the largest WP, followed by pork and eggs. In terms of protein content of the final product (Figure 18B), poultry products (chicken meat, turkey meat, and eggs) have the largest WP, followed by pork and cattle milk.

The quality of the feed plays an important role in determining the WP of livestock products. Swine and poultry depend fully on energy dense concentrate feeds, such as corn, soybeans and oil meals. On the other hand, beef cattle rely largely on low energy density pasture (42%) and forage (39%). Such low-quality feed plays an important role in lowering the WP of beef. The type of feed and how it is sourced has an important implication on water sustainable livestock production. The beef cattle and dairy cows to a certain extent depend on pasture that is rainfed and on land that may not be suitable for crop production or other alternative uses. Thus, the low WP of beef doesn't directly translate to high impact on freshwater systems. On the other hand, swine and poultry production is highly intensive and dependent on concentrated feeds that are grown in intensive agricultural production systems with irrigation and fertilizer use. Under such conditions, swine and poultry products, which have higher WP, may have larger impacts on the quality and quantity of freshwater.

By increasing the livestock productivity and decreasing the feed's WF, the WP of livestock products can be enhanced. Selecting feeds with lower WF, using by-products and crop residues instead of primary crops, and getting feeds from places where the WF is lower will help to reduce the feed's WF. In the case of Nebraska, where more than 80% of the irrigation water is pumped from the Ogallala Aquifer, the use of by-products and crop residues will help to reduce the overall groundwater pumping to produce feed.

Comparison of the WP of beef in Nebraska and other selected states

The WP of beef in Nebraska is relatively larger compared to Texas, Kansas and Colorado, but smaller than Wisconsin, California and the U.S. average (Figure 19). The WP of beef in Nebraska is 21% larger than the WP of beef in Texas and Kansas, but 23% smaller than California's average. The higher WP of beef in Nebraska compared to Texas, Kansas and Colorado is due to the combined effect of difference in the livestock productivity (production of beef per head of animal) and differences in the water footprint of the feeds the animal consume. Cattle in Nebraska produce on average 2-9% more meat per head compared to the other states and the U.S. Kansas and Texas have the smallest WP of beef compared to other states due mainly to their larger WF of cattle feeds. Corn yield in Nebraska, for example, is 23% higher than in Kansas and 32% higher than in Texas. In Texas, beside the low yield of the feeds, the dry and hot climate increase the evaporative demand further increasing the water footprint of the feeds. Among the major beef producing states, California has relatively large WP of beef because of the lower WF of forage feeds compared to the other states. The lower WF of forages in California is due to higher yields in the state compared to the others. Yield of alfalfa hay in California is 70% larger than in Nebraska and the yield of other hay in California is more than double that of Nebraska.

Sugarcane crop growing in Brazil.

7. The water, energy, and carbon footprint of bioethanol from Nebraska and Brazil

Over the last few decades, the bioethanol industry has become an important source of fuel and source of income in Nebraska. With a bioethanol production capacity of about 8 million cubic meters, Nebraska is the second largest bioethanol producing state after Iowa in the country (USDA-ERS, 2018). Globally, the bioethanol industry is promoted as a means to reduce greenhouse gas (GHG) emissions, secure domestic energy supply, and promote economic development. However, several questions were raised regarding its actual benefits in reducing GHG emissions, its energy balance, and its effects on water quality and quantity. In this section, we present the results from the assessment of the water, energy and carbon footprint of bioethanol from Nebraska's corn and compare it against bioethanol from Brazil's mostly rainfed sugarcane.

To estimate the energy and carbon footprint of bioethanol from corn and sugarcane, we used the GREET model developed by the Argonne National Laboratory, U.S. Department of Energy. Detail on the method and result per state are available in a separate published article (Mekonnen et al., 2018).

Water footprint of bioethanol

The water used in bioethanol plants contributes very little to the total WF of bioethanol. Almost all of the WF is related to the direct and indirect water consumption in crop production, which accounts for 99.2% of corn and 95.1% of sugarcane bioethanol WF (Table 4). The total consumptive WF of bioethanol from Brazil's sugarcane is 1.4 times larger than that of bioethanol from Nebraska's corn. The smaller WF of corn bioethanol per unit of ethanol compared to sugarcane bioethanol is mainly due to corn's larger bioethanol yield per unit mass and the large WF credited to the co-product distiller grains (DGS). About 45% of the WF of corn bioethanol is credited to the DGS that displaces corn and soybeans in animal feed and urea in nitrogen fertilizer production. In Nebraska, 65% of the corn is produced from irrigated fields, thus

Inputs	Water footprint (L/ Mg of crop)			
	Corn		Sugarcane	
	Blue	Green	Blue	Green
Seed	345	947	125	3,208
Fertilizer & agrochemicals	11		1.9	
Energy inputs	182		34	
Limestone	1,650		762	
Crop water footprint	166,458	386,972	3,934	100,801
Total agricultural phase	168,646	387,919	4,858	103,909
	Water footprint (L/ L of bioethanol)			
Total agricultural phase	397	913	56	1,204
Bioethanol production	2.7		19	
Total water footprint	400	913	76	1,204
Water credit to co-product	108	430	10	155
Water input allocated to bioethanol	292	484	66	1,049

Table 4. The consumptive (green and blue) water footprint of corn and sugarcane bioethanol.
Source: Result is taken from Mekonnen et al. (2018)

	Unit	Corn	Sugarcane
A. Crop production and transport	MJ/L of bioethanol	3.03	3.17
B. Bioethanol production stage	MJ/L of bioethanol	9.24	0.37
C. Energy credit to co-product	MJ/L of bioethanol	1.90	
D. Net energy input (A+B-C)	MJ/L of bioethanol	10.4	3.54
E. Energy output in the form of bioethanol	MJ/L of bioethanol	21.3	21.3
F. Energy balance (E-D)	MJ/L of bioethanol	10.9	17.7
G. Energy Ratio (E/D)	MJ of output/MJ of input	2.1	6.0

Table 5. Energy footprint, energy balance, and energy ratio of bioethanol.
Source: Result is taken from Mekonnen et al. (2018)

The scenic Platte River in Nebraska.

the blue WF of bioethanol of Nebraska's corn is 4.4 times larger than the WF of bioethanol from Brazils sugarcane. There is also a difference in the WF credited to the co-products of corn and sugarcane bioethanol. In the case of bioethanol from sugarcane, the credit to co-products was only 13%. For corn bioethanol, about 41% of the WF of corn bioethanol is credited to DGS that is co-produced and a useful animal feed. This underlines again the important contribution of DGS in replacing corn and soybean crops in animal feed, thus reducing the WF of corn bioethanol and, at the same time, improving the WP of livestock products as shown earlier.

Energy and carbon footprint of bioethanol

Recent studies have shown that corn bioethanol provides more energy than required to produce it, settling the debate whether bioethanol has a positive or negative energy balance. The current study confirms the findings from these studies (Farrell et al., 2006; Liska et al., 2009), that corn bioethanol indeed has a positive energy balance and lower GHG emissions than gasoline. Bioethanol from Nebraska's corn and Brazil's sugarcane have a positive energy balance (Table 5). Bioethanol from sugarcane produces more energy per unit of fossil fuel inputs, with an energy ratio of 6.0, compared to bioethanol from Nebraska's corn. The energy ratio of corn bioethanol is 2.1, indicating that for every unit of fossil fuel input in the production of corn bioethanol, 2.1 times more energy is produced as bioethanol.

The carbon footprint of bioethanol from Nebraska's corn and Brazil's sugarcane is summarized in Table 6. Both the corn and sugarcane bioethanol have lower GHG emission intensities, with 53% and 59% lower GHG emission than gasoline, respectively. Bioethanol from sugarcane again performs better in terms of GHG reduction compared to corn bioethanol.

In the case of Nebraska's corn, since more than 99% of the WF of the bioethanol is related to water that is used during the crop production stage, raising the corn WP will reduce the overall WF of bioethanol. On the other hand, the bioethanol production stage contributes about 75% to the total energy use (Table 5) and 61% to the GHG emission (Table 6) of the corn bioethanol. Therefore, actions directed at improving the energy and carbon footprints of bioethanol from corn need to focus on the bioethanol processing stage.

	Corn	Sugarcane
A. Crop production and transport	18.7	19.0
B. Bioethanol production stage	29.9	3.29
C. Credit to co-product	-9.93	
D. Net GHG emission without LUC (A+B+C)	38.7	22.3
E. Land use change (LUC)	7.88	16.00
F. Credit to DGS related to LUC	-2.14	
G. Net emission with LUC (D+E+F)	44.4	38.5
H. GHG reduction relative to gasoline (%)*	53%	59%

Table 6. Carbon footprint of bioethanol from corn and sugarcane (g CO_2eq/MJ).
** The GHG intensity of gasoline is taken as 94 g CO_2eq MJ-1 (Farrell et al., 2006)*
Source: Result is taken from Mekonnen et al. (2018)

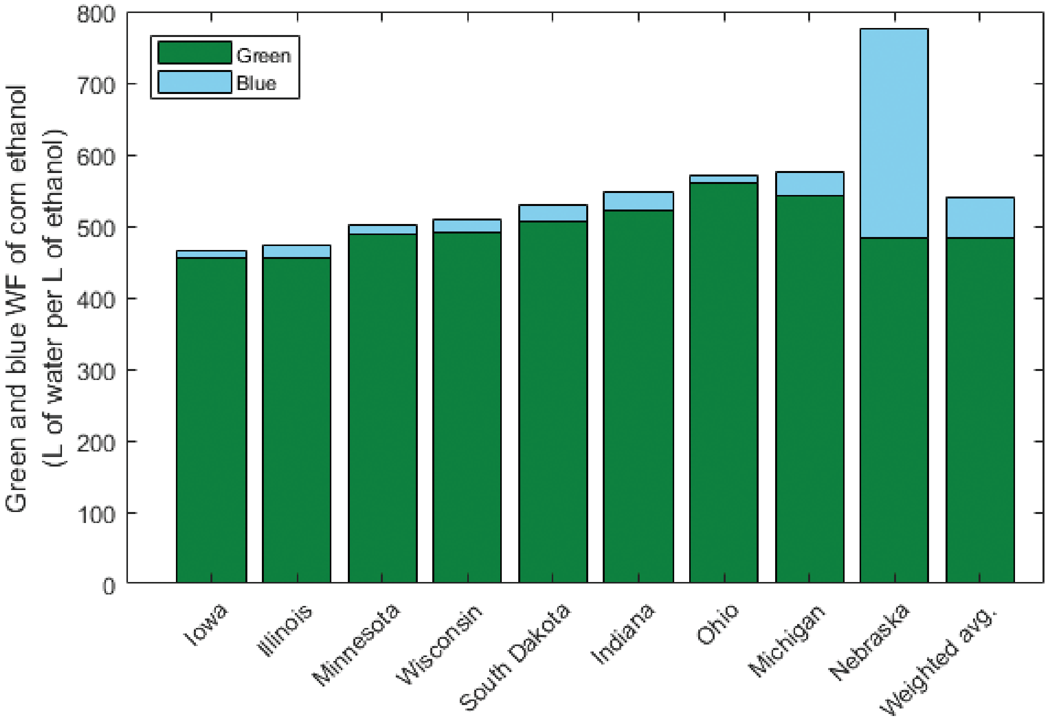


Figure 20. The green and blue WF of bioethanol for the nine major bioethanol producing states in the US. Source: Mekonnen et al. (2018)

An expansive Nebraska cornfield. Photo: Frances Hayes | DWFI

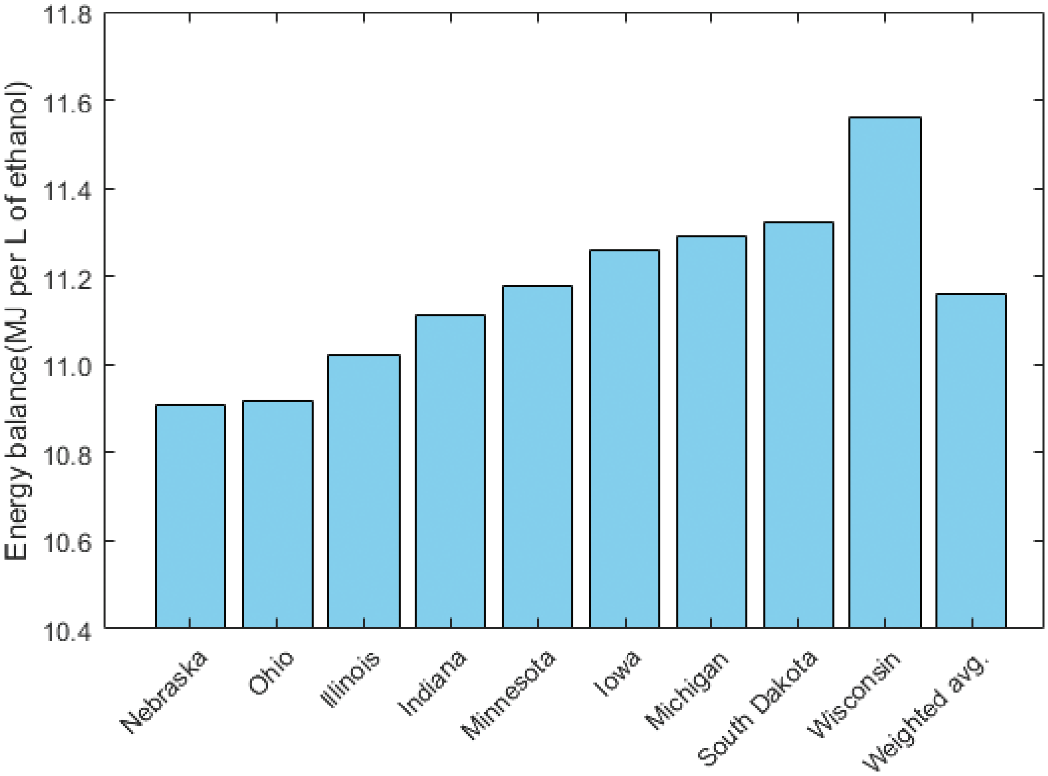


Figure 21. The energy balance per unit of bioethanol produced for the nine major bioethanol producing states in the US. Source: Mekonnen et al. (2018)

Comparison of the water footprint and energy balance in Nebraska and other selected states

Figure 20 shows the WF of bioethanol for the major bioethanol producing states in the U.S. The WF of corn bioethanol shows spatial variation due to differences in crop yield and evapotranspiration in the nine states. Due to a relatively large crop water use (m^3/ha) from extensive irrigation and a relatively low crop yield, Nebraska has a large blue and total WF compared to the other states. Nebraska's crop water use (m^3/ha) was 32% larger and its corn yield in the period 2014-2016 was 5% lower than that of Iowa, where rainfed corn has the smallest consumptive WF. About 65% of the corn Nebraska's production comes from irrigation, which is reflected in the larger blue WF of bioethanol in the state compared to others.

Figure 21 shows that Wisconsin and South Dakota have the most positive energy balance (net energy produced per liter of bioethanol), with Nebraska and Ohio have the smallest net energy per unit of bioethanol produced. Nebraska's relatively low net energy per volume of bioethanol produced is primarily due to the relatively large diesel and electricity consumption per unit of corn produced. Approximately two-thirds of the corn produced in Nebraska comes from irrigated fields. Most of the irrigation water comes from groundwater, requiring considerable energy to pump groundwater. Iowa, which accounts for 19% of the corn and 26% of national bioethanol production in 2016 (RFA, 2017; USDA, 2017), has a relatively high positive energy balance, due to rainfed crop production and high crop yields. Iowa has some of the US highest corn yields and the lowest energy input per unit of corn produced compared to the other states. Farmlands in Iowa rely heavily on rainfall, which requires less energy for irrigation, contributing to the state's low energy intensity of corn.

Discussion

Corn silks on a farm near Albion, Nebraska.   Photo: Frances Hayes | DWFI

8. Discussion

Nebraska has one of the most highly productive cropping systems in the country and world. Over the last 25 years, corn and soybean yields have grown considerably. This significant increase in grain yields, combined with the adoption of improved farm level management, advanced irrigation systems, and regulatory limits on irrigation pumping, has helped improve the WP of crop production in the state. From 1990 to 2014, the WP of soybeans and corn increased by 79% and 71% respectively.

The irrigation application rate in the three NRDs (Central Platte, Lower Niobrara, and Tri-Basin) studied has dropped on average by 20% for corn fields and by 8% for soybean fields between 2004 and 2013. Farmers benefit from reducing applied irrigation in the form of reduced pumping cost, and reduced fertilizer and chemical leaching.

Geospatial gradients in precipitation and soil quality have large impacts on the spatial variation of WP across the state. WP, particularly for corn, showed spatial trends, increasing from the western to eastern part of the state. This spatial variation is consistent with the variation in precipitation and soil productivity that exists across the state. Such variation indicates the potential opportunity to increase WP in those areas where the current WP is low or to find alternative crops for those regions. In addition, the relationship between the yield and applied irrigation is curvilinear by nature, illustrating the diminishing rate of return at higher applied irrigation levels. The yield initially increases at a faster rate with an increase in applied irrigation depth but level out as it reaches its maximum. Further increases in irrigation will not provide an equivalent increase in yield. This curvilinear relationship highlights the need to optimize both the yield and WP, instead of aiming for higher yield alone. Combining different field-level management strategies can enable raising WP. What's more, aiming for the maximum WP may not optimize the farmers income; therefore, WP should not be an objective by itself (Giordano et al., 2017).

Beside the WP, other objectives such as increasing crop production, raising the income of farmers, limiting groundwater decline and drying up of streams, and limiting water pollution from excessive nutrient use are very important and need to be taken into consideration.

The livestock sector is an important part of Nebraska's economy, contributing about 54% of the total economic value of the agricultural sector in 2016. Livestock production has increased considerably in the last few decades. There was also a large increase in livestock productivity, which has helped to minimize the rate of increase in livestock feed requirement. The WP of the different livestock products has increased significantly. These improvements in livestock productivities are very encouraging. The issue is how to further increase and sustain higher WP. Unlike the different crops, livestock products lack WP benchmarks that could be used as a yardstick to measure the progress in the WP. Therefore, setting benchmarks, estimating the WP gaps, and identifying the critical factors affecting consumptive water use are potential future research areas in the livestock sector.

The current study also confirmed earlier findings that bioethanol from corn generates more energy than is required for production. Bioethanol from corn contains 2.1 times more energy for every unit of fossil fuel input and reduces the GHG emission by 53% relative to gasoline. The DGS from the bioethanol industry is an important livestock feed. The use of the DGS as livestock feed improves the WP of livestock products and reduces pressure on freshwater resources.

The WF of biofuels is considerably larger than that of fossil fuels. For example, it requires about 187 times more water to travel one kilometer with corn bioethanol (66 L of water/km traveled) compared to conventional gasoline (0.4 litre of water/km) (King and Webber, 2008). Therefore, policymakers should consider water sustainability when developing biofuel policies.

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