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Key Points:
- Just as in physical hydrology, both flows and stocks of virtual water resources must be considered
- Approximately 728 km^3 of water can be virtually stored as grain in the United States, with roughly 86% coming from precipitation
- Virtual water storage capacity represents roughly 62% of normal U.S. dam storage or 75-97% of precipitation receipts

Supporting Information:
- Supporting Information S1

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Grain and Virtual Water Storage Capacity in the United States

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Abstract Extensive research has evaluated virtual water trade, the water embodied in traded commodities. However, relatively little research has examined virtual water storage or the water embodied in stored commodities. Just as in physical hydrology, both flows and stocks of virtual water resources must be considered to obtain an accurate representation of the system. Here we address the following question: How much water can be virtually stored in grain storage in the United States? To address this question, we employ a data-intensive approach, in which a variety of government databases on agricultural production and grain storage capacities are combined with modeled estimates of grain crop water use. We determine the virtual water storage capacity (VWSC) in grain silos, map the spatial distribution of VWSC, calculate contributions from irrigation and rainwater sources, and assess changes in VWSC over time. We find that 728 km^3 of water could be stored as grain in the United States, with roughly 86% coming from precipitation. National VWSC capacities were 777 km^3 in 2002, 681 km^3 in 2007, and 728 km^3 in 2012. This represents a 6% decline in VWSC over the full 10-year period, mostly attributable to increased water productivity. VWSC represents 62% of U.S. dam storage and accounts for 75–97% of precipitation receipts to agricultural areas, depending on the year. This work enhances our understanding of the food-water nexus, will enable virtual water trade models to incorporate temporal dynamics, and can be used to better understand the buffering capacity of infrastructure to climate shocks.

1. Introduction

An extensive body of research has developed on "virtual water" (Allan, 1998) or the volume of water embodied in products. This represents the water physically consumed in the production process rather than the physical moisture content of a product (Hoekstra, 2003). The majority of research on this topic has focused on "virtual water trade" (VWT) or the water embodied in traded commodities (Hoekstra & Mekonnen, 2012; Oki, 2010). Global VWT research has examined the sources of water embodied in trade (Konar et al., 2012), determined that trade saves water (Dalin et al., 2012; Yang et al., 2006), quantified virtual water fluxes under a changing climate (Konar et al., 2013, 2016), and evaluated drivers of VWT (Tamea et al., 2013), among others. VWT research within the United States has focused on agricultural commodity transfers (Dang et al., 2015), overexploited aquifers (Marston et al., 2015), implications of drought (Marston & Konar, 2017), and urban areas (Chini et al., 2017). Now, it is important to evaluate "virtual water storage" (VWS) or the water embodied in stored commodities. This is because, just as in physical hydrology, it is essential to consider both the flows and stocks of virtual water resources to obtain an accurate representation of the system.

The idea of VWS has been presented in the literature (Hoekstra, 2003). Hoekstra (2003) suggest that storing water in virtual form may actually be a more efficient and environmentally friendly way of bridging drought periods than building dams. For example, Hoekstra (2003) describe the case of Syria, in which 1988 was a good year for cereal production (yields of 1.6 $[\frac{ton}{ha}]$), enabling 1.9 million tons of cereal to be stored that year. The following year was a very dry one (yields of 0.4 $[\frac{ton}{ha}]$), in which 1.2 million tons of cereal was used from internal storage to complement internal production and imports. The use of 1.2 million tons of cereals from storage was equivalent to 4×10^9 m^3 of virtual water. This example illustrates the potential importance of grain (and embedded virtual water) to buffer production shortfalls. However, relatively little work has been done to empirically characterize VWS, particularly at the subnational scale. We aim to address this knowledge gap through a statistical assessment of spatiotemporal patterns of VWS in the United States. Specifically, we examine the *capacity* of grain and VWS, since grain storage data is provided in terms of capacity rather than stocks.

Most grain production relies on rainfall (Baker et al., 2012; Marston et al., 2018). However, irrigation is an important infrastructure system that both improves crop productivity and acts as a buffer against extreme events in agriculture (Davis et al., 2017; Troy et al., 2015). As such, agriculture is responsible for approximately 70% of freshwater withdrawals and is by far the largest consumptive user of freshwater resources (Gleick & Palaniappan, 2010). However, both the supplies and demands placed on water resources will likely face changes in the near future. Demands from other water users, including industry, allocations for environmental flow requirements, household water use, and recreation, are increasing (McDonald et al., 2011). Additionally, changes in climate variability and extremes will alter both the availability and demand for water resources (Devineni et al., 2015). For example, agricultural areas that experience more extreme heat will increase their demand for irrigation. These climate changes will make it more difficult for farmers to grow crops as they have done in the past, with potential food security implications (Lobell et al., 2011; Schmidhuber & Tubiello, 2007). This makes it important to understand connections between water and food systems and the potential role of infrastructure in improving both water and food security.

Grain storage is an infrastructure system that enables farmers to store their produced grain crops in time. Grain can be stored for several years if the proper storage process is used (Liu et al., 2017), but in the United States grain is typically only stored until the next harvest (i.e., sold within a year). In this way, grain storage introduces temporal dynamics into food and virtual water exchange networks. During years with plentiful production, farmers may use storage to hold on to grains until some point in the future when prices become more favorable for them. In this way, grain silos help farmers to buffer their income against crop production and grain price shocks (Shukla & Gupta, 2014). To do this, farmers decide between storing their grain production in their own grain silos (i.e., "on-farm storage") or selling and/or storing their grain at their local grain elevator (i.e., "off-farm storage"). In this way, grain supplies are not immediately contributed to the grain exchange network, adding a critical temporal element to grain supply chains. Grain storage is also used to buffer potential future shortfalls of grain, since stores can be drawn upon when the harvest is poor (Marchand et al., 2016). Going forward, grain storage will likely play an increasingly important role as an infrastructure system that buffers interannual variation in climate and crop production. Grain storage capacities limit this buffering capability, and for this reason many nations either have or are actively developing strategic grain reserves (Shukla & Gupta, 2014). This also means that it is important to evaluate grain and VWS *capacities*.

Shocks are transmitted through global grain trade networks (Fair et al., 2017; Puma et al., 2015) and the entire food (Distefano et al., 2018; Ercsey-Ravasz et al., 2012) and virtual water (Tamea et al., 2016) trade networks. Recent work has shown that grain stores buffer production shortfalls, making them important to consider in assessments of food network reliability (Marchand et al., 2016). An empirical assessment of grain and virtual water stocks will enable future evaluations of shock transmission in the global food systems to add this component (Lant et al., 2018). Food storage dynamics are complex due to spatial heterogeneities, distinct typologies, and interactions with the food supply-demand system (Laio et al., 2016; Von Braun, 2007). Recent research has presented a data-based framework to assess global food storage dynamics (Laio et al., 2016). When converted to calories, per capita food storage dynamics are surprisingly steady in time. However, there is a significant probability that global food stores will decline by 2050 (Laio et al., 2016). Reductions in food stores may threaten future food security, particularly in Africa (Laio et al., 2016). Existing global assessments of food storage also likely mask important heterogeneities at the subnational scale. For these reasons, we present a data-intensive assessment of grain and virtual water storage capacity (VWSC) dynamics within the United States.

As a leading producer and exporter of staple grains, the United States plays an important role in feeding the world (United States Department of Agriculture [USDA], 2013). Over 30% of the world's corn and over 50% of the world's soybeans are produced by the United States. The United States contributes a significant fraction of this production to global export markets for several key grains: about 60% for corn, 40% for soybeans, 25% for wheat, and 70% for sorghum (USDA, 2013). These grains are responsible for a large share of the world's food energy intake (Food and Agriculture Organization [FAO], 2013), making the United States an important contributor to global food security. The United States is able to maintain its role as a key agricultural producer, consumer, and trade power due to its supporting agricultural production, water resources, and food storage and distribution infrastructure (Lant et al., 2018; Lin et al., 2014; Xu et al., 2011). The ability to grow and store crops and then efficiently move food around enables the United States to provide domestic and global food security. Additionally, the United States provides extensive government databases of its

Table 1
Data Used in This Study Including Variable Name, Spatial Resolution Provided at, Units in Which the Variable Is Reported, and the Data Source Citation

Variable	Resolution	Units	Source
On-farm grain storage capacity	County	Bu	USDA (2017)
Off-farm grain storage capacity	State	Bu	USDA (2017)
Harvest	County	Acre	USDA (2017)
Irrigated harvest	County	Acre	USDA (2017)
Production	County	Bu, lb (pounds), CWT, T	USDA (2017)
Crop water use	County	m^3/year	Marston et al. (2018)

Note. USDA = United States Department of Agriculture.

agricultural and water resources systems, making it a suitable choice for an empirical assessment of grain and virtual water storage capacities.

Research on VWT over the last several decades has shown that it is not a panacea to the problem of growing water scarcity (Horlemann & Neubert, 2007; Kumar & Singh, 2005), with implications for how we think about VWS. For an overview of the debate surrounding VWT please see Antonelli and Sartori (2014). However, recent work, using advanced econometric methods, has demonstrated that trade does, on average, lead nations to use less water in agriculture (Dang & Konar, 2018). It is important to note that water is only one of a suite of factors of production in agriculture (Kumar & Singh, 2005). Other factors of production—such as arable land, nutrient fertilizers, farm labor, and agricultural machinery—are also critical in agriculture. In fact, it is the *relative* endowment between factors that determine each country's comparative advantage to trade in commodities (Dang et al., 2016; Reimer, 2012), and many factors of production are more important than water (e.g., labor and capital; Debaere, 2014). The economic structure, composition, and productivity of a nation will influence how it uses its water (and other) resources (Debaere et al., 2015; Marston et al., 2018). Here, we focus solely on the water resources (precipitation and irrigation) that enable grain production and are embodied in grain silos and not all agricultural items nor the full suite of inputs required to grow them.

The primary focus of this paper is to empirically determine the volume of water that can be virtually stored in grain silos in the United States. We use spatially detailed information on agricultural production, harvested area, grain storage capacity, and crop water use to answer the following questions: (1) What is the total volume of VWSC in the United States? (2) How is VWSC spatially distributed in the United States? (3) Does the VWSC of grain rely mostly on rainfall or irrigation? (4) How has VWSC changed in time? and (5) How does the VWSC of grain compare to water stores and fluxes? Answering these questions will generate knowledge on the role of food storage in increasingly complex water-food supply systems.

2. Methods

Here, we detail the methods that we use to estimate the VWSC in grain silos in the United States. Section 2.1 explains the data that underpin this work. All data sources are summarized in Table 1. Section 2.2 details the calculation of VWSC. In section 2.3 we explain how we quantify the volume of rainfall receipts to grain harvested areas in the United States.

2.1. Data

2.1.1. Agricultural Statistics

We obtained data on agricultural storage capacity, harvested area, and production from the USDA National Agricultural Statistics Service (NASS) online database (USDA, 2017). USDA-NASS provides agricultural census and survey data for a large variety of crops grown in the United States.

USDA-NASS supplies data on the grain storage capacity (bushels) for both “on-farm” and “off-farm” silos. Storage capacity data do not represent that actual mass of specific crops that are available in storage. On-farm grain storage capacity includes all bins, cribs, sheds, and other structures physically located on farms, which typically store whole grains, oilseeds, or pulse crops (AgWeb, 2015). Off-farm grain storage capacity includes all grain elevators, warehouses, terminals, merchant mills, other storage, and oilseed crushers (AgWeb, 2015). Off-farm storage typically includes whole grains, soybeans, canola, flaxseed, mustard seed, safflower,

Figure 1. Example photographs of on-farm (left) and off-farm (right) grain storage. On-farm image from https://sciencing.com/grain-silos-work-4927013.html and off-farm image from https://storage-movers.com/storing-grains-and-regarding-aspects/.

sunflower, rapeseed, Austrian winter peas, dry edible peas, lentils, and chickpeas/garbanzo beans (USDA, 2018). Capacity data for off-farm storage exclude facilities used to store only rice or peanuts, oilseed crushers processing only cottonseed or peanuts, tobacco warehouses, seed warehouses, and storage facilities that handle only dry edible beans, other than chickpeas/garbanzo beans (USDA, 2018). Figure 1 shows examples of on-farm and off-farm grain storage capacity.

On-farm grain storage capacities are provided at the U.S. county resolution (approximately 3,000 spatial units), while off-farm grain storage capacities are available at the United States state resolution (approximately 50 spatial units). An additional contrast is the point in time represented: off-farm storage capacity is available for the first of December, and on-farm storage capacity is available for the "end of December." This distinction would be important to avoid double counting of grain stocks but is not problematic in this study since we consider storage capacities. While off-farm grain storage capacity is available every year since 1964 as a survey product, on-farm grain storage capacity is available only as a census product for the years 2002, 2007, and 2012. For this reason, we restrict our analysis to these years.

The USDA classifies 18 crops as being stored in silos: barley, canola, corn (grain), corn (silage), flaxseed, lentils, mustard (seed), oats, peas (Austrian winter), peas (dry edible), rapeseed, rye, safflower, sorghum (grain), sorghum (silage), soybeans, sunflower, and wheat (USDA, 2018). We retrieved additional data from USDA-NASS for these crops. For these stored crops, we collected county-level data on total harvested area, irrigated harvested area, and total crop production. Note that we use data on irrigated harvested area rather than irrigated production data, since neither irrigated production nor yield data are available for half of our crops: canola, flaxseed, lentils, mustard (seed), peas (Austrian winter), peas (dry edible), rye, safflower, and sunflower. We provide a table with all unit conversions used in this study in the supporting information (SI) document. Regional shapefiles were retrieved from the U.S. Census Bureau for visualizations.

National-scale stock variation data are available for several agricultural commodities between 1961 and 2013 from the Food and Agriculture Organization of the United Nations (FAO, 2018). To estimate national grain stocks, we follow Marchand et al. (2016) and convert FAO stock variations to actual stores. The FAO grain commodities that most closely map to the USDA grains are barley and products (barley), maize and products (corn grain and corn silage), oats (oats), oilcrops, other (flaxseed and safflower), pulses (dry edible peas, Austrian winter peas, and lentils), rape and mustardseed (canola and mustard seed), rye and products (rye), sorghum (sorghum grain and sorghum silage), soyabeans (soybeans), sunflower (sunflower), and wheat and products (wheat). To calculate stocks for each of these FAO commodity groups individually, we assume that stocks were zero in 1961 and add the stock variations to this value. This results in negative stocks in many years, so we add the smallest (most negative) stock to all stocks such that 1 year is assumed to have zero stocks and all other years are positive.

2.1.2. CWU

Crop water use (CWU) data were retrieved from Marston et al. (2018). This CWU data are temporally averaged (10-year normal, from 1996 to 2005) for 145 commodities in all counties and states within CONUS The Conterminous United States (CONUS). Note that these CWU values were originally modeled by Mekonnen and Hoekstra (2011) at the 5 × 5-arcmin spatial scale. CWU was converted to county values, by averaging the pixels within each county by Marston et al. (2018). In this process, Marston et al. (2018) converted the original CWU raster data from cubic meters per hectare to cubic meters by multiplying the original CWU values by each crop's harvested area. These volumetric CWU values are provided for each county as two categories: (1) blue CWU representing the volume of irrigation water consumed by irrigated crops and (2) green CWU representing the volume of precipitation consumed by both irrigated and rainfed crops. Thus, CWU data are the volume of water consumption for each county-crop-water source pair.

2.2. VWSC

To estimate VWSC, we need to partition the grain storage capacity data by specific crops. The grain storage capacity data are lumped across all grain crops and do not indicate which grains are stored by location or time period. We need to approximate the storage capacity attributed to each crop in order to match with crop-specific CWU and convert to VWSC. To do this, we assume that the local crop harvested area fraction represents the local crop storage fraction. So, the harvested area fraction is used to partition total grain storage capacity by crop. VWSC was thus estimated by

$$VWSC_{r,c,t} = \left(S_{r,t} * F_{r,c,t}\right) * \frac{CWU_{r,c}}{P_{r,c,t}} \tag{1}$$

where VWSC is the virtual water storage capacity (m^3), S is the grain storage capacity (bushels), F is the harvested area percentage (%), CWU is the crop water use (m^3), and P is the production (bushels). The subscript r indicates the region (county or state), c indicates the crop commodity (i.e., barley and corn), and t is the time period (i.e., years 2002, 2007, or 2012). In this way, VWSC represents a mass (i.e., the term in parenthesis) multiplied by a water productivity term (i.e., $\frac{\text{CWU}}{P}$, which is a water volume [m^3] per unit mass [bushels]).

VWSC was calculated for all states and counties in the CONUS. On-farm VWSC was calculated at the county spatial scale and also aggregated to the state spatial scale. Off-farm VWSC was calculated at the state spatial scale only, since the data for off-farm grain storage are only available at this scale. Total VWSC (the sum of on-farm and off-farm VWSC) was then calculated at the state level. These results were summed over the entire CONUS to arrive at a national value for VWSC. This approach assumes that grain production is stored locally.

Note that, in equation (1), we pair time-varying storage data with temporally averaged CWU estimates. Although it would be better to have matching annual estimates of CWU, there is currently no available database of annual CWU at high-resolution within the United States. However, recent work has shown that evapotranspiration (both irrigated and rainfed) does not vary significantly in time in the United States (Velpuri & Senay, 2017). Importantly, recent work has also shown that crop water use is most sensitive to agricultural statistics on crop yield (Tuninetti et al., 2015). This gives us confidence that our measure of CWU is also most likely driven by agricultural statistics, which we do have time-varying information on (note that S, F, and P have subscripts t associated with them in equation (1)).

Even though total CWU may be relatively time invariant, the partitioning between green and blue water may change with time. Estimating the relative contribution of blue and green water sources to total CWU requires a hydrological model, such as the one developed by Mekonnen and Hoekstra (2011). Modeling time-varying CWU is beyond the scope of the current study. The partition between green and blue water sources would vary in time for certain locations. Our assumption of a stable partition would be most problematic for locations that irrigate grain crops in drought years. This is because farmers with the option to irrigate during drought will switch to blue water sources, as was shown by the recent work of Marston and Konar (2017). Despite this, we anticipate that green water will remain the dominant source of water for grain across the country in most time periods, despite potential local heterogeneities during dry periods.

2.3. Precipitation Receipts to Harvested Areas

We quantify the total volume of precipitation receipts to the harvested areas of the crops considered in our study. We calculate this volume since it represents a bound to total annual green VWS. Precipitation will also go into surface runoff and groundwater recharge, with some fraction going to consumptive crop demands. As such, precipitation represents the physical maximum that can be utilized by rainfed crops in a single growing season. Irrigation supplies would increase this value. In this way, our physical threshold is conservative in irrigated systems. However, since we determine VWSC, it is possible that our estimates of green VWSC will exceed the annual precipitation volume received. This lack of direct connection to physical constraints highlights a major drawback to analyzing storage capacity rather than actual mass stocks.

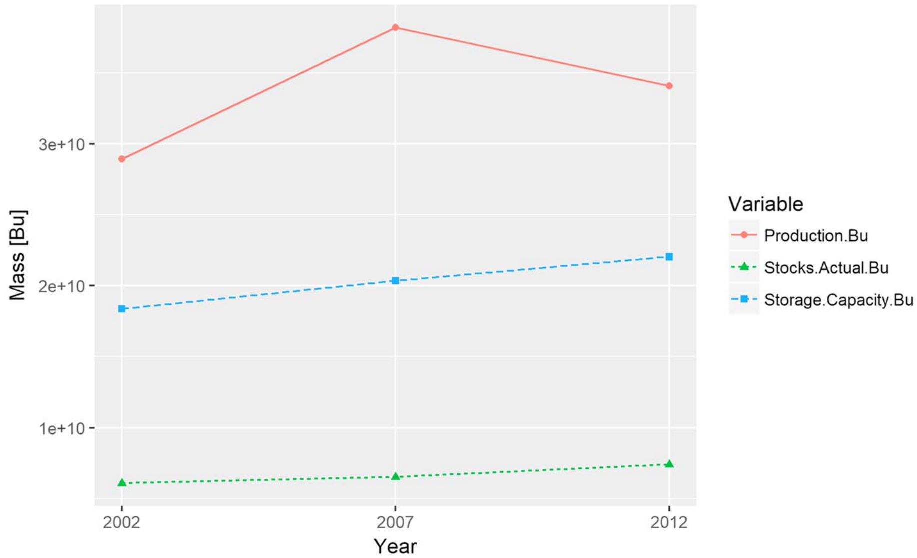

Figure 2. Grain production, storage capacity, and stocks over time. Values are provided in units of mass (bushels). Note that production always exceeds both grain stocks and storage capacity. Grain stocks represent roughly one third of storage capacity.

Precipitation data are retrieved from PRISM (Prism climate group, 2018) for the years 2002, 2007, and 2012 at 4 × 4-km resolution. Precipitation depths are averaged for all states containing grain storage data within the CONUS, using the zonal statistics python package (Perry, 2017). These averaged precipitation depths were then multiplied by grain harvested acreage to determine the total volumetric rainfall over grain harvested areas.

3. Results

Here, we summarize the agricultural statistics used as inputs to our VWSC calculations. Then, we answer the questions posed in section 1.

Table 2
VWSC for On-Farm Storage (Counties), Off-Farm Storage (States), and the Sum of Both

Year	Region	VWSC_ir (km^3)	VWSC_rf (km^3)	VWSC (km^3)
2002	County	48.26	370.26	418.52
	State	63.01	295.01	358.01
	Total	111.27	665.27	776.53
2007	County	43.56	326.13	369.69
	State	51.39	259.89	311.28
	Total	94.95	586.02	680.97
2012	County	45.09	334.29	379.38
	State	57.50	290.79	348.29
	Total	102.59	625.08	727.67

Note. Also included are results for irrigated VWSC (using irrigated CWU), rainfed VWSC (using rainfed CWU), and the sum of both. Total U.S. irrigated VWSC is always significantly smaller than the total U.S. rainfed VWSC. Counties consistently have higher rainfed VWSC than states, while states consistently have higher irrigated VWSC than counties. This implies a difference in water dependencies between on-farm and off-farm storage alternatives. Variable details: _ir = irrigated, _rf = rainfed. VWSC = virtual water storage capacity.

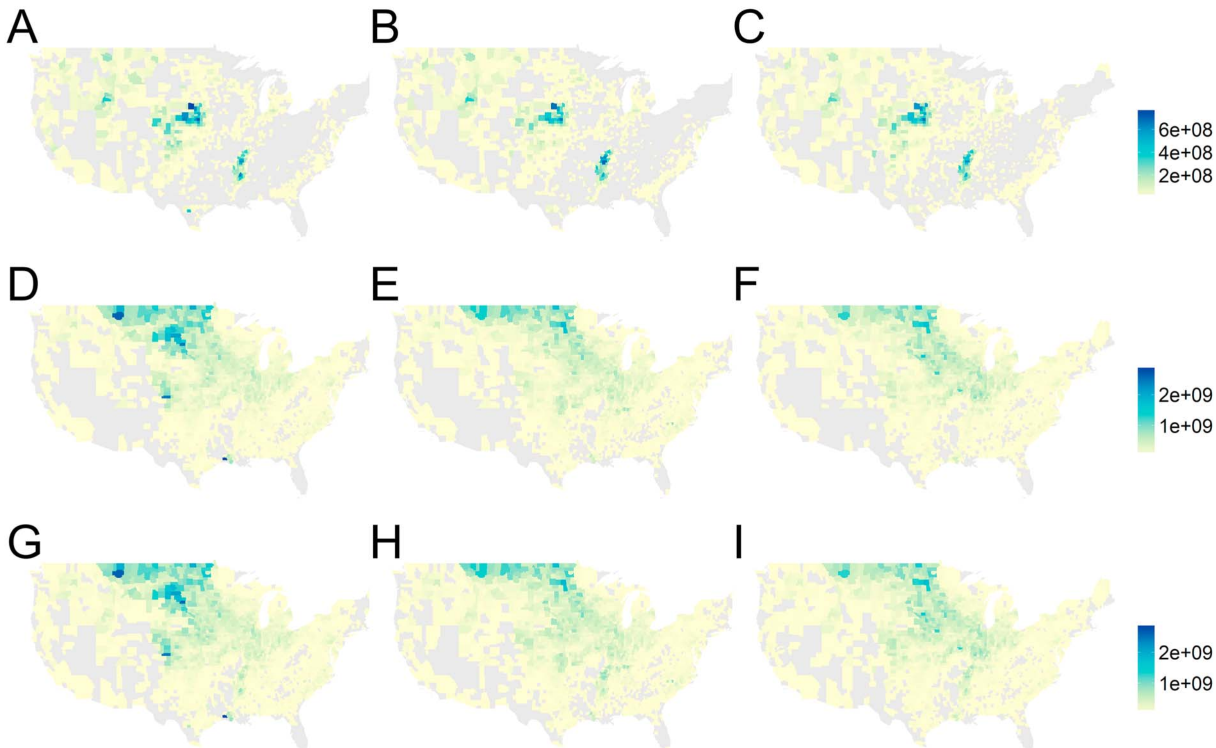

Figure 3. On-farm virtual water storage capacity (VWSC) in time. (a) On-farm irrigated VWSC in 2002. (b) On-farm irrigated VWSC in 2007. (c) On-farm irrigated VWSC in 2012. (d) On-farm rainfed VWSC in 2002. (e) On-farm rainfed VWSC in 2007. (f) On-farm rainfed VWSC in 2012. (g) On-farm total (irrigated plus rainfed) VWSC in 2002. (h) On-farm total VWSC in 2007. (i) On-farm total VWSC in 2012. Irrigated on-farm VWSC is largest in Nebraska and along the Arkansas/Mississippi border. Rainfed on-farm VWSC is largest along the Northern border of the country. Total on-farm VWSC looks nearly identical to rainfed on-farm VWSC because rainfed VWSC is significantly larger than irrigated VWSC. VWSC decreases from 2002 to 2007 then increases slightly to 2012, resulting in the largest VWSC values seen in 2002.

3.1. Agricultural Variables

The mean and standard deviations of all agricultural input data for CONUS are calculated and provided in the SI document. These values are provided for the total of all crops considered in this study for each year. Note that the storage capacity values are not directly comparable as county data represents on-farm storage capacity and state data represents off-farm storage capacity. Interestingly, all variables increase over time, with the exception of production, which decreased from 2007 to 2012 due to the 2012 Midwest drought. Storage capacities increased over the study time period, at a fairly consistent rate for off-farm storage, yet at a slower rate for on-farm storage. National off-farm storage capacity is 8.52×10^9 (bushels) in 2002, 9.05×10^9 (bushels) in 2007, and 1.03×10^{10} (bushels) in 2012 compared with national on-farm storage capacity of 9.87×10^9 (bushels) in 2002, 1.13×10^{10} (bushels) in 2007, and 1.18×10^{10} (bushels) in 2012. On-farm and off-farm grain storage capacities are similar in mass capacity, with on-farm storage representing slightly larger capacities in each year. This means that both forms of grain storage capacity are significant and should be included in an assessment of national storage capacities.

Figure 2 compares production, grain storage capacity, and grain stocks over time. Production always exceeds storage capacity and stocks. From FAO data, we estimate that national grain stocks are 6.08×10^9 (bushels) in 2002, 6.51×10^9 (bushels) in 2007, and 7.39×10^9 (bushels) in 2012. This indicates that stocks are on the same order of magnitude as storage capacity. Yet stocks are roughly one third as much as the storage capacity. So transforming grain storage capacity into VWSC will, of course, be overestimating the actual volume of virtual water being stored across the country. However, the goal of this study is to estimate national capacity to store virtual water resources. Figure 2 indicates that national production exceeds national storage capacity, such that an entire year's production would overwhelm the storage infrastructure.

The top 10 states are ranked for total production, yield, and storage capacity in the SI. A map of grain harvested area for counties and states in time is provided in the SI. Grains are predominantly grown in the corn

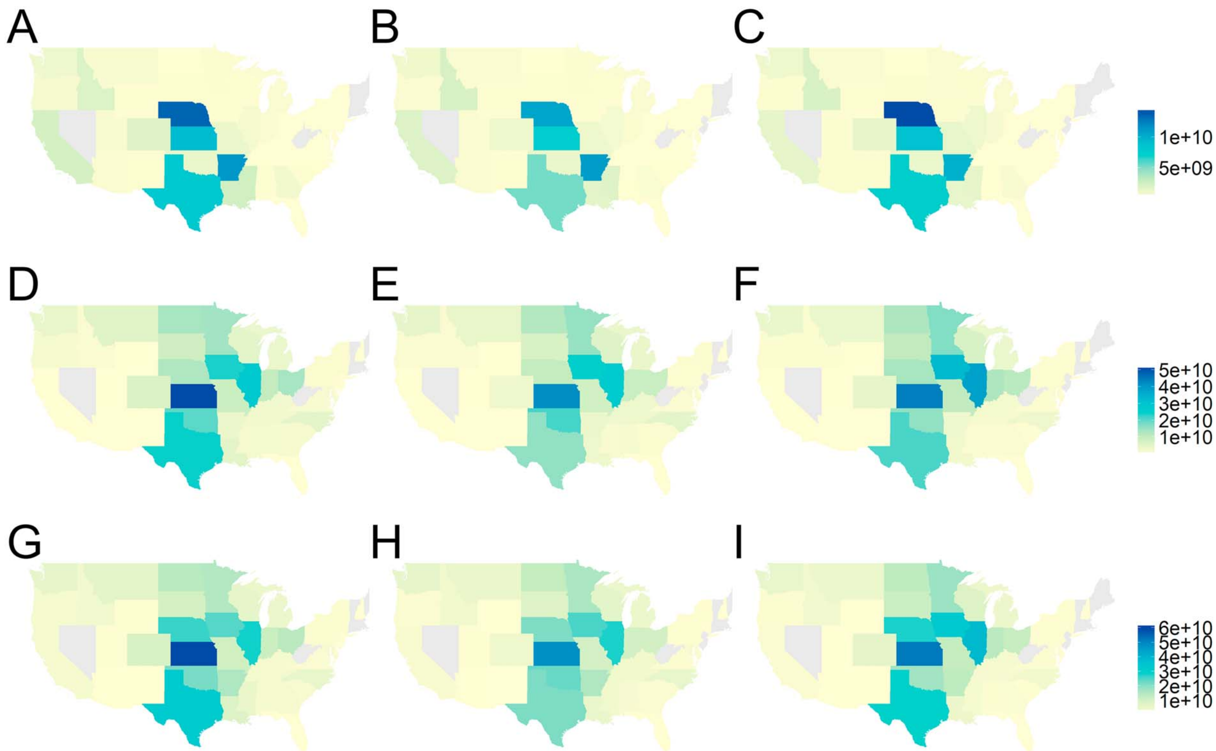

Figure 4. Off-farm virtual water storage capacity (VWSC) in time. (a) Off-farm irrigated VWSC in 2002. (b) Off-farm irrigated VWSC in 2007. (c) Off-farm irrigated VWSC in 2012. (d) Off-farm rainfed VWSC in 2002. (e) Off-farm rainfed VWSC in 2007. (f) Off-farm rainfed VWSC in 2012. (g) Off-farm total (irrigated plus rainfed) VWSC in 2002. (h) Off-farm total VWSC in 2007. (i) Off-farm total VWSC in 2012. Irrigated off-farm VWSC is largest in Nebraska and Arkansas, with other large values seen in Kansas and Texas. Rainfed off-farm VWSC is largest in the Midwest and southward in Oklahoma and Texas. Total off-farm VWSC looks nearly identical to rainfed off-farm VWSC because rainfed VWSC is significantly larger than irrigated VWSC. VWSC also decreases from 2002 to 2007 then increases slightly to 2012, resulting in the largest VWSC values seen in 2002.

belt in the U.S. Midwest, and this is relatively stable in time. This leads to most grain production being concentrated in the corn belt, as shown in the SI. The decline in grain production in the 2012 drought is shown around Illinois and Iowa. In contrast, Minnesota shows an increase in production despite the drought. This is because the drought was severe in the Midwest but had relatively mild impacts in Minnesota and in the Pacific Northwest, the Northeast, and in Florida (National Drought Mitigation Center, 2018). Maps of grain storage capacities for counties, states, and both combined in time are provided in the SI. On-farm grain storage capacity is concentrated in the grain producing parts of the country, but off-farm storage capacity is more concentrated in the U.S. South and, in particular, Texas.

CWU for all counties and states is mapped in the SI. Note that irrigated CWU is most prevalent in the U.S. Southwest and especially in California, while rainfed CWU is largest in the Midwest. Rainfed CWU accounts for a significantly larger water volume than does irrigated water contributions on an annual basis (Marston et al., 2018). Note that this map is invariant in time in our study (see section 2.1.2) due to data limitations.

3.2. What Is the Total Volume of VWSC in the United States?

VWSC totals are summarized in Table 2. In 2002, total VWSC was 776.53 km^3. This value drops to 680.97 km^3 in 2007 then increases to 727.67 km^3 in 2012. On-farm and off-farm VWSC follow similar trends. On-farm VWSC was 418.52 km^3 in 2002, 369.69 km^3 in 2007, and 379.38 km^3 in 2012. Off-farm VWSC was 358.01 km^3 in 2002, 311.28 km^3 in 2007, and 348.29 km^3 in 2012. This shows that both on-farm and off-farm VWSC are similar in magnitude and that it is important to consider both to accurately understand total storage capacity.

3.3. How Is VWSC Spatially Distributed in the United States?

The distribution of reserves has been shown to matter more than their aggregate quantity in terms of conferring resilience to production shocks (Marchand et al., 2016). This provides motivation to explore the subnational spatial distribution of VWSC. Maps of total VWSC are presented in Figures 3–5. Figures 3g–3i map total VWSC at the county spatial scale. Figures 4g–4i map total VWSC at the state spatial scale. County

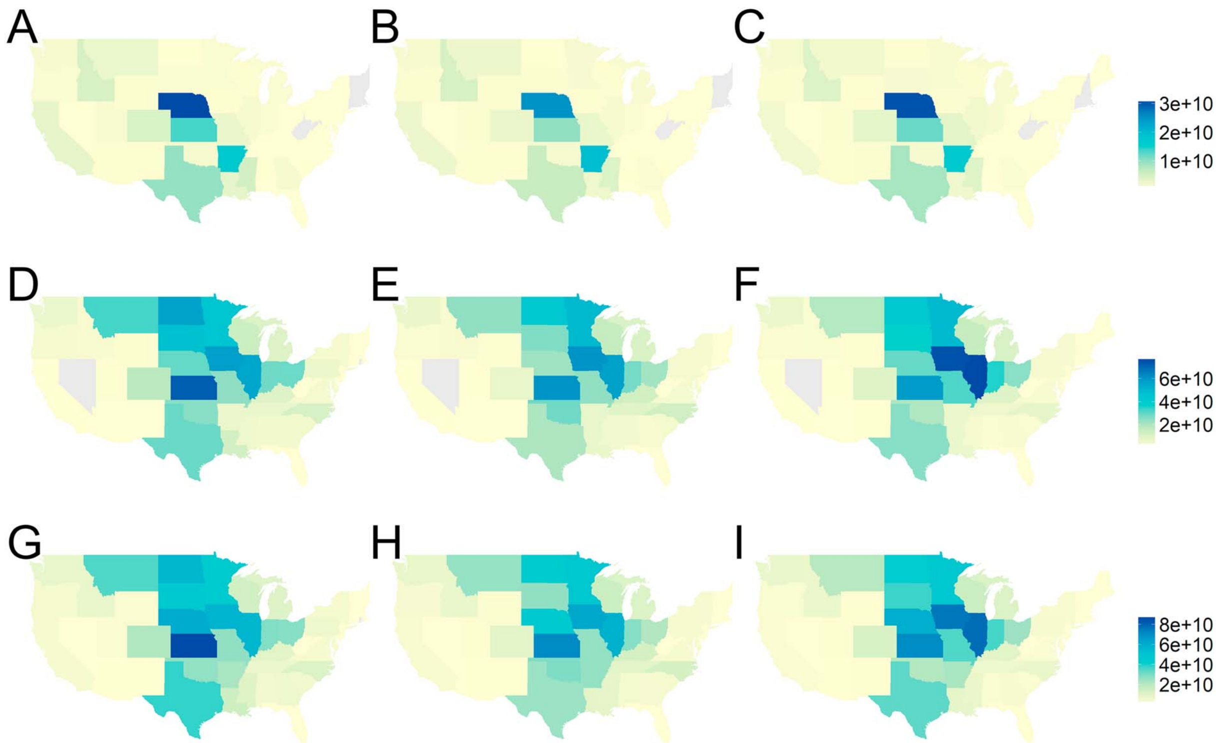

Figure 5. Combined (on-farm and off-farm) virtual water storage capacity (VWSC) in time. (a) Combined irrigated VWSC in 2002. (b) Combined irrigated VWSC in 2007. (c) Combined irrigated VWSC in 2012. (d) Combined rainfed VWSC in 2002. (e) Combined rainfed VWSC in 2007. (f) Combined rainfed VWSC in 2012. (g) Combined total (irrigated plus rainfed) VWSC in 2002. (h) Combined total VWSC in 2007. (i) Combined total VWSC in 2012. Irrigated combined VWSC is largest in Nebraska, with large values observed in Arkansas, Kansas, and Texas. Rainfed combined VWSC is largest throughout the Midwest, extending both Northwest to Montana (due primarily to on-farm storage) and South to Texas (due primarily to off-farm storage). Total (irrigated and rainfed) combined VWSC looks nearly identical to rainfed combined VWSC because rainfed VWSC is significantly larger than irrigated VWSC. Combined VWSC also moves around: in 2002 combined VWSC is highest in Kansas, yet in 2012 combined VWSC is highest in Illinois. Seeing as irrigated combined VWSC is always largest in Nebraska, this movement in total combined VWSC is almost entirely due to changes in rainfed VWSC.

and state values were combined to obtain total VWSC in Figures 5g–5i. The volume of VWSC at the state spatial scale is roughly an order of magnitude larger than VWSC at the county spatial scale. Note that this is just due to spatial aggregation at the state spatial scale; national totals of on-farm and off-farm VWSC are comparable (compare county and state values in Table 2).

The distribution of on-farm and off-farm grain silos varies across the country (refer to SI), with implications for the distribution of VWSC. In particular, off-farm VWSC is much more skewed toward the U.S. South and Texas than it is for on-farm VWSC (see Figure 4). The state-scale magnitudes of off-farm VWSC are much larger than county-scale on-farm VWSC (due to spatial aggregation). This drives the map of combined VWSC presented in Figures 5g–5i. Table 3 provides the top 10 states in terms of total VWSC. Over the study time period, Kansas, Nebraska, Iowa, and Illinois are the top states. In 2012, the top five states in terms of total VWSC are Illinois, Iowa, Kansas, Nebraska, and Minnesota.

3.4. Does the VWSC of Grain Rely Mostly on Rainfall or Irrigation?

Total VWSC depends on both irrigated and rainfed crops. Figure 6 maps the fractional contribution of irrigation and rainfall supplies to total grain VWSC across the country. As we would expect, rainfed grains contribute the most to total VWSC. The Southwest biases heavily toward irrigated grains, while the remainder of the country relies more on precipitation to grow grain crops. This is consistent with the U.S. climate, where most precipitation falls in the East and Northwest (Prism climate group, 2018). Note that the maps in Figure 6 are inverses of each other, since the fractional contributions are shown and must sum to 100% across blue and green maps.

On-farm irrigated VWSC is consistently smaller than off-farm irrigated VWSC (refer to Table 2). The reverse relationship is revealed for rainfed VWSC: on-farm rainfed VWSC is consistently larger than off-farm rainfed VWSC. This means that rainfed grains are preferentially stored in on-farm grain storage. Conversely,

Table 3
Top 10 States Ranked by Irrigated, Rainfed, and Total VWSC for Each Year (Ranked by Sum of On-Farm Storage and Off-Farm Storage)

	Irrigated VWSC			Rainfed VWSC			Total VWSC		
Rank	2002	2007	2012	2002	2007	2012	2002	2007	2012
1	NE	NE	NE	KS	IA	IL	KS	KS	IL
2	AR	AR	AR	IA	KS	IA	NE	IA	IA
3	KS	KS	KS	ND	IL	KS	IA	IL	KS
4	TX	TX	TX	IL	MN	MN	IL	MN	NE
5	MS	ID	ID	SD	ND	ND	ND	NE	MN
6	ID	MS	MS	MN	OK	SD	SD	ND	ND
7	CO	MO	MO	MT	IN	IN	MN	OK	SD
8	CA	CO	CO	NE	SD	MO	TX	IN	IN
9	LA	MT	LA	TX	MT	NE	MT	SD	MO
10	MO	CA	IL	OH	MO	TX	IN	MO	TX

Note. Similar to many of the input data trends, irrigated VWSC tends to stay the same year after year: Nebraska is always on top, Arkansas is always second, etc. Instead, rainfed VWSC shuffles around quite a bit, which is unsurprising considering climate variability. The result of the rainfed VWSC shuffling is variable total VWSC ranking: Illinois was fourth in 2002 but first in 2012, while Kansas dropped from first to third. NE = Nebraska; KS = Kansas; IA = Iowa; IL = Illinois; AR = Arkansas; TX = Texas; MN = Minnesota; NE = Nebraska; OK = Oklahoma; CO = Colorado; LA = Los Angeles; SD = South Dakota; OH = Ohio; MO = Missouri; VWSC = virtual water storage capacity.

irrigated grains are biased toward off-farm storage. This relationship might relate to the fact that farmers that use more intensive inputs (i.e., more irrigation) are also more likely to use off-farm storage to store/sell their grains. On-farm storage is typically cheaper (free to store but sunk cost to build) to store grains, which might be why farmers that rely on rainfall also rely on their own storage.

Irrigated on-farm storage capacity pops out over the High Plains and Mississippi Embayment aquifers (see Figures 3a–3c). Rainfed VWSC is more prevalent along the northern border of the country and throughout the U.S. Midwest corn belt (see Figures 3d–3f). Note that the total VWSC maps are most driven by rainfed VWSC, due to the larger volumes of rainfall embodied in stored grains (see Figures 3g–3i). These relation-

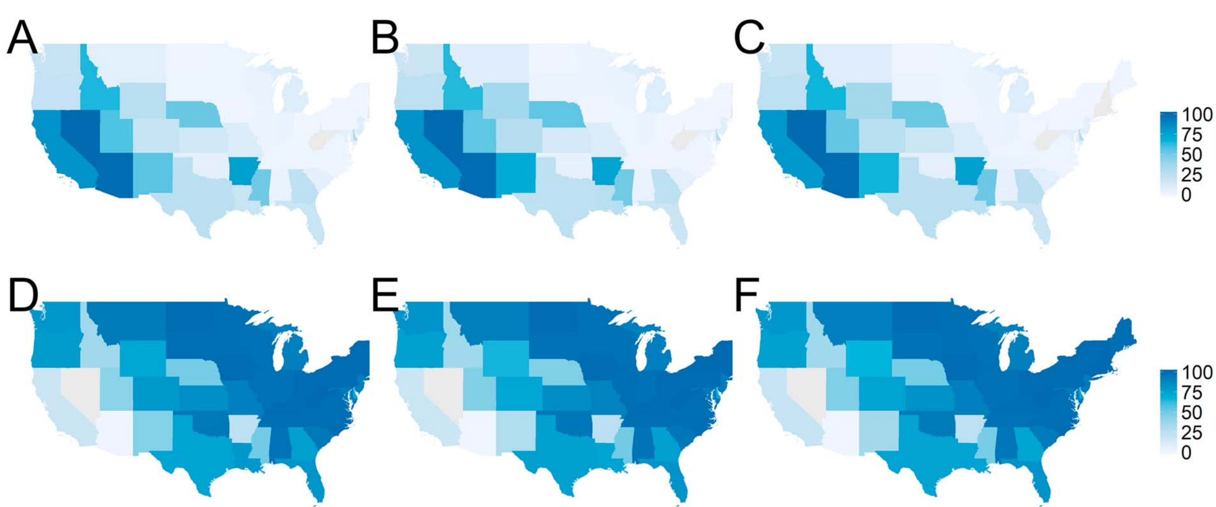

Figure 6. Fractional contributions of irrigated and rainfed combined (on-farm and off-farm) virtual water storage capacity (VWSC) to total (irrigated plus rainfed) VWSC. (a) Irrigated VWSC contributions to combined total VWSC in 2002. (b) Irrigated VWSC contributions to combined total VWSC in 2007. (c) Irrigated VWSC contributions to combined total VWSC in 2012. (d) Rainfed VWSC contributions to combined total VWSC in 2002. (e) Rainfed VWSC contributions to combined total VWSC in 2007. (f) Rainfed VWSC contributions to combined total VWSC in 2012. Trends for all 3 years are nearly identical. Differences between irrigated and rainfed VWSC contributions are very consistent with climate: the arid Southwest relies much more on irrigation, whereas the rest of the country is more humid and can therefore meet more crop water demands with precipitation.

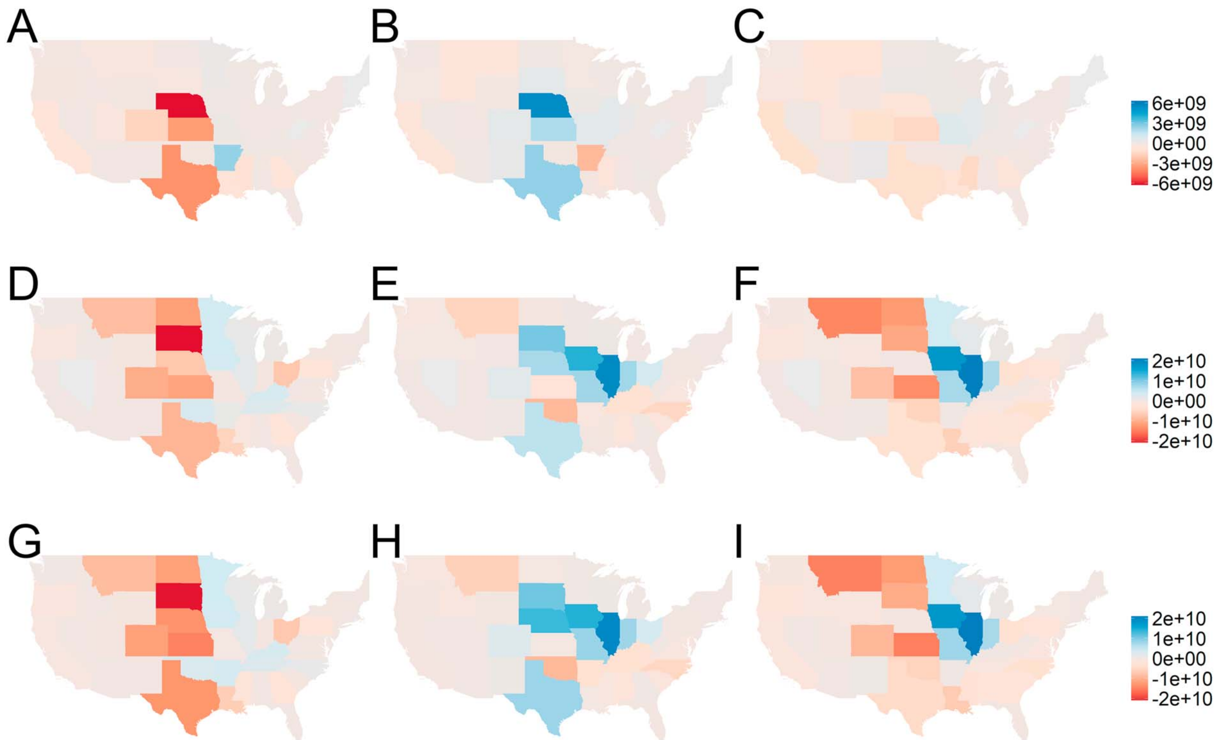

Figure 7. Change over time of virtual water storage capacity (VWSC). (a) Irrigated VWSC change between 2002 and 2007. (b) Irrigated VWSC change between 2007 and 2012. (c) Irrigated VWSC change between 2002 and 2012. (d) Rainfed VWSC change between 2002 and 2007. (e) Rainfed VWSC change between 2007 and 2012. (f) Rainfed VWSC change between 2002 and 2012. (g) Total (irrigated plus rainfed) VWSC change between 2002 and 2012. (h) Total VWSC change between 2007 and 2012. (i) Total VWSC change between 2002 and 2012. Between 2002 and 2007, storage increases which would suggest increases in VWSC, but the large decreases in production throw off this trend and ultimately cause VWSC to decrease. Storage again increases between 2007 and 2012, yet production decreases, causing significant increases to VWSC in most states. The overall result of these two changes is shown in the 2002–2012 map, where many states particularly along the center of the U.S. see large drops in VWSC. Instead, a few Midwestern states, which saw very large decreases in production between 2007 and 2012 due to the 2012 drought, experience significant increases in VWSC. This shows the inverse relationship between VWSC and production. As production increases, VWSC decreases because the same quantity of water produced more crops resulting in less water-intensive grains.

ships are fairly similar for off-farm VWSC. Table 3 ranks the top 10 states by VWSC by water source and time period. VWSC is concentrated in the center of the country, particularly around the corn belt and especially in Illinois and Iowa. Irrigated VWSC is most prevalent in Nebraska, while rainfed VWSC is more scattered throughout the center of the country. Total VWSC is similarly spatially distributed to rainfed VWSC, with large magnitudes seen from North Dakota and Minnesota all the way down to Texas, with especially large values in Illinois, Iowa, and Kansas.

The 2012 cornbelt drought led to grain production losses (see Figure 2). Our estimates of blue VWSC will be conservative in irrigated locations of the cornbelt, such as Nebraska, since we use time-invariant CWU in our methodology. However, grain is predominantly rainfed in the cornbelt—that is, Illinois, Iowa, and Minnesota—which gives us confidence that we are capturing the major trends between green and blue water sources in these locations. Production losses in these locations during the drought indicate that irrigation resources were not applied to mitigate the drought, and hence, that the partition between green and blue water did not vary dramatically in these rainfed locations. Our time-invariant partition between green and blue water sources will also underestimate the contribution of irrigation water sources in California during their drought in 2012, during which groundwater was increasingly relied on (Marston & Konar, 2017). However, California is not a major state in terms of VWSC and their drought predominantly impacted high-value crops that are not considered in this study.

3.5. How Has VWSC Changed in Time?

Table 2 presents the national trend in VWSC. There is a decline in 2007, which is surprising at first, since grain storage capacity increases in all study years, as does grain production and harvested areas. However, there is an inversely proportional relationship between VWSC and production. This relationship is shown

Table 4
Comparison Between VWSC and Physical Water Storage in the United States

Source	Total storage (km^3)
Off-farm total VWSC, 2012	348
On-farm total VWSC, 2012	379
Total VWSC, 2012	728
Normal dam storage, 2016 (U.S. Army Corps of Engineers, 2016)	1,178
Maximum dam storage, 2016 (U.S. Army Corps of Engineers, 2016)	1,626
Largest Lakes, 1993 (Gleick, 1993)	22,115
Groundwater storage, 2015 (Richey et al., 2015)	673–59,800

Note. Total VWSC from 2012 represented roughly 62% of normal U.S. dam storage and 45% of maximum dam storage capacities in 2016. Total VWSC also represented 3.3% of all water stored in the five great lakes shared between the United States and Canada. As compared to groundwater stored in the five largest North American aquifers, total VWSC is greater than the smallest estimates of groundwater storage (108%) but makes up only 1.2% of the largest estimates. VWSC = virtual water storage capacity.

by equation (1). In equation (1) the term outside of the parenthesis is the "water productivity" term, that is, CWU (m^3) divided by crop production (P, [bushels]). So this is a water volume per unit crop mass term.

In our database, grain storage capacity is increasing over time. Additionally, our CWU values do not vary in time, so this variable cannot be responsible for time trends in total VWSC. This leads us to conclude that gains/losses in crop water productivity translate into less/more water being virtually stored per unit of grain storage capacity. When grain production declines, there will be a gain in VWSC, holding all else constant, due to the mechanics of equation (1). Grain production increases between 2002 and 2007 but declines in 2012 during the drought (refer to Figure 2). This indicates that the time trend of VWSC is explained by time trends in grain production.

Temporal dynamics in crop harvested area also may play a role in total VWSC trends. We use harvested area to approximate the distribution of grain storage capacity by crop. Total crop harvested area does not exhibit time trends that could explain national VWSC trends (see SI). It is possible that the composition of crops being grown in 2007 may have shifted to include relatively few water-intensive crops. However, the fraction of harvested area by grain crop is stable over time (see SI) which indicates that the composition of crops produced in each year does not drive variation in VWSC. This means that the magnitude of the grain production trend outweighs grain storage gains, which explains why VWSC decreased in 2007. These trends are observed in mapped differences of irrigated, rainfed, and total VWSC for all three study years in Figure 7.

3.6. How Does the VWSC of Grain Compare to Water Stores and Fluxes?

Here we provide information to benchmark our VWSC volumes. Note that these numbers are not provided to indicate that one form of storage is substitutable for another. Rather, these values are provided solely to determine the relative scale of VWSC. First, we compare VWSC to the storage capacities of all dams, the largest lakes, and groundwater storage capacities of CONUS. Details are reported in Table 4. Second, we compare VWSC to rainfall receipts over grain harvested areas and to the green water embodied in domestic U.S. food trade. Detailed estimates are provided in Table 5.

Reservoir storage in the United States was approximated twice, as the sum of normal storage and as the sum of maximum storage, for all dams listed in the U.S. Army Corps of Engineers National Inventory of Dams (U.S. Army Corps of Engineers, 2016). Normal storage is defined as the total storage space in a reservoir below the normal retention level, including dead and inactive storage and excluding any flood control or surcharge storage, while maximum storage is defined as the total storage space in a reservoir below the maximum attainable water surface elevation, including any surcharge storage (i.e., storage capacity). Comparing dam storage capacity with VWSC (i.e., one capacity with another) is a suitable comparison. For normally dry flood control dams, the normal storage will be a zero value. If unknown, the value will be blank and not zero. Dam data were retrieved from a Github repository containing cleaned and compiled data for all NID entries available in March 2014, totaling 73,826 dams (Stachelek, 2016). Some duplicate entries exist, mostly denoting dam upgrades and related changes. These duplicate entries were removed, and the greatest storage

Table 5
Comparison Between VWSC and Both Virtual and Physical Water Fluxes

Source	Total storage (km^3)
Off-farm total VWSC, 2007	311
On-farm total VWSC, 2007	370
Total VWSC, 2007	681
Domestic U.S. virtual water trade, 2007 (Dang et al., 2015)	100
International virtual water trade, 2007 (Dang et al., 2015)	524
Rainfed VWSC (on-farm and off-farm), 2007	586
Precipitation in harvested areas, 2007	785

Note. VWSC is larger than both domestic and international VWT of grain. This may be due to the fact that VWSC represents a capacity rather than an actual stock. Comparing rainfed VWSC to the precipitation over harvested areas is important as it confirms the feasibility of the rainfed VWSC results. Rainfed VWSC must be smaller than the total local precipitation to be realistic. We calculate that rainfed VWSC is 586 km^3 which is less than 785 km^3 in rainfall receipts to harvested areas. VWSC = virtual water storage capacity.

values out of all upgrades are selected, resulting in a total of 62,448 dams. In 2016 there were 1,178-km^3 normal dam storage and 1,626-km^3 dam storage capacity. The total VWSC in 2012 is in the same order of magnitude at 728 km^3 (refer to Table 4).

Surface water availability was approximated due to a lack of a comprehensive surface water database. Using data from Gleick (1993), the volumes of all five great lakes were summed together, to obtain a total volume of approximately 22,115 km^3. Some of these lakes are shared with Canada (resulting in an overestimate), and many smaller lakes exist within CONUS (resulting in an underestimate). Consequently, this represents a very rough approximation of total surface water availability in the CONUS. So total VWSC is 728 km^3 while the surface water volume of the United States is roughly 22,115 km^3 (see Table 4).

There is much uncertainty in groundwater storage (Richey et al., 2015), which means that a range of values is appropriate for this hydrologic stock of water. Here the total U.S. groundwater storage is approximated as the sum of all storage in the five major North American aquifers (Richey et al., 2015). According to the USGS, the California Central Valley Aquifer System contained approximately 800 million acre-feet (986 km^3) in 1986 (Bertoldi et al., 1991; Faunt et al., 2009), while the Ogallala (High Plains) Aquifer system contained approximately 2.9 billion acre-feet (3,577 km^3) in 2007 (Qi & Christenson, 2010). While these results are outdated and uncertain, the magnitudes match well with the results from Richey et al. (2015). The Northern Great Plains Aquifer is shared with Canada, resulting in an overestimate of groundwater storage within CONUS. So total groundwater storage ranges from 673 km^3 to 59,800 km^3 (Richey et al., 2015). Our VWSC volume of 728 km^3 is at the lower end of this range.

Precipitation receipts to grain harvested areas are 683 km^3 in 2002, 785 km^3 in 2007, and 661 km^3 in 2012. In these same years, green VWSC was 665, 586, and 625 km^3, respectively. The green VWSC is less than precipitation receipts in all years, which means that our green VWSC values are physically feasible. This is an important check on our results. However, since the underlying data are based upon grain storage capacity—rather than actual grain stores—it could be possible that calculated VWSC exceeds rainfall receipts. This would happen if grain storage capacity dramatically exceeds local grain production capabilities of the area. However, the green VWSC is within the physical bounds imposed by rainfall fluxes.

Domestic VWT associated with grain in the United States was 100 km^3 (Dang et al., 2015). For global trade, the VWT of grains was 524 km^3 (Dang et al., 2015). This means that our estimate of 681 km^3 of VWSC in the United States exceeds both domestic and international VWT of grain. This is probably due to two potential data issues. Grain storage capacity data present a capacity rather than a stock value. This means that our VWSC also represents a capacity rather than actual virtual water stores. It is unclear what fraction of the VWSC capacity is actually stored. However, these values indicate that the U.S. grain storage infrastructure is large enough to store over 6 years of domestic VWT fluxes or over 1 year of global VWT fluxes.

4. Conclusion

This work improves our understanding of the grain and VWSC within a key country, the United States. This extends the existing VWT literature by empirically characterizing subnational VWSC for the first time. We show that VWSC is 728 km^3 in 2012. This volume is roughly 62% as much water as is normally stored in U.S. dams and represents 75–97% of precipitation receipts to agricultural areas, depending on the year. Most VWSC is concentrated in the U.S. Midwest, due to large grain storage capacities and plentiful rainfall. Rainfall contributes 86% to total VWSC, with the remaining 14% reliant upon irrigation. Total VWSC decreased from 2002 to 2007 (−12.3%) and then increased from 2007 to 2012 (+6.9%), though ultimately VWSC decreased from 2002 to 2012 by 6.3%. Over our study time period, VWSC increased around Illinois and Iowa but decreased in Montana and the Dakotas, as well as in Kansas and Colorado. National crop production trends seem to be the main driver of these VWSC changes.

Here we only determined the water footprint of grain storage in the United States. However, many other factors of production (e.g., labor, farm machinery, and fertilizer) are critical in agriculture and could be included in future work. Future work to comprehensively examine trade-offs and synergies across all factors of production (i.e., footprints) in agriculture would be a worthy addition to the literature. Additionally, future work to evaluate the "banking" value of grain and VWS would enable a better financial assessment of this infrastructure. For example, it is important to understand if the rainfall from good years that is stored in silos provides future value and if so what that value is. Future work quantifying actual storage—rather than the capacity—would further our understanding of this system.

We suggest that future work evaluates the dynamics of food storage during a drought. To evaluate how VWS operates during a drought event, high-resolution (space, time, and water source) information on crop water use is required, such as calculated by Marston and Konar (2017) to evaluate VWT during the California drought. In particular, research should strive to estimate the annual quantities of grain and virtual water stocks during drought, to evaluate how and if/when stocks buffer these extreme events. We hope that coupled agricultural production, storage, and trade models will strive to evaluate their complex interactions, as well as the buffering capacity of grain silos as a critical infrastructure system in the coupled water-food nexus.

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