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Key Points:

- We evaluate the impacts of global shale development on local water availability for food production and other human and environmental needs
- We find that many shale deposits worldwide are located in water-scarce regions, where cropland irrigation is critical for agricultural production
- In water-stressed areas, countries that decide to extract their shale energy sources would also need to develop water management plans to ensure that other human water needs and environmental flows are not adversely impacted

Supporting Information:

- Supporting Information S1

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The Water-Energy Nexus of Hydraulic Fracturing: A Global Hydrologic Analysis for Shale Oil and Gas Extraction

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Abstract Shale deposits are globally abundant and widespread. Extraction of shale oil and shale gas is generally performed through water-intensive hydraulic fracturing. Despite recent work on its environmental impacts, it remains unclear where and to what extent shale resource extraction could compete with other water needs. Here we consider the global distribution of known shale deposits suitable for oil and gas extraction and develop a water balance model to quantify their impacts on local water availability for other human uses and ecosystem functions. We find that 31–44% of the world's shale deposits are located in areas where water stress would either emerge or be exacerbated as a result of shale oil or gas extraction; 20% of shale deposits are in areas affected by groundwater depletion and 30% in irrigated land. In these regions shale oil and shale gas production would likely compete for local water resources with agriculture, environmental flows, and other water needs. By adopting a hydrologic perspective that considers water availability and demand together, decision makers and local communities can better understand the water and food security implications of shale resource development.

Plain Language Summary We present a global analysis of the impact of shale oil and gas extraction on water resources, particularly on irrigated crop production. Using a water balance analysis, we find that large areas underlain by shale deposits are either already affected by water stress or would become water stressed in the event that local water resources were to be used for shale oil or gas extraction. In these areas, the extraction of shale oil and shale gas is expected to compete with irrigated food production and other human water demands. The development of unconventional oil and gas from shale in water stressed areas of the world would need to overcome water scarcity challenges and would likely enhance competition for water in agriculturally important areas.

1. Introduction

Shale oil and shale gas have recently emerged as new important energy sources expected to play a fundamental role in meeting energy demand in the near future (International Energy Agency, 2017). Shales are low-permeability sedimentary rocks that might contain high quantities of hydrocarbons (Holditch et al., 2007). Various recent studies have shown how hydraulic fracturing, the technology generally used for shale hydrocarbon extraction, is associated with substantial amounts of water withdrawal and consumption (Chen & Carter, 2016; Horner et al., 2016; Nicot & Scanlon, 2012; Scanlon et al., 2014) and declines in regional water quality (Jackson et al., 2013; Osborn et al., 2011; Rozell & Reaven, 2012; U.S. Environmental Protection Agency, 2016; Vidic et al., 2013). Other possible environmental consequences of unconventional oil and gas extraction from shale are methane migration and groundwater contamination from faulty seals around well casings (Brantley et al., 2018; U.S. Environmental Protection Agency, 2016; Vidic et al., 2013; Warner et al., 2012), impacts on regional air quality (Vidic et al., 2013), low weights at birth in babies born near wells (Currie et al., 2017), seismic triggering associated with the choice to use deep wells as a disposal method for returned fracturing fluids, and the so-called "produced water" (the water resulting from oil and gas extraction; Kharak et al., 2013; Rutqvist et al., 2013). The development of shale deposits may also entail land use change (Jordaan et al., 2017), forest removal, habitat fragmentation, and biodiversity loss (Kiviat, 2013).

Shale oil and gas extraction also has important social, political, and economic implications. In the last decade, the North American fracking "boom" has changed the world hydrocarbon industry and energy economy. Shale gas has provided an abundance of natural gas, a bridge fuel toward a low carbon future (Moniz et al., 2011). For example, power generation in the U.S. is shifting from coal to the lower emitting natural gas (Obama, 2017). In addition, the shale revolution has created new jobs and economic benefits in North America (Peplow, 2017). Thus, shale extraction has the potential to enhance the economic growth and energy security of some regions and nations. Unconventional oil and gas from shale rocks are an opportunity for some countries to increase their energy security, while reducing costs of fossil fuel imports and potentially changing their import-export balance (Vidic et al., 2013). However, leakages from natural gas infrastructure can offset the benefit in reduction of greenhouse gas emissions from a combustion process that is more efficient and cleaner than that of coal (Alvarez et al., 2012; Brandt et al., 2014; Caulton et al., 2014; Howarth, 2014; Jenner & Lamadrid, 2013). Despite the growing interest in shale resources, there is only a limited understanding of the pressure that their extraction could place on local water resources worldwide (Reig et al., 2014). Globally, it remains unclear to what extent the water consumption of shale gas and shale oil production would compete with other human and environmental water needs and induce or exacerbate local water scarcity. Such a potential trade-off among water allocations is especially worrisome for regions already prone to water stress, where additional water may also be needed to support growing populations and the expansion of irrigation (Davis et al., 2017).

This limited understanding of the potential impacts of shale development on the local water balance thus prevents the implementation of a sustainable water management plan in places where shale extraction is possible. There is therefore a pressing need for a quantitative assessment and mapping of where shale resource mining could lead to an inadequate management of local water resources and intensify the competition for water between food and energy production (Chiarelli et al., 2018; Cook & Webber, 2016; D'Odorico et al., 2017; Habib et al., 2018; Rosa et al., 2017; Rulli et al., 2016).

Previous efforts (Clark et al., 2013; Jiang et al., 2014; Kondash & Vengosh, 2015) have assessed the water footprint of unconventional oil and gas extraction from shale from the life cycle assessment perspective, focusing on a comprehensive accounting of all water costs associated with production and processing, but without examining the availability or source of the required water. Here we assess the impacts of global shale extraction on the local water balance using a hydrologic approach that links shale fuel extraction with hydrologic and environmental impacts. We examine the global distribution of known shale deposits suitable for oil and gas production (Kuuskraa et al., 2013) and identify the regions in which water consumption for hydraulic fracturing could compete with agriculture and other human activities. We analyze the average annual water stress (Mekonnen & Hoekstra, 2016) at 0.5° resolution (~50 km at the equator) for the world's shale deposits and highlight those deposits in which shale hydrocarbon extraction would induce or enhance water stress. While water quality concerns by local population may be a limiting factor for the development of world shale deposits (e.g., Goho, 2012; Williams, 2017), here we focus on physical and environmental constraints resulting from water limitations.

Previous studies have quantified water stress resulting from water withdrawals for hydraulic fracturing in some shale deposits in the United States, Argentina, China, and Mexico (e.g., Freyman, 2014; Galdeano et al., 2017; Guo et al., 2016; Mauter et al., 2014; Scanlon et al., 2014). In response to the need for a global-scale analysis of the hydrologic impacts of shale extraction, the World Resources Institute estimated that 39% of global shale deposits lie within surface water-stressed regions (Reig et al., 2014). However, a global-scale quantitative analysis of the extent to which water consumption for shale gas and shale oil production would compete with agriculture and induce or exacerbate local water stress is still missing.

Here we also quantify and analyze the possible impacts of global oil and gas extraction from shale on groundwater resources, environmental flows, agricultural, industrial, and domestic water consumption. We use an updated global shale deposit data set that includes all known deposits where the most profitable opportunities for oil and natural gas extraction exist (Kuuskraa et al., 2013). We adopt a water balance approach (Mekonnen & Hoekstra, 2016) to quantify the impact of shale extraction on the local water resources while accounting for the water required for other human needs (e.g., irrigation) and environmental flows. We conclude by comparing local volumes of water consumption by shale extraction to the amount of current irrigation water consumption (Hoekstra & Mekonnen, 2012).

2. Methods

2.1. World Shale Deposits

Global maps of shale deposits were acquired from Advanced Resources International, Inc., who have developed an up-to-date internationally recognized georeferenced data set of the spatial extent of shale areas (Kuuskraa et al., 2013). In the case of the United States, the map of shale areas came from the U.S. National Energy Technology Laboratory (U.S. National Energy Technology Laboratory, 2016). In this study we focus on shale areas (or "shale plays") that offer the most profitable opportunities for oil and natural gas extraction in the near future, while lower quality and less explored deposits, which likely hold additional shale resources, are not included in this assessment (Kuuskraa et al., 2013).

2.2. Generation of Water Stress Maps

Water stress (WS) is defined as the ratio of the local water consumption of human activities (WC) (i.e., municipal, agriculture, mining, and other industries) and the renewable blue water availability in a grid cell (Mekonnen & Hoekstra, 2016). In water-stressed areas, water is consumed at greater rates than local renewable water availability. This means that there is an unsustainable use of water resources typically associated with the use of environmental flows and/or groundwater depletion. Blue water stocks include freshwater resources in surface water bodies and aquifers but do not include soil water storage in the unsaturated zone (Falkenmark & Rockström, 2004). Renewable blue water availability was calculated following the methods by Mekonnen and Hoekstra (2016). Aggregated values of water consumption and blue water availability—from grid cells to the boundaries of a shale deposits—are shown in supporting information Table S1.

2.3. Assessment of Local Renewable Blue Water Availability

The global distribution of annual renewable blue water availability (WA) (at 0.5° resolution) was calculated following the methods by Mekonnen and Hoekstra (2016), whereby the value of WA in a grid cell was expressed as the sum of the local renewable blue water availability in that cell (WA_{loc}) and the net blue water flow from the upstream grid cells, defined as the local surface renewable water availability in the upstream cells (WA_{up}) minus the blue water consumption by human activities in the upstream cells (WC_{up}). The net surface blue water flows were calculated using the upstream-downstream routing "flow accumulation" function in ArcGIS®, where the subscript i denotes the cells upstream from the cell j under consideration:

$$WA_j = WA_{loc,j} + \sum_{i=1}^{n} \left(WA_{up,i} - WC_{up,i}\right)$$

Local blue water availability was calculated as the local blue water flows generated in that grid cell minus the environmental flow requirement. We assumed that a fraction (y) of runoff is allocated to maintain environmental flows and the remaining fraction ($1 - y$) is considered blue water locally available for human needs, WA_{loc} (Pastor et al., 2014; Steffen et al., 2015). Environmental flow is defined as the minimum surface runoff that is required to sustain ecosystem functions; for irrigation to be sustainable, these minimum flow requirements need to be met even during dry season and low flow conditions (Pastor et al., 2014; Richter et al., 2012). Three flow regimes were considered, low, intermediate, and high corresponding to less than the 25th percentile, between the 25th and 75th percentiles, and greater than the 75th percentile of annual runoff, respectively. Following Steffen et al. (2015), a different environmental flow requirement (i.e., value of y) was used for each flow regime (see supporting information Table S2; Pastor et al., 2014).

To calculate the upstream to downstream surface water availability, we used the flow direction raster (at 0.5° resolution) from the World Water Development Report II (Vörösmarty et al., 2000a, 2000b). Surface runoff estimates (at 0.5° resolution) were obtained from the Composite Runoff V1.0 database (Fekete et al., 2002).

2.4. Assessment of Local Water Consumption

Water consumption (WC) is the volume of water that is withdrawn and not returned back to the environment as liquid water (i.e., consumptive use). Estimates of agricultural (crops and livestock), industrial, and domestic water consumption at 0.0833° resolution were from Hoekstra and Mekonnen (2012) and were aggregated to 0.5° resolution to match with the water availability data set. Crop water consumption was estimated using a crop-specific model of irrigation water requirements (Hoekstra & Mekonnen, 2012). The rates of domestic and industrial water consumption were taken from Hoekstra and Mekonnen (2012) using country-specific per capita values and population density maps.

2.5. Shale Deposits and Groundwater Depletion

Water used for shale gas and oil extraction can be taken either from surface water bodies or from groundwater resources (Freyman, 2014). Because the recharge and recovery of groundwater reserves occur at much longer time scales, these resources can be more vulnerable to depletion under prolonged rates of

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Table 1
Annual Water Potentially Consumed Globally to Extract Oil and Gas From Shale Resources Under the 18 Scenarios Considered in This Study

	Low injection scenario (10^9 m^3/yr)	High injection scenario (10^9 m^3/yr)
No recycling		
1.50 wells/km^2	3.49	8.73
2.13 wells/km^2	4.96	12.39
3.62 wells/km^2	8.43	21.06
80% recycling		
1.50 wells/km^2	1.54	3.84
2.13 wells/km^2	2.18	5.45
3.62 wells/km^2	3.71	9.27
50% recycling		
1.50 wells/km^2	2.27	5.67
2.13 wells/km^2	3.22	8.06
3.62 wells/km^2	5.48	13.69

Note. Results are represented using two values of water consumed per well (*W*) of 12,000 m^3 (low injection scenario) and 30,000 m^3 (high injection scenario), three well densities scenarios (1.50 wells/km^2, 2.13 wells/km^2, and 3.62 wells/km^2), and three water recycling (*R*) options (no recycling, 50%, recycling, and 80% recycling).

withdrawals. With this in mind, we analyzed world shale deposits and their possible extraction impacts on freshwater aquifer stocks contained in global major groundwater basins (BGR/UNESCO, 2008). In this study we do not consider brackish or saline aquifers.

If groundwater consumption occurs at higher rates than it is replenished by hydrologic processes, the aquifer is undergoing unsustainable use or "depletion." In some cases freshwater stocks that were formed in the past centuries or millennia are depleted ("mined") in just a few decades (Gleeson et al., 2012). To identify shale deposits located in areas affected by groundwater depletion, we overlaid a groundwater depletion map (Gleeson et al., 2012) with the global distribution of shale deposits.

2.6. Assessing Water Consumption for Shale Extraction

The water consumption of shale resource extraction (WC_{Frac}) was calculated as

$$WC_{Frac}\left(\frac{m^3}{year}\right) = (1 - F \cdot R) \cdot n \cdot W$$

where *W* is the water injected into one well using today's hydraulic fracturing technology, *n* is the number of wells, and *F* and *R* are the fraction of the returning fracturing fluid and its recycled fraction, respectively.

The amount of water required to stimulate a horizontal well through hydraulic fracturing (*W*) depends greatly on local geology, deposit depth, technology used, and operational factors applied (e.g., average well lateral length; Gallegos et al., 2015; Nicot & Scanlon, 2012; Scanlon et al., 2014). Unfortunately, only limited data and scholarly work exist for shale deposits outside the United States. Therefore, given the complexity and uncertainty of modeling water consumption for global deposits, our analysis requires simplifications and assumptions. We therefore considered 18 water management scenarios (Table 1) based on the same parameters available for U.S. shale development and applied them to the other shale deposits outside North America. According to the literature, we assumed two values of water consumed per well (*W*) of 12,000 m^3 (low injection scenario) and 30,000 m^3 (high injection scenario; Chen & Carter, 2016; Kondash & Vengosh, 2015) and three water recycling (*R*) options ("no recycling," 50%, and 80% recycling). Depending on the geology, the returning hydraulic fracturing fluid (*F*) can be up to 70% of the injected water. To make a conservative analysis, we assumed that flow back water is equal to 70% (Gregory et al., 2011).

The number of potential wells (*n*) that can be drilled in each shale deposit was assessed as the product of the area of each shale deposit (km^2) and the typical well spacing values (wells/km^2). Well spacing from developed shale oil and gas deposits ranges from 1.50 wells/km^2 (low) to 2.13 wells/km^2 (average) and 3.62 wells/km^2 (high; Kuuskraa et al., 2011; McGlade et al., 2013; Rezaee, 2015). In our analysis we used these three well spacing values. The rate at which wells are drilled and completed depends on numerous factors, including existing infrastructure availability (e.g., drilling rigs, trucks, pumps, water tanks, roads, and pipelines), economics (e.g., oil and gas prices and marginal costs of extraction), existing production within the shale basin, and technology adopted by shale companies (Kuuskraa et al., 2013). Therefore, the wells are not drilled and stimulated all at once but are drilled within a timeframe of a few decades, here assumed to be 30 years (U.S. Energy Information Administration, 2014). In other words, we assume that the above values of well spacing are attained within a timeframe of 30 years, with *n*/30 wells added each year.

Results presented in the main text of this study consider an average scenario of water consumption, that is, a well spacing equal to 2.13 wells/km^2, 80% recycling of the flow back water under the case "low injection scenario" or 12,000 m^3 of water injected per well (supporting information Table S1).

2.7. Assessing Other Related Impacts

To identify shale deposits in which the extraction of oil and gas is expected to compete with food production in the near future, we examined areas in which the increase in agricultural production by closing the yield gap of major crops (i.e., wheat, maize, and rice)—the difference between actual and attainable yields—to within

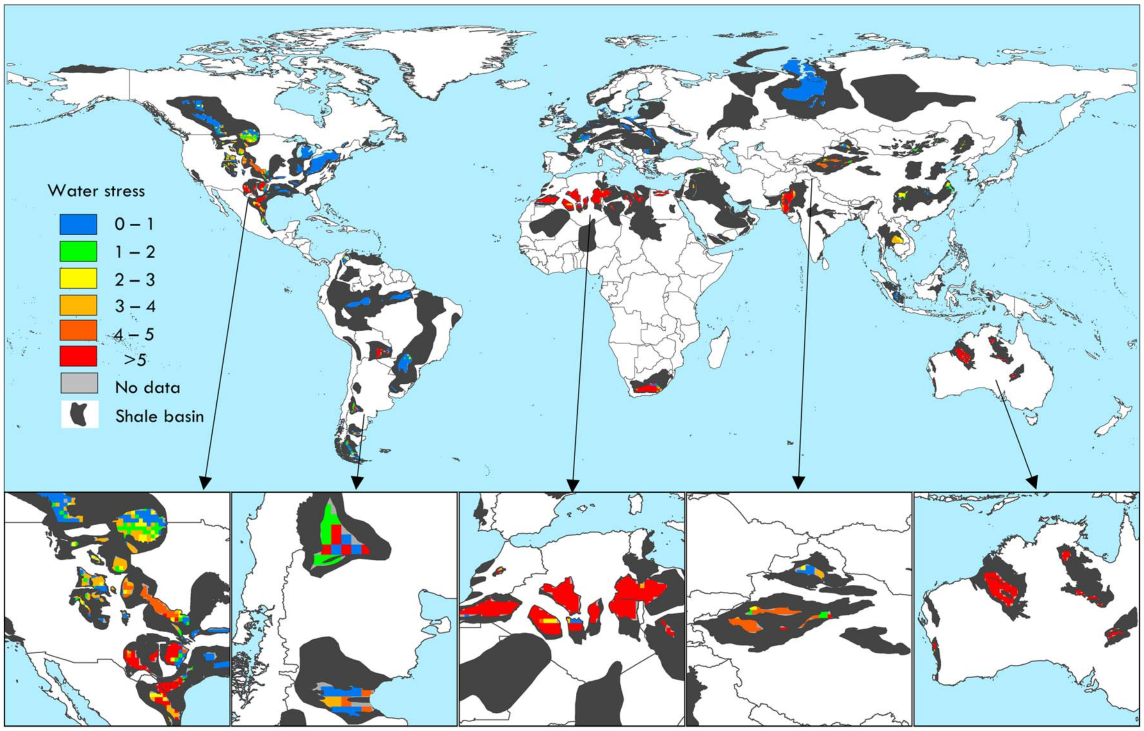

Figure 1. Map of water stress within shale deposits. Pixels with water stress indexes greater than one are subjected to unsustainable water consumptions (i.e., water consumption for human activities exceeds the limit imposed by environmental flow requirements).

75% of attainable yield will require an increase in irrigation. To that end, we utilized data on the global assessment of irrigation-controlled yield gaps by Mueller et al. (2012).

The number of people living in areas underlain by shale deposits was estimated using population distribution data taken from CIESIN's Gridded Population of the World map (GPWv4) for the year 2010 (Center for International Earth Science Information Network-CIESIN–Columbia University, 2015).

Percentages in the results section are expressed as fractions of the total global shale area times 100.

3. Results

3.1. Regions in Which Hydraulic Fracturing Will Intensify Pressures on Local Water Resources

We estimate that 31% of global extent of shale areas are located in water-stressed regions, defined as areas in which human consumptive water demand already exceeds local renewable blue water availability (i.e., surface + groundwater). Our global analysis of additional water stress potentially generated by shale deposit exploitation shows that depending on future water consumption from hydraulic fracturing (Table 1), water-stressed areas over shale deposits could expand to as much as 44% of shale deposit areas. Deposits in currently stressed areas include those occurring in the south central United States, Canada, Argentina, South Africa, northern Africa, China, India, and Australia (Figure 1).

Depending on the fraction of returning fracturing fluid that is recycled and well spacing adopted by shale companies, a total water demand ranging from 1.54 and 21.06 km^3 per year will be required to extract the global shale oil and shale gas reserves using current technology (Table 1). Even though the volume of water for shale oil and gas production is an order of magnitude smaller than that required for crop irrigation globally (899 km^3 annually; Hoekstra & Mekonnen, 2012), we find that the effect of hydraulic fracturing on water resources could be substantial at the scale of individual shale deposits where the water demands of shale extraction can exceed local renewable blue water availability (Figure 2). Depending on future water consumption by hydraulic fracturing, the majority (51–74%) of global shale areas will require less than 1% of the locally available water availability for the extraction of natural gas or oil. However, certain arid regions

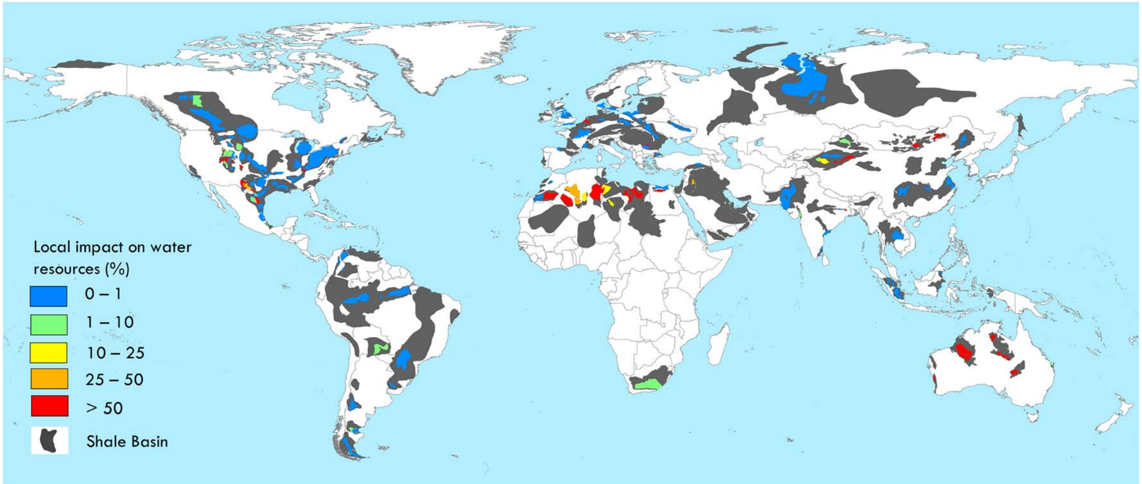

Figure 2. Fraction of local water availability needed for unconventional oil and gas extraction from shale rocks.

(17–33% of world shale areas) will require more than 50% of regional water resources for complete shale extraction (Figure 2). Shale deposits in such arid regions also include the Cambay shale (India), Etel shale (Libya), Frasnian shale (Algeria and Tunisia), Gacheta shale (Colombia), Lower Silurian shale (Morocco), and Goodwood/Cherwell shale (Australia; Figure 2).

3.2. Shale Deposits and Groundwater Depletion

The extraction of shale deposits is expected to affect not only surface water resources but also more ubiquitous groundwater resources (Jasechko & Perrone, 2017). In areas affected by water stress, the extraction of shale deposits could entail the reliance on unsustainable groundwater mining. Therefore, we investigated where the extraction of shale deposits could have an impact on freshwater aquifers around the world by analyzing the colocation of shale deposits and major groundwater basins (BGR/UNESCO, 2008). Interestingly, we found that 59% of world's shale deposits are in the footprint of major freshwater aquifers (Figure 3). In addition, we find that 20% of shale deposits are located in regions affected by groundwater depletion (Figure 3).

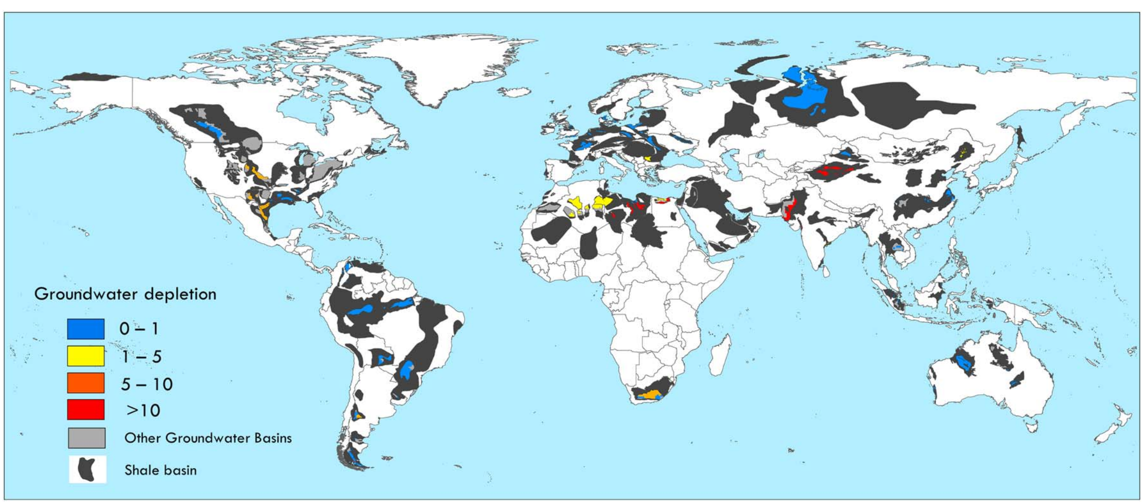

Figure 3. Groundwater-depleted aquifers in the footprint of world shale deposits. Freshwater aquifers considered are major groundwater basins (Gleeson et al., 2012). Pixels with groundwater depletion indexes greater than one indicate unsustainable water withdrawals (i.e., groundwater depletion).

Table 2
Overlap Between Shale Deposits and Irrigated Croplands

Shale deposits (country)	WC_{IRR} (10^9 m^3/yr)	WA (10^9 m^3/yr)	$\frac{WC_{Frac}}{WA}$ (%)	WS
Sembar (Pakistan)	33.624	4.069	0.16	8.68
Khatatba (Egypt)	6.264	13.682	0.05	1.16
Niobrara (US)	3.433	5.497	0.01	0.75
Permian-Triassic (India)	2.490	18.784	0.07	0.15
Mississippian Lime (US)	2.243	8.519	0.07	0.28
Nam Duk Fm (Thailand)	2.145	12.174	0.05	0.27
Wufeng/Gaobiajian (China)	1.672	35.520	0.02	0.18
Ketuer (China)	1.197	0.601	1.10	2.11
Collingham Whitehill Prince Albert (South Africa)	1.069	0.309	2.14	4.10
Colorado Group (Canada)	0.675	5.062	0.13	0.26
Cambay Shale (India)	0.643	0.000	100.00	>10
Longmaxi Permian Qiongzhusi (China)	0.497	10.279	0.08	0.05
Pimienta (Mexico)	0.407	5.773	0.04	0.13
Baxter (U.S.)	0.406	0.604	1.09	0.71
Banff/Exshaw (Canada)	0.363	2.144	0.308	0.18
Other deposits	7.640	984.263	-	-
All deposits	64.768	1105.135	-	-

Note. Current water consumption from irrigation (WC_{IRR}), blue water availability (WA), fraction of local blue water availability needed for shale extraction (WC_{Frac}/WA), and current water stress (WS) over shale deposits. Values for blue water availability are reported after accounting for environmental flows. Note that only the top 15 shale areas with the highest demand for irrigation water are listed.

Some deposits in the south central United States, northern India, and Pakistan are situated in groundwater basins that are experiencing substantial depletion (e.g., the U.S. High Plains and Indo-Gangetic Plain aquifers) because of groundwater pumping for irrigation (Rodell et al., 2009; Scanlon et al., 2012). Further, 17% of the world's shale areas are affected by both water stress and groundwater depletion (supporting information Figure S1). These areas are found across the south central United States, Mexico, Argentina, northern Africa, South Africa, South Asia, and China.

3.3. Future Shale Development in Irrigated Areas

Globally, 7% (65 km^3/yr) of total global annual irrigation water is consumed on croplands overlying shale deposits (Table 2). Some agricultural baskets over such shale deposits include the U.S. High Plains (Barnett, Niobrara, and Woodford shale), South and East Texas croplands (Eagle Ford and Haynesville shale), North Dakota's Great Plains (Bakken shale), Nile Delta (Khatatba shale), China's Sichuan Province (Sichuan shale basin), China's Xinjiang Province (Tarim shale basin), Indo-Gangetic Basin (Sembar and Cambay shale), and Thailand croplands (Nam Duk Fm shale; Table 2 and Figure 4).

To better evaluate possible future competition for water resources between shale deposit extraction and agriculture, we examined the global distribution of areas in which irrigation is expected to increase to accommodate the growing demand for food products (Figure 4). We find that 30% of shale areas worldwide underlie irrigated agricultural areas. Some of these shale deposits in China, India, South Africa, Egypt, and Pakistan are located in water-stressed regions (Table 2). We estimate that 6% of the shale areas are located in regions where water consumption for irrigation has been projected to increase in order to reduce crop yield gaps by 75%—the difference between actual and attainable yields (Mueller et al., 2012). Thus, pressure on water resources in these areas may not only increase due to potential shale energy production but may also be exacerbated by a greater need for irrigation water.

3.4. Domestic and Industrial Water Consumption in Areas Underlain by Shale Deposits

Currently, 303 million people worldwide live over shale deposits. In these regions, water is also consumed in industrial production and for domestic water supply. We estimate that 43 km^3/yr of freshwater are consumed for domestic and industrial purposes over shale deposits—which is about 6% of the total global annual water consumption by these sectors (Hoekstra & Mekonnen, 2012; Table 1). Those deposits are located in relatively highly populated regions of the United States, China, Ukraine, Pakistan, Egypt, and Thailand.

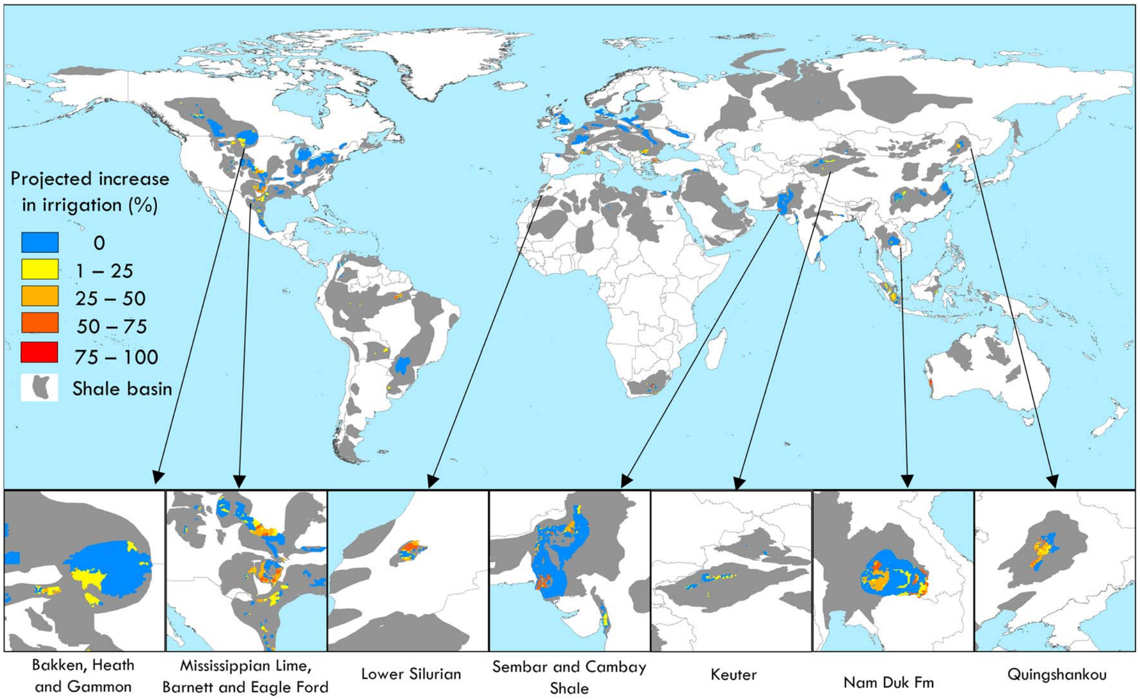

Figure 4. Irrigated areas overlying shale deposits. Projected increase in irrigated areas necessary to reduce the yield gaps of maize, rice, and wheat to 75% of attainable yields (Mueller et al., 2012). Bottom panels show the case of shale deposits in Canada, United States, Mexico, Morocco, Pakistan, India, China, and Thailand where we predict the occurrence of future competition between water for shale resource extraction and food production.

3.5. Use of Water Resources in Shale Plays Where Extraction Has Recently Started

Besides the United States and Canada, shale oil and gas are commercially extracted in Argentina and China (U.S. Energy Information Administration, 2015). In Argentina, oil and gas are extracted from shales in the Neuquén Basin. This basin is partly located in areas affected by water stress (Figure 1) and groundwater depletion (Figure 3). Here water is stored in three artificial reservoirs along the Neuquén and Limay Rivers. We estimate that 8% of water availability (Table 3) is locally consumed to irrigate local crops, and the remaining fraction flows downstream where it is also consumed for irrigation. To overcome the additional water consumption from fracking activities and to prevent a further groundwater depletion, policy makers enacted a provincial decree that regulates water allocations associated with oil and gas extraction (Ministerio de Energia, 2012). In particular, the decree prohibits groundwater withdrawal for hydraulic fracturing and requires the oil industry to report the amount of water consumed for fracking (Ministerio de Energia, 2012). However, no limits are imposed on the rates of surface water withdrawal for hydraulic fracturing. Therefore, even though fracking activities account for only 1–2% of the local annual water availability (Table 3), in the event of prolonged extraction they are expected to enhance water stress, deplete freshwater storage in reservoirs, and reduce the amount of water available for irrigation (Mauter et al., 2014). To address these concerns, a River Basin Management plan has been developed to resolve water demand conflicts in the Rio Negro, Neuquén, and Limay River Basins (Ministerio de Energia, 2012).

In China, shale exploration and development is underway in the Sichuan, Tarim, and Junggar Basins. The Sichuan Basin is neither affected by groundwater depletion nor water stress. Hence, local water availability does not represent a significant constraint on production (Table 3). Chinese oil companies are procuring water using existing water withdrawal rights from the Wujiang River (the major tributary of the Yangtze River) (Guo et al., 2016). Conversely, the Tarim Basin and Junggar Basin are located in intensively irrigated areas (Table 3) subjected to water stress (Figure 1) and groundwater depletion (Figure 3). Here additional water consumption from hydraulic fracturing would likely require a significant fraction of locally available water resources, enhance water stress, and compete with irrigation in the region (Yang et al., 2013).

Table 3
Water Resources in Emerging Shale Plays Outside North America

Country	Shale basin	Shale deposit	WA (10^6 m^3/yr)	WC_{IRR} (10^6 m^3/yr)	$WC_{dom\&ind}$ (10^6 m^3/yr)	WC_{Frac} low injection scenario (10^6 m^3/yr)	WC_{Frac} high injection scenario (10^6 m^3/yr)
China	Sichuan Basin	Longmaxi	10278.80	496.82	3650.38	20.90	52.26
	Tarim Basin	L. Cambrian	14.24	236.14	36.10	6.23	15.58
		L. Ordovician	174.74	49.52	32.82	19.23	48.08
		M.-U. Ordovician	30.15	0.00	9.54	20.70	51.76
		Ketuer	600.75	1196.93	62.80	15.45	38.63
	Junggar Basin	Pingdiquan/Lucaogou	5.69	60.10	25.57	8.32	20.80
		Triassic	146.44	22.71	17.11	7.21	18.02
Argentina	Neuquen	Los Molles	1482.57	224.45	27.49	12.89	32.22
		Vaca Muerta	2864.14	124.75	26.19	11.33	28.32

Note. Current water consumption from irrigation (WC_{IRR}), blue water availability (WA), water consumption from the domestic and industrial sectors ($WC_{dom\&ind}$), and estimated water consumption from shale oil and gas extraction (WF_{Frac}). WF_{Frac} is reported for the high injection scenario and low injection scenario (30,000 m^3 and 12,000 m^3 of water injected per well, respectively) considering a well spacing equal to 2.13 wells/km^2 and 80% recycling of the flow back water.

Shale resource exploration efforts are underway in several countries, including Mexico (Castro-Alvarez et al., 2017), Algeria, Australia, Colombia, South Africa, and India (U.S. Energy Information Administration, 2015). Their shale deposits are located in water-stressed, groundwater-depleted, or arid areas (Figures 1 and 3). In those regions, careful water resources management plans are required to avoid the enhancement of water stress or further depletion of freshwater aquifers. For example, regulations might require fracking companies to adopt water saving practices (e.g., reuse produced water, sourcing brackish groundwater, invest in low water and waterless technologies, or transport water from farther away) or prohibit oil companies from acquiring freshwater from the agriculture sector.

4. Discussion

Many shale deposits worldwide are located in water-scarce regions, where irrigation is critical for crop production and millions of people live. Although their extraction requires a small percentage of the annual local water resources available for human needs, in the long term the development of shale resources in these water-scarce areas could generate a depletion of water resources if water is consumed at rates exceeding those of replenishment by hydrological processes. Further, an increasing recycling volume of fracturing water could make an important contribution to alleviating the depletion of local freshwater resources.

While our analysis accounts for the total potential water consumption of shale development worldwide, many of the assessed shale areas are unlikely to be put under commercial production—for various economic, environmental, social, political, and technical reasons. Moreover, while our results show that large volumes of water will be required, future technological development and water management improvements offer promise for minimizing water appropriations for shale extraction (International Energy Agency, 2016). For instance, industry is using brackish water—a globally abundant and underutilized resource—and is maximizing the reuse of returning hydraulic fracturing water (Nicot et al., 2014). Research and development is also focusing on nonwater alternatives for hydraulic fracturing fluid, including foams, which can reduce water usage but require more chemicals and extra safety precautions, while limiting the efficiency of hydrocarbon production (International Energy Agency, 2016).

The United States is the global leader in shale oil and gas production, and numerous studies show that water shortage is not a critical issue to the development of shale deposits (e.g., Marcellus, Barnett, Eagle Ford, and Bakken shale deposits; Barth-Naftilan et al., 2015; Nicot et al., 2014; Nicot & Scanlon, 2012; Scanlon et al., 2014). Our results are in overall agreement with these findings, in that global water use for shale deposit extraction is dwarfed by the local volumes used in agriculture and other activities. Nevertheless, water consumption by the shale industry would compete with other sectors (e.g., agriculture) in areas with limited water resources, such as Colorado, where recent reports show that shale oil and gas extraction has occurred at the expenses of water availability for irrigation (The Denver Post, 2015; The New York Times, 2012). Indeed, oil and gas industry is willing to pay a premium price for the small amount of water (relative to agriculture) they use. For example, in Colorado, farmers trying to secure water for irrigation have been outbid by shale developers willing to pay US$0.81 or even US$1.62 per cubic meter for auctioned surplus water (versus US $0.02 to US$0.08, the price farmers would typically pay; The New York Times, 2012).

Our estimates, which are based on current North American technology and estimated size of extractable hydrocarbon deposits (Kuuskraa et al., 2013), are affected by the uncertainty associated with the lack of detailed knowledge on the length of the wells (vertical and lateral), local geology, shale company, number of fracturing stages, type of water used, water recycling, technological, and economic factors (Gallegos et al., 2015; Kondash & Vengosh, 2015; Nicot & Scanlon, 2012). Moreover, the resolution of the hydrological model used (~50 km at the equator) and the annual scale of this analysis limit our ability to identify smaller-scale impacts. However, the complexity of a global analysis lends itself to a scenario-based approach and to the use of suitable assumptions. These results will serve as a starting point for studies undertaking a finer scale, local analysis of the impacts of shale oil and gas extraction on water supplies.

Our global analysis does not account for regional site-specific factors that can be crucial to the feasibility of hydraulic fracturing in water-stressed areas, where water availability is critical for shale development. Indeed, in water-stressed regions of the United States, shale deposits are currently extracted using brackish water or withdrawing water from freshwater artificial reservoirs. Industry is using brackish groundwater resources in the Permian and Eagle Ford shale deposits (in West Texas and Texas-Mexico border regions, respectively; Scanlon et al., 2014). Shale companies in the Bakken shale deposit (in North Dakota) are withdrawing water from Lake Sakakawea, the third largest water reservoir in the United States (Horner et al., 2016). Future research is required to investigate these site-specific factors that could allow for shale oil and gas development even in water-stressed areas and minimize competition for freshwater resources with other human and environmental needs.

5. Conclusions

Economic, social, environmental, technical, and policy-related factors will combine to influence commercial-scale production from shale areas in the coming years. For water-scarce or water-stressed areas in particular, the development of shale deposits will need to overcome the additional challenge of regional water limitations and will likely enhance competition for water in many populated or agriculturally important areas. In some of these regions, oil and gas production from shale rocks could place unsustainable pressure on the water resources required to support other human needs. By adopting a hydrologic perspective that considers water availability and demand together, decision makers can better understand the water and food security implications of shale resource development.

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