ARTICLE CASE

The Food-Energy-Water Nexus, Regional Sustainability, and Hydraulic Fracturing: An Integrated Assessment of the Denver Region

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ABSTRACT Intersections of food, energy, and water systems (also termed as the FEW nexus) pose many sustainability and governance challenges for urban areas, including risks to ecosystems, inequitable distribution of benefits and harms across populations, and reliance on distant sources for food, energy, and water. This case study provides an integrated assessment of the FEW nexus at the city and regional scale in ten contiguous counties encompassing the rapidly growing Denver region in the United States. Spatial patterns in FEW consumption, production, trans-boundary flows, embodied FEW inputs, and impacts on FEW systems were assessed using an urban systems framework for the trans-boundary food-energy-water nexus. The Denver region is an instructive case study of the FEW nexus for multiple reasons: it is rapidly growing, is semi-arid, faces a large projected water shortfall, and is a major fossil fuel and agricultural producer. The rapid uptake of high-volume hydraulic fracturing (HVHF) combined with horizontal drilling in populated areas poses ongoing risks to regional water quality. Through this case study, fracking is identified as a major topic for FEW nexus inquiry, with intensifying impacts on water quantity and quality that reflect nationwide trends. Key data gaps are also identified, including energy for water use and food preparation. This case study is relevant to water and sustainability planners, energy regulators, communities impacted by hydraulic fracturing, and consumers of energy and food produced in the Denver region. It is applicable beyond Denver to dry areas with growing populations, agricultural activity, and the potential for shale development.

KEY MESSAGE

Readers of this case study will be able to define the food-energy-water nexus and describe emerging conceptual frameworks for examining the FEW nexus at local and regional scales. Readers will become familiar with both challenges in applying such frameworks and insights the FEW nexus approach can offer into complex issues surrounding sustainability.

Key substantive content: An integrated spatial assessment of the food-energy-water (FEW) nexus, focusing on (a) production, (b) consumption, (c) trans-boundary flows, (d) embodied water and energy inputs, and (e) embodied impacts (e.g., the impact of energy systems on regional water supplies).

Key message: As the water footprint of hydraulic fracturing continues to intensify in the United States alongside the country's escalating oil and gas extraction, fracking poses particular risks to water and food systems in regions where energy and food production are co-located. Given its role in expanding fossil fuel production and potential impacts on water and food systems, hydraulic fracturing is a critical subject for emerging trans-disciplinary FEW nexus inquiry.

INTRODUCTION

Global food, energy, and water (FEW) systems are profoundly interconnected: 70% of global freshwater withdrawals are for agricultural production [1]; 8% of total global energy is used for water pumping, treatment, and distribution [2]; and the amount of water withdrawn for electricity generation rivals used by the agricultural sector in U.S. [3]. Solutions focused on just one of these systems,

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or on one geographic region, often have unintended consequences for other systems and regions. Interconnected FEW systems also have profound impacts on the overall environment, reshaping and profoundly altering land and ecosystems at large scales.

The FEW nexus has been broadly defined as the intersections among food, energy, and water systems that have major impacts on (a) natural resources, particularly water, energy, and nutrients, (b) pollution and greenhouse gas emissions, and (c) "the security of FEW supplies essential to the well-being of the world's population" [4]. The FEW nexus approach is seen as a promising way to identify and quantify the potential synergies in food, energy, and water security, while also reducing trade-offs, increasing efficiency, improving governance, and working to protect ecosystems [5]. Integrated nexus assessments often focus on understanding the linkages between domains, such as water to generate thermoelectric power [6, 7]. Central to these assessments are attempted quantifications of the embodied or virtual, water and energy required across different segments of FEW life cycles, but there are major gaps in the data and methodological approaches needed for such efforts [4].

HVHF—"fracking"—combined with horizontal drilling is a timely, important, and contentious example of the interconnection between water and energy systems: it is a water-intensive process that uses high-pressure water to create cracks in underground shale formations to extract previously inaccessible gas and petroleum [8]. It has been described as a "wicked" problem: one involving complex and opaque science and policymaking, overlapping areas of policy jurisdiction, requiring coordinated action among divided stakeholders, and resulting in limited solutions with complex consequences [9, 10].

Fracking and drilling have potentially far-reaching impacts on water systems [11–13]; recent research also maps the linkages between fracking and food systems [14]. These impacts are unevenly distributed both in space [15–17] and across populations [18–20], with the potential to compromise water quality if not carefully managed [21, 22]. In the United States, vast shale reserves extend from the Appalachian Mountains to the Northern Plains to the Gulf Coast [23]. These processes have become widely used in the span of less than a decade [23] and have propelled the United States to become the top global producer of petroleum and gas in the world, surpassing Russia in natural gas in 2009 and Saudi Arabia in petroleum in 2013 [24], with output set to increase even further in the coming years.

It has been widely noted that the water inputs for HVHF are small compared to the requirements of agriculture and other industries [25, 26], and the growing FEW nexus literature generally has not considered fracking to be a subject of inquiry. In this case study, however, the FEW nexus approach led to the identification of hydraulic fracturing as a key issue at the intersection of regional food, energy, and water systems. Systematic consideration of both *inputs to* and *impacts on* FEW systems is vital to a full picture of the challenges posed by hydraulic fracturing for regional communities, i.e., both the *quantity* of water inputs needed for fracking and the observed and potential impact of fracking on regional water *quality*.

However, as with FEW nexus data in general, water quality data related to hydraulic fracturing are limited, diverse, and often difficult to access [9]. In 2014, one review called the physical science literature on fracking "remarkably inconclusive" [27], and much is unknown about current and potential impacts of HVHF and drilling on water quality. At the same, understanding how frequently these operations impact groundwater quality is essential to assessing drinking water safety and public health risks in regions around the country where these practices are common [28], particularly as nationwide oil and gas production continues to increase.

CASE EXAMINATION

The Denver region has several characteristics that make it an instructive case study of the trans-boundary FEW nexus: rapidly growing, semi-arid, diminishing groundwater reserves, and a principal fossil fuel exporter and major agricultural producer. The ten counties included in this study had an estimated total population of 3,375,000 in 2015, grew by 20% in the preceding 10 years, and are projected to gain an additional 1.2 million residents by 2035 [29]. Eight of the ten counties in the region sit at least partially atop the Niobrara, a major shale formation that has among the highest oil and gas outputs in the country [30].

The Denver region receives between 6 and 16 inches of precipitation annually and sits atop the Denver Basin aquifer, a largely nonrenewable and extensively drilled groundwater reserve (Figure 1). Regional agriculture and Denver area municipalities already rely on major diversions of water from the Western slope of the Rocky

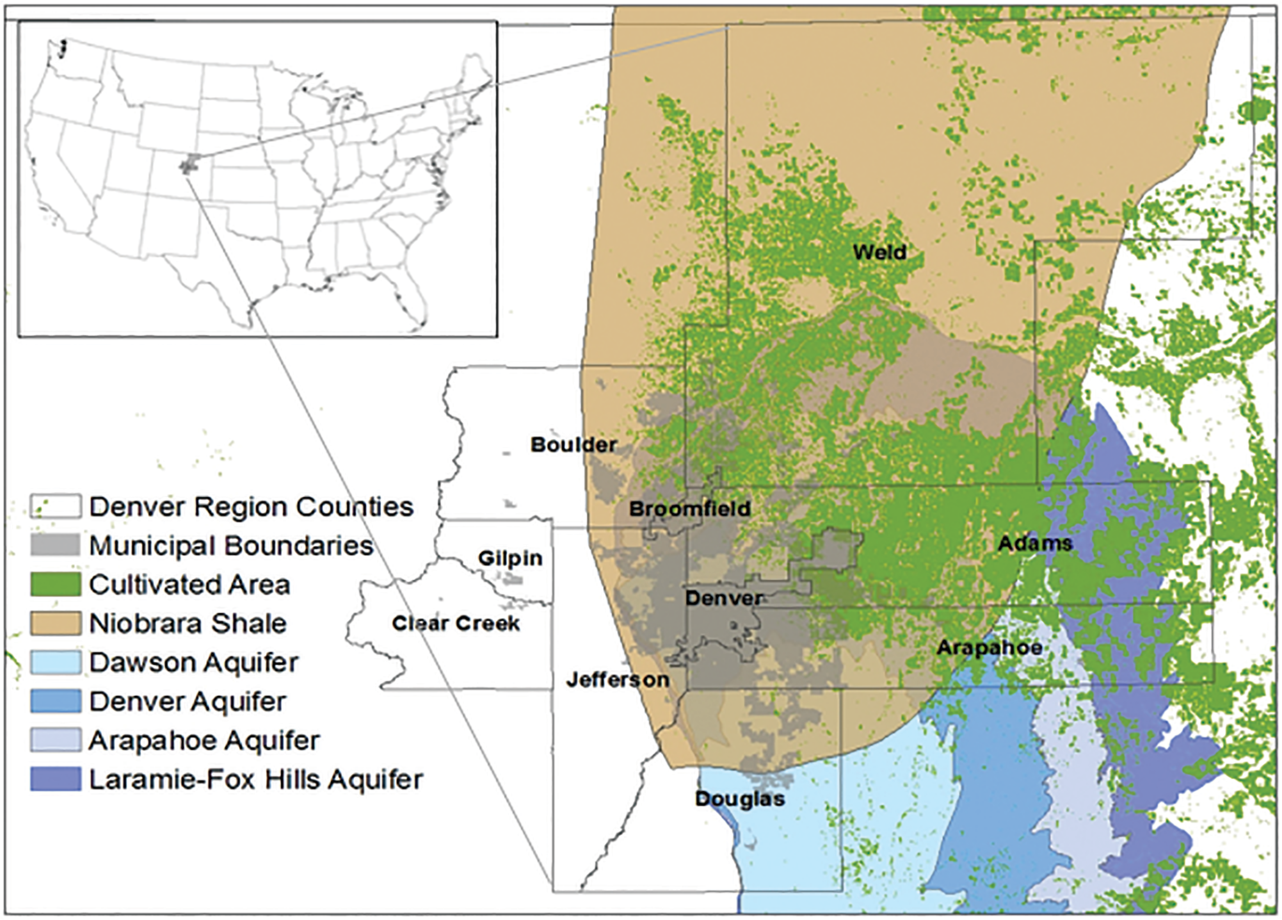


FIGURE 1. The ten-county study area. Cultivated land, the Denver Basin aquifer system, and the Niobrara Shale Formation are overlaid with municipal extents. The inset depicts the location of the Denver region within the southwestern United States. Data sources: USDA Cropland Data Layer, DRCOG, US Geological Survey, and US Energy Information Administration.

Mountains over the Continental Divide to the Eastern Slope. As human settlements encroach on land previously used for agriculture, growing municipalities are permanently buying water rights from farmers, a policy known as "buy and dry." The state is facing an anticipated 163 billion gallon (500,000 acre-feet) water shortfall by 2050, twice the amount currently used by Denver Water's 1.3 million residents [29, 31].

Similar to rapidly growing counties located above the rich gas reserves of the Barnett shale in Texas, Weld, Boulder, Broomfield, and Adams Counties in the Denver region are in the midst of a "perfect storm" where expanding surface development meets mineral extraction [32]. In Colorado, this "split-estate" system creates conflict between surface owners and those who own the mineral rights located below the surface [22]. Responsibility for well and land reclamation in the case of abandoned wells is also a major concern under this system [33].

The following research questions, relevant to identifying more sustainable system interconnections at multiple spatial scales, are addressed:

1. To what extent can the FEW nexus in the region be described and quantified?
2. What types of ecosystem risks are associated with FEW system intersections?
3. How are risks distributed across the landscape and how are they changing over time?
4. What available and emerging indicators are needed to address these questions? In what ways are such metrics limited?

Methods

EXTENDING AN EXISTING URBAN SYSTEM FRAMEWORK. One way to assess FEW system intersections is through the concept of embodied water and energy. Embodied energy refers to the energy needed for food and water-related activities across the life cycle, including energy for pumping, distribution, and wastewater treatment [35–36]. Similarly, embodied water refers to the water needed for energy and food-related activities across the life cycle (Figure 2a) [37]. This case study builds on the urban systems framework to assess the trans-boundary FEW nexus first proposed in 2017 by Ramaswami et al. that they used to quantify direct and embodied flows of food, energy, and water for the city of Delhi, India [4]. Not considered in that case were intra-city differences, changes over time, and in-boundary FEW production.

The current study extends that framework by including data from ten counties and more than forty municipalities. Also included is an assessment of in-boundary energy and food production for export, as well as changes to FEW systems over the past decade. Embodied *impacts on* FEW systems situated within broader ecosystems as well as embodied *inputs to* FEW systems are also systematically considered (Table 1 and Figure 2b).

This characterization focuses on (a) FEW production, (b) FEW consumption, (c) trans-boundary flows of food, energy, and water (d) embodied FEW inputs, and (e) embodied FEW impacts. Where such data were not already available in GIS format, geo-referenced maps based on state, county, and regional boundary files were created. Additional details about data sources, processing steps, and calculations are included in Supplementary Materials.

Co-production of supply and demand metrics with regional FEW experts was also undertaken. Analysts from regional utilities, regional data providers, infrastructure consultants, and city sustainability coordinators were consulted to gain additional perspectives on regionally important FEW nexus topics. During June–August 2016, semi-structured interviews were conducted with representatives from several organizations involved in FEW nexus governance, service provision, and research. These organizations included the Denver Region Council of Governments (DRCOG), Xcel Energy, Denver Water, the National Center for Atmospheric Research, and the National Renewable Energy Laboratory. The goal of these interviews was to obtain feedback on our initial research questions, identify relevant data sources, and build working relationships.

FOOD, ENERGY, AND WATER DEMAND IN THE DENVER REGION

Per day, the Denver region consumes an estimated amount of 68.9 GWh of electricity; 378,000 MCF of natural gas for residential and industrial heating; and 1,403 M gallons of water [39, 40]. Approximately 114,000 tons of coal, crude petroleum, transport fuels, and natural gas; and 46,000 tons of food and agricultural products are imported into the region per day. Energy imports totaled US$9.67 billion and food-related imports totaled US$17.6 billion in 2015, including food and energy products that are produced within the region [41].

City-wide and per capita FEW consumption within the region varies widely (Figure 3). Aggregate energy demand is greater within more densely populated cities and towns, but per household demand in these areas tends to be lower. Denver and Boulder, for example, consume the most electricity and natural gas in aggregate but have the lowest energy consumption per household (Figure 4; see Supplementary Materials for additional details and calculations).

FOOD, ENERGY, AND WATER SUPPLY IN THE DENVER REGION

Per day, approximately 186,000 tons of coal, crude petroleum, transport fuels, and natural gas and 39,000 tons of food and agricultural products are exported from the region. Fossil fuel extraction and food production are major activities: 44,000 oil and gas wells yielded 120 million barrels of oil and 686 million MCF in 2017 [42]. 24% of the land area was categorized as cultivated in 2015 [43]. Energy exports totaled US$19.7 billion, while food-related exports totaled US$13.8 billion in 2015, including goods consumed within the region [41]. Notably, much of this fossil fuel extraction and food production is occurring in the same place: 68% of the region's 44,000 oil and gas wells are located on farmland (Figure 5), directly impacting land and water resources used for regional food production.

Intraregional differences in food and energy production are significant. Energy and agricultural activities are concentrated in Weld County, which has 81% of the region's oil and gas wells [42]. Agriculture sales (80% livestock and 20% crops) are consistently in the top ten

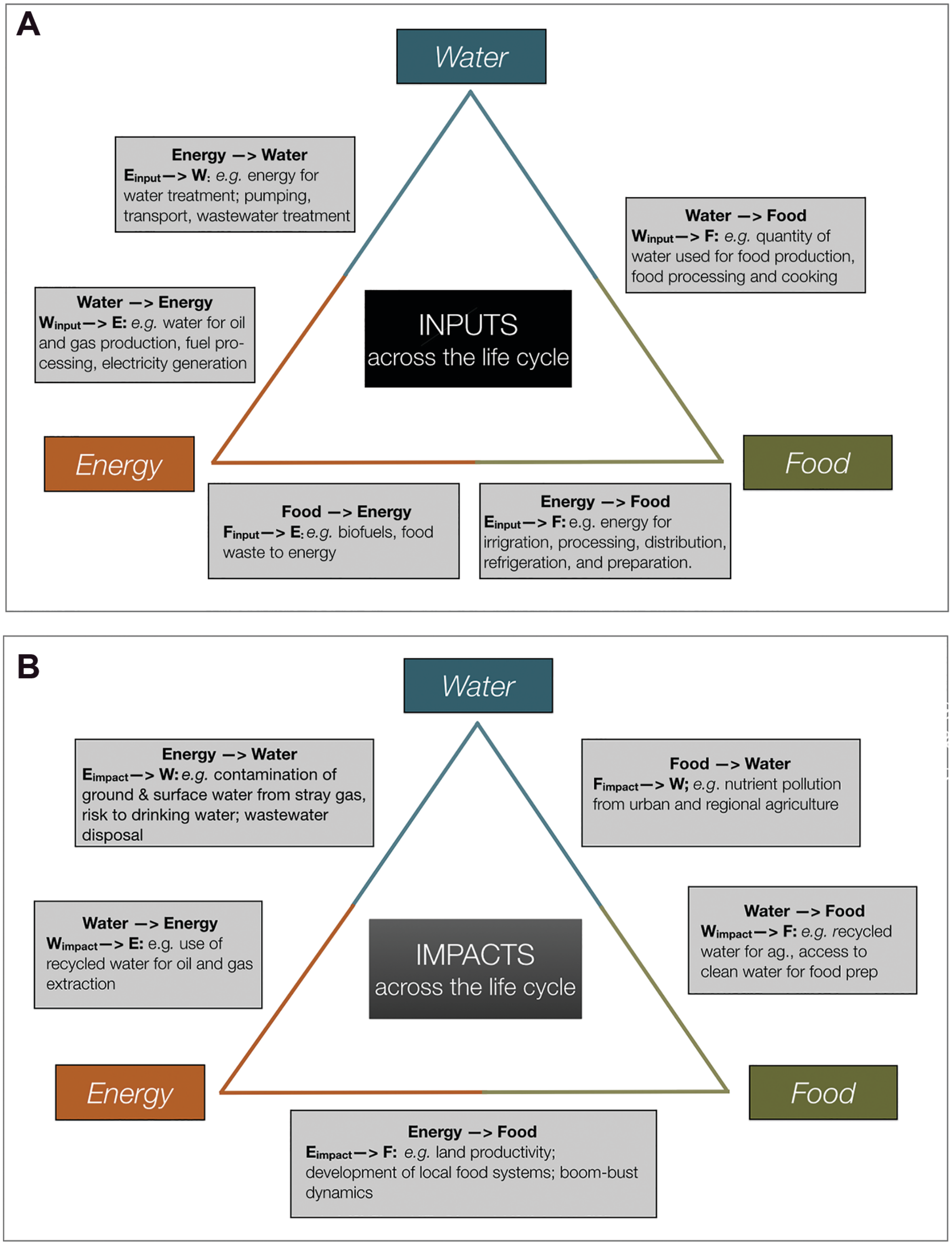


FIGURE 2. Illustration of the pairwise relations in the FEW nexus framework for developing spatially explicit indicators at the urban-regional scale, considering (a) inputs to and (b) impacts on food, energy, and water systems.

nationwide; in 2012 sales amounted to US$1.86 billion, a 21% increase from 2007 [44]. Annual oil output in Weld County increased ninefold to 118 million barrels and natural gas output more than tripled to 678 million MCF between 2006 and 2016. In neighboring Boulder County, by contrast, annual oil output fell from 27% to 97,000

TABLE 1. FEW relations, focusing on impacts, including examples specific to hydraulic fracturing

	Pairwise relation	Examples
W_{impact} → E	Impact of water quality across the energy life cycle	*Use of recycled water for oil and gas extraction
W_{impact} → F	Impact of water quality across the food life cycle	Recycled water for agriculture; access to clean water for food preparation; *Impacts from the decline in water quality on soil, land, and ecosystem productivity (crops/animal health)
E_{impact} → W	Energy-related risks to/ impacts on water systems	*Aquifer contamination through gas leakage from improper construction or failing wells; water resource contamination through spills, leaks, and waste management; accumulation of metals and radioactive elements in aquatic sediments at disposal and spill sites [13, 21]
E_{impact} → F	Energy-related impacts on food systems	*[Second order] impacts from the decline in water quality on soil, land, and ecosystem productivity (crops/animal health); effects of fracking-related air pollution on pollinators; effects on development of local, alternative food systems; fracking-related boom-bust dynamics [14] Extent of interactions among frac fluid and wastewater constituents is not well-understood [34]
E_{impact} → Ecosystems	Energy-related impacts on the social-ecological system as a whole	*Total environmental study paradigm for the impacts of fracking, including the anthroposphere, atmosphere, hydrosphere, lithosphere, and biosphere [38]
F_{impact} → W	Food-related impacts on water systems	Nutrient pollution of lakes, rivers, and streams from agricultural runoff [4]

*Specific to hydraulic fracturing.

barrels and natural gas output fell from 38% to 1.5 MCF during the same period [42], due to a county-wide moratorium on fracking from 2012 to 2017, renewed for another 2 years in 2018 [45] (see Supplementary Materials for additional details and calculations).

TRANS-BOUNDARY FLOWS

According to freight data, in 2015, the region exported 14 megatons of food and agricultural products, generating US$13.8 billion in revenue, and 67 megatons of energy-related products, generating US$19.7 billion (Figure 6). Per megaton, the value of food produced in the region was about US$1 billion, while per megaton of fossil fuels the value is US$295,000 [41].

Food

The region is a net food importer. In 2015, 10 megatons of food-related commodities were imported into the Denver region. By contrast, 7.6 megatons were exported to destinations around the country. An additional 6.5 megatons produced in the region were also consumed in the region.

Energy

The region is a net energy exporter. In 2015, 37 megatons of energy-related commodities were imported into the Denver region. By contrast, 63 megatons were exported to destinations around the country. An additional 4.7 megatons produced in the region were consumed in the region.

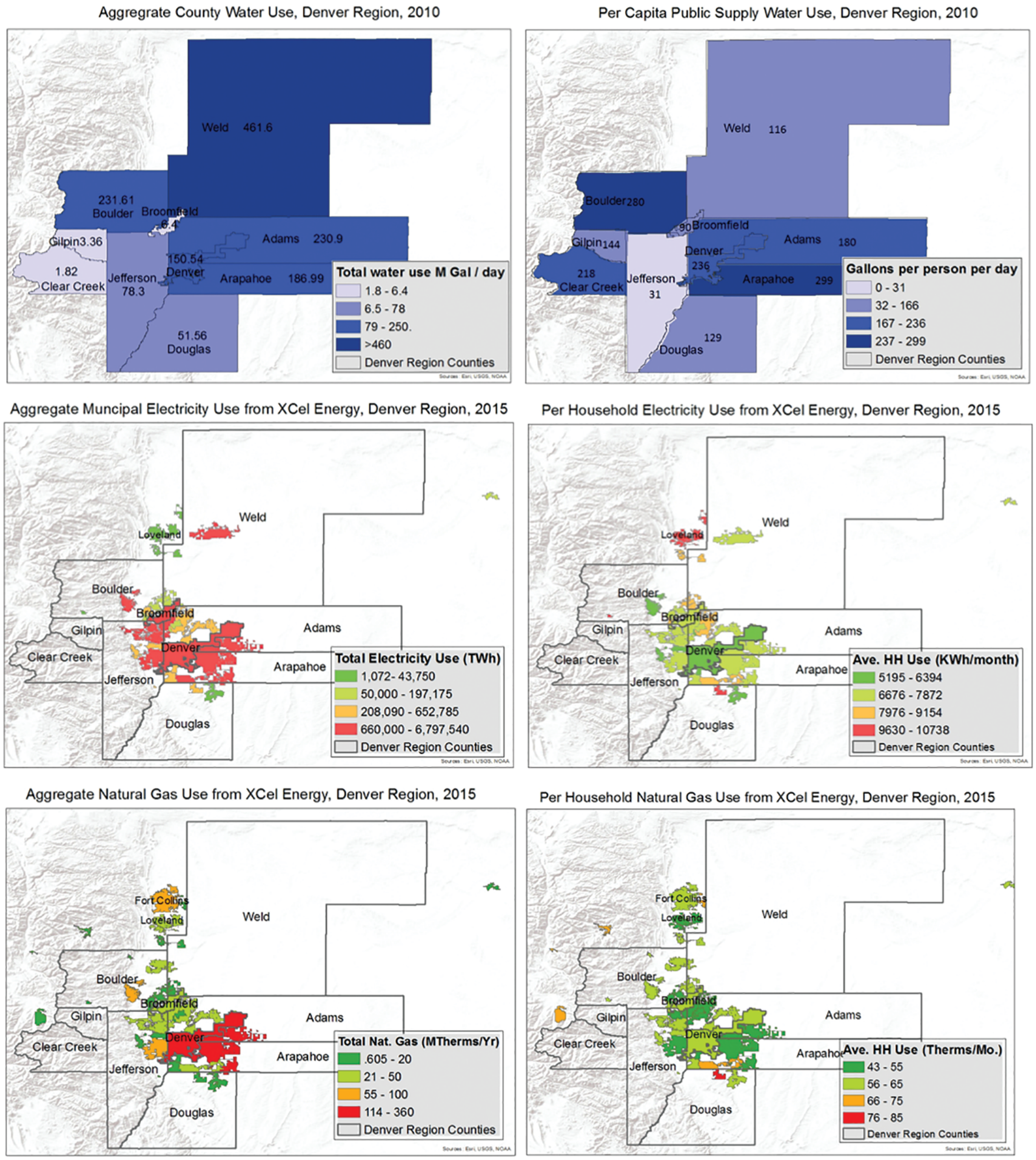
Water

About 70–80% of Colorado's precipitation falls west of the Continental Divide and 80–90% of the state's population lives east of the Divide. The Colorado-Big Thompson Project (C-BT), built between 1938 and 1956, supplies water more than 2.6 Gm^{2} of irrigated farmland and approximately 880,000 people in northeastern Colorado in eight counties, including Boulder, Broomfield, and Weld [8].

EMBODIED FOOD, ENERGY, AND WATER: INPUTS

Embodied Water: Inputs

Export-based agriculture and energy production consume a significant portion of the region's limited water resources. While much of the water used for agriculture


Aggregrate County Water Use, Denver Region, 2010

Per Capita Public Supply Water Use, Denver Region, 2010

Aggregate Muncipal Electricity Use from XCel Energy, Denver Region, 2015

Per Household Electricity Use from XCel Energy, Denver Region, 2015

Aggregate Natural Gas Use from XCel Energy, Denver Region, 2015

Per Household Natural Gas Use from XCel Energy, Denver Region, 2015

FIGURE 3. Region-wide and per household water, electricity, and natural gas consumption. Data sources: USGS and Xcel Energy.

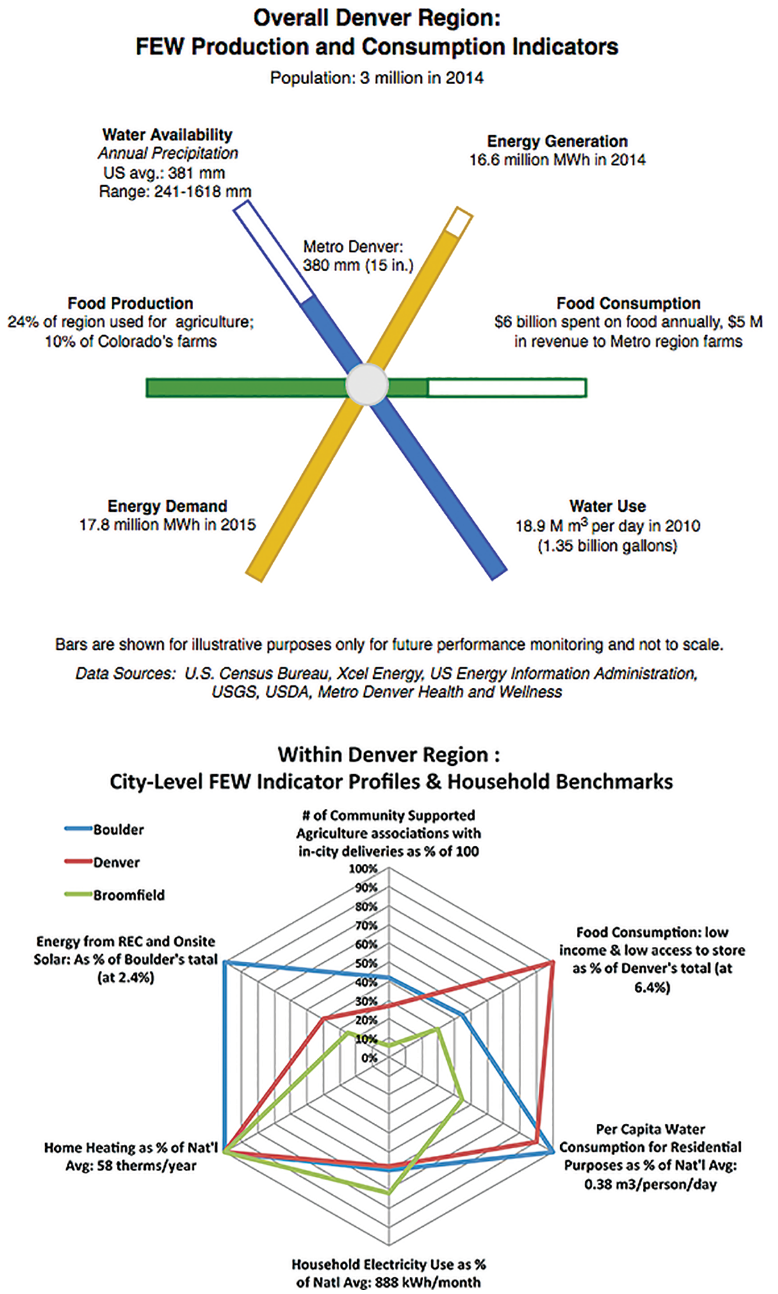
percolates through the soil (to become recycled groundwater), the water used for hydraulic fracturing cannot be re-used for other purposes because of the toxic chemical additives needed for the fracking process.

W$_{inputs}$ *→ F: Water Inputs to Food Systems*

Irrigation in the Denver Region is the major water use. In 2010, almost one billion gallons per day were used for irrigation/agriculture [39].

W$_{inputs}$ *→ E: Water Inputs to Energy Systems*

WATER INPUT FOR HYDRAULIC FRACTURING. Water input for hydraulic fracturing poses risks to the regional *quantity* of water supplies. As identified in a technical report issued by the National Renewable Energy Laboratory, these risks include: (a) the number of wells drilled, (b) the amount of water used per well, (c) the amount of recycling of fluids used to offset freshwater requirements, and (d) local water availability [21].



Bars are shown for illustrative purposes only for future performance monitoring and not to scale.

Data Sources: U.S. Census Bureau, Xcel Energy, US Energy Information Administration, USGS, USDA, Metro Denver Health and Wellness

FIGURE 4. FEW Multi-Metric Visual Tools. (Top) The three axes display regional production and consumption of food (green), water (blue), and energy (orange). (Bottom) City-level FEW sustainability metrics for selected municipalities in the region.

a) *Number of wells drilled*: There are approximately 44,000 oil and gas wells in the region. Since 2010, 9,060 were reported to have used hydraulic fracturing [[42, 46]; Figure 7].

b) *Amount of water used per well*: Reflecting national trends, the reported average water use per well has steadily increased over time, from 2.43 MG in 2013 to 8.8 MG in 2017 (Table 2).

c) *Amount of recycling of fluids used to offset freshwater requirements*: In Colorado, the amount of produced water reused is not tracked and the reuse of produced water is not mandatory [8, 21, 47].

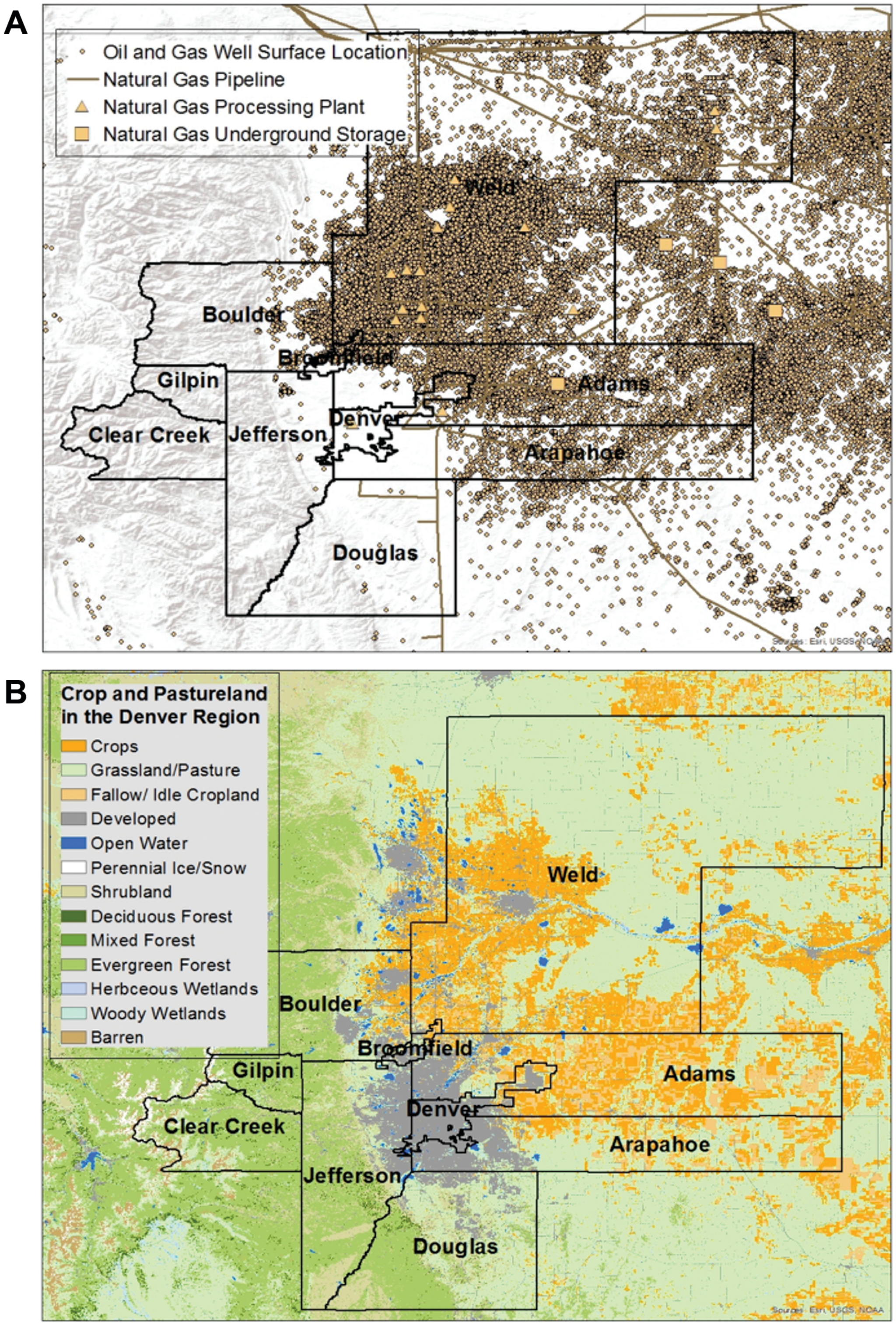


FIGURE 5. Energy and food production in the Denver region. (a) Surface locations of oil and gas wells: as of January 2018, the region has a total of approximately 44,000 oil and gas wells. Data sources: COGCC and EIA. (b) Extent of the Denver region's crop and pastureland. Human settlement is encroaching onto land previously used for irrigated agriculture. Data sources: USDA and DRCOG.

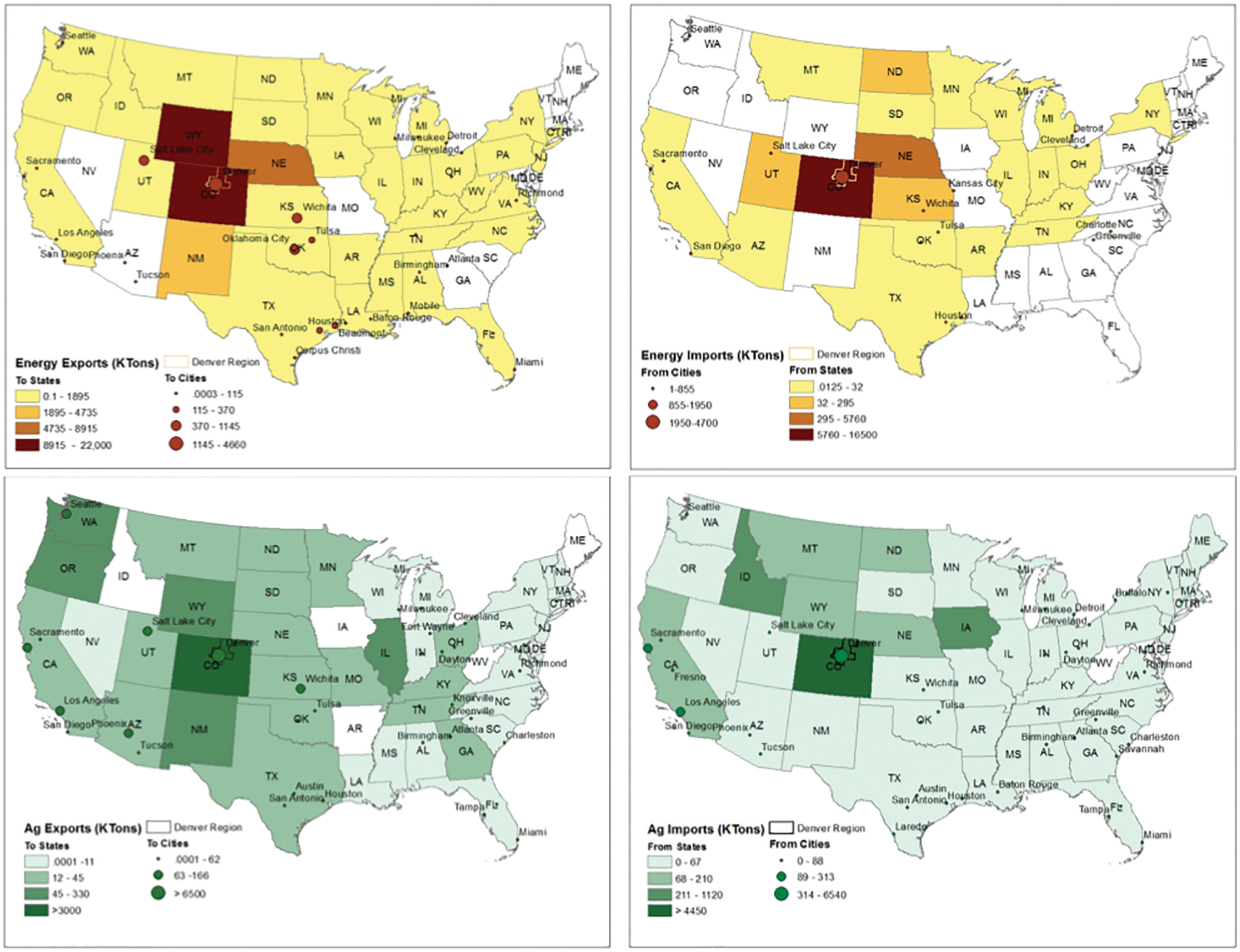


FIGURE 6. (panel; 4 maps) Food and energy imports and exports from the Denver region. Food and agricultural imports (top left) and exports (bottom left) from the Denver region in 2015. Energy imports (top right) and exports from the Denver region (bottom right) in 2015. Data source: Center for Transportation Analysis.

d) *Local water availability*: Reflecting national trends, the total base water volume for hydraulic fracturing has steadily increased over time, doubling from one-half billion gallons in 2016 to almost 1 trillion in 2017 [46]. (Water source not included in the dataset.)

SHALE DEVELOPMENT IMPACTS ON REGIONAL WATER AND FOOD SYSTEMS

Impacts on Water Across the Life Cycle

Water quality risks posed by unconventional shale oil and gas development arise from: (a) seismic exploration and discovery, (b) onsite road and well pad construction techniques, (c) drilling and onsite chemical management practices, (d) wastewater management practices, and (e) interim and final reclamation [21, 48]. Publicly available data on impacts to water quality resulting from oil and gas development are confined to violations issued by state regulators, reported spills, accidental releases, groundwater impacts, and uncontained berms (Table 3).

ONSITE PRACTICES. One indicator of risk to water quality is the number of spills associated with the drilling process. There were 451 spills in the Denver region from operations in 2014 (Figure 8). This number dropped to 366 in 2015 and 293 in 2016 but rose again in 2017. Another indicator of the risk to water quality from unsafe onsite chemical management practices is the number of violations issued by regulators to well operators. In 2017, 18 violations were issued, a 50% decrease from 2016, while public complaints increased almost sixfold during the same period, from 190 in 2016 to 1,124 in 2017 [[42]; Figure 9].

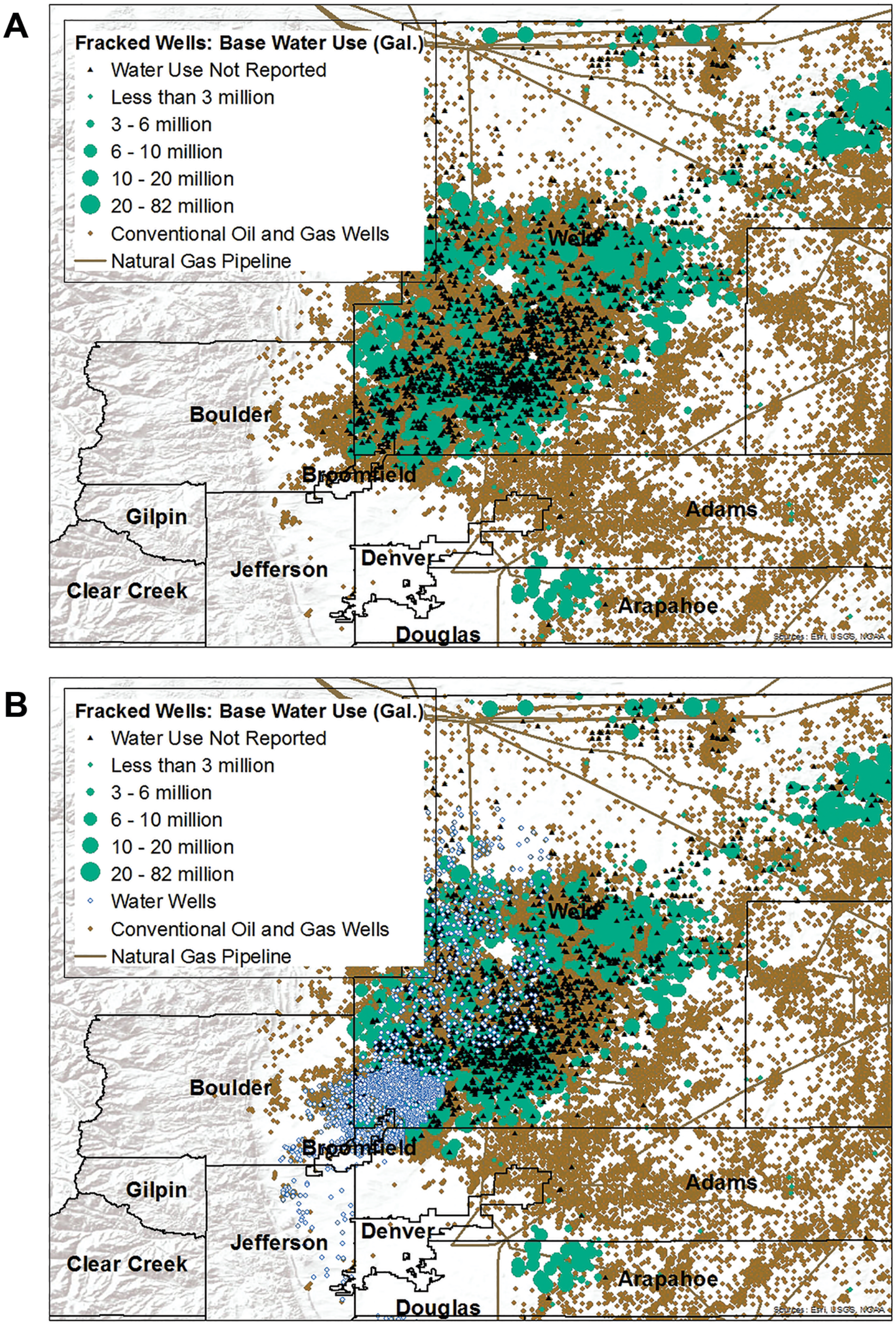


FIGURE 7. Water inputs for hydraulic fracturing. (a) The locations of conventional oil and gas wells and hydraulic fracturing wells along with total base water use for each well, if reported; (b) locations of water wells overlaid with oil and gas wells. Data sources: COGCC, https://www.fracfocus.org, USGS, and DRCOG.

WASTEWATER MANAGEMENT. Wastewater (also referred to as produced water) found in hydrocarbon formations, is a major by-product of the fracking and drilling process. High in salt and naturally occurring groundwater contaminants, it returns to the surface along with chemical-laced frac-flowback water. In Colorado, a majority of

TABLE 2. Industry-reported water use for hydraulic fracturing on the Niobrara Shale

Year	Total base water volume (Mgal)	#Frack jobs started	Average water use (Mgal)
2013	3,160	1,300	2.44
2014	5,750	1,450	3.97
2015	5,450	1,120	4.88
2016	4,920	721	6.32
2017	9,770	1,111	8.80

Data derived from the FracFocusRegistry database (https://www.fracfocus.org).

TABLE 3. Energy impacts on water, food, and ecosystems in the Denver region

Pairwise relation	Systems analysis: type of impact and relevant indicators
$E_{impact} \rightarrow W$: Energy-related impacts on water systems (Figures 9, 10) *Data sources: COGCC Daily Activity Dashboard (DAD)*; https://www.fracfocus.org	Aquifer contamination through gas leakage from improper construction or failing wells. Violations issued: In 2017: 18 (50% decrease from 2016) Water resource contamination through spills, leaks, and waste management. Spills/accidental releases: Between 2014 and 2017: 1,537. In 2017 in Weld County: 399 (36% increase from 2016) Accumulation of metals and radioactive elements in aquatic sediments at disposal and spill sites: Between 2014 and 2017: • Reported groundwater impacts at 314 sites and surface water impacts at 10 sites • 160 uncontained berms holding produced and frac flowback water Consumption of valuable freshwater in arid regions/overexploitation of diminished water resources: Water use in 2017 to 1 trillion gallons (100% increase from 2016); 8.8 million gallons per well
$E_{impact} \rightarrow F$: Energy-related impacts on food systems (Figures 10, 11) *Data sources: COGCC DAD; USDA 2016*	Second order impacts from the decline in water quality on soil, land, and ecosystem productivity, including crops/animal health [14] 30,000 wells on farmland in the region: 12,000 wells on pastures/grassland; 12,000 on active cropland; 6,000 on fallow/idle cropland
$W_{impact} \rightarrow E$: Impact of water quality across the energy life cycle	Use of recycled water for oil and gas extraction. Data on the amount of water recycled not available; re-use by industry is not mandatory in Colorado
$E_{impact} \rightarrow$ Social-ecological system as a whole (Figure 10) *Data sources: COGCC DAD; COGCC Annual Report, 2017*; https://www.fractracker.org	Disposal of waste (produced) water: About 50% is disposed by underground injection Most produced water not injected is disposed in evaporation and percolation pits or discharged under the Colorado Discharge Permit System. Data on how much water are discharged and where these releases occur are not available. Seismic activity caused by injection wells for wastewater 34 Class II injection wells Public complaints: nearly sixfold increase from 190 in 2016 to 1,124 in 2017 Home explosion in the town of Firestone caused by abandoned gas line from existing well

wastewater is injected into the ground or taken to evaporation ponds [8]. Metals and radioactive elements accumulate in aquatic sediments at disposal and spill sites [[13]; Figure 10]. The Denver region's oil and gas drilling activities generated >35 million barrels of wastewater in 2016, compared with 8.4 million barrels in 2006 quadrupling in 10 years [42].

Impacts on Food Across the Life Cycle

EIMPACT → FSYSTEM. Second order impacts of hydraulic fracturing on food systems result from declining water quality on soil, land, and ecosystem productivity, including crops/animal health [14]. The surface locations of 30,000 of the region's 44,000 oil and gas wells are on farmland: about 12,000 on pastures/grassland, another

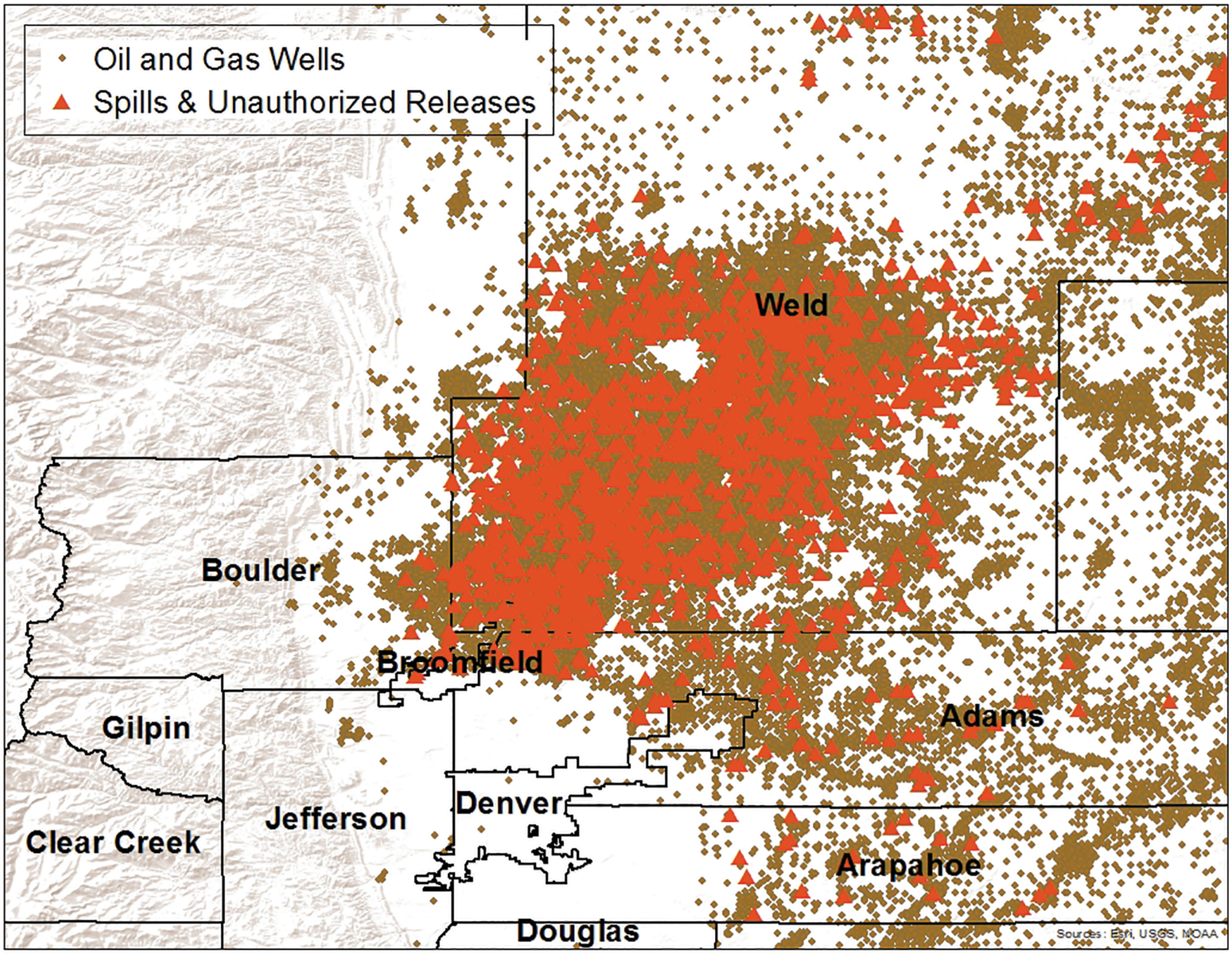


FIGURE 8. Spills and unauthorized releases. The oil and gas extraction industry reported 1,537 occurrences from 2014 to January 2018. The white spot in the middle of Weld County is the town of Greeley. Data Source: COGCC.

12,000 on active cropland, and 6,000 on fallow/idle cropland [43].

DISCUSSION

Framework Implementation

Building on an urban systems framework developed by Ramaswami et al. for FEW nexus analysis [4], the regional-level results above are synthesized within an expanded regional framework (Figure 11). Where data are available, quantifiable flows of food, energy, and water in and out of the region are depicted. The embodied water and energy associated with these activities are also shown (e.g., the water used for irrigation, electricity generation, and fracking). This approach highlights the additional vulnerabilities of water-intensive production of food and energy in the populated, semi-arid Denver region. The original framework is also extended in an initial attempt to incorporate the risk posed to the region's scarce water supplies and arable land from hydraulic fracturing to meet fossil fuel demand from outside the region.

Data Availability and Gaps: Informed by Diverse Institutions, Agendas, and Contexts

The implementation of this urban systems framework for the Denver region also illustrates the many gaps in data availability surrounding the interdependency of regional food, energy, and water systems (dashed lines and red boxes, Figure 11). The total amount of water pumped from the Denver Basin aquifer is not monitored [49], and gaps and discrepancies in federal data on water usage by thermoelectric power plants are well-known [6]. Other key data gaps include energy for water use and food preparation. We also include

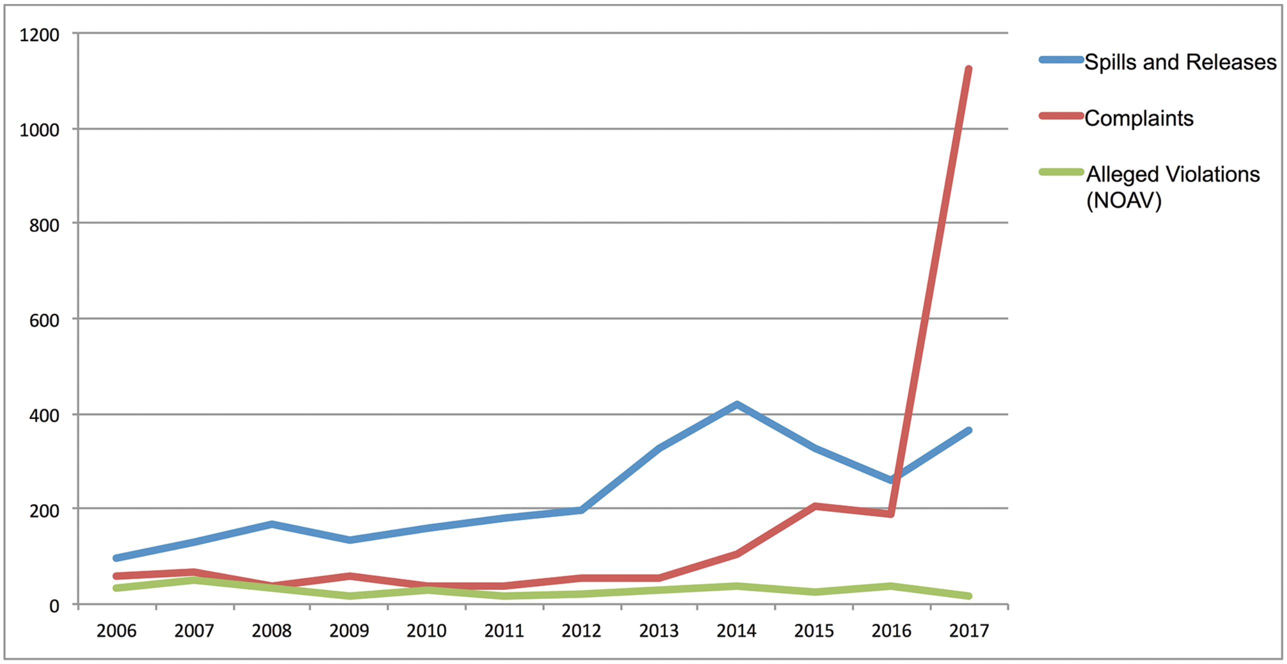


FIGURE 9. Spills and releases, public complaints, and alleged violations in Weld County from 2011 to 2017. Data sources: COGCC DAD and the Colorado Oil and Gas Information System.

sources and dates for available data, adding an additional layer of transparency to reflect the constructed nature of publicly available information for city/regional indicators [50] as they pertain to the FEW nexus. For example, according to self-reported industry data 28 Mgal/day of water were used in fracking jobs on the Niobrara shale that had a start date in 2017 [46], while 18 Mgal/day were used for electricity generation in 2010, according to the USGS [39].

FRACKING DATA. Because oil and gas industry data are proprietary, with rights to privacy protected by law, such data are not accessible to citizens and researchers working in the public interest. Local political activity has prompted public access to information on drilling operations in the state of Colorado since 2012, including disclosure of the chemicals used in the fracking process and the amount of water used per frack job [51]. In the wake of a house explosion in the town of Firestone in 2017 caused by a stray gas line, Denver-area communities have demanded public maps of the state's 120,000 flow-lines [52].

Data on the impacts of hydraulic fracturing on water quality, in particular, are sparse and contested. Underground injection of oil and gas wastewater, for example, has not yet been researched as a source of systemic groundwater contamination on the state or national level [53] and there are no regulations requiring detailed data disclosure that could allow scientists in academia and industry to develop best practices [9]. Citizens groups have stepped in to fill knowledge gaps through surface and groundwater monitoring projects [54–56]. Distrust of the ability of industry and government regulators to produce valid, unbiased water quality data are common among these groups [9].

Hydraulic Fracturing and the FEW Nexus

This case study illustrates that hydraulic fracturing can be viewed as a defining issue at the intersection of food, energy, and water systems. It has been emphasized in the literature that water use and produced water intensity for fracking is lower than other energy extraction methods and represents only a fraction of total industrial water use nationwide [25]. While this may be true at a large scale, this narrative misses several crucial points that are clearly illustrated in the Denver case:

WITH RESPECT TO WATER QUANTITY

1) Fracking poses unique risks in semi-arid, agricultural, and rapidly growing areas. In the Denver region, fracking water use not only competes with municipal demand and agriculture but also occurs within municipal boundaries and on the region's farmland.

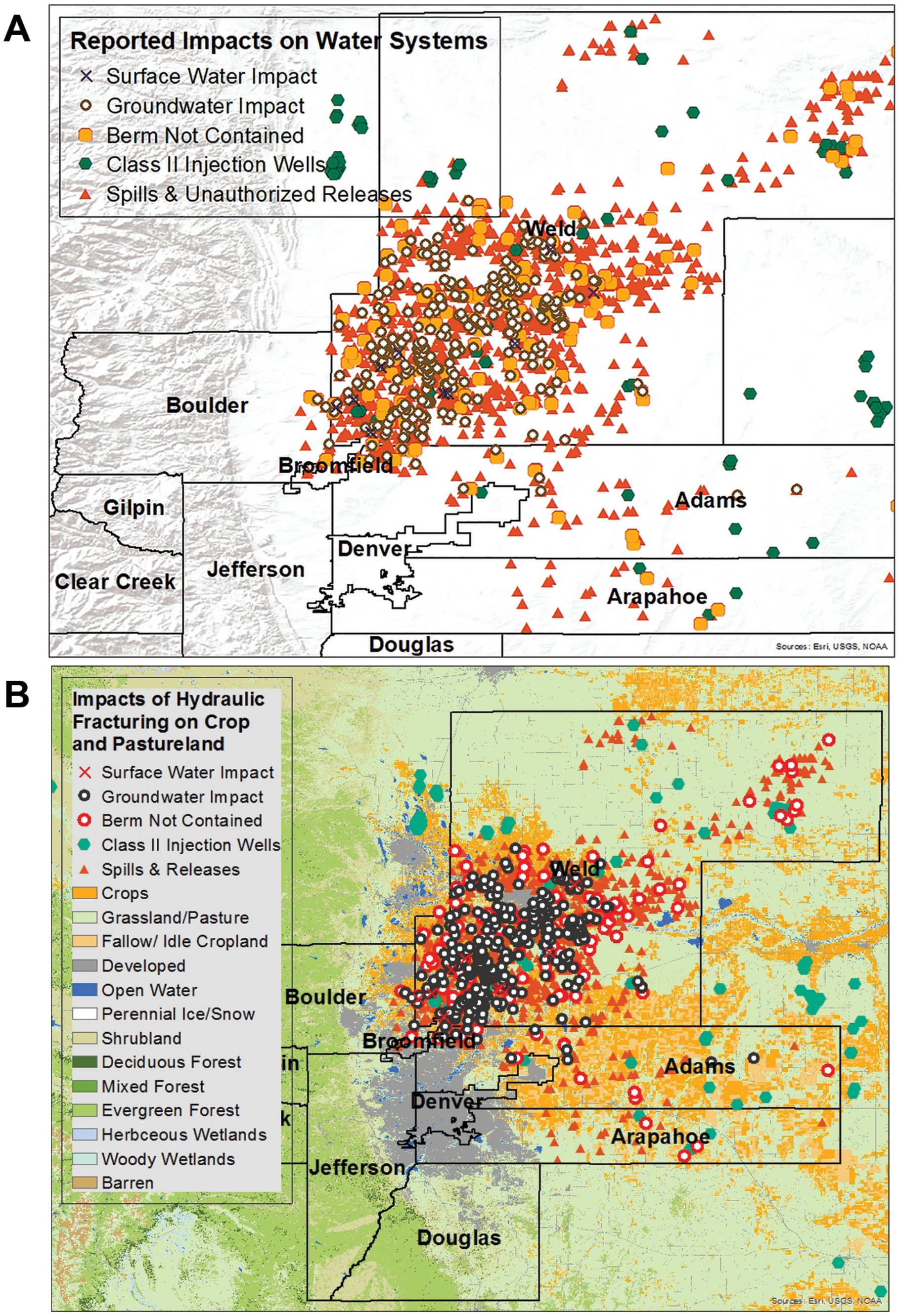


FIGURE 10. Class II injection wells, uncontained berms, and groundwater and surface water impacts. (a) Locations where ground and surface water impacts and uncontained berms were reported between January 2014 to January 2018 and (b) overlaid with human settlement, cropland, and pastureland. Data sources: COGCC DAD, https://www.fractracker.org.

2) Water use for hydraulic fracturing has intensified in the region over the past 5 years, as it has in rest of the United States; the water footprints of both inputs and wastewater are increasing.

WITH RESPECT TO WATER QUALITY

1) The Niobrara shale and Denver Basin aquifer are co-located (Figure 1), with both drilling and wastewater injection posing risks to groundwater, a concern even in non-water scarce areas.

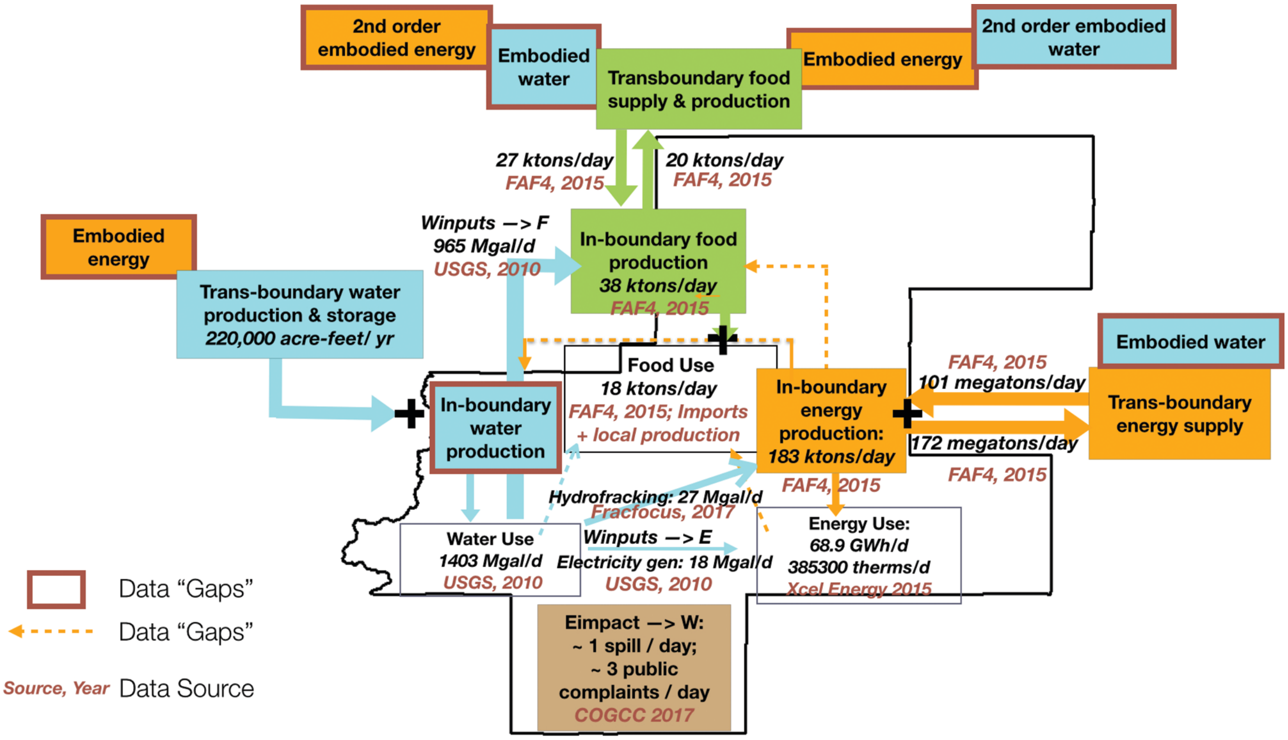


FIGURE 11. Implementation of the trans-boundary urban systems framework for the FEW nexus. Flows of food, energy, and water to, from, and within the Denver region are depicted. Data gaps, data sources, and time periods for numerical estimates are included. This representation focuses on inputs, with some attempt to incorporate impacts.

Globally, 59% of the world's shale deposits are in the footprint of major freshwater aquifers [26].

2) In Colorado, the majority of Class II injection wells and aquifer exemptions are located in regions with higher quality water, including the Denver Region, potentially jeopardizing those resources [53].

WITH RESPECT TO REGULATION AND GOVERNANCE

1) Water quality impact depends on construction, drilling, onsite chemical management practices, and wastewater handling, and is thus greatly impacted by regulation, monitoring, and enforcement.

2) Federal power to regulate shale gas development is limited due to fracking exemptions from the Safe Drinking Water Act and the Clean Water Act, as well as drilling exemptions from the National Emission Standards, Hazardous Air Pollutants, and other federal environmental statutes [32, 57].

3) Colorado's air emissions and water-testing regulations have been called the most rigorous in the country by state officials [58]; however, the COGCC employs approximately 23 inspectors to monitor the 52,000 wells around the state [59], leading some stakeholders to question their effectiveness [60].

4) Regional intensification of the water footprint of hydraulic fracturing shows signs of increasing even further since January 2017, the start of a new presidential administration, which favors less federal regulation of the energy industry and less environmental regulation in general.

5) At the same time, inadequate enforcement may be intensifying: 2017 also saw a 36% increase in spills/releases; a 600% increase in public complaints in Weld County, and a 50% drop in Notice of Alleged Violations compared with 2016 [42].

WITH RESPECT TO JUSTICE, EQUITY, AND THE RIGHT TO BAN. A nuanced grasp of "*how* energy, water, and food have been produced, historically, under particular social formations" [61: 656] is vital to developing a full picture of the complex social, political, and environmental dimensions of FEW nexus issues in general, and hydraulic fracturing in particular. Such perspectives address the power relations that underpin a given resource nexus, termed the "critical social science" of the FEW nexus [61], and are especially relevant to the governance of fracking, distributional and environmental justice, and greater regional and global sustainability.

The lack of centralized authority over oil and gas drilling in U.S. has left decision-making in the hands of state and local authorities. While the U.S. mandates environmental impact assessment of development projects, there is no required equivalent assessment of the social impacts of these projects on affected communities. The newly-proposed concept of "embodied energy injustice" focuses attention on "the hidden and distant injustices arising from the extraction, processing, transportation and disposal of energy resources," including fracking [17: 219]. At present, however, municipalities and communities are burdened with the responsibility of addressing the costs and benefits of energy development. This can further reinforce existing inequities, as wealthier and less marginalized communities are better able to marshal the resources necessary to do this effectively.

Within this context, the potential for multiple, unknown, or contested risks related to oil and natural gas extraction has led to increased community activism across Colorado [56].

The Colorado Supreme Court has struck down several local bans on hydraulic fracturing (*City of Longmont v. Colo. Oil and Gas Association; City* of *Fort Collins v. Colo. Oil and Gas Association*), based on lawsuits filed by the oil and gas industry against Denver-area cities Broomfield and Longmont, as well as nearby Fort Collins. In November 2018, Proposition 112, which would have required the setback distance for fracking from schools, homes and water sources be increased from 500 to 2,500 feet, was defeated in statewide elections. The oil and gas industry spent US$41 million in a campaign to reject the proposition [62]; 57% ultimately voted against it.

This makes state enforcement of existing environmental, health, and safety regulations the only immediate recourse for local residents seeking to limit fracking impacts on their communities. The fracking moratorium in Boulder County has not yet been contested by industry, emphasizing the lack of consistency in *de facto* protection for residents across the region. Additionally, the municipal land area comprises a mere 11% of the Denver region; even if local bans were upheld, large areas would remain open to shale development.

SUSTAINABILITY TRANSITIONS: TELECONNECTIONS, NEXUS TRADEOFFS, AND ENERGY ALTERNATIVES. The Denver region exports 93% of the energy and 54% of the food it produces to cities and states around the country, particularly the mid- and south-western U.S. The trans-boundary FEW nexus approach allows ecosystem and health risks to the Denver region's 3.2 million inhabitants to be linked indirectly to fossil fuel consumption across the country. More directly, these risks can be linked to a patchwork of local, state, and federal regulation and court rulings on hydraulic fracturing. While the region's water-intensive agricultural sector nearly rivals the energy sector in economic value, it involves fewer material flows and less groundwater risk. Co-location of renewable energy infrastructure with farming is another model for regional energy-food production that poses reduced risk to water supplies [63].

CONCLUSION

This case study illustrates the potential for the FEW nexus approach to identify interconnections between demand and supply networks, incorporating embodied FEW as well as ecosystem impacts and risks at multiple spatial scales. Consideration of *impacts on* as well as *inputs to* FEW systems in the Denver region places hydraulic fracturing firmly within the FEW nexus scope. This is important because FEW nexus research is the target of major funding efforts [64, 65] and directly relevant to the intensifying water footprint of fracking in the United States [25], particularly when it is co-located with agriculture. FEW nexus research is also well-poised to articulate the need for more and better data on system and trans-boundary interconnections that are vital to assessing the impact of fracking on regional water quality and soil fertility that so far have not been systematically undertaken [9, 34]. In addition, this emerging trans-disciplinary effort has the potential to offer key insights into so-called "wicked problems" that fracking exemplifies.

CASE STUDY QUESTIONS

On Describing and Quantifying the FEW Nexus

1. What is the "data gap" in FEW nexus based research?
2. What other types of knowledge might be needed to assess nexus interconnections and identify sustainable solutions at multiple spatial scales and across food, energy, and water systems?
3. What historical factors have contributed to the current FEW systems in place in the Denver region? Why is this important?

On Hydraulic Fracturing

1. What is the role of public policy in improving scientific understanding of the impacts of hydraulic fracturing on water quality?
2. What monitoring systems, industry regulations, and environmental protections are needed to ensure that regional water supplies are not impacted by hydraulic fracturing?
3. Should municipalities be allowed to ban hydraulic fracturing within their boundaries? Why or why not?

On Local Sustainability, Regional Interdependence, and Distributional Equity

1. What are the links between local solutions to meet the food, energy, and water needs of a community and sustainable solutions? In what cases might local production of food or energy be unsustainable?
2. Why is it important that sustainable solutions also be equitable ones? Provide some examples to support your reasoning.

Investigating the FEW Nexus

1. Consider your hometown or other geographic areas of interest. What indicators would you need to describe the interconnections between energy, water, and food systems in this region? From what sources would you obtain this data?
2. What important issues related to food, energy, and water sustainability might such indicators overlook?
3. What historical factors have contributed to the current FEW systems in place in your area of interest? Why is this important?

Envisioning Sustainable and Interconnected Systems

1. What might sustainable and equitable food, water, and energy systems look like for your area of interest? How would these systems depend on each other?
2. In what ways would your region depend on other regions? How would its FEW-related activities impact other regions?

AUTHOR CONTRIBUTIONS

SA: conceptualization, writing—original draft, data curation, validation, formal analysis, visualization, and methodology. JS: conceptualization, writing—review and editing, and methodology. GG: writing—review and editing, formal analysis, and methodology. JCS: writing—review and editing, formal analysis, and funding acquisition. DA: conceptualization, funding acquisition, and supervision.

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COMPETING INTERESTS

The authors have declared that no competing interests exist.

SUPPLEMENTARY MATERIALS

Supplemental Information with details on methods, data sources, and calculations of region-wide and municipal FEW demand, supply, trans-boundary FEW flows, embodied FEW and FEW system impacts (PDF).

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