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Constraints to implementing the food-energy-water nexus concept: Governance in the Lower Colorado River Basin

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ABSTRACT

The food-energy-water (FEW) nexus concept has emerged as a powerful approach to address the social and environmental challenges created by land and climate change. We present an analysis of the impact of the governance structure of the Lower Colorado River Basin (LCRB) on the implementation of the FEW nexus concept. Specifically, we quantified the linkages between food, energy, and water systems and then used two different future scenarios: (1) drought and (2) increased demand for alfalfa to look for the emergence of resource scarcity and/or vulnerabilities. Our results indicate that fluctuations in food production are not controlled by water availability but by the governance structure. Additionally, there is proportionally more water used for food than energy, and more energy used to move water to cities than water for agricultural production. Analysis of the production scenarios indicate tipping points of food, energy, and water resources based on climatic and consumptive trends that are not yet addressed by the rigid water laws in the LCRB. These results highlight the need for resource governance to play a strong formative role in the analysis and implementation of FEW nexus management strategies.

1. Introduction

The food-energy-water (FEW) nexus is a concept that acknowledges that food, energy, and water systems are inextricably linked, are dependent upon one another (Fig. 1) and in concert mediate access to resources as well as resilience of human-natural systems (Beck and Villarroel Walker, 2013). A constraint in one system could not only affect economic security in that system but could inhibit access in another (Sanders and Masri, 2015). Therefore, the nexus provides a powerful means to improve synergies in food, energy, and water production (Hoff, 2011), to identify how stressing food, energy and/or water systems creates resource vulnerabilities and/or resource scarcities in all three, to understand and quantify the production of ecosystem services, and to develop climate adaptation strategies (Bizikova et al., 2013; Rasul and Sharma, 2015). However, historically, food, energy, and water systems have been pigeonholed politically as well as broken up into small disjointed pieces that cross political boundaries and do not align with bioregions or watersheds (Perrone et al., 2011; Sharmina et al., 2016; Liu et al., 2017). This type of disjointed management leaves policy makers ill-equipped to provide resilient management strategies. Thus, the success of using the nexus concept to improve food, energy, and water systems will likely depend on how it incorporates issues surrounding resource governance (Allouche et al., 2015), including how governance and the discourse of securitization become a way to legitimize political agendas.

Many have argued that the nexus discourse of security places economic variables over access to resources for the world's poor, an idea that can be traced back to Foucault's theory of the linkages between security and the circulation of the global economy (Leese and Meisch, 2015; Srivastava and Mehta, 2014). In addition to this discursive 'securitization', resource governance outcomes are based on the larger political goals of the government or states involved in policy making (Singh et al., 2009). The connections between discourse, policy, and land management, therefore, raise important questions regarding how policy is already impacting nexus outcomes and communities on the ground.

Given the recent emergence of the FEW concept, few studies to date have explored the use of the nexus concept simultaneously with an analysis of governance structures (but see the following recent studies: Karan et al., 2018 Siciliano et al., 2017; Zhang and Vesselinov, 2017). To address this gap, we present a quantitative application of the FEW nexus concept to study resource vulnerabilities and scarcities in the

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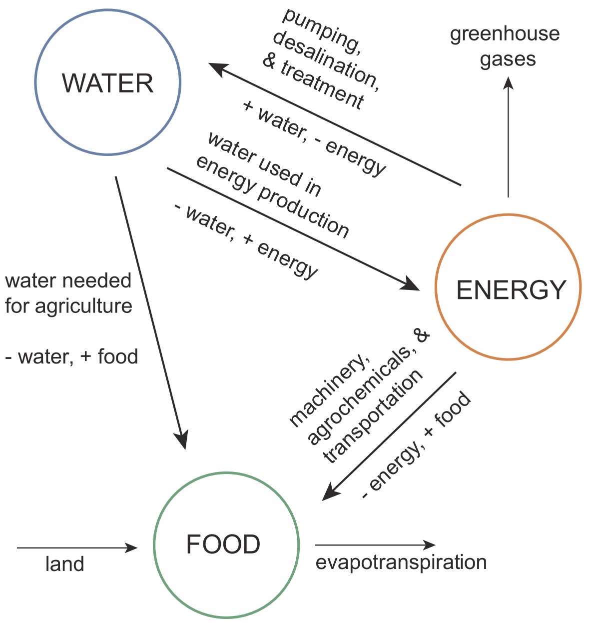

Fig. 1. Conceptual FEW nexus diagram illustrating the linkages between the three systems.

Lower Colorado River Basin (LCRB) in California, Arizona, and Nevada, U.S.A. We analyze the nexus within its sociopolitical, economic, and bioregional context that determine what resources are available, used, produced, and traded (Helmstedt et al., 2018). We take a case study approach, as case studies are best able to translate the on-the-ground nexus realities of a variety of institutions, bureaucracies, and stakeholders across space, time, and scale (Al-Saidi and Elagib, 2017).

Our goal was to understand how the governance structure of the Colorado River constrains the utility of the nexus approach to deal with future stresses. To do this, we first quantified the nexus by identifying the local and global linkages between food, energy, and water as well as the choices confronting water managers, and the Indian Reservations in the study area. We use these findings to look for the emergence of tipping points under two different scenarios: drought and increased demand for alfalfa. We then discuss how the very rigid water laws in the LCRB constrain the ability to improve resource management and respond to these tipping points using nexus thinking. While the main focus of this paper is on how economic and hydraulic factors influence FEW's nexus governance, in the discussion we also examine the impact of institutional and political factors as well as geopolitics across the transnational boundary between the U.S. and Mexico.

2. Background information on study site

The LCRB and Upper Colorado River Basin (UCRB) span 629,100 km^2 across Arizona, and small areas of California, Colorado, Nevada, Utah, Wyoming, and Mexico (Fig. 2A). Our study focused on the part of the watershed that begins just below the Hoover Dam in Nevada. This area discharges to the Basin and Range aquifer and to the Gulf of California. The area of this watershed in Mexico was not included in this analysis since accurate data was unavailable.

2.1. Climate

The Colorado River Basin has a semiarid to arid climate with an average of 40 cm annual precipitation that originates as snowpack in the Rocky Mountains and contributes to about 70% of the total streamflow in the basin (Dawadi and Ahmad, 2012). However, temperatures have been rising for the past century, with winter temperatures increasing more than summer temperatures on average by 2 °C (Fig. 2D; Dawadi and Ahmad, 2012). Temperatures are predicted to rise at least another 1.1 to 2.0 °C by 2050 (Christensen et al., 2007). These higher temperatures increase evaporation rates and have coincided with a reduction in snow pack and snowmelt in the UCRB (Christensen et al., 2004).

In addition, the LCRB has been in a drought since 2002, though at the same time the UCRB has experienced less severe or no drought conditions, outside of extremely dry periods in 2003 to 2004, and 2012. Historically, paleoclimatic records indicate pervasive and long-lasting periods of drought occur in the region (Meko et al., 2007). However, more recently, the area has received significantly more snowfall. The level of Lake Mead is often used as a proxy for water availability in the basin. Its water elevation has been decreasing since 2000, which can be seen visually in aerial imagery (Fig. 2B, 2C).

2.2. Water policy & use

The Colorado River is operated under the "Law of the River," which is comprised of a variety of U.S. federal laws, agreements, court decisions, and regulatory guidelines (Cordalis and Cordalis, 2014). These laws apply to seven Western U.S. states: Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming, and Mexico that utilize water from the river. The Law of the River allocates to each basin 7.5 million acre-feet (MAF)[1] of water per year in perpetuity, with some exceptions that account for water scarcity (Department of Interior, 2007). High variability in precipitation in the Rocky Mountains results in 5 MAF to 25 MAF of flow in any given year with an average annual flow of less than 16.4 MAF/yr. In terms of usage, on average 91.4% of the allocated water is used by municipalities, for power, or agriculture (not including the 1.5 MAF of water that Mexico receives).

The UCRB Indian reservations receive 1 MAF a year, while the LCRB Native American reservations are allotted 0.9 MAF a year. While this water is split amongst the 20 reservations in the LCRB, only six reservations have had their water rights quantified (Cordalis and Cordalis, 2014). Five of these six tribes are located in our study area. This has resulted in a disproportional amount of water allotted per person on these reservations compared with the rest of the basin. Specifically, 6.7 AC-FT per person per year is allotted to Lower Basin Indian reservations while 0.9 AC-FT per person per year is allotted to the rest of the LCRB. It should be noted that the water allotments of both basins (15 MAF), Mexico (1.5 MAF), and the Native American Reservations (1.9 MAF), adds up to 18.4 MAF, 2 MAF more than the yearly average stream flow of the Colorado River not accounting for climatic fluctuations.

The rigid allotments based on the Law of the River have also resulted in most of the agriculture production in the study area taking place on Indian reservations. Prior to the Law of the River, American Indians practiced flood farming practices for thousands of years based on characteristic seasonal rains (Cordalis and Cordalis, 2014), as well as dry farming. Today, however, practices are much more water-intensive on Indian Reservations (Author notes, 2016).

In 2007, the Department of Interior signed *Interim Guidelines for Lower Basin Shortages* (Department of Interior, 2007). This designated made the following changes to Lower Division state's water allotments based on water shortage severity indicated by Lake Mead elevation:

Light shortage (1050 - 1075 ft): 7.167 MAF
Heavy shortage (1025 - 1050 ft): 7.083 MAF
Extreme shortage (below 1025 ft): 7.0 MAF

Additionally, at water level less than 1050 ft, the Hoover Dam stops producing electricity. These measures provide the LCRB with some amount of response to drought, although it is a reactive, small-scale solution in lieu of a long-term management plan. The guidelines do not

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[1] 1 MAF = 1.23348185532 billion m^3. MAF is used because it is widespread in water management.

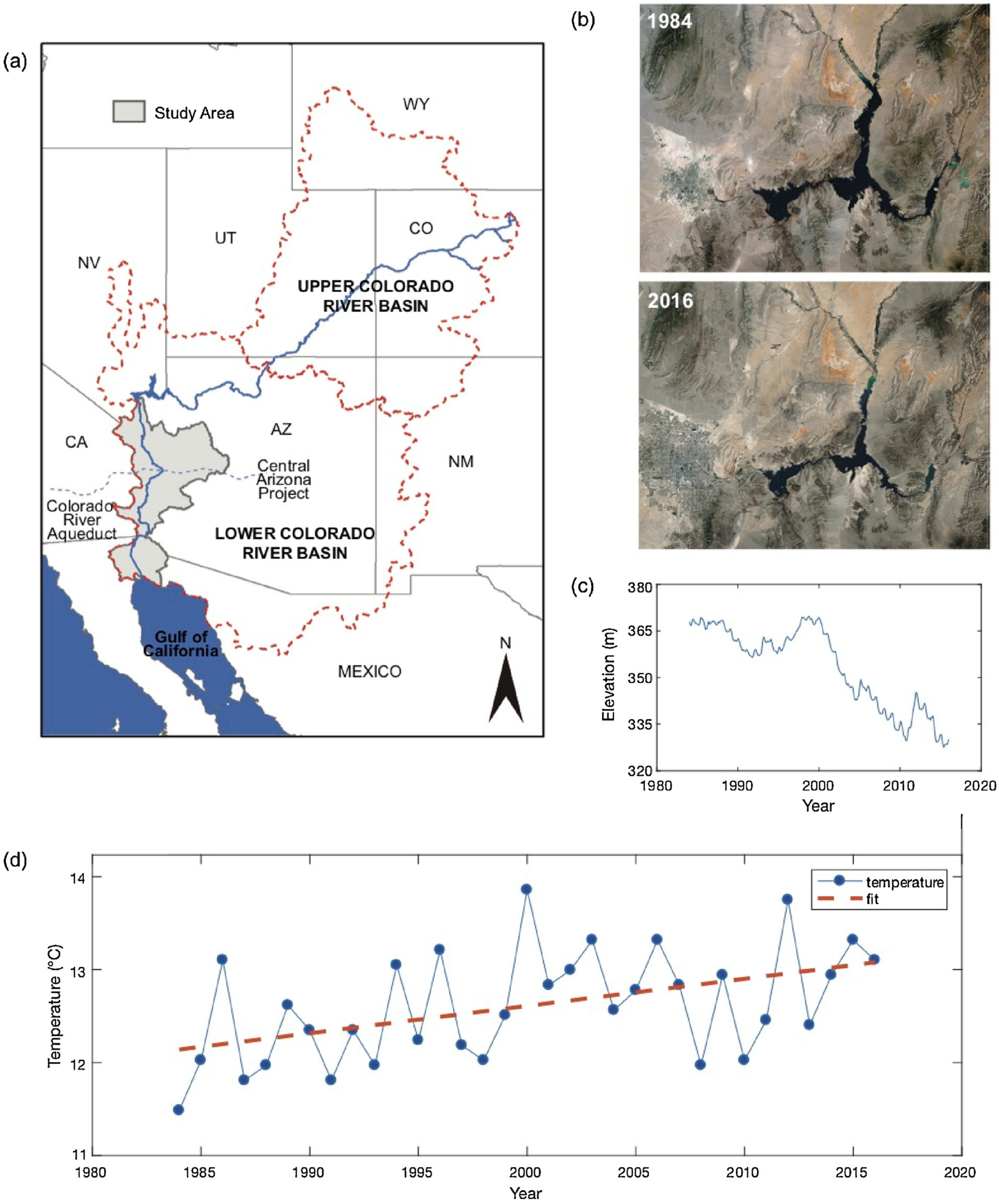

Fig. 2. (a) The Upper and Lower Colorado River watersheds along with the study area. (b) Aerial images of Lake Mead and Las Vegas in 1984 and 2016. Source: NASA Earth Observatory. (c) Elevation of Lake Mead from 1935 to 2016. Source: Bureau of Reclamation. (d) Southwestern monthly temperatures from 1984 to 2016. Source: National Climatic Data Center.

indicate any changes for water to Indian Reservations.

In addition to its use for irrigation, energy, and natural areas, the Colorado River provides water to millions of people for municipal use. Municipal and industrial water demand is projected to grow in upcoming decades alongside of population growth (Bureau of Reclamation, 2012). The most recent U.S. Census estimate indicated that Arizona, California, and Nevada had population growth rates of 9.8%, 6.1%, and 11%, respectively, from 2010 to 2017.

2.3. *River economy*

The Colorado river allows local economies to exist in a semi-arid environment with two-thirds of Arizona's, California's, and Nevada's state gross products dependent on the Lower Colorado River (James et al., 2014). The river provides 657.5 billion dollars of direct, indirect, and induced GDP to California; 185 billion dollars to Arizona; and 115.4 billion dollars to Nevada (James et al., 2014).

Focusing on food systems, agricultural production in the study area is largely situated on Indian reservations due to their high allotment of river water. Water is often delivered through an extensive canal system. For alfalfa, one of the most common crops in the region, the water that is used to flood the fields is sent back into the canals. The high-water availability along with the warm climate allows the production of twelve harvests of alfalfa each year (Author notes, 2016). Most of the alfalfa is exported as fodder to China, followed by Japan, Mexico, South Korea, and the EU (USDA-NASS, 2016).

3. Methods

3.1. Quantifying the Nexus

A diversity of data sources drawn from the Food and Agriculture Organization of the United Nations (Food and Agriculture Organization of the United Nations, 2018), the United States Department of Agriculture (United States Department of Agriculture, 2009, 2014), and the Energy Information Association (Energy Information Association, 2016) (see Table S1 in 'Supplementary Material' for a complete list of data sources) were used to quantify the connections between food, energy and water. Water was quantified in terms of consumption types (AC-FT/YR) for 2008-2016. Energy was quantified in terms of net generation (MWH/YR) and cost (cents per kilowatt-hour) for hydroelectric, natural gas, solar, and wind generated in the region for 2001 to 2016. Food production was quantified in terms of area of agricultural crops (acres/year of different crops) as well as the price that farmers spent on production (referred to as cost of production) for 2008 to 2015. Only crops that took up greater than 1% of total area were analyzed.

To determine the total impact of one sector on another (cross-sectoral impacts), we combined the total amount of water used in energy or food, and the total amount of energy used to pump water or produce food (Fig. 1).

3.2. Water-energy

Water-energy linkages were quantified in two different ways. First, the amount of water used in energy production 2001 to 2016 was calculated by multiplying the appropriate water consumption factors of electricity generated from natural gas from Spang et al., 2014 (Table S2 in 'Supplementary Material') by the amount of energy produced monthly from 2001 to 2016. Water used in natural gas extraction for gas used in the study area was not included since there are no natural gas extraction operations within the basin. Hydroelectric projects have no net water consumption, but reservoirs make evaporation rates higher, especially with higher temperatures.

Second, energy used to transport water in the Colorado River Aqueduct was quantified using data obtained from the Metropolitan Water District of Southern California for 2001 to 2016. The aqueduct conveys water from Lake Havasu over the Santa Ana Mountains and to cities in Southern California, including Los Angeles. In addition, energy used to transport water from Lake Havasu to Phoenix and Tucson via the Central Arizona Project was drawn from a previous study by Kleiman (2016). A final water-energy linkage, the amount of energy need to purify wastewater for domestic consumption was not quantified due to lack of data. Generally, however, wastewater treatment accounts for ~3% of energy used in the United States (McCarty et al., 2011).

3.3. Water-food

The linkage between water and food production was estimated in two different ways. First, information on specific crop water usage was estimated using evapotranspiration rates in ft/growing period and average area cultivated annually for six of the seven most common monocrops in the LCRB. All data came from FAO estimates except for lettuce (http://www.fao.org/land-water/databases-and-software/crop-information/en/; Barbosa et al., 2015). FAO evapotranspiration estimates are given in mm/growing period, however, we converted the units to ft/growing period so we could easily translate the measurement to volume of water in AC-FT.

Second, data for 2007, 2012, and 2013 from the National Agricultural Statistics Service (NASS) for the entire Lower Colorado River Basin (USDA-NASS, 2007, 2012, & 2013) was used to estimate yearly water used for irrigation (AC-FT). In order to calculate the data at the watershed subunit level, we used the United States Agriculture Service 2012 Census and Cropland Data Layer to estimate the percent of irrigated land out of the total acres of cropland (USDA-NASS Cropland Data Layer, 2008 to 2015). The proportion of cropland that was irrigated varied based on data year, in 2013, 67.74% of cropland was irrigated; in 2012, 75.82% of cropland was irrigated; and in 2007, 71.21% cropland was irrigated. We averaged the percent of cropland irrigated in the watershed subunit for 2007, 2012, 2013 to extrapolate to the remaining years from 2008 to 2015. The average irrigation estimate was used in the production scenarios to understand responsiveness of irrigation and crop production to changes in climate.

3.4. Energy-food

The linkage between food and energy was quantified in two ways. First, we estimated the amount of direct usage of fossil fuels by calculating the amount of fuel farmers purchased to run farm machinery in 2012 (USDA-NASS, 2012). Second, using the 2013 NASS estimation for energy expended in irrigation for the entire LCRB, estimated at $49.00 per acre, we estimated the cost for irrigation in the study area. Using the cost per amount of energy (cents per KWH; see Section 3.1) we converted $49.00 per acre to the amount of energy in MWH used for irrigation in the study area. Assuming that the price of energy needed to irrigate remained constant, we calculated the energy expense for all years using the estimated irrigated cropland and cost per amount of energy for those years.

3.5. Future scenarios

To look at the impact of future stresses on the FEW system in the LCRB, we investigated two future scenarios:

(i) Drought: 5% less water in Lake Mead than the January 2017 level of 1085 ft. At 1050 ft Lake Mead is at the lower end of the 'Light Shortage' bracket for water allocation reductions, where the amount that the LCRB receives decreases from 7.5 MAF to 7.167 MAF.
(ii) Demand: 3% increased international demand for alfalfa in line with the 2.5% increase in exports, especially of fodder, from Arizona, California, and Nevada over the ten-year period from 2000 to 2010.

4. Results

The following section is organized by FEW subsystem with subsequent sections describing the inputs into the subsystem of focus. We do not include food inputs into the water as it does not have a direct impact. The food input into the energy pillar is also not included as biofuels or energy generation from food waste are not utilized in the study area.

4.1. Water

As expected for a temperate semi-arid climate, the amount of water consumed followed a seasonal pattern with increased use during the summer months and decreased use during winter (Fig. 3a).

Across Arizona, California, and Nevada, the main consumptive water use was either irrigation or municipal use, depending on the year. In 2013, the biggest consumers in Arizona and California were large cities such as Phoenix, Tucson, and irrigation districts. Water to cities in

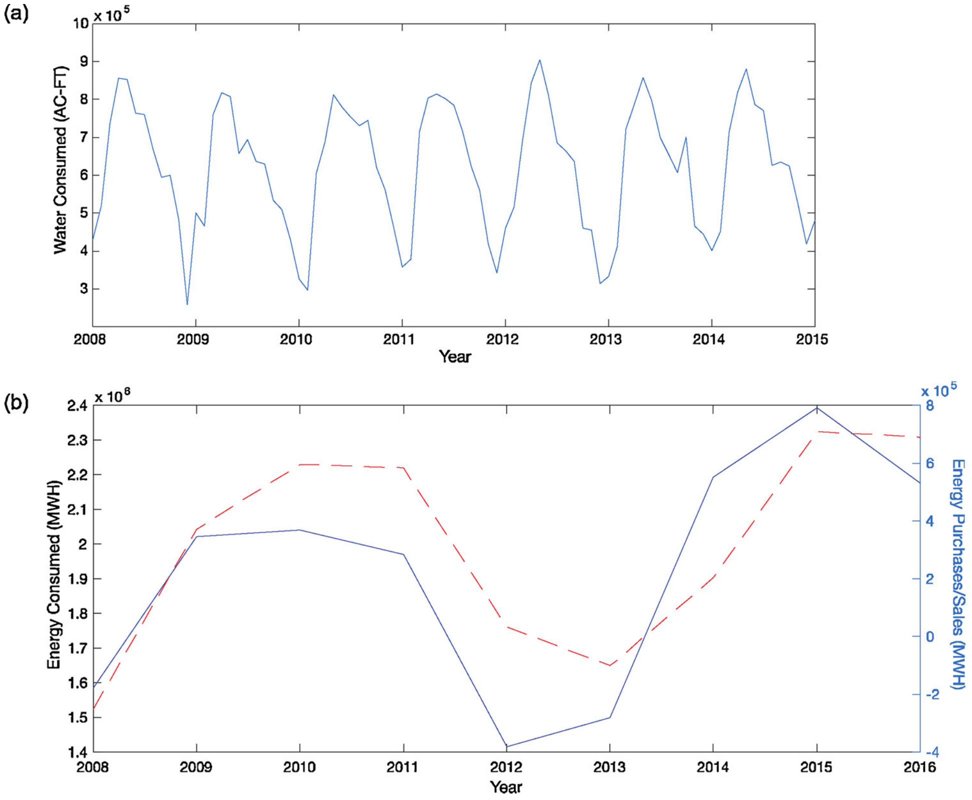

Fig. 3. (a) AC-FT of water consumed from the Lower Colorado River from 2008 to 2015. (b) The amount of energy consumed in the Colorado River Aqueduct (MWH), and the amount of energy bought or sold by Metropolitan Water District of Southern California; negative values indicate energy sold, positive values indicate energy bought.

Table 1

Volume of water consumed in AC-FT (data source: Bureau of Reclamation). 'Municipal' includes water consumed in cities and water districts and can also include water provided for irrigation and/or energy. 'Recreational and conservation' includes water used for recreation areas, wildlife refuges, and conservation districts. 'Other' includes water used on military bases; for distribution, such as the water consumed by dams and for pumping; and for industry.

Type of use (AC-FT)	Year							
	2008	2009	2010	2011	2012	2013	2014	2015
municipal	3,127,348	3,412,815	3,438,599	2,960,985	3,035,016	3,375,937	3,553,808	3,489,435
irrigation	3,662,914	3,317,008	3,263,540	3,736,702	3,792,246	3,498,025	3,485,765	3,372,108
Indian Reservation	459,683	665,275	434,006	408,719	388,278	378,034	383,240	358,709
energy	491	520	370	0	0	0	0	0
recreational & conservation	23,388	23,936	25,136	19,787	22,409	28,125	26,089	27,025
other	9,471	8,581	8,469	3,022	3,000	2,818	2,971	2,844

Arizona was transferred through the Central Arizona Project with over 1.5 MAF consumed. The Imperial Irrigation District was California's largest water consumer in 2013, consuming more than 2.5 MAF of water. The Metropolitan Water District that transfers water to Los Angeles consumed less than the Central Arizona Project with just over one MAF. In Nevada, there are no consumptive uses over 100,000AC-FT. However, the City of Las Vegas receives its water right before it reaches Lake Mead, so this is not accounted for in our analysis (Table 1).

4.1.1. Energy-water

The amount of energy consumed to pump water from Lake Havasu to Los Angeles in the Colorado River Aqueduct varies from year to year depending on the constancy of pumping. For example, while the lowest amount of water diverted to the Metropolitan Water District of Southern California (MWD) was 0.55 MAF in 2005, the lowest amount of energy consumed was 1.3 million MWH in 2007. If water does not need to be pumped from Lake Havasu to Southern California consistently, the MWD is able to produce energy and sell it. Thus, the irregularity of the amount of energy used to transport water in the Colorado River Aqueduct correlates with the amount of energy bought or sold per fiscal year (Fig. 3b). The amount of water pumped to Southern California has, on average, increased from 2001 to 2016. In some years, such as in 2011 and 2012, MWD intentionally left water in Lake Mead so that it did not fall below "shortage conditions," (below 1075 elevation; Department of Interior, 2007).

The Central Arizona Project pumps 1.6 MAF of water up 2800 feet of elevation, 336 miles from Lake Havasu to Phoenix and Tucson (Central Arizona Project). To do this, requires 2.8 million MWH of energy, which is supplied from a coal plant: Navajo Generating Station in Page, AZ (Kleiman, 2016; Navajo Generating Station). While this plant is not in the study area, it is considered a regional connection, and is important to consider given the large supply of energy it provides to the study area (Bain and Acker, 2018) as the eighth-largest plant in the United States (Talbot et al., 2003).

4.2. Energy

In the LCRB, the dominant types of power generation are hydroelectricity and natural gas, with a yearly average energy production of 5.5 million MWH and 2.9 million MWH, respectively. Hydroelectric production gradually decreased over the study time frame from roughly

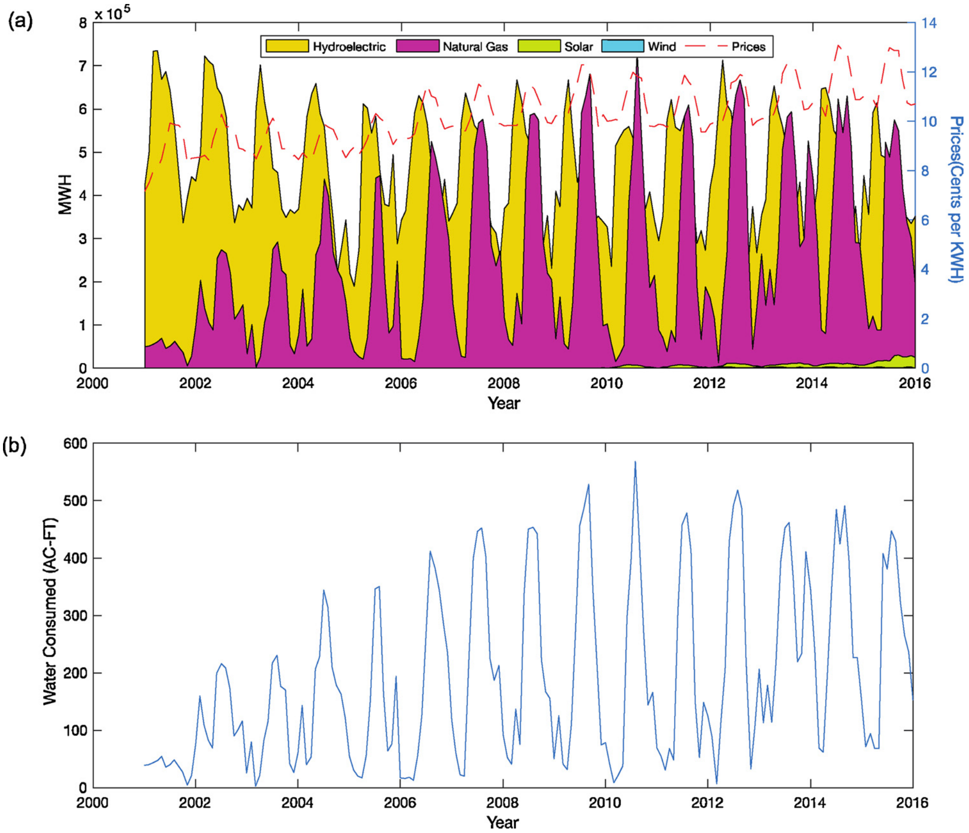

Fig. 4. (a) Net energy generation (MWH) and price index (cents per KWH) from 2001 to 2016. (b) Water consumption of electricity produced from natural gas in the study area.

6.6 million MWH in 2001 to 5.5 million MWH in 2016, while natural gas increased from 560,000 MWH in 2001 to 3 million MWH in 2016. Despite their individual trends over time, hydroelectricity and natural gas both follow a seasonal trend, with the highest net generation of energy occurring during the summer months, and natural gas peaking directly after hydroelectricity (Fig. 4a). The presence of solar in the region has grown since 2010, with the highest annual production in 2016 at about 860,000 MWH, and an average annual production of just 180,000 MWH. There is one wind power plant, but the amount of electricity this plant produces is negligible when compared to the other electricity sources. The price of electricity gradually increased from 8.7 cents/KWH in 2001 to 11.3 cents/KWH in 2016, while still following the same seasonal trend.

4.2.1. Water-Energy

The water consumed in electricity generation fluctuated seasonally just as energy generation does. 2800 AC-FT of water was used per year, on average, from 2008 to 2015 in electricity generation (Fig. 4b). As mentioned previously, consumption of water in hydroelectricity is negligible.

4.3. Food

The top six crops that took up at least 1% of production areas in at least one year of the study timeframe, 2008 to 2015, included alfalfa (54%), cotton (11%), durum wheat (9%), double-crop lettuce/durum wheat (7%), lettuce (4%), and citrus (4%). In each year of food production analyzed, alfalfa had the highest percentage (Fig. 5a), followed by fallowed cropland, with average annual acreage of about 142,000, and 70,000, respectively, and a total average active cropland of about 271,000 acres. There was a slight overall upward trend of total production area from 294,000 acres in 2008 to 303,000 acres in 2015 of active cropland. This trend holds even when considering the drastic decrease of areas under production in 2009 at 142,000 acres down from 294,000 acres in 2008, and another small drop in 2015 by just 6000 acres. From 2012 to 2013, a drought year in the UCRB, areas under production increased from 292,000 acres to 295,000 acres.

4.3.1. Water-food

On average from 2008 to 2015, 750,000 AC-FT of water was used for agricultural production. Alfalfa received around 59% of this water annually, followed by lettuce (20%), cotton (11%), durum wheat (5%), citrus (4%), winter wheat (1%), and cantaloupes receive a negligible amount (Fig. 5b). These percentages are based on the average amount of cropland for each crop type and their evapotranspiration estimates.

Of the total amount of active cropland (271,000 acres), the average annual amount of land irrigated was about 195,000 acres, with an average of 799,000 AC-FT of water. Even though during the drought year of 2012 to 2013 average acreage increased, the amount of water used for irrigation decreased from 908,000 AC-FT to 820,000 AC-FT.

4.3.2. Energy-food

In 2012, $62,853,203 was spent on gasoline, fuels, and oils to run machinery. This equates to 527,778 MWH, an entire order of magnitude more than the 88,889 MWH used to pump water for agriculture. Thus, more energy from the outside in the form of fossil fuels was used for agriculture than energy needed to pump water.

As stated previously, the cost of energy for irrigation was approximately $49 per acre. This equates to 89,075 MWH in 2013, or 0.45 MWH/acre, to move 819,852 AC-FT of water over 199,964 acres.

4.4. The nexus

Based on the data available for this analysis, the strongest

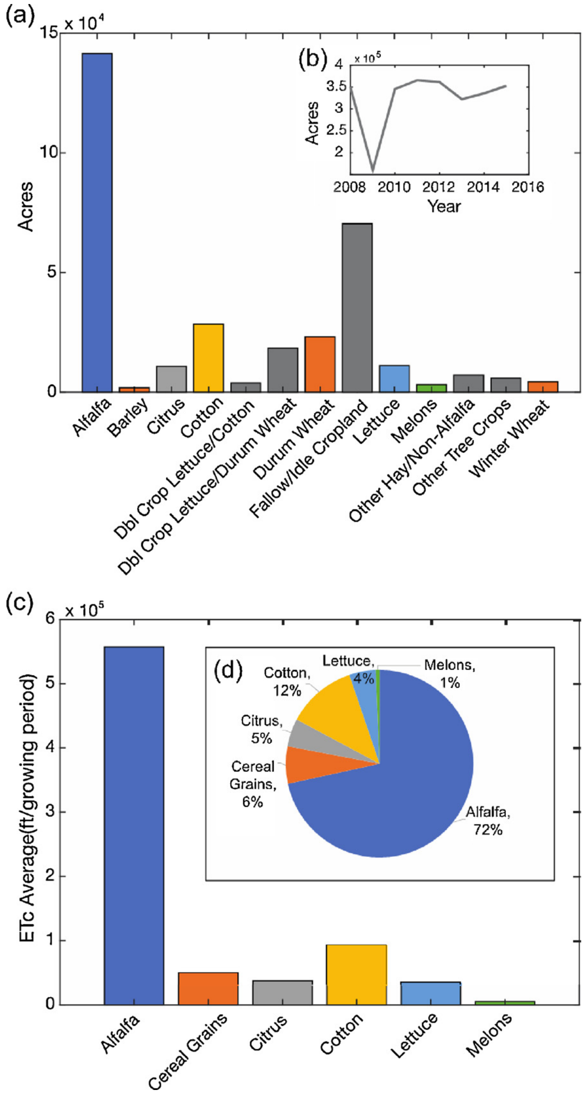

Fig. 5. (a) Average acres produced per crop type for crops that take up at least 1% or more of production in the study area and time frame. (b) Total number of acres of cropland. (c) Average evapotranspiration rates for most commonly grown crops in the study area. (d) Percent of average annual water received per crop type from 2008 to 2015.

connections in the study area were the water input into food and energy input into water for cities. Ninety-nine percent of water used in energy or food was used in agricultural production, on average from 2008 to 2015 in the study area. On average from 2008 to 2015, 2.89 million MWH were required to move water to Arizona, and 1.42 million MWH were required to move water to Los Angeles. When compared to energy used for food production, 87% of the total energy was used to move water to cities. This percentage includes machine fuels used in agriculture production but does not include fuels needed to export agricultural products.

4.5. *Future scenarios*

The FEW nexus changes with environmental and economic stresses, depending on the flexibility of the governing and market systems. The scenarios were meant to be an example of how governance, market supply and demand, and climate vulnerabilities may impact the FEW nexus and create resource tipping points. In the study area, water governance particularly influences drought management and crop production strategies, giving the system less room to respond to climatic and economic changes.

4.5.1. *Drought scenario*

The first scenario depicts how the costs and supply of water, energy, and food production might change in an extreme drought situation. With a decrease in water availability, water and energy prices would increase, but agriculture production would roughly stay the same due to water governance in the region. This would have occurred, for example, if Lake Mead had decreased to 1030.75 ft (5% below its January 2017 elevation of 1085).

At or below an elevation of 1075 ft, Lake Mead is at a critical drought state. At 1050 ft, Lake Mead is below the capacity at which the Hoover Dam can produce hydroelectricity (Department of Interior, 2007). If it were to stay at this elevation for an entire year, this would amount to a decrease of 36% of the average annual electricity generation from 2001 to 2016. Reduced water availability has previously been shown by Bain and Acker (2018) to result in higher operating costs, and higher prices of energy for hydroelectricity in the Colorado River Basin.

Additionally, for those that pay for water from a utility, a drought of this magnitude could increase water prices. According to a report from the Public Policy Institute of California, the 2012-16 California drought resulted in an increase in water prices through drought surcharges due to increased supply and treatment costs for suppliers (Mitchell et al., 2017). However, those that rely on water rights for their water, such as on certain Indian Reservations, would continue to receive the same amount of water with no price increase. The Bureau of Reclamation could make a deal with Reservations to hold onto some of their water with some form of compensation. In this case, irrigation will decrease, which was assumed for the drought scenario.

However, a decrease in water available for irrigation does not necessarily mean production will decrease as seen in the increase of production of agricultural products during the drought year from 2012 to 2013, with a decrease in the total amount of water used for irrigation. However, higher energy costs to irrigate cropland coupled with higher water costs for farmers outside of Indian Reservations could potentially decrease the amount of production in areas that rely mostly on hydropower.

4.5.2. *Increased demand for alfalfa*

Where the drought scenario depicts climate pressures on water availability, the global demand for alfalfa is a representation of demand for water. In this scenario, we look at the implications of the governance structure of the LCRB in supplying water in a static snapshot of global agricultural commodity markets. Specifically, we investigate the impact of a 3% increase in demand for alfalfa, the most widely cultivated crop in the study area. This scenario seems likely to occur due to the 160% increase in fodder exports from 2000 to 2010 from the United States, and 2.5% overall increase in fodder exports specifically from California, Nevada, or Arizona over the same 10-year period. Under this scenario, there would either be an increase in the overall total cropland from 271,500 acres to 279,600 acres, or a decrease in cropland for food crops. In either scenario, more water would be needed for crop production, assuming the current mode of production remains constant, with fodder production consuming the largest amount of water when compared to other crops. Demand on energy would increase for producing and transporting alfalfa and water, potentially meaning a higher demand for water to produce that energy. This increased demand on energy includes the energy needed to move water for irrigation, energy needed to export alfalfa, and increased demand for agricultural chemicals and machinery fuels.

5. Discussion

The goal of this study was to understand how the governance structure of the Colorado River constrains the utility of the nexus approach to deal with future stresses. A consideration of governance structures should be central to the development of food-energy-water nexus thinking to better understand and identify how stressing food, energy and/or water systems creates resource vulnerabilities and/or resource scarcities in all three sectors. To understand how food, energy, and water affect one another's availability, individual sector units can be analyzed together to give a quantified picture of use. In addition, price trends can be analyzed to look for correlations with other sector price trends or climatic changes. In the study area, we found that water is the limiting factor due to governance constraints, especially with predictions of increased drought in the future (Christensen et al., 2007). The following sections describe the ways that governance constrains the possibility of implementation of FEW management strategies in the LCRB, and why therefore, it is a critical component of FEW nexus research. We also discuss how power, geopolitics, and institutional factors impact nexus implementation. We conclude with ideas for future FEW nexus and governance research.

5.1. Governance constraints

We found that governance impacts the FEW nexus in three different ways. First, policies limit the ability of resource systems to respond to market and climatic changes. In the LCRB in particular, we found that the Law of the River limits the prospect of responding to climatic changes such as increasing drought frequency and severity (Bureau of Reclamation, 2008). With predictions by the IPCC that the southwestern United States is to become hotter and drier, a lack of adequate response due to rigid policy structures will impact all three sectors (Christensen et al., 2007). The small response to drought in water used in agriculture in the study area was likely because much of the production occurs on Indian reservations, which have a high proportion of water rights in comparison to the rest of the Lower Basin states. While Metropolitan Water District leaving water in Lake Mead during drought years is a good example of a response to drought, it is a reactive response, similar to the DOI Interim Guidelines. Drought coupled with increased demand for water through more alfalfa production will strain water resources even further.

Second, rigid policies in the most 'geopolitical' sector impacts the ability of that sector to respond to the needs of the other sectors. Management of the Colorado River is a complex geopolitical issue with many stakeholders, including governments of U.S. states and nation-states, separated by rigid political boundaries. This directly impacts the ability of water managers to meld water allotments to current or predicted conditions. This is a very real concern as the IPCC has predicted that the Southwestern U.S. will experience higher temperatures and decreased precipitation. Since water is the life blood of this region, with over ¾ of the economy relying on its presence (James et al., 2014), drought will severely affect the region's livelihood. In addition to drought, population growth could put more stress on the water system. Depending on the system analyzed, there will likely be a 'limiting factor'. While some have argued against a focus on water (Smajgl et al., 2016), sector weights are context dependent. In semi-arid cases with access to a large amount of water, it is frequently a geopolitical issue, which often presents itself as transboundary conflict.

Although we did not include Mexico in the analysis due to data constraints, it is well known that most years since 1960 the Colorado River has run dry before reaching the Sea of Cortéz (Bark et al., 2016). The impacts of this have presented themselves as a lack of access to a water resource in Northern Mexico that has resulted in social impacts such as a decline in the regional shrimp and fishing industries (Bark et al., 2016; All, 2006). The river's riparian ecosystems were briefly restored through the implementation of Minute 319, a 2014 treaty between the U.S. & Mexico that authorized a pulse flow to the Gulf of California (Kendy et al., 2017; Nelson et al., 2017). This move "marked a sustainable reconciliation with the land and its people" by connecting communities back to a water source that was highly valued (Bark et al., 2016).

Restoration projects such as this one harness the local to the international through governance, power, and the larger ecological and political systems at work (Watts, 2015; Ribot, 2014). Entrenched in these cross-boundary water sources and restoration projects are politics of power at the international level. Through subnational division of power at the state level, the U.S. monopolized control over the Colorado River, partly out of fear that "Mexico might lay claim to large quantities of the river's flow," a notion that maintains itself in the almost-century-year-old Colorado River Compact (Moore, 2017). Transboundary politics therefore directly complicates the economic and hydraulic foundations of the nexus, specifically through divisions of power that persist through long-term subnational agreements. While the Colorado River is an extreme form amongst global transnational boundaries, it should be considered at the regional-nexus level.

Third, and similarly to the second, rigid policies in one of the sectors impacts the production and availability of resources in other sectors. Stresses on the sector where rigid policies exist, might not reverberate across sectors, such that the nexus is able to conform in a sustainable way to existing conditions. Our results indicate that fluctuations in food production are not controlled by water availability in the region but rather, access to water rights, which signals the decoupled response between agricultural markets, especially alfalfa, and climatic changes. In drought years, we observed a slight decrease in irrigation but an overall increase in total active cropland. Similarly, the amount of hydroelectricity produced is dependent on a minimum water level in Lake Mead (1050 ft) that is below the level that indicates a period of critical drought (1075 ft). If an extreme drought were to occur, water allocations based on the Law of the River would occur to an extent, but electricity production would not. This is an example of how national, regional, and global objectives of food, water, and energy are often in conflict, making win-wins difficult or impossible to achieve (Campbell, 2008).

Inherent in each of the ways discussed above that resource governance impacts the nexus are power differentials that are reified by politics and institutions. Resource governance is inherently political and often results in outcomes based on the larger goals of the government or states involved in policy making (Singh et al., 2009). Rigidity and the ability to respond to market and climatic changes are therefore largely determined by the modes of distribution, appropriation, and allocation of water decided by the states, in this case those of the Lower Colorado River Basin managed by the Bureau of Reclamation. These material forms of resource management are also reflected in nexus discursive practices, that Leese and Meisch (2015) describe as a reframing of "the conflict between distributional justice and the needs of the world economy under the paradigm of security." By emphasizing hydraulic and economic variables, the nexus concept risks placing the needs of the global poor as secondary (Leese and Meisch, 2015).

5.2. Future research

This analysis, while not a complete picture due to data constraints, gives insight into how the FEW nexus can be used to better understand what drives production or access to food, energy, and water.

However, there are many opportunities for future research to improve the accuracy of nexus quantitative research. In order to fully describe and quantify the components of the nexus for any region, consistent data is needed at the watershed level, for yearly irrigation including pumping costs and energy amounts, on the amount of energy needed to produce and encompassed in agricultural chemicals, of water treatment and prices, and export information that details how much product, where it is from, and where it is going. Consistent data will allow for frequently updated, automated, and dynamic production scenarios, though static snapshots still provide insight to how resource use or production might change.

Analysis at the watershed scale, is valuable because of regional ecosystem characteristics; however, it is complicated because of stakeholder conflict and the arbitrary political boundaries that data often conforms to (Castro et al., 2016). In order to ground the nexus in a study area such that it lends to conversations about water management to ensure healthy habitat or the value of ecosystem services in a region, analysis should be done at the watershed level (Rasul and Sharma, 2015). The international border of the Colorado River Basin between the U.S. and Mexico further exemplifies historical geopolitical struggles, where resource needs coincide and conflict with each other as transboundary struggles at the watershed level (Srivastava and Mehta, 2014).

While it is clear based on this analysis that the nexus is deeply connected to policy and economics, the way our social, cultural, and technological systems change will also impact the way resources are produced and used. Energy technology, for example, is improving rapidly, requiring those who study the nexus to understand technological advances as they relate to large scale production, conveyance, fuel use, and emissions. Science silos will not help us manage resources for the future, cross-discipline communication is key (Howarth and Monasterolo, 2016).

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2018.11.027.

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