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Quantitative modeling of interconnections associated with sustainable food, energy and water (FEW) systems

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A B S T R A C T

The increasing costs of energy and water, fossil fuel depletion, and food shortages caused by climate change challenge long-term sustainability of food, energy, and water (FEW) systems. In working toward sustainable development, a fundamental question for deciding on whether and how to invest in FEW systems is "how sustainable FEW systems are?". In order to measure sustainability across the FEW systems, an integrated sustainability index (SI) is developed. The SI is comprised of three components; food, energy, and water. These components each consist of different sub-components (e.g. transportation fuel for energy component) that make up integrated FEW systems. The sustainability of an FEW system can be calculated using the integrated FEW SI, but a more thought provoking question is to understand how each sub-component affects overall sustainability of the system. This cannot be achieved without formulating the interconnections associated with FEW components. This study formulates interconnections associated with FEW components. In an effort to increase the degree to which the results would generalize to FEW systems with different scales, the calculations of the study are performed for a sustainable FEW system that can consistently yield food for a family of four (two adults and two children) and supply its own water and energy needs from sustainable sources. Also, the sustainability is measured for two systems located in two different climates; one is relatively cloudy and humid and the other is sunny and arid. The results show that the highest sustainability improvement in both climates is associated with irrigation sub-component. Not only a sustainable water supply for irrigation sub-component improves the sustainability of water component, it also improves food sustainability and consequently energy sustainability. This finding can be explained by the fact that the irrigation sub-component is a resource supplier for grain sub-component, and that is a resource supplier for transportation fuel sub-component.

1. Introduction

The increasing costs of energy and water, fossil fuel depletion, and food shortages caused by climate change have left us with no choice but to accelerate the world's transition to sustainability. In the coming decades, we are likely to see increasing pressure on the food, energy, and water (FEW) demands from increasing population and rising threat on the FEW supplies from climate change. As discussed in a recent report published by the International Renewable Energy Agency (IRENA), patterns of FEW systems are changing and the move to more sustainable supply systems may be inevitable (Ferroukhi et al., 2015). Increasing populations as well as resource scarcity challenge long-term FEW systems sustainability. Previously, many researchers had studied and analyzed sustainability across the FEW sectors in a fragmented and isolated way. Recent studies show that FEW systems are highly interconnected, and improving system function while ensuring sustainability cannot be borne by research on food, energy or water systems individually (Daher and Mohtar, 2015; Kurian, 2017; Larcom and van Gevelt, 2017). More nexus-wide research is needed to pursue both understanding the behavior of FEW systems and developing technological enablers necessary to improve the system performance.

A sustainable FEW system is defined as a system that can

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consistently meet its food, energy, and water demands with sustainable inputs rather than using non-renewable sources. A food production system can be sustainable if it relies on renewable water and energy technologies. Collecting water from precipitation, recycling wastewater, and desalinating seawater are the most sustainable methods of water supply. Renewable energy sources such as solar, wind, biogas, and geothermal are considered as sustainable sources of energy. Measuring sustainability across FEW systems is difficult because interactions between FEW sectors are complex and not fully understood and the metrics such as indicators, indexes, and benchmarks are still evolving.

Over the past years, many researchers and organizations have recognized the importance of sustainability and realized that unless they measure sustainability they do not know if it is getting better or worse. They have been striving to develop a comprehensive set of metrics, scorecards, ratings, and tools for measuring and tracking sustainability. The formal development of sustainability metrics began in 2001 with the United Nation (UN)'s Commission on Sustainable Development that published a list of about 140 indicators to cover economic, environmental, institutional, and social aspects of sustainable development (UN, 2001). Perhaps the most relevant sustainability indicators to the FEW nexus are composite or aggregate indicators that represent one single comparable index for the evaluation of a multitude of aspects. Krajnc and Glavic (2005) developed a standardized composite sustainable development index to track integrated information on economic, environmental, and social performance of the company with time. Willis et al. (2016) developed an integrated FEW index that is comprised of three sub-indices; one each for food, energy, and water. Each sub-index is comprised of two or more indicators reflecting dimensions related to availability and accessibility. Although previous efforts have paved the way for the assessment and modeling of FEW nexus, but they relatively present calculations for the two-sector linkages (e.g. energy-water or food-water). As discussed by Chang et al. (2016), the comparability of different sustainability metrics needs to be further improved by integrating and harmonizing FEW system boundaries, definitions, and methodologies adopted for quantification.

The objective of this paper is to formulate interconnections associated with FEW components. Food, energy, and water components each consist of different sub-components (e.g. transportation fuel for energy component) that make up integrated FEW systems. The proposed formulation is independent of the system scale, although it is solved with United States (U.S.) population data (which is over 323 million at the time of the study) to demonstrate its applicability to large-scale FEW systems. The scale of FEW systems can be as small as a greenhouse and as large as a city or a country. In an effort to increase the degree to which our results would generalize to FEW systems with different scales, the calculations of the study are performed for a sustainable FEW system that can consistently yield food for a family of four (two adults and two children) and supply its own water and energy needs from sustainable sources. This typical household family also allows us to better understand the dynamics among the nexus.

Fig. 1 shows integrated FEW systems, their components and sub-components in this study. Interconnections within the integrated FEW systems are shown by connecting lines and interactions with built environments by self-loop back to the FEW sub-components (e.g., electricity consumption in the residential sector, not associated with food or water). In Fig. 1, numbers above each line refer to the quantity of the resource supplied from a sub-component. They are normalized and weighted by total energy (measured in kWh or Btu), water (measured in lit or gallon), and food (measured in kg or pound) consumptions at the national level (EIA, 2017b; Maupin et al., 2014; USGS, 2010). We might use these

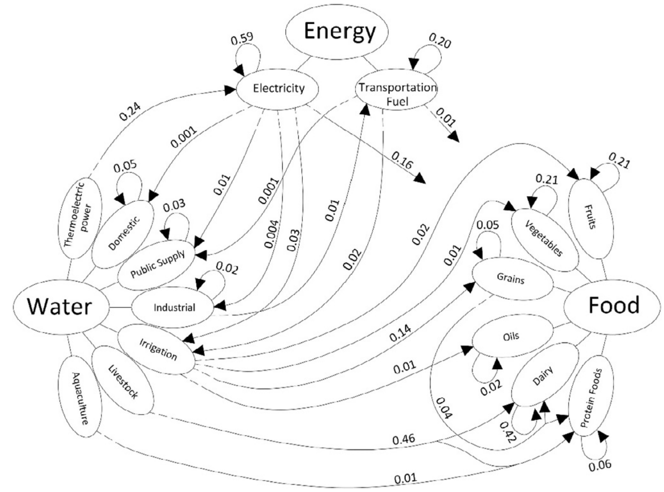

Fig. 1. Interconnections associated with FEW Systems.

quantities to gauge the relative importance of each sub-component in a FEW system but we are not able to understand how each sub-component affects overall sustainability of the system. Using the results of this study, we will update these numbers with contribution of each sub-component on the overall sustainability of the system.

The paper is structured as follows. After this introduction, the next section describes how sustainability of FEW systems is measured. This is followed by a description of the research method and explanations of sustainability indices for FEW components and FEW nexus. Calculations of the sustainability indices for food, energy, and water components for two systems located in two different climates are then presented. Finally, a summary and the conclusion of the paper are presented.

2. Methods and materials

The challenge of understanding FEW policy interactions, and addressing them in an integrated manner, appears daunting. Given the interconnections between FEW resources, a holistic approach to understanding the state of these resources can improve economic efficiency, resource efficiency, population livelihood, and public health. The first step toward developing integrated FEW system modeling is to quantify these interconnections. Metrics can help to formulate them and to measure key facets of sustainability, enabling us to make decisions about how best to become more sustainable. This section presents a novel framework for such a support tool.

As seen in Fig. 1, the FEW sub-components exist in many different forms. To deal with this inconsistency and to ensure the ultimate goal of system sustainability, we define an index to compare the impact of each decision variable on the system's output. Although decision variables may appear to be quite different with respect to FEW sub-components (e.g. what to plant, size of solar system, decisions regarding water treatment method), but their impact on the sustainability of the FEW system can be measured and compared by the cost of achieving sustainability across the FEW system. A metric is needed to investigate the relationship between the sustainability and cost. This cannot be achieved without formulating the interconnections associated with FEW components. A sustainability index (SI) is defined as the probability of meeting food, energy, or water demand as follows:

$$SI_i = P(S_i \geq D_i), i = food, energy, water \tag{1}$$

where, S_i is the expected supply from sustainable sources and D_i is the expected demand for resource i.

The SI is stochastic in nature because of the weather fluctuations, water quality, energy demand, and climate change. The SI is calculated at three levels; system level, called the integrated FEW SI, component level (SI_{food}, SI_{water}, and SI_{energy}), and sub-component level.

The sub-components defined in this paper match those in Fig. 1, but different sub-component structures can be quantitatively modelled by the proposed method. The diagram in Fig. 2 shows the steps and their order in measuring the sustainability of FEW systems regardless of the sub-component structure. A sub-component is a resource consumer when it uses food, energy, or water for its production (e.g. vegetable sub-component) and is a resource supplier when it provides food, energy, or water for another sub-component (e.g. irrigation sub-component). Detailed descriptions of calculations for each sustainability index are discussed in the next section.

2.1. Developing an integrated FEW sustainability index

In order to measure how sustainable FEW systems are, an integrated index to measure sustainability across the nexus is needed. The integrated FEW SI is comprised of three components; food, energy, and water. To ensure that a given change in any of the components has the same effect on the integrated FEW SI, an unweighted, geometric mean is used to combine these three components:

$$FEW\ SI = \sqrt[3]{SI_{food} \times SI_{energy} \times SI_{water}} \tag{2}$$

SIs for food, energy, and water each consist of different sub-components, as shown in Fig. 1. The SI for each component is calculated as the arithmetic mean of SIs for their sub-components (SI_{ij}), in which they are weighted based on their impact on the component sustainability:

$$SI_i = \sum_{j=1}^{j=z} W_{ij} \times SI_{ij} \tag{3}$$

i = food or energy or water, $1 \leq j \leq z$.

Where, *i* is the FEW component, *j* is the food, energy, or water sub-component (e.g., thermoelectric power, irrigation, and industrial for the water component), z is the total number of sub-component (e.g., z = 7 for i = water), and W_{ij} is the impact weight for each sub-component. W_{ij} is calculated as the percentage of total cost of achieving 100% sustainability for the sub-component j to total cost of achieving 100% sustainability for the component i. The FEW system is sustainable only if SI = 100%. The SI is calculated on a yearly basis. Because we can use oversupply to compensate for the lack of water and food later when they are scarcer (i.e. when SI<100%), a food or water component is considered sustainable when we achieve an average of 100% sustainability over a year. But we must ensure that a minimum of 100% sustainability is achieved for the energy component every month.

There may exist some sub-components that need food, energy, or water resources for their production (e.g. Fruits sub-component needs energy and water to produce fruits). In such cases, the SI cannot be calculated without formulating the interconnections associated with FEW sub-components. The SI for each sub-component is calculated as the geometric mean of supply/demand ratios for the sub-component and its resource suppliers:

$$SI_{ij} = \sqrt[n+1]{\frac{S_{ij}}{D_{ij}} \times \sum_{i'=1}^{3} \sum_{k=1}^{n} \frac{S_{i'k}}{D_{i'k}}} \tag{4}$$

where S_{ij} is the expected supply for component i (i = food, energy, water) sub-component j, D_{ij} is the expected demand for component i - sub-component j, $S_{i'k}$ is the expected supply from component i' - sub-component k, $D_{i'k}$ is the expected demand for resource i', and n is the total number of resource suppliers (n = 0 if the sub-component *ij* is not a resource consumer). It is necessary to list all resource suppliers for each sub-component.

Due to interdependencies between FEW components, the behavior of the FEW system changes with the change of the SI for each component and sub-component. For example, seawater desalination for sustaining agricultural production (irrigation sub-component) can potentially improve the SI_{water} and consequently the SI_{food}. However, the desalination methods, such as membrane and thermal, are energy intensive and thus decrease the SI_{energy}. The high greenhouse gas emissions linked to the intensive use of energy could ultimately undermine the sustainability of FEW systems.

2.2. Sustainability index for energy component (SI_{energy})

Energy component may exist in many different forms (e.g. gas for heating or cooking), but they all can end up as electricity or

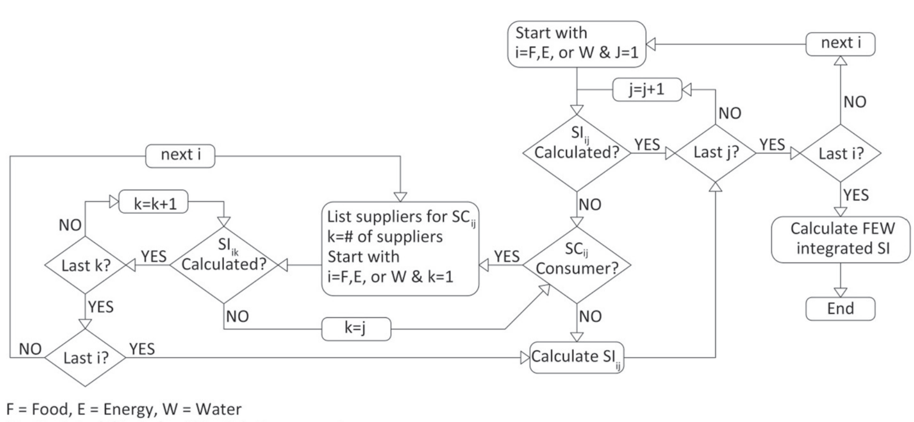

Fig. 2. Steps for measuring the sustainability of FEW systems.

transportation fuel. Even the transportation fuel will probably be dominated by some forms of electricity in the near future with the advent of electric aircrafts and more electric vehicles. We represent the energy component as an entity that consists of two sub-components; electricity and transportation fuel. In order to calculate the SI for the energy component, the supply and demand for each sub-component, and their dependency on other sub-components must be formulated (refer to Eq. (4)).

The expected energy supply can be calculated for different sustainable sources, such as solar, wind, biogas, and geothermal for electricity and biofuel for transportation fuel. There are several different types of biofuel such as ethanol, biodiesel, bioalcohol, vegetable oil, and biothers. The SI is analyzed only for ethanol, the most common type of alternative transportation fuel.

- When solar is used as the primary energy source, the expected supply, S_{energy}, can be calculated as follows:
- When wind is used as the primary energy source, the expected supply, S_{energy}, can be calculated as follows:
- When biogas is used as the primary energy source, the expected supply, S_{energy}, can be calculated as follows (Homan et al., 1980):

$$S_{energy} = E_{cell} \times G \times A_{cell} \times (1 + (TkP \times (AT - 25))) \tag{5}$$

where S_{energy} is measured in watts, E_{cell} is the solar cell efficiency (%) under standard test conditions (temperature of 25 °C, irradiance of 1000 W/m^2, air mass 1.5 spectrum), G is the irradiance of input light (measured in W/m^2), A_{cell} is the surface area of the solar panels (measured in m^2), TkP is the temperature coefficient of solar panel (%/^{o}C), and AT is the ambient temperature (^{o}C).

$$S_{energy} = \frac{1}{2}\rho \times A_{turbine} \times (V_{wind})^3 \times C_p \tag{6}$$

where ρ is the air density, $A_{turbine}$is the swept area of the turbine, V_{wind} is the wind speed, and C_p is the power coefficient.

$$S_{energy} = M \times G_{manure} \times E_{collection} \times E_{biogas} \tag{7}$$

where M is the animal's manure per day, $G_{manure}$is the gas production ratio from animal's manure, $E_{collection}$ is the manure collection efficiency (100% if we could collect all manure produced), and E_{biogas} is the energy value of biogas (0.26 kW/m^3). It is assumed that a dairy cow produces around 40 kg of manure per day per 500 kg, or 8% of live weight.

- When geothermal is used as the primary energy source, the expected supply, S_{energy}, is assumed to be around 3.5 kW for each deep geothermal well (80–110 m deep) (Dickson and Fanelli, 2013).
- When biofuel is used as the primary energy source, the expected supply, S_{energy}, can be calculated as follows:

$$S_{energy} = Coef_{feedstock} \times W_{feedstock} \tag{8}$$

where $W_{feedstock}$ is the feedstock weight (e.g. kg of corn, wheat), and $Coef_{feedstock}$ is the feedstock coefficient factor, representing the amount of biofuel (ethanol in particular) produced from unit weight of feedstock. Table 1 shows coefficient factors for major types of feedstock.

We assume deterministic values for the expected energy demands. It was estimated that a person in the U.S. used about 33 kWh electricity per day in 2014 (CIA, 2015). Thus, the $D_{energy\text{-}electricity}$ is assumed to be 33 kWh/d/person. According to U.S. Energy Information Administration (EIA), total finished motor gasoline per person in the U.S. was about 4.6 L/d day in 2016 (EIA, 2016).

Table 1
Coefficient factors for major types of feedstock.

Feedstock	Coefficient factor
Corn	0.50 L/kg
Sugar cane	0.10 L/kg
Sugar beet	0.12 L/kg
Wheat	0.52 L/kg

Source: (NCGA, 2016; Shapouri and Salassi, 2006)

Thus, the $D_{energy\text{-}trans.\ fuel}$ is assumed to be 4.6 L/d/person. With the average fuel economy of 10.5 km/L (EPA, 2016), this results in the daily average traveled distance of 48.5 km per person. The authors have previously created an electronic spreadsheet composed of a database of 13 electric vehicles currently available and found that the average optimum energy use is around 5.4 km/kW (Karan et al., 2016). Therefore, the expected demand for transportation sub-component is assumed to be 18.4 L/d for the study household, equivalent to 35.9 kW/d. In the U.S., on average, 1.5 L of water are used for every liter of oil refined (McMahon and Price, 2011). As a result, refining 18.4 L of petroleum per day for the study household consumes around 27.6 L of water.

The energy sector is currently one of the largest water consumer in the U.S. Unlike renewables, fuel-based thermoelectric power is highly dependent on water resources. The estimates of operational water consumption factors for electricity generating technologies in the U.S. are adopted from Macknick et al. (2012) and presented in Table 2. These factors are normalized by the percentage of water consumption for each cooling technology. For example, when the fuel type is coal and the cooling technology is once-through, we need around 946 L water to produce one MWh electricity. The factor for recirculating technology is around 2990 lit/MWh and dry cooling technology does not need water for electricity generation. Since about 53% of coal plants in the United States use once-through cooling, and 40% use wet-recirculating, then the water consumption factor for coal is equal to $53\% \times 946 + 40\% \times 2990 = 1697$ L/MWh.

2.3. Sustainability index for water component (SI_{water})

The water component comprises seven sub-components that deal with water consumption in seven different sectors (refer to Fig. 1). The expected water supply can be calculated for different sustainable sources;

- When precipitation is used as the primary water source, the expected supply, S_{water}, can be calculated as follows:

$$S_{water} = PRC \times A_{surface} \tag{9}$$

where is the amount of precipitation (rainfall or snow), and A_{roof} is the surface area of the precipitation harvesting system (e.g. roof, driveway).

- When wastewater is used as the primary water source, the expected supply, S_{water}, is assumed to be equal to the domestic water use (or domestic sub-component):

$$S_{water} = D_{water-domestic} \tag{10}$$

- When seawater is used as the primary water source, the expected supply, S_{water}, depends on the desalination capacity. Seawater is a nearly unlimited supply.

Table 2
Water consumption factors for fuel-based technologies.

Fuel Type	Water Consumption per MWh	% Shares of U.S. Electricity Generation
Coal	1697 L	30%
Nuclear	1643 L	20%
Natural gas	1200 L	34%

The EIA and the U.S. Geological Survey (USGS)'s National Water-Use Science reports appear to be the sole sources of water demand data (EIA, 2017; USGS, 2010). As shown in Fig. 1, national patterns of water use indicate that the largest demand for water use is for livestock with around 1136 billion L/d (46%), followed by thermoelectric generation with around 605 billion L/d (24%). More details are provided in Table 3. Domestic, public, industrial, irrigation, livestock, and aquaculture water supply depends on energy through pumping, transportation, and treatment. Table 3 also provides the data needed to estimate the energy usage of water sub-components. This data can be used in Eq. (4) for $D_{i^{\cdot}k}$ to estimate the expected demand for energy resource.

Energy consumption source (EPA, 2010; Goldstein and Smith, 2002):

2.4. Sustainability index for food component (SI_{food})

Each food component is represented by an entity, which consists of six sub-components; fruits, vegetables, grains, protein foods, dairy, and oils. The food sub-components adopted in the study are food patters suggested by the U.S. Departments of Agriculture (USDA) (USDA, 2010). For each sub-component, a dataset of common foods was prepared. These datasets varied in number between 3 and 15 options depending on the variety of foods available in each sub-component. Table 4 shows the initial list of food options for each sub-component. The food datasets were compiled with the required amounts of water and light, average yield per plant (or farm for protein foods), and other relevant requirements (e.g. chilling requirements representing the number of hours at 7 °C or less for fruits and vegetables). The daily water (L/d) and light (Wh/m^2) requirements as well as average daily yield (gr/d) for each food option were then calculated. Fluctuations in water and energy requirements due to different growth periods (e.g., bloom, maturity, and yield) were taken into consideration.

In order to achieve 100% sustainability for each food sub-component, it is necessary to supply sufficient food to meet the demand and provide the water and energy needed to produce food from sustainable sources. The sustainability index for food sub-component j, $SI_{food\text{-}j}$, is obtained by Eq. (4). The expected supply for food sub-component, $S_{food\text{-}j}$, is formulated as the average yield per plant ($Yield_{avg}$) as follows:

$$S_{food-j} = \begin{cases} 0 & \text{if } S_{energy-food-j} < D_{\min(energy-food-j)} \text{ or } S_{water-food-j} < D_{\min(water-food-j)} \\ \min\left(\dfrac{SL_{avl}}{SL_{demand}} \times Yield_{avg}, Yield_{\max}\right) & \end{cases} \tag{11}$$

where $D_{\min(energy\text{-}food\text{-}j)}$ is the minimum amount of energy required by the plants in sub-component j to survive which obtained from the temperature and chilling requirements of the plants available in the food dataset, $D_{\min(water\text{-}food\text{-}j)}$ is the minimum amount of water required by the plants in sub-component j to survive which is assumed to be 60% of potential evaporation, SL_{avl} is the available sunlight (irradiance) or artificial light (if used), SL_{demand} is the sunlight (irradiance) or artificial light requirement obtained from the food dataset, and $Yield_{max}$ is the maximum yield per plant. If the $Yield_{max}$ is not available in the food datasets, it is assumed to be 150% of the average yield.

The expected food demand, $D_{food\text{-}j}$, is calculated based on the dietary information provided by the Food and Agriculture Organization (FAO) of the United Nations (UN) (Kennedy et al., 2011). The amounts of calories needed for a household consists of one male and one female adult, 36–45 years old, and two children, 2–10 years old, is estimated to be 54,600 cal/wk (or 7800 cal/d). For adults, the reference man is 178 cm tall and weighs 70 kg and the reference woman is 162 cm tall and weighs 57 kg. The level of activity for the study household is considered as moderately active which means a lifestyle that includes physical activity equivalent to walking about 2.4–4.8 km/d at 4.8–6.4 km/h, in addition to the light physical activity associated with typical day-to-day life.

3. Measuring the sustainability of FEW systems

The SI depends largely on the climate condition, as formulated in equations 5–11. Sunlight, temperature, wind speed, and

Table 3
Energy consumption factors for water supply systems.

Water Type	Water Consumption per day[a]	% Shares of U.S. Water Consumption	Electricity Usage
Public Supply	81 B L	3%	0.62 Wh/L
Domestic	121 B L	5%	0.75 Wh/L
Irrigation	435 B L	18%	0.55 Wh/L
Livestock	1136 B L	46%	0.66 Wh/L
Aquaculture	36 B L	1%	0.49 Wh/L
Thermoelectric	605 B L	24%	N/A
Industrial	60 B L	2%	0.68 Wh/L

[a] B = billion.

Table 4
List of options for each food sub-component.

Sub-component	Food options
Fruits	Avocado, Apple, Banana, Grape, Melon, Berry, Cherry, Grapefruit, Lemon, Peach, Plum, Pomegranate, Strawberry, Kiwifruit, Orange
Vegetables	Broccoli, Lettuce, Spinach (dark-green vegetables), Beet, Carrot, Tomato (red and orange vegetables), Bean, Lentil, Pea (beans and peas), Corn, Potato, Cucumber (starchy vegetables), Cabbage, Onion, Pepper (other vegetables)
Grains	Wheat, Oat (Oatmeal), Brown Rice (whole grains), Barley, White Rice, Cornmeal (Maze) (enriched grains)
Proteins	Seafood, Meat, Poultry and Eggs, Nuts, Seeds, Soy products
Dairy	N/A
Oils	Olive, Sunflower, Palm

precipitation are among the factors influencing the sustainability of FEW systems and vary across different climates. In order to examine the applicability of the proposed method to real FEW systems and to demonstrate its capability, two systems located in two different climates are selected and their integrated FEW SI are modelled; one is relatively cloudy (with an average solar radiation of 3.6 kWh/m^2/d) and humid (with an average rainfall of 1000 mm/yr) (hereafter humid climate) and the other is sunny (with an average solar radiation of 5.6 kWh/m^2/d) and arid (with an average rainfall of 100 mm/yr) (hereafter arid climate). Since dollars are the only measure common to food, energy, and water components, the changes in the SI is formulated in terms of dollars. The formulation indicates the amount of SI improved per dollar spent. It also allows us to make optimal decisions with highest SI improvement and lowest cost. First improvements on the SI are associated with solutions with higher cost-effectiveness ratios and therefore are typically much less costly and faster to put in place. In the following sections, the SI for three FEW components in two different climates are calculated.

Table 5 lists the estimated price for different sources of water and energy and the average values for the related parameters. The total cost of water and energy supply systems is evenly distributed over the whole lifetime of the system (e.g. 20 years for solar systems). To achieve sustainability improvements with minimal cost, cheaper sources of water and energy are preferred. Using the temperature, solar irradiance, and wind speed data for the humid and arid climates, solar is identified as the preferred source of energy in both climates. However, inability to store solar energy without storage battery and relatively high cost of batteries make biogas the preferable choice for producing energy, when applicable. The amount of energy produced from biogas depends to a large extend on the population of livestock, which itself determines the protein and dairy productions. We formulate the biogas production rate in terms of protein and dairy sub-components. If the biogas energy is not sufficient to cover the demand, energy is delivered by the solar system. The cost of energy supply from sunlight depends mainly on input light, and therefore it is higher in the humid (or cloudy) climate compared to the arid (or sunny) climate. The average precipitation over the last 16 years (1998–2014) was used to obtain predictions for collecting rainfall or snow. Collecting rainfall or snow is identified as the preferred method of water supply in the humid climate, while recycling wastewater is preferred in the arid climate. The cost of water supply from rainfall (or snow) depends on precipitation, and therefore it is higher in the arid climate compared to the humid climate.

4. Results and discussions

Using the described methods, one can calculates the FEW SI for any climate region. While the long-term goal is to use the integrated index in decision making, the collection of sub-indices provide insight themselves. Analyzing of the index and its component sub-indices provides insight into how much variation exists among resource insecurity in each climate, how that variation is distributed, and what factors contribute to resource insecurity for specific climate region in this case. Using this approach not only reveals geographic patterns of resource insecurity, but also the FEW Index describes sources of resource strengths and weaknesses within each studied climate region. To illustrate these patterns, we have calculated the SI for each component and its sub-component and an integrated index for two climate regions.

4.1. Calculations for the SI_{food} in two climates

We need water and energy to produce food. The cost of water and energy supply is not only required to investigate the relationship between the SI_{food} and cost but also to calculate the impact weight for each food sub-component (refer to Eq. (3)). Table 6 presents the yearly water and energy consumption, cost of achieving 100% sustainability, and impact weights for food sub-components. The details of the calculations for the SI_{food} are provided in the forthcoming subsections. The protein sub-component appears to be the major contributor. A sustainable protein sub-component ($SI_{food\text{-}protein} = 100\%$) has the potential to increase the food sustainability by around 60%.

Fig. 3 shows the relationship between the SI_{food} and cost and the

Table 5
Estimates of supply system capital and operating costs.

Source	Average price	Cost parameters
Energy		
Solar	330(# of panels)+1360	A_{cell} (avg) = 1.7 m^2 E_{cell} (avg) = %15.86
Wind	600($A_{turbine}$)+6400 if $A_{turbine}$<500 m^2 285($A_{turbine}$)+9.15 × 10^3 if $A_{turbine}$>1000 m^2	$A_{turbine}$ is measured in m^2C_p (avg) = 35%
Biogas	40 × M × G_{manure}	M = 8% of animal's weightG_{manure} (avg) = 0.0335 m^3/kg
Geothermal	1925(well depth in m) + 3750	$180,000 (avg) per deep well
Water		
Precipitation	5.74 × $A_{surface}$	
Wastewater	IF(D < 255,0.009,IF(D < 360,0.017,IF(D < 690,0.019,IF(D < 760,0.023,0.039)))), D = lit	
Seawater	0.017 × $D_{water-domestic}$	$D_{water-domestic}$ is measured in lit

Table 6
Water and energy consumption of a household for food sub-components.

Food sub-component	Water use (L/yr)		Energy use (MWh/yr)		Cost of SI = 100%		Impact weight (W_{fj})	
	Humid	Arid	Humid	Arid	Humid	Arid	Humid	Arid
fruit	32.5 K	25.9 K	2.2	1.9	$449	$215	1.9%	0.4%
vegetable	147.3 K	147.3 K	11.0	1.9	$1851	$1739	7.9%	3.4%
grain	162.6 K	161.9 K	1.1	1.8	$999	$1545	4.2%	3.0%
protein	1883.6 K	1883.6 K	14.3	14.5	$12,905	$32,515	54.9%	63.1%
dairy	867.5 K	867.5 K	1.8	5.3	$5251	$14,959	22.3%	29.1%
oil	402.5 K	200.1 K	1.2	1.2	$2057	$520	8.7%	1.0%

K = thousand.

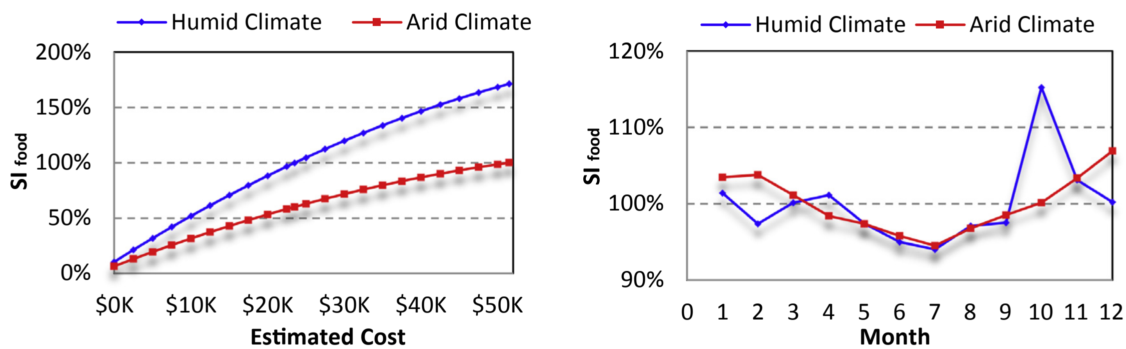

Fig. 3. Cost of SI_{food} improvement (left) and Monthly SI_{food} for optimal investment (right) (note: K = thousand).

monthly SI_{food} for optimal investment (i.e., $23,511 for the humid and $51,493 for the arid climates). The results show that water is the critical resource for producing food. The FEW system in the humid climate spends more than 80 percent of its investment on water supply, while only 2% of the investment in the arid climate is spent on energy supply. The only exceptions are the fruit and vegetable sub-components in the humid climate, where more than 75 percent of the investment should spend on energy supply to achieve 100% sustainability. The critical role of water in achieving the sustainable food system and the high cost of water supply in the arid climate make the system much more expensive in the arid climate than the humid climate. Sufficient precipitation and mild temperature of the humid climate in October resulted in achieving higher sustainability of food.

4.1.1. SI_{food} for fruit sub-component ($SI_{food\text{-}fruit}$)

The first improvements on the SI_{food} must be associated with higher cost-effectiveness ratios. Since all options for the fruit sub-category need about the same amount of sunlight, this can be translated to plants with higher water per yield ratio. For instance, water consumption is estimated to be 15 L/d for producing 1 kg of grapefruit, 70% less than water consumption for producing 1 kg of apple (Bryla et al., 2011). Therefore, grapefruit is given a higher priority than apple. The water/yield ratio for each food option is calculated and they are sorted for the humid and arid climates. The recommended average daily intake amounts of fruit for the study household is found to be 1400 gr/d. When applicable, fresh foods are only available during the yield period. Otherwise, preserved food can be used. Fig. 4 shows the daily water requirement and preferred fruit option for the study household in two different climates.

The optimum $SI_{food\text{-}fruits}$ is achieved when the ratio of supply/demand for water and energy are equal (refer to Eq. (4)). Eq. (4) is solved for $SI_{food\text{-}fruits}$; total cost of achieving 100% sustainability is estimated to be $449 in the humid climate and $215 in the arid climate. These numbers are used to calculate the impact weight for fruit sub-component. The FEW system in the humid climate needs around $180 to meet the water demand for fruit sub-component, while it would cost around $233 in the arid climate. Also, the FEW system in the humid climate needs around $352 to meet the

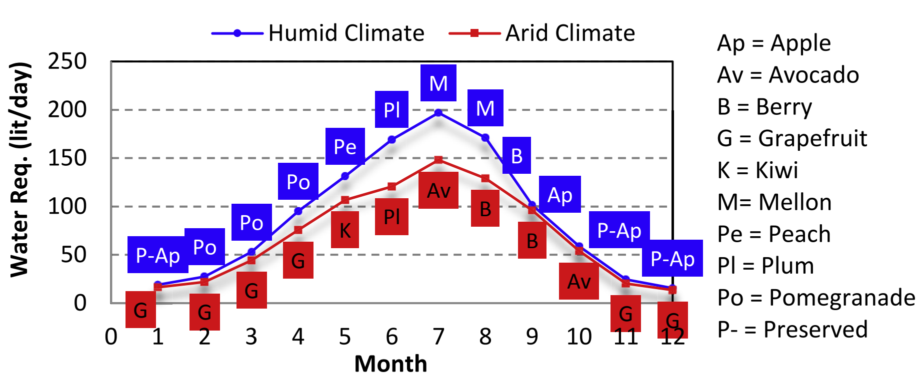

Fig. 4. Water requirement for fruit sub-component.

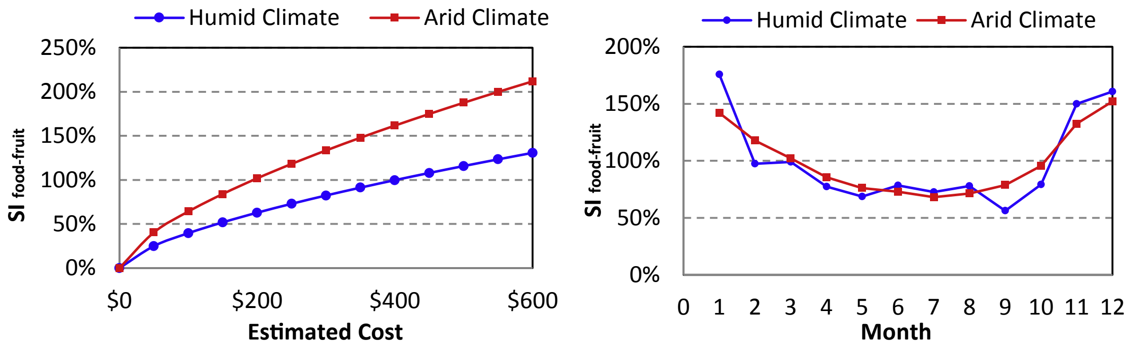

Fig. 5. Cost of $SI_{food\text{-}fruits}$ improvement (left) and Monthly $SI_{food\text{-}fruits}$ for optimal investment (right).

energy demand for fruit sub-component, while it would cost around $90 in the arid climate to meet the energy demand. This can be explained by the different cost of water and energy supply in humid and arid climates. To achieve the optimum $SI_{food\text{-}fruits}$, thus, 35% of overall investment should be allocated to water supply in the humid climate but 72% of overall investment should be allocated to water supply in the arid climate. The relationship between $SI_{food\text{-}fruits}$ and cost is plotted in Fig. 5. The monthly $SI_{food\text{-}fruits}$ for optimal investment (i.e. $449 for the humid and $215 for the arid climates) is also shown in Fig. 5.

4.1.2. SI_{food} for vegetable sub-component ($SI_{food\text{-}veg}$)

The recommended average daily intake amounts of vegetable for the study household is 2000 gr/d. Although vegetables can also be preserved by drying, but only fresh vegetables are used in calculations. Also, each FEW system is analyzed independently and thus the imported vegetables are not taken into consideration. In both climates, fresh vegetables are not available all year around but gardening in a greenhouse can expand the growing seasons for vegetable sub-component. Due to being unavailable for a considerable period of time in the case of outdoor planting and high energy costs in the greenhouse, vegetables are a relatively expensive source of food. Biogas can be used to heat the greenhouse for growing vegetables. The total potential of biogas available is 0.047 KWh/d, 97% is produced from dairy farms (dairy sub-component) and 3% from livestock farms (protein sub-component). To demonstrate the role of greenhouse in the sustainability of vegetable sub-components, calculations are performed with and without greenhouse gardening (see Fig. 6). Overall, growing greenhouse vegetables appears to be less costly, especially for the arid climate where a major portion of investment should be directed into the water supply (95% for outdoor planting and 86% for greenhouse option). By growing vegetables in a greenhouse, we need around $1851 to achieve $SI_{food\text{-}veg} = 100\%$ in the humid climate, 18% less than growing vegetables without greenhouse. The investment needed to achieve $SI_{food\text{-}veg} = 100\%$ in the arid climate is estimated to be around $1739 when vegetables are grown in a greenhouse, 65% less then growing vegetables outdoor.

4.1.3. SI_{food} for grain sub-component ($SI_{food\text{-}grains}$)

The recommended average daily intake amounts of grains for the study household is 3162 gr/d, 76% is used to feed the livestock (protein and dairy sub-components). The grains intake is classified into two categories (1) whole grains (e.g. wheat, oat); and (2) enriched grains (e.g. barley, corn). The grains can be stored in silos or warehouses for several months and thus they can be available all year around. The grains sub-component is a resource supplier; the protein sub-component makes up 37% of the grain consumption and nearly 39% of grain is used for dairy sub-component. Eq. (4) is solved for $SI_{food\text{-}grains}$; total cost of achieving 100% sustainability is estimated to be $999 in the humid climate and $1545 in the arid climate. The cost of sustainable water supply is nearly three times higher in the arid climate compared to the humid climate. This helps the humid climate to achieve 100% sustainability at a lower cost. On the other hand, sunlight is a major key to high grain yields and therefore the expected supply for the grains sub-component, $S_{food\text{-}grain}$, (with the same amount of water and energy supply) in the arid climate is higher in the arid climate than in the humid climate. But even with this advantage, improving sustainability for the grains sub-component in the humid climate is less costly than that in the arid climate.

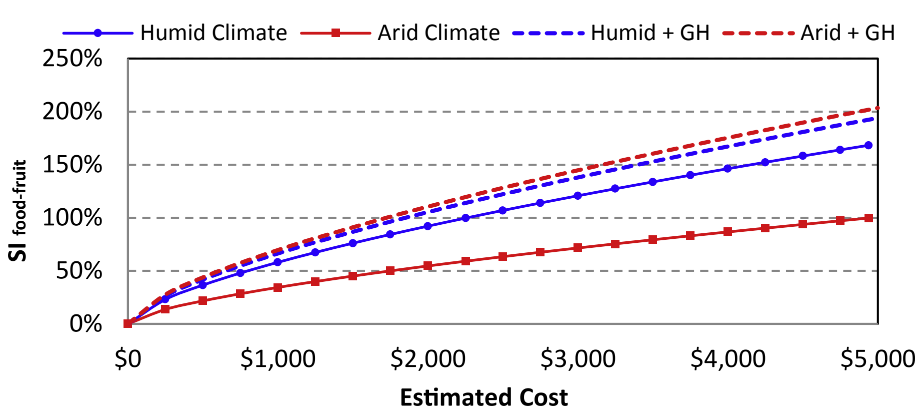

Fig. 6. Cost of $SI_{food\text{-}veg}$ improvement.

4.1.4. SI_{food} for protein sub-component ($SI_{food\text{-}protein}$)

The protein intake is classified into three categories; (1) seafood, (2) meat, poultry, and eggs, and (3) seeds and soy products. The calculation for the protein sub-component is similar to equation (4), with the exception that the ratio of expected supply/demand, $S_{food\text{-}protein}/D_{food\text{-}protein}$, is omitted from the equation (note: the protein production is independent of climate conditions). In addition to water and energy, cereal grains are also needed to produce animal protein. We need around 292 L of water, 1.3 kg feed, and 159 kWh of energy to produce a 1 kg fish protein (Love et al., 2015). Dairy cows, beef cattle, sheep and goats are usually fed grass and maize silage, or barley. On average, 5.86 kg of plant protein is fed to livestock to produce 1 kg of animal protein. About 63% of the livestock feed comes from grains (Pimentel, 1997). The recommended average daily intake amounts of meat protein for the study household is 425 gr/d and therefore around 1163 gr/d of grains is needed to feed the livestock. The protein sub-component is heavily dependent on water. Producing 1 kg of chicken requires 3500 L of water and 15,415 L of water is needed to produce 1 kg of beef (Pimentel and Pimentel, 2003). Hence, it is not surprising to see that achieving sustainability for protein sub-component is more expensive than other sub-components, especially in the arid climate where water is more expensive to supply. The total cost of achieving 100% sustainability for $SI_{food\text{-}protein}$ is estimated to be $12,905 in the humid climate and $32,515 in the arid climate.

4.1.5. SI_{food} for dairy sub-component ($SI_{food\text{-}dairy}$)

Calculations for the $SI_{food\text{-}dairy}$ are similar to those for the $SI_{food\text{-}protein}$. The recommended average daily intake amounts of meat protein for the study household is 2400 gr/d. Producing 1 kg of milk requires 990 L of water, 0.94 kg feed, and 1.87 kWh energy (Eide, 2002). Grains accounts for about 55% of the livestock feed, and around 7% comes from proteins (Pimentel, 1997). The dairy sub-component is also heavily dependent on water. Because the cost of sustainable water supply is nearly three times higher in the arid climate compared to the humid climate, the total cost of achieving 100% sustainability for $SI_{food\text{-}dairy}$ is estimated to be three times higher in the arid climate compared to the humid climate ($5251 in the humid climate and $14,959 in the arid climate).

4.1.6. SI_{food} for oil sub-component ($SI_{food\text{-}oils}$)

The recommended average daily intake amounts of oil for the study household is 105 gr/d. The oil can be stored for several months and thus they can be available all year around. Eq. (4) is solved for $SI_{food\text{-}oil}$; total cost of achieving 100% sustainability is estimated to be $2057 in the humid climate and $520 in the arid climate. There are more water efficient options for producing oils in the arid climate compared to the humid climate, resulting in less water demand for the oil sub-component in the arid climate. Furthermore, sunlight is a major key to high plant oil production and therefore the expected supply for the oil sub-component, $S_{food\text{-}oil}$, (with the same amount of water and energy supply) in the arid climate is much higher in the arid climate than in the humid climate. Therefore, improving sustainability for the grains sub-component in the arid climate is less costly than that in the humid climate.

4.2. Calculations for the SI_{water} in two climates

Table 7 presents the yearly water and energy consumption, cost of achieving 100% sustainability, and impact weights for water sub-components. The values in Table 7 may differ from the values in Table 3 because they represent the water and energy consumptions for the study household when sustainable sources are used and do not include the virtual water trade (water consumption if food or other commodities are exported from the U.S to another country). In contrast, Table 3 presents the national water consumption in the U.S. for each sub-component. The details of the calculations for the SI_{water} are provided in the forthcoming subsections. We assume deterministic values for the expected water demands for all sub-components other than food-related sub-components. Therefore, there is only one value for the water use column in Table 7 for both humid and arid climates. As expected, the thermoelectric power and livestock sub-components appear to be the major contributors, accounting for more than 60 percent of water sustainability.

Fig. 7 shows the relationship between the SI_{water} and cost and the monthly SI_{water} for optimal investment (i.e. $49,169 for the humid and $74,974 for the arid climates). The high cost of water supply in the arid climate makes the system more expensive in this region than the humid climate. High water demands over the summer, particularly for thermoelectric and irrigation sub-components, resulted in low sustainability of water during this period.

4.2.1. SI_{water} for public supply and domestic sub-components ($SI_{water\text{-}public}$ and $SI_{water\text{-}domestic}$)

Public supply sub-component refers to water used for public services (e.g. municipal buildings, firefighting, public parks). Domestic sub-component refers to potable and non-potable water used for households for drinking, bathing, washing dishes and clothes, flushing toilets, and watering gardens and lawns. Groundwater and surface-water are main sources of public supply and domestic withdrawals, none of them are sustainable sources of water supply. The public supply and domestic sub-components require high-quality water to use and therefore they are more expensive to treat and supply than other water sub-components. Total water demands are estimated to be around 1000 L/d for public supply and 1500 L/d for domestic. With 15 L/d, drinking water accounts for 1% of the total domestic demand, shower usage is estimated as 17%, faucet accounts for 16% (half for kitchen, half for bathroom), laundry and toilet are estimated to be 22% and 27%, respectively. 17% is used for irrigation or unaccounted for because of

Table 7
Water and energy consumption of a household for water sub-components.

water sub-component	Water use (lit/yr)		Energy use (MWh/yr)		Cost of SI = 100%		Impact weight (W_{fj})	
	Humid	Arid	Humid	Arid	Humid	Arid	Humid	Arid
public	365.0 K		0.19	0.22	$5390	$8488	11.0%	11.3%
domestic	547.5 K		0.24	1.21	$6759	$10,120	13.7%	13.5%
irrigation	744.9 K	535.2 K	0.17	0.29	$4294	$4847	8.7%	6.5%
livestock	2619.3 K		0.60	1.44	$15,098	$23,724	30.7%	31.6%
aquaculture	81.1 K		0.02	0.04	$468	$735	1.0%	1.0%
thermoelectric	2733.8 K		N/A	N/A	$15,601	$24,604	31.7%	32.8%
industrial	272.0 K		0.04	0.41	$1552	$2448	3.2%	3.3%

K = thousand.

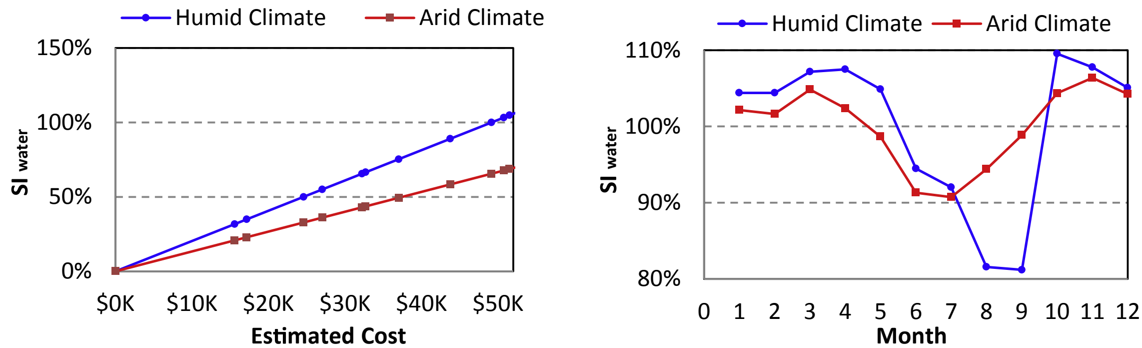

Fig. 7. Cost of SI_{water} improvement (left) and Monthly SI_{water} for optimal investment (right) (note: K = thousand).

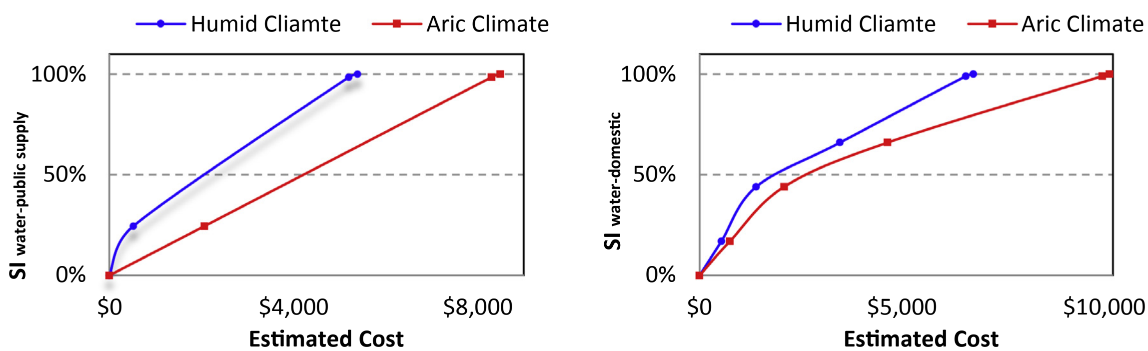

Fig. 8. Cost of SI improvement for public-supply (left) and domestic (right) subcomponents.

leaks and other system losses. On average, 74% of the total public supply water in the U.S. is used in buildings for flushing toilets and cleaning (EIA, 2012), 1.5% for drinking, and the rest is used for other purposes (e.g. irrigation and firefighting). In regions where precipitation is low (e.g. the arid climate in the present study), we should rely more on other sustainable methods of water supply such as treating wastewater or desalinating seawater. Fig. 8 shows the cost of $SI_{water\text{-}public\ supply}$ and $SI_{water\text{-}domestic}$ improvements.

4.2.2. SI_{water} for irrigation, livestock, and aquaculture sub-components ($SI_{water\text{-}irrigation}$, $SI_{water\text{-}livestock}$ and $SI_{water\text{-}aquaculture}$)

The expected water demands for irrigation, livestock, and aquaculture sub-components are calculated in the previous section. The main fruit and oil plants cultivated in the arid climate have more plant species options than plants cultivated in the humid climate (or northern U.S.). This results in higher water demand for the irrigation sub-component in the humid climate than the arid climate. The cost of this high water demand in the humid climate is compensated by using rainfall instead of wastewater or seawater ($4294 for $SI_{water\text{-}irrigation} = 100\%$ in the humid climate compared to $4847 for $SI_{water\text{-}irrigation} = 100\%$ in the arid climate). The expected water demand for the livestock and aquaculture sub-components is independent of climate. Because the cost of supplying water from sustainable sources is much higher in the arid climate than the humid climate, achieving 100% sustainability for the livestock and aquaculture sub-components is more expensive in the arid climate.

4.2.3. SI_{water} for thermoelectric and industrial sub-components ($SI_{water\text{-}thermo}$ and $SI_{water\text{-}industrial}$)

Water for thermoelectric power is used in cooling power generation equipment and generating electricity with steam-driven turbine generators. According to the USGS's Estimated Use of Water in the United States, total water use for thermoelectric power was about 605 billion L/d in 2010, accounting for about 7490 l/d for the study household (Maupin et al., 2014). The thermoelectric sub-component is a resource supplier because it provides water for another sub-component (i.e. electricity). Water for industrial purposes is used for fabricating, producing, processing, washing, or transporting a product. The expected water demand for the industrial sub-component is about 745 L/d for the study household. The industrial sub-component is also a resource supplier because it provides 3.7% of its water for energy-transportation sub-component.

4.3. Calculations for the SI_{energy} in two climates

Out of the total energy produced in the U.S., around 21% is consumed in the food and water sectors. In the previous sections, we calculated the expected energy demands for food and water components in a sustainable FEW system. The household in the humid climate consumes around 86 KWh/d to supply sustainable foods and 2 KWh/d to supply water from sustainable sources. The household in the arid climate consumes around 73 KWh/d and 5 KWh/d for supplying food and water from sustainable sources. These values are added to the expected demand of 132 KWh/day for the electricity sub-component and 18.4 L/d for the transportation sub-component to calculate the SI_{energy}. Table 8 presents the yearly water and food consumption, cost of achieving 100% sustainability, and impact weights for energy sub-components. The calculated impact weights can be easily explained by the high energy cost in the humid climate when compared to the high water cost in the arid climate.

Fig. 9 shows the relationship between the SI_{energy} and cost and the monthly SI_{energy} for optimal investment (i.e. $45,318 for the humid and $38,777 for the arid climates). Fluctuations in demand to electricity and transportation fuel along with electricity supply

Table 8
Water and food consumption of a household for energy sub-components.

energy sub-component	Water use (lit/yr)		Food use (ton/yr)		Cost of SI = 100%		Impact weight (W_{fj})	
	Humid	Arid	Humid	Arid	Humid	Arid	Humid	Arid
electricity	N/A		N/A		$28,877	$9730	63.7%	25.1%
trans. fuel	2523.6 K	1675.9 K	13.17		$16,441	$29,047	36.3%	74.9%

K = thousand.

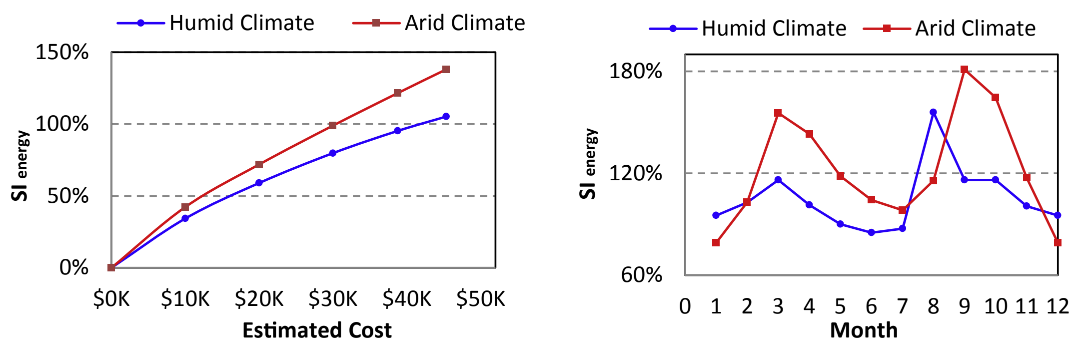

Fig. 9. Cost of SI_{energy} improvement (left) and Monthly SI_{energy} for optimal investment (right) (note: K = thousand).

(e.g. solar power) can significantly affect the SI_{energy}. For example, the feedstock plants (as sustainable source of transportation fuel) need plenty of water during the late spring and early summer (May–August) and eventually leads to lower sustainability index during this period.

4.3.1. SI_{energy} for electricity sub-component ($SI_{energy\text{-}electricity}$)

In both climates, solar energy is the most efficient sustainable source of electricity. When the solar system is not producing enough energy, for example during cloudy weather or night, we need to use battery tanks to store the energy. The optimal solar system (minimum cost for achieving $SI_{energy\text{-}electricity} \geq 100\%$ every month) in the humid climate is found to be a system of 1244 modules of solar panels with 781 kWh storage capacity. This system costs around $28,873/yr and leads to an average $SI_{energy\text{-}electricity}$ of 108%. The optimal solar system in the arid climate is comprised of 504 modules of solar panel with 127 kWh storage capacity that costs around $9730/yr. The average $SI_{energy\text{-}electricity}$ for this optimal system is 186%. The high cost of energy supply in the humid climate makes the system more expensive in this region than the arid climate. Fig. 10 shows the relationship between the $SI_{energy\text{-}electricity}$ and cost and the monthly $SI_{energy\text{-}electricity}$ for optimal investment in both climates.

4.3.2. SI_{energy} for transportation fuel sub-component ($SI_{energy\text{-}trans.\ fuel}$)

All major types of feedstock need about the same amount of sunlight and energy to produce. Therefore, first improvements on the $SI_{energy\text{-}trans.\ fuel}$ must be associated with higher water-yield and coefficient factors such as corn and wheat. Eq. (4) is solved for $SI_{energy\text{-}trans.fuel}$; total cost of achieving 100% sustainability is estimated to be $16,441 in the humid climate and $29,074 in the arid climate. The high cost of supplying water from sustainable sources in the arid climate makes the system more expensive in this region than the humid climate. Unlike the expected electricity demand that varies considerably throughout the year (as changes in temperature and humidity affect the demand), the expected demand for the transportation fuel is assumed to be constant over the year. In contrast, the expected supply for the transportation fuel is not constant and varies over time because it depends highly on feedstock yields and consequently on climate, sunlight, and rainfall.

4.4. Calculations for integrated FEW sustainability index

Once the SI is estimated for each FEW component, we can calculate the integrated FEW SI using equation (2). The inconsistency between FEW units of measurement at this level can be resolved by formulating the changes in the SI in terms of dollars. If

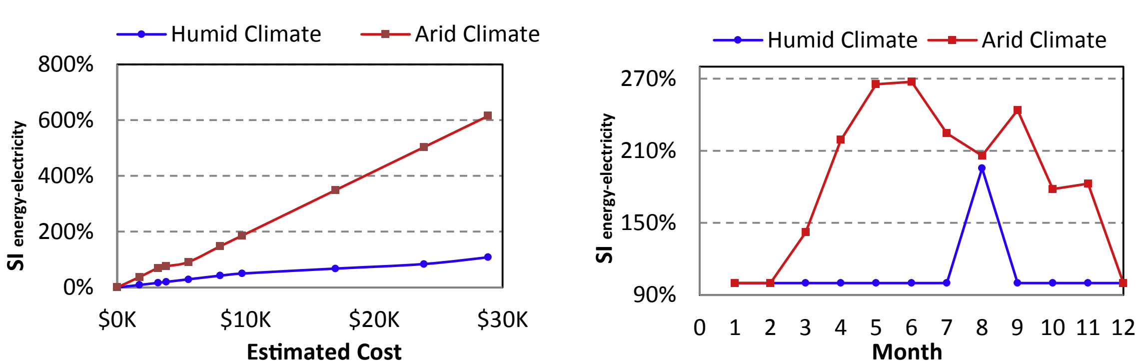

Fig. 10. Cost of $SI_{energy\text{-}electricity}$ improvement (left) and Monthly $SI_{energy\text{-}electricity}$ for optimal investment (right) (note: K = thousand).

Table 9
Role of FEW sub-components in the nexus sustainability.

Component	Sub-component	% of improvement		Rank	
		Humid	Arid	Humid	Arid
water	public supply	3.5%	3.4%	13	14
	domestic	3.5%	3.4%	14	13
	irrigation	12.5%	20.1%	1	1
	livestock	8.3%	9.6%	4	3
	aquaculture	10.9%	8.3%	2	4
	thermo. electric	3.4%	3.4%	15	15
	industrial	3.6%	3.6%	12	12
food	fruit	7.1%	4.7%	8	11
	vegetable	7.2%	4.9%	5	7
	grain	10.7%	11.1%	3	2
	protein	7.2%	4.9%	6	9
	dairy	7.2%	4.9%	7	8
	oil	7.1%	4.8%	9	10
energy	electricity	4.0%	6.6%	10	5
	trans. Fuel	3.7%	6.5%	11	6

resource supply or demand quantities exist under more than one classification, they must be counted only once in calculating the integrated FEW SI. In such cases, the integrated FEW SI is only influenced by the resource provider. For example, the aquaculture sub-component accounts for 1% of the water sustainability and contributes to the food sustainability by providing water needed for producing protein. The water supply regarding the protein sub-component is subsequently excluded from the calculations. Resource provider sub-components are given higher priority so that decisions can lead to higher sustainability improvement per dollar spent.

The interconnections associated with FEW components are two sides of the same coin. We may view the situation as a challenge or an advantage. It is a challenge because these dependencies may increase the nexus vulnerability since a disruption in one component may produce consequences in the others. It is an advantage because improving the sustainability of one component may enhance another and increase the nexus sustainability. The integrated FEW SI is calculated for two climates and the results are presented in Table 9. A sustainable FEW system (integrated FEW SI = 100%) in the humid climate costs \$76,888 while it costs \$113,832 in the arid area. Considering the high cost of water supply in the arid climate, this indicates the crucial role of sustainable water use in achieving FEW sustainability. In both climates, the irrigation sub-component results in highest sustainability improvement. The results are not surprising; not only a sustainable water supply for irrigation sub-component improves the sustainability of water component (SI_{water}), it also improves SI_{food} and consequently the SI_{energy} (as it is a resource supplier for grain sub-component, and that is a resource supplier for transportation fuel sub-component). The sustainability improvement that is achieved by a given investment is almost three times higher for the irrigation sub-component than the electricity sub-component.

The results also enable us to understand how each sub-component affects overall sustainability of the system. Fig. 11 shows an integrated FEW system, its components and sub-components, the impact weight of each sub-component (numbers above each connecting line) and the contribution of each sub-component on the overall sustainability of the system (relative size of blocks for each sub-component). Note that the impact weights and relative size of sub-component blocks are the average values for both climates. Fig. 11 is similar to Fig. 1, however, the quantities in Fig. 1 (which represented the total consumptions at the national level) are updated with contribution of each sub-component on the overall sustainability of the system.

5. Conclusion

The increasing costs of energy and water, fossil fuel depletion, and food shortages caused by climate change have left us with no choice but to accelerate the world's transition to sustainability. In

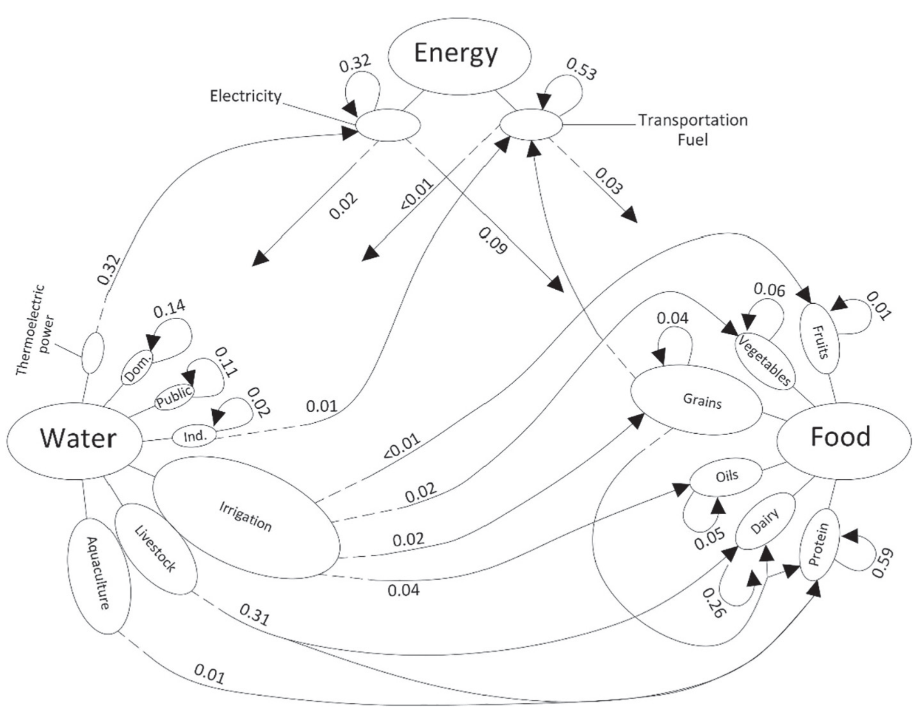

Fig. 11. Impact weight of FEW sub-components (numbers above lines) on the component sustainability (note: size of blocks represents contribution of FEW sub-components on the system sustainability.

working toward sustainable development, a fundamental question for deciding on whether and how to invest in FEW system is "how sustainable FEW systems are?". In order to measure sustainability across the FEW systems, an integrated sustainability index (SI) is developed. The developed FEW sustainability index represents an integrated index to measure sustainability across the nexus. This study quantifies the level of sustainability in each system and provides comparable integrative index to evaluate how sustainable a system is in compare with other systems. This approach will not only advance our understanding of FEW systems but also will show us the key components and sub-components contributing to the sustainability of the FEW systems and identify the strongest and weakest links of the systems.

The goal of this study was to develop an integrated FEW sustainability index that can simply be used by policymakers, the development community, scientists, and the public to assess the trade-offs among possible future trends. As shown in this research, the integrated index values for the case study are correlated with indicators of climate condition such as sunlight, temperature, wind speed, and precipitation. However, this relationship is interesting in two ways which can be seen as a challenge or an advantage. It is a challenge because these dependencies may increase the nexus vulnerability as a disruption in one component may produce consequences in the others. It is an advantage because improving the sustainability of one component may enhance another and increase the nexus sustainability. Such structure provides potential for future nexus analysis.

The results of this study will also help decision makers to assess the potential impact from changes in any of each decision variable on the FEW sustainability index and understand how each sub-component affects overall sustainability of the system. For example, in this study we found the significant contribution of the irrigation sub-component on the sustainability of the system in compare with other sub-components. Such relationships between the sustainability index and decision variables such as population or consumption rates could be utilized to predict changes in the index that may come from unexpected factors affecting the index. Some of the examples of these unexpected factors are the effects of climate change on water availability or agricultural productivity; the effects of new technologies on energy efficiency or availability; and the effects of shifts in population or changes in population growth rates. Understanding the relationship among the indicators and influencing factors affecting them, could allow decision makers to utilize the FEW sustainability Index as a tool to support scenario analyses and long-term development planning.

Notations

A_{cell}	Surface area of the solar panels
A_{roof}	Surface area of the precipitation harvesting system
AT	Ambient temperature
$A_{turbine}$	Swept area of the turbine
$Coef_{feedstock}$	Feedstock coefficient factor
C_p	Power coefficient of wind turbine
$D_{energy\text{-}ij}$	Energy needed to meet the demand for component i (i = food, energy, water) sub-component j
D_i	Expected demand for resource i
D_{ij}	Expected demand for component i (i = food, energy, water) sub-component j
$D_{min(energy\text{-}food\text{-}j)}$	Minimum amount of energy required by the plants in sub-component j to survive
$D_{min(water\text{-}food\text{-}j)}$	Minimum amount of water required by the plants in sub-component j to survive
$D_{water\text{-}ij}$	Water needed to meet the demand for component i (i = food, energy, water) sub-component j
E_{biogas}	Energy value of biogas
E_{cell}	Solar cell efficiency (%) under standard test conditions
$E_{collection}$	Manure collection efficiency
FEW SI	Sustainability index at the system level
G	Irradiance of input light
G_{manure}	Gas production ratio from animal's manure
KPL	Kilometers per L
M	Animal's manure per day
MPH	Miles per gallon
ρ	Air density
PRC	Amount of precipitation
$S_{energy\text{-}ij}$	Expected energy supply from sustainable sources for component i (i = food, energy, water) sub-component j
S_i	Expected supply from sustainable resource i
SI	Sustainability index
SI_{energy}	Sustainability index for energy component
SI_{food}	Sustainability index for food component
SI_{water}	Sustainability index for water component
SI_{ij}	Sustainability index for component i (i = food, energy, water) sub-component j
SL_{avl}	Available sunlight (irradiance) or artificial light (if used)
SL_{demand}	sunlight (irradiance) or artificial light requirement
S_{ij}	Expected supply for component i (i = food, energy, water) sub-component j
$S_{water\text{-}ij}$	Expected water supply from sustainable sources for component i (i = food, energy, water) sub-component j
TkP	Temperature coefficient of solar panel (%/^{o}C)
V_{wind}	Wind speed
$W_{feedstock}$	Feedstock weight
$Yield_{avg}$	Average yield per plant
$Yield_{max}$	Maximum yield per plant

References

Bryla, D.R., Gartung, J.L., Strik, B.C., 2011. Evaluation of irrigation methods for highbush blueberry—I. Growth and water requirements of young plants. Hortscience 46 (1), 95–101.

Chang, Y., Li, G., Yao, Y., Zhang, L., Yu, C., 2016. Quantifying the water-energy-food nexus: current status and trends. Energies 9 (2), 65.

CIA, 2015. The World Facebook - Electricity Consumption (2017). https://www.cia.gov/library/publications/the-world-factbook/rankorder/2233rank.html#us.

Daher, B.T., Mohtar, R.H., 2015. Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. Water Int. 40 (5–6), 748–771.

Dickson, M.H., Fanelli, M., 2013. Geothermal Energy: Utilization and Technology. Routledge.

EIA, 2012. Water consumption in large buildings summary. In: Commercial Buildings Energy Consumption Survey (February 9, 2017). https://www.eia.gov/consumption/commercial/reports/2012/water/.

EIA, 2016. How Much Gasoline Does the United States Consume? (2017). https://www.eia.gov/tools/faqs/faq.php?id=23&t=10.

EIA, 2017. Energy consumption estimates by sector. In: Monthly Energy Review, U.S. Energy Information Administration (EIA).

Eide, M.H., 2002. Life cycle assessment (LCA) of industrial milk production. Int. J. Life Cycle Assess. 7 (2), 115–126.

EPA, 2010. Evaluation of energy conservation measures for wastewater treatment facilities. In: U.S. Environmental Protection Agency (EPA).

EPA, 2016. Light-duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends Report Overview. https://www.epa.gov/fueleconomy/trends-report.

Ferroukhi, R., Nagpal, D., Lopez-Peña, A., Hodges, T., Mohtar, R., Daher, B., Keulertz, M., 2015. Renewable Energy in the Water, Energy & Food Nexus. The International Renewable Energy Agency (IRENA).

Goldstein, R., Smith, W., 2002. Water and Sustainability: U.S. Electricity Consumption for Water Supply & Treatment—the Next Half Century. Electric Power Research Institute (EPRI), Palo Alto, CA.

Homan, E., Shaw, M., Bartlett, H., Persson, S., 1980. Biogas from Manure (2017). http://extension.psu.edu/natural-resources/energy/waste-to-energy/resources/biogas/projects/biogas-from-manure.

Karan, E., Mohammadpour, A., Asadi, S., 2016. Integrating building and transportation energy use to design a comprehensive greenhouse gas mitigation strategy. Appl. Energy 165, 234–243.

Kennedy, G., Ballard, T., Dop, M.C., 2011. Guidelines for Measuring Household and Individual Dietary Diversity. Food and Agriculture Organization (FAO) of the

United Nations.
Krajnc, D., Glavič, P., 2005. A model for integrated assessment of sustainable development. Resour. Conserv. Recycl. 43 (2), 189–208.
Kurian, M., 2017. The water-energy-food nexus: trade-offs, thresholds and transdisciplinary approaches to sustainable development. Environ. Sci. Pol. 68, 97–106.
Larcom, S., van Gevelt, T., 2017. Regulating the water-energy-food nexus: interdependencies, transaction costs and procedural justice. Environ. Sci. Pol. 72, 55–64.
Love, D.C., Uhl, M.S., Genello, L., 2015. Energy and water use of a small-scale raft aquaponics system in Baltimore, Maryland, United States. Aquacult. Eng. 68, 19–27.
Macknick, J., Newmark, R., Heath, G., Hallett, K., 2012. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing Lature. Environ. Res. Lett. 7 (4), 045802.
Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L., Linsey, K.S., 2014. Estimated Use of Water in the United States in 2010. US Geological Survey (USGS), p. 56.
McMahon, J.E., Price, S.K., 2011. Water and energy interactions. Annu. Rev. Environ. Resour. 36, 163–191.
NCGA, 2016. How Much Ethanol Can Come from Corn? (2017). http://www.cie.us/documents/HowMuchEthanol.pdf.
Pimentel, D., 1997. Livestock production: energy inputs and the environment. In: Canadian Society of Animal Science, Proceedings, 47, pp. 17–26.
Pimentel, D., Pimentel, M., 2003. World population, food, natural resources, and survival. World Futures J. Gen. Evolut. 59 (3–4), 145–167.
Shapouri, H., Salassi, M.E., 2006. Economic Feasibility of Ethanol Production from Sugar in the United States. U.S. Department of Agriculture (USDA), p. 69.
UN, 2001. Indicators of sustainable development: guidelines and methodologies. In: DiSano, J. (Ed.), United Nations (UN), New York, USA.
USDA, 2010. Dietary Guidelines for Americans. US Department of Agriculture (USDA), p. 112.
USGS, 2010. Water use in the United States. In: National Water-use Science Project (November, 2014). https://water.usgs.gov/watuse/.
Willis, H.H., Groves, D., Ringel, J., Mao, Z., Efron, S., Abbott, M., 2016. Developing the Pardee RAND Food-energy-water Security Index. RAND Corporation, Santa Monica, CA, p. 72.