Resources, Conservation and Recycling 122 (2017) 319–325

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Energy, water and nutrient impacts of California-grown vegetables compared to controlled environmental agriculture systems in Atlanta, GA

Steven W. Van Ginkel, Thomas Igou, Yongsheng Chen*

School of Civil and Environmental Engineering, Georgia Institute of Technology, 200 Bobby Dodd Way, Atlanta, GA 30332, United States

ARTICLE INFO

Article history:
Received 6 January 2017
Received in revised form 10 March 2017
Accepted 11 March 2017
Available online 30 March 2017

Keywords:
Hydroponics
Aquaponics
Controlled environment agriculture
Urban farming
Urban resource management
Food, energy, water nexus
FEW
Nutrient recovery
Low impact development
Sustainability
Resilience
Agriculture

ABSTRACT

The Central Valley in the State of California alone produces most of our nation's fruits and vegetables and represents just 1% of the nation's farmland. Since California's recent drought was the worst in the last 1200 years, supply of these products may decrease and new sources are needed. To understand the efficacy of growing fruits and vegetables more locally, the energy, water and nutrient impacts of growing fruits and vegetables in local hydroponic and aquaponic controlled environment agriculture systems are compared to vegetables grown in California and shipped to Atlanta, GA. Hydroponically and aquaponically grown fruits and vegetables have areal productivities 29 and 10 times higher than CA-grown vegetables while hydroponically grown vegetables consume 30 times more energy than the CA-grown vegetables. There appears to be no difference in energy consumption between aquaponically- and CA-grown vegetables. On average, 66 and 8 times more water is used in CA-grown vegetables compared to the hydroponic and aquaponic growing techniques. Approximately double the nitrogen needed by plants is applied to CA-grown fruits and vegetables which suggests nitrogen is lost in runoff causing eutrophication downstream. There are 20, 348 and 10 times twenty times more rainfall, nutrients in domestic wastewater and vacant land needed to supply the water, nutrient and space requirements for vegetable production in Atlanta, GA.

Published by Elsevier B.V.

1. Introduction

This paper compares the energy, water and nutrient impacts of locally grown fruits and vegetables using hydroponic and aquaponics growing systems to the status quo which is primarily dominated by traditional land-based agricultural practices in California. In order of decreasing consumption, America's most popular vegetables are potatoes, tomatoes, lettuces, onions, sweet corn, and chili peppers at 24, 14, 5, 4, 2 and 2 kg/person-year (USDA, 2013). California produces 54% of our nation's fruit and vegetable supply yet represents just 1% of the nation's farmland (Cone, 1997). California produces approximately 99% of artichokes, 95% of kiwis, plums, tomatoes, broccoli, celery and garlic, 90% of strawberries and cauliflower, and 70% of raspberries, spinach, carrots, lettuce, and peppers. Nearly all the fruits and vegetables are grown in the Central Valley, approximately 46,620 km^2 of near perfect soils, flat terrain, snow melt for water, year-round growing temperatures and 300 days of sunlight/yr. The Central Valley itself is arid to semiarid and receives 15–36 cm of rainfall/yr, yet its watershed is 207,199 km^2 (Tolomeo et al., 2011). To put the productivity of this area into perspective, the Atlanta Metro consists of 21,694 km^2 of land, clay soils, piedmont terrain, reoccurring droughts yet receive 127 ± 13 cm of rain on average annually for the last 50 years.

The American food system represents 17% of the nation's fossil fuel usage, 70% of its freshwater demand while delivering 70% of the nitrogen and phosphorus and 80% of the pesticide pollution (Pimentel et al., 2004; USGS, 2016a; USGS, 2016b). In California, this super concentration of fruits and vegetables and its associated water withdrawals is decimating wildlife, poisoning the water supply with selenium and salts and compacting the ground as much as 28 feet in some areas due to excessive groundwater withdrawals (Galloway and Riley, 1999; Presser and Ohlendorf, 1987). More than 13,468 km^2 of irrigable land have been affected — one-half the entire San Joaquin Valley has sunk 1 foot or more (Poland et al., 1975). Considering California's recent drought was the worst in the last 1200 years, the supply of CA-grown fruits and vegetables may

* Corresponding author.
E-mail address: yongsheng.chen@ce.gatech.edu (Y. Chen).

http://dx.doi.org/10.1016/j.resconrec.2017.03.003
0921-3449/Published by Elsevier B.V.

decrease and new sources are needed (Bittman, 2012; Griffin and Anchukaitis, 2014; Palmer, 2016; Philpott, 2015). Thus, there is a need to modify or supplement our current food system in case of a climatic emergency.

In addition to supplying vegetables, aquaponic growing systems supply fish which may be more sustainable than other meats. Aquaponics is the merger of two profitable and well-established food production technologies – aquaculture and hydroponics. Aquaponics is superior to both because it is inherently organic, reduces water consumption and repurposes waste from aquaculture as hydroponic fertilizer, creating two products from the same resources in the same space. Commercial aquaponic fish and animal feeds are grain-based and American vegetable consumption is dwarfed by grain consumption. If American-style grain consumption rates were averaged over the entire world population, the world's grain harvest would support less than half the current world population (Brown, 2010). Of the 801 kg/person-year of grains Americans consume, about 100 kg is eaten directly as bread, pasta, and breakfast cereals and the bulk of the rest (701 kg) is primarily consumed as corn indirectly in the form of livestock, poultry products and a small fraction directly as high fructose corn syrup (Brown, 2010). Although U.S. corn is a highly productive crop, with typical yields between 140 and 160 bushels per acre, the resulting delivery of food by the corn system is far lower (Foley, 2013). Approximately, 36% becomes animal feed (Foley, 2013; Wright and Wimberly, 2013). Rearing livestock on corn is inefficient due to poor livestock feed conversion ratios (FCR) and water usage – beef needs 15,000 L/kg (Lewis, 2013). Aquaponically-grown fish is a better consumer of grains as fish have better FCRs than warm-blooded livestock. Tilapia, the most common fish in aquaponic systems, have an FCR of 1.5 while poultry, pigs and cattle have FCRs ranging from 2 to 6 depending on the feed (i.e. grass or corn) (Best, 2011; Delong et al., 2009; Shike, 2013). Thus, the consumption of grains via aquaponics is a more-efficient food production system to allow for future population growth.

Regardless of the sheer quantity of American grain consumption which primarily pertains to just calories, a better gauge of our food supply is the delivery of nutrition; here defined as the protein, fatty acids, vitamins and minerals people need to maintain ideal body weight, physical activity level and a healthy immune system. Hypocrites in 1763 stated "let thy food be thy medicine and thy medicine be thy food". Yet, today, more Americans suffer from food-related illnesses such as obesity, cancer and diabetes than ever before. Furthermore, our children are becoming increasingly disconnected from their food supply and dependent on processed foods.

In order to bridge the gap between today's food system and a more sustainable one for tomorrow, we offer an Urban Farming – Food System Supplement (UF-FSS) to our current food system. In tomorrow's food system, grains will still come from the Midwest, yet our protein and fatty acid requirements will be partially satisfied through aquaponically grown seafood while our vitamin and mineral requirements will be partially satisfied through hydroponically grown fruits and vegetables. These ponic-type technologies are best for the UF-FSS because they 1) use less nutrients and water than traditional agriculture as the water never leaves the system other than due to harvesting and evapotranspiration, 2) have higher areal productivities than traditional agriculture and thus can warrant the high cost of land in urban areas and 3) are more able to utilize urban waste nutrient resources and provide fresh produce if they are situated in urban areas close to demand.

In order for UF-FSS to succeed, four things must happen: 1) Future American generations must reconnect to their food supply – i.e. becoming active in the complete food life-cycle from the rearing of seafood and the cultivation of fruits and vegetable, to the harvesting, processing, cooking and consumption at the home and in the retail and service industries, to the recycling of the nutrients in food, animal and domestic wastewaters, 2) UF-FSS energy, water and nutrient impacts must be known, 3) UF-FSS must take advantage of existing urban infrastructure and waste energy, water and nutrient flows, and 4) UF-FSS must incorporate algae to serve as a nutrient-rich fish feed supplement as commercial fish feeds are primarily grain-based with 5% fish meal which is derived unsustainably (Troell et al., 2004).

A new and improved food, energy and water system can be accomplished in society through the diversification and decentralization of our food supply to urban areas where energy, water and nutrient inputs are readily available and often currently exist as a wasted resource. Synergistic benefits can be achieved by utilizing urban waste streams in urban farming. UF-FSS will ease the fruit and vegetable burden on California and reduce our dependence on corn while conserving water and fossil fuel resources. While Brown (2010) states we ought to replace corn with a higher diversity of foodstuffs, he does not focus on urban farming systems which are most firmly embedded within society's energy, water and nutrient supplies. Furthermore, the food produced can be consumed fresh at high nutrient densities. As shown below, even land is not lacking due to the much higher areal productivities of hydroponic and aquaponic growing systems.

2. Methods

The energy, water and nutrient impacts of commercial hydroponic and aquaponic growers are compared to vegetables grown in California and shipped to Atlanta, GA. To compare data on an equal basis, the energy and water usage is divided by the yield to arrive at kWh and liters of water per kg of produce. While all values are 'per crop', yield values are per year as multiple crops can be planted per year. We conclude by showing what percentage of Atlanta's food demand could be satisfied by using urban farming methods supplied by urban waste water and nutrient streams.

2.1. California-grown vegetables

All the California vegetable production data (yields, hours of labor, and nitrogen, phosphorus, fuel and water usage) were acquired from the University of California-Davis site – http://coststudies.ucdavis.edu. This data can be considered 'on-the-farm' data as it does not include data regarding the impacts of growing seedlings for transplant or after the produce has been harvested and shipped to a central cooler and then transported to Atlanta. This study focused on broccoli, lettuces, tomatoes, spinach, leafy greens, strawberries and peppers as these grow well in hydroponic systems (Table 1).

Energy needed to grow these crops includes gasoline and diesel fuel, electricity for irrigation pumps and human labor. On-the-farm diesel use represented $95 \pm 3\%$ of total fuel use. The energy in the diesel fuel was converted to kWh using the conversion factor of 8.8 kWh/L diesel. The irrigation water pumping power requirement was assumed to be 600 kWh per acre-foot (CAWSI, 2016). All the irrigation water was pumped from wells except tomatoes where half of the water was pumped from canals. The human power requirement as labor was estimated by multiplying the number of hours worked per crop by 75 W which is the average power output sustainable by a human over an 8 h day (Avallone et al., 2007).

Off the farm, additional energy is needed to cool the produce for an average of two days before it is shipped to Atlanta (Dara, 2016). Approximately 95% of vegetable transport occurs by truck and here we use an average of 3700 km and 2.2 km/L of diesel to both transport and cool the produce during transport to Atlanta (Paggi et al., 2012). The normalized energy (kWh/kg) and water