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Optimal strategies for monitoring irrigation water quality

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ABSTRACT

The quality of irrigation water drawn from surface water sources varies greatly. This is particularly true for waters that are subject to intermittent contamination events such as runoff from rainfall or direct entry of livestock upstream of use. Such pollution in irrigation systems increases the risk of food crop contamination and require adoption of best monitoring practices. Therefore, this study aimed to define optimal strategies for monitoring irrigation water quality. Following the analysis of 1357 irrigation water samples for *Escherichia coli*, total coliforms, and physical and chemical parameters, the following key irrigation water collection approaches are suggested: 1) explore up to 950 m upstream to ensure no major contamination or outfalls exists; 2) collect samples before 12:00 p.m. local time; 3) collect samples at the surface of the water at any point across the canal where safe access is available; and 4) composite five samples and perform a single *E. coli* assay. These recommendations comprehensively consider the results as well as sampling costs, personnel effort, and current scientific knowledge of water quality characterization. These strategies will help to better characterize risks from microbial pathogen contamination in irrigation waters in the Southwest United States and aid in risk reduction practices for agricultural water use in regions with similar water quality, climate, and canal construction.

1. Introduction

Historically, water quality guidelines have focused on drinking, waste, and recreational sectors, excluding waters used throughout the production of food crops. The recently developed "Standards for Growing, Harvesting, Packing, and Holding Produce for Human Consumption" establish safety guidelines for the US agriculture industry (Food and Drug Administration, 2015). Although these guidelines are scientifically based, they fail to grasp the complexity of irrigation systems and offer few suggestions for the appropriate monitoring of irrigation water safety.

The US Food and Drug Administration (FDA) Food Safety Modernization Act (FSMA) includes microbiological rules for irrigation water that are based on epidemiological studies undertaken at ocean and freshwater beaches. Little evidence exists that relates FSMA to the associated risks for fresh produce and irrigation waters. FSMA guidelines require untreated surface water used for irrigation be tested for *Escherichia coli* (*E. coli*) 20 times over 2–4 years and then <5 times annually. In water used for any purpose besides the growing of sprouts, hand washing, or direct application to food surfaces, *E. coli* concentrations cannot exceed 126 colony forming units (CFU)/100 ml, using a geometric mean of at least five samples taken over multiple days (e.g., a monthly geometric mean) or 410 CFU/100 ml in a single sample (i.e., a statistical threshold value [STV]). If the *E. coli* concentration exceeds this STV, the water can still be used to irrigate food crops if an appropriate time prior to harvest is allowed, assuming a 0.5-$\log_{10}$ die-off of *E. coli* per day. For water used in sprout irrigation, applied directly to food surfaces, or used for hand washing, *E. coli* regulations are as stringent as for drinking water (i.e., 0 CFU/100 ml). If *E. coli* concentrations exceed any of these thresholds, the water cannot be used for irrigation (Food and Drug Administration, 2015). These rules aimed at food safety fail to take under consideration the rapid spatial and temporal changes of microbial concentrations in water.

Water research undertaken in rivers, lakes, oceans, reservoirs, and irrigation canals has routinely demonstrated significant changes in microbe concentrations on short spatial and temporal scales (Boehm, 2007; Haack et al., 2004; Juahir et al., 2011; Song et al., 2012; Verhougstraete and Rose, 2014; Won et al., 2013). For instance, one study determined that *Enterococcus* concentrations at California beaches typically varied by 60% over 10 min, but could vary by as much as 700% (Boehm, 2007). Similarly, the

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FDA guidelines fail to consider the spatial variations of microbial water quality, potentially leaving the food product vulnerable to contamination.

Bacterial concentrations undergo rapid change along stream length, throughout the vertical water column (Agogué et al., 2011; Karl, 1978; Krempin and Sullivan, 1981; Llirós et al., 2010), and across stream width (Byappanahalli et al., 2003; Jones et al., 1995; Whitman et al., 2006). Thus, a single sample may not provide an adequate representation of the true microbial water quality in an irrigation water canal. Water quality scientists have also noted the implications of a single sample versus multiple samples for management actions (e.g., opening or closing of a beach) (Bertke, 2007; Reicherts and Emerson, 2010). Kinzelman et al. (2006) determined that compositing multiple lake water samples and assaying with a single test was not statistically different ($P > .02$) than analyzing multiple individual samples and reporting an average; both approaches called for similar management actions. The benefits of compositing samples include the ability to collect multiple samples from various locations (more representative of water quality) and reduced costs (by performing a single test), while still providing at least the same level of protection as collecting single or multiple samples. Considering previous research in non-irrigation systems, it is inadequate to base the safety of an entire irrigation canal on the results of a single sample.

In addition to the numerous surface water studies previously mentioned, irrigation waters have been examined for microbial contamination. Fecal indicator bacteria (e.g. total coliforms, *E. coli*, enterococci), *Salmonella* spp., *Staphylococcus aureus*, Microsporidia, *Giardia*, and *Cryptosporidium,* Noroviruses, *Campylobacter* spp., and *Clostridium perfringens* have been measured in irrigation waters throughout the world (Gerba and Choi, 2006; Ijabadeniyi et al., 2011; Kayed, 2017; Thurston-Enriquez et al., 2002). One study found irrigation water is a major risk factor for bacterial contamination of fresh lettuce due to the detection of *E. coli* and *Campylobacter*. spp. (Holvoet et al., 2014). Irrigation water and food safety concerns are further highlighted by a study that demonstrated hepatitis A virus and *Salmonella* present in water used to irrigate iceberg lettuce was associated with exceedances of the U.S. Environmental Protection Agency's acceptable annual risk level of 1:10,000 (Stine et al., 2005). Produce commonly grown using irrigation water includes corn, orchard crops, and vegetables,all of which have to potential to be consumed raw and further increasing the potential for infection from contaminated irrigation water ("USDA Economic Research Service," 2017). Together, these studies represent the diversity of microbial water quality and the importance of understanding irrigation water quality to protect fresh produce.

To help ensure adequate water safety and reduce the risks for agricultural water, microbial testing practices must be based on irrigation water-specific research, not adapted from drinking and recreational water studies. This is critically important given that during the winter months, more than 90% of all leafy greens consumed in the US are grown in the Southwest region of Yuma, AZ (http://bit.ly/2jhuwb1, accessed on 8 February 2017). In addition, Southern California produces 15% of the lettuce and leafy greens consumed by the US overall (http://bit.ly/2k4ceHK, accessed on 8 February 2017). Due to the importance of this region for fresh produce production and the current knowledge gaps in irrigation water quality science, this study aimed to better understand the spatial and temporal variations of microbial concentrations in irrigation canals, to produce a comprehensive monitoring plan, and to reduce pathogen exposure risks at the point of irrigation water application to food crops. To this end, there were four study objectives: 1) determine the most effective time of day for irrigation water monitoring; 2) define canal cross-sectional sampling locations; 3) delineate the transport of microorganisms in irrigation canals; and 4) determine the suitability of collecting single, multiple, or composite irrigation water samples for analysis.

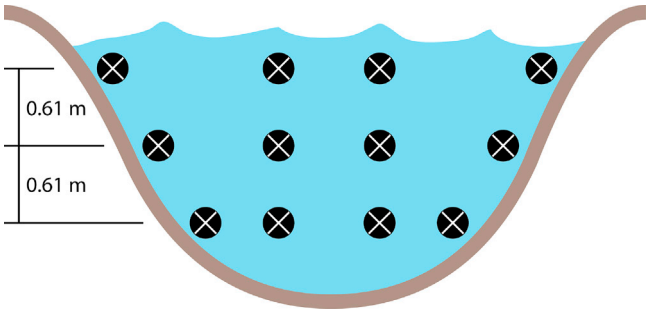

Fig. 1. Sampling schematic for defining the appropriate canal transect sample collection point.

2. Materials and methods

2.1. Site location

Sampling sites were selected following discussions with scientists from the University of Arizona and local agricultural extension centers. Samples were collected from a total of 93 unique sites among Yuma and Maricopa Counties, AZ and Imperial County, CA in the southwestern US. Sampling sites included a mixture of main, lateral, and sub-lateral canals and both cement-lined and unlined canals with varying flow dynamics. In addition, some locations were located in urban and others in rural areas.

2.2. Field analysis and sample collection

For all samples, the water temperature, air temperature, conductivity, total dissolved solids, pH, and relative humidity were measured in the field using the Multiparameter PCS Testr 35 (Oakton Instruments, Vernon Hill, IL) and the Fisherbrand Traceable Memory Hygrometer/Thermometer (Thermo Fisher Scientific, Waltham, MA). Samples were placed on ice in a cooler and transported to the laboratory for microbial processing and additional analyses (e.g., turbidity). Continuously recorded environmental variable data (wind speed and direction, barometric pressure, and antecedent precipitation) from National Weather Service stations were retrieved from the University of Utah's MesoWest interface (MesoWest, http://mesowest.utah.edu/, accessed on 10 December 2015).

To account for seasonal variations in microbial concentrations, weather variability, crop production, and water use practices, grab samples were collected between December 2014 and November 2015 using sterile 1L wide-mouth HDPE bottles (Nalgene Co., Rochester, NY). The depth below surface, the distance from the bank, the time of day, and collection location were study objective-dependent as detailed below.

To determine the most suitable time of day for irrigation water sampling, grab samples were collected 0.15 m below the water surface near the canal bank at the same site four times per day (i.e., before 09:00, 09:00–12:00, 12:00–13:00, and after 13:00). To define appropriate collection points in a canal cross-section, grab samples were collected vertically through the canal water column (at the water surface and 0.61 m and 1.22 m below the surface) and horizontally across canal transects (at both banks and ¼ of the distance of the canal width from each bank). A schematic of this sampling approach is presented in Fig. 1. To determine the best collection, processing, and results representation approach, three sampling approaches were investigated: approach A included collecting a single sample from a single collection point at 0.33 m