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ABSTRACT

The landscape of water in Utah is changing due to population growth, conversion of agricultural land to urban development, and increasing awareness of water scarcity. At the same time, Utah is experiencing a growing number of urban and small farms, but knowledge of water use in this sector is limited. Better understanding of what occurs at the field level on urban and small farms can aid state water use estimates and conservation efforts, and assist farmers in moving towards wiser water management. For the 2015 growing season, we performed irrigation evaluations for 24 urban and small farms in Cache Valley, Utah and we explore the results through case studies and identify trends among gross irrigation depth and field variables including field size, irrigation method, application uniformity, and scheduling practices. Results show a great degree of heterogeneity in irrigation methods, equipment used, and management practices. The beneficial consumed fraction of irrigation water ranged from 0.06 to 1.0. Small fields had lower application uniformities and greater irrigation depths than large fields. Surface irrigated fields had higher irrigation depths than sprinkle and drip irrigated fields. Additionally, fields using a fixed irrigation schedule had higher depths than fields that were irrigated inconsistently due to other factors. The results show that urban and small farm irrigators need improved knowledge of proper irrigation management. Irrigators, university extension services, and state water authorities working in this sector need to recognize the link between proper management and total water use, and focus more efforts on improving management, specifically how to use 1) low-cost methods to measure flow rates, 2) simple irrigation scheduling tools, and 3) improve application uniformity.

1. Introduction

The socioeconomic landscape of water in Utah is undergoing a transformation, and there is much debate about how water should be managed to meet the present and future needs of the state. According to the U.S. Census Bureau, the 2010 Utah population is expected to more than double by 2060, giving the state the fourth highest growth rate in the country (United States Census Bureau, 2016). The growth is happening largely by sprawl of new residential and commercial land onto agricultural land at the edge of urban boundaries. This sprawl creates a mosaic of mixed agricultural, residential, and commercial land use (Li, 2013; McGinty, 2009) that is the second highest rate of urban sprawl by percentage in the U.S. (Kolankiewics et al., 2014). In Utah between the years 1982 and 2012, over 26,100 ha (64,500 acres) of farmland converted to urban use, an increase in developed land of 16%. The Utah Division of Water Resources (DWRe) estimates that by 2050 an additional 10% of farm land will be urbanized (Utah Division of Water Resources, 2013). As agricultural land is developed, the spatial and temporal water use on the landscape changes and can affect other water users in the basin by changing the quantities and timing of water demands, environmental flows in rivers and wetlands, and the quantity and destination of agricultural return flows.

In 2015 Utah ranked the second highest state in Municipal and Industrial (M&I) per capita water use (USGS, 2014). Being the second driest state in the nation, this exceptionally high use is due to the large volumes of water used for outdoor irrigation coupled with a culture that encourages verdant landscapes and gardens. Additionally, many urban areas in Utah have unmetered secondary water systems where users typically pay a flat fee for outdoor landscape water use. The term secondary water system is used in Utah to describe any non-potable water delivery system (i.e. not treated to drinking water standards). Non-potable systems typically consist of either a canal network or a piped,

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pressurized supply intended for irrigation. While these secondary systems are usually metered at the original diversion, the actual water delivered to each end user is unmetered and typically unknown. Yet numerous studies have shown that providing unmetered water results in 39%–100% increases in use (Cole, 2015; Richards, 2009). To address water use in the urban environment, Utah has invested in numerous conservation efforts including Utah State University's Center for Water Efficient Landscaping (CWEL), water conservation programs sponsored by water conservation districts and municipalities, and the state's "Slow the Flow" campaign, among others. However, these programs focus on landscape irrigation rather than urban agricultural irrigation.

Simultaneous with urban growth, Utah is experiencing a quickly growing sector of urban and small farm agriculture. Urban agriculture is defined as "the growing, processing, and distribution of food and other products through intensive plant cultivation and animal husbandry in and around cities" (Brown and Carter, 2003). Nationwide the number of farms and total acreage is decreasing as agricultural land is converted to urban development. Similarly in Utah, agricultural acreage is likewise decreasing but the number of farms is increasing. For example, in Weber, Davis, and Salt Lake counties that are mostly urbanized, the number of farms between 0.4 and 4 ha (1 and 9 acres) has increased 245% from 1974 to 2007. In Cache County, the number of farms in this category increased 24% between 2007 to 2012 (Downen, 2009; USDA, 2016). A recent survey of 253 urban farms around the country found that the median income of the farms in their study was $5000. This income amount suggests that recent growth is not motivated by economics but rather factors such as interest in locally produced foods, nutrition and health, food security, education, environmental benefits, and community building (Dimitri et al., 2015; Curtis, 2013). Salt Lake City, for example, set a goal of increasing direct access to fresh foods; community groups and public officials are actively working to identify vacant lots that can be used to grow food in the city (Utah Division of Water Resources, 2003).

Most of the academic literature pertaining to urban and small farms is focused on developing countries where farmers face very different situations than in developed countries. Most U.S. irrigation research focuses on large field sizes and irrigated areas (USDA, 2013). Of the limited documentation that does exist for small farms, two particular trends stand out. First, there is little knowledge exchange between academia and small farmers. Second, farmers adopt more efficient practices only if they see benefits or economics gains to do so (Levidow et al., 2014).

New research into urban and small farms must identify the issues and challenges these irrigators face at all scales of consideration from the field to basin level. Additionally, research must apply the right metrics to determine beneficial and reasonable use of water based on the scale of interest, for use of the wrong term can lead to misinterpretation of its value and meaning (Perry, 2007, 2011). At the field level, irrigators have a high incentive to apply the minimum amount of water necessary to obtain a good yield to reduce pumping costs, labor, leaching of nutrients, and water logging from over irrigation. At the district level, excess applied water may not be available to other irrigators depending on the pathway of the return flows. At the basin level, over irrigating at the field level does not necessarily result in wasted water, as in multiple-use cycle basins this water may be available to other users lower in the basin (Keller and Keller, 1995).

In this study we investigate what is occurring at the field level on urban and small farms. The volume of applied irrigation water was measured on 24 urban and small farm fields in Cache Valley, Utah for the entirety of an irrigation season and full field irrigation evaluations were conducted. The fields selected were typical and representative of urban and small farm fields in the arid intermountain west. The results are explored through case studies and trends in gross irrigation depth (GID) (the total depth of applied irrigation water) and field size, irrigation method, uniformity, and irrigation scheduling are identified. Insights from the study can help the participants and other urban and small farm irrigators across the U.S. recognize trends between total water use and irrigation parameters, improve irrigation practices, and grow healthier crops with fewer resources. Results also help University Extension (hereafter referred to as Extension) and state water authorities gain insights about actual irrigation practices, see shifts in agricultural and urban water uses, and develop more effective technical programs and approaches to water conservation in the growing urban and small farm sector. All of the above can help managers reach state water goals.

2. Materials and methods

2.1. Collect field data

2.1.1. Find participants

Numerous irrigation districts, local farms, and regional water planners were contacted and asked to recommend small farm and urban irrigators to participate in the study. Participation criteria were that participants need to produce an agricultural product on more than 93 square meters (1000 square feet) (to rule out plots that were not producing a marketable good or a significant share of the irrigator's diet) and less than 8.1 ha (20 acres) in area (a size which is increasingly less common on the urban fringe). Through a snowball sampling approach, we identified 20 participants irrigating a total of 24 fields across Cache Valley (Fig. 1). The fields consisted of small commercial farms, community gardens, large backyard gardens, orchards, pastures, alfalfa fields, and university research farms. The crops included mixed vegetables, grass pasture, grass and alfalfa hay, apples, wheat, corn, quinoa, tomatoes, peppers, winter squash, and watermelon. A wide range of methods were used for irrigation including surface, drip, and numerous methods of sprinkle. To maintain the anonymity of the fields we refer to each field with a letter A through X. A complete table of field metadata is provided in Table 1 on page 28 in Pratt (2016).

2.1.2. Install measurement devices

From a site visit, we determined the most practical method to measure flow rates throughout the season. Methods used included flumes, weirs, flowmeters, and a one-time volumetric measurement for fields with challenging layouts that would necessitate multiple meters. For those fields with open channel flow measurements, the irrigation schedule and staff gauge readings were recorded manually by the irrigator. For the fields with a one-time volumetric measurement, the schedule was recorded with pressure event dataloggers. For one site where the event datalogger was impractical, the schedule was recorded manually. The methods used are shown in Table 1.

2.1.3. Conduct field measurements

The collected field data included field size, planting and harvest dates, observations of overspray and runoff, maintenance, and application uniformity. Field size was determined using aerial imagery in GIS software. For sprinkle and drip irrigated fields, an evaluation team conducted catch can tests to calculate the coefficient of uniformity (CU). For the drip irrigated field we calculated the emission uniformity (EU) using specifications from the drip tape datasheet and equations from Keller and Bliesner (1990) as shown in Pratt (2016, Appendix D).

2.2. Calculate irrigation performance

This section provides a general overview of the methods and equations used to calculate the irrigation variables in this study. For a more thorough explanation of these methods refer to Pratt (2016, pp. 14–24).

2.2.1. Gross irrigation depth

We calculated the average depth of water applied to the field over the season by dividing the total applied volume by the field size, giving

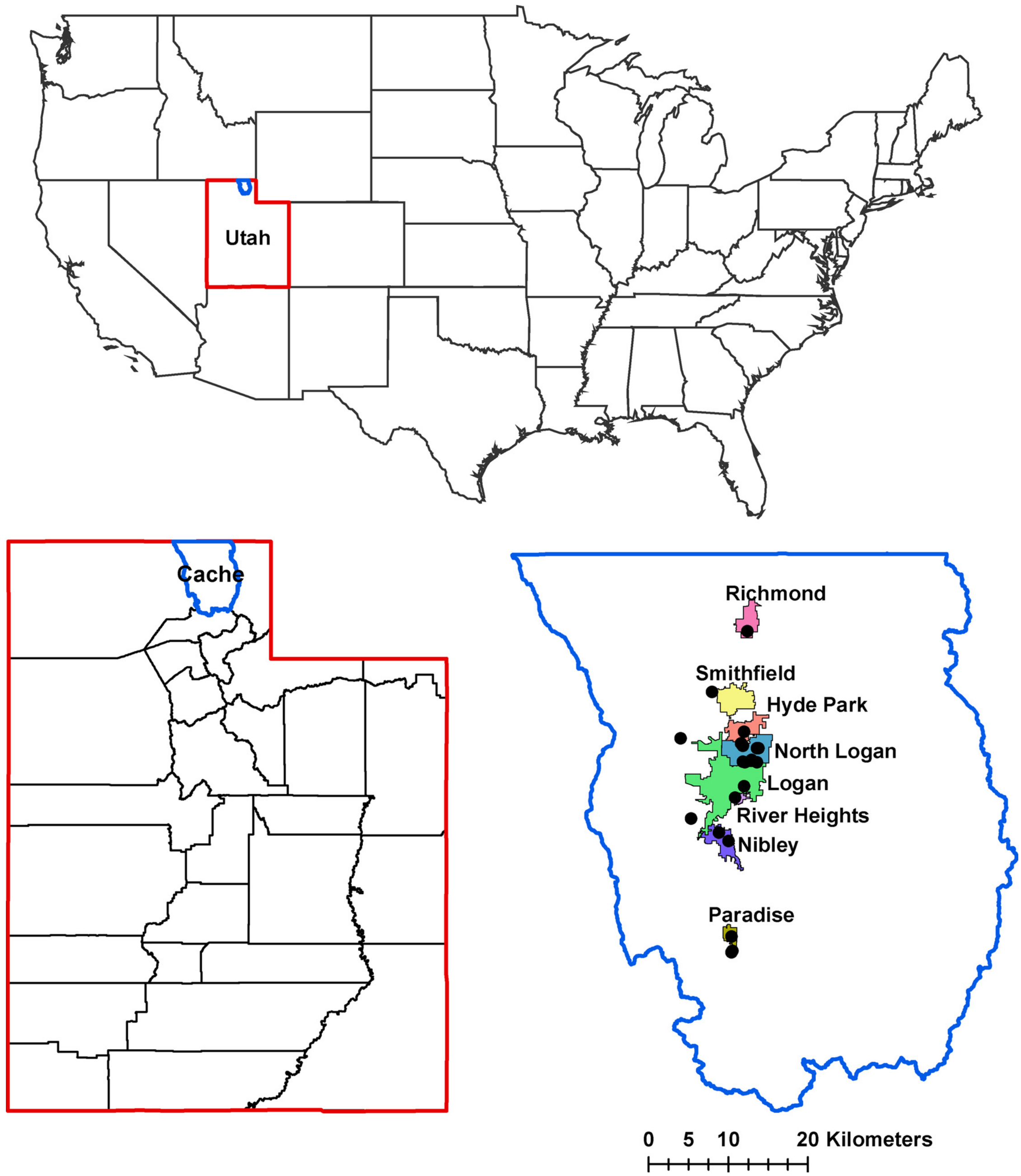

Fig. 1. Locations of fields in Cache Valley, Utah.

Table 1
Total fields with each flow and volume measurement method.

Irrigation Method	Number of Fields	Flow Measurement Method	Datalogging Method
Surface	1	Parshall Flume	Manual Table
	1	S&M Flume*	Manual Table
	2	Rectangular Weir	Manual Table
Sprinkle	9	Flowmeter (Electromagnetic, Turbine)	Flowmeter
	9	Single flow rate measurement	Event Datalogger
	2	Single flow rate measurement	Manual Table
Drip	1	Electromagnetic Flowmeter	Flowmeter

(Samani and Magallanez, 2000).
* The S&M Flume was designed by Samani and Magallanez at the University of New Mexico.

a season gross irrigation depth (GID). The accuracies used are explained in detail in Appendix C in Pratt (2016).

2.2.2. Time series water balance

A time series soil water balance was calculated using irrigation (I) and precipitation (P) events, crop ET (ET_{crop}) calculated from crop coefficients and adjustment factors, change in soil moisture storage ΔSM, and return flows RF using a control volume of field area by mature rooting depth of the crop, as shown in Eq. (1). A spreadsheet with the time series calculation is available in an open source repository (Pratt, 2018). The daily time step of the water balance allows for the temporal variability to be observed.

$$RF = I + P - ET_{crop} - \Delta SM \quad (1)$$

Precipitation P and reference evapotranspiration (ET_{ref}) data for each field were collected from the Utah Climate Center's Agricultural

Weather Network station with the closest proximity to the field. We assumed that the effective precipitation (P_{eff}) was 80% of the total precipitation for reasons including: 1) it was impractical to measure soil moisture with sensors due to the number of fields in our study and the spatial variability within fields, 2) most effective precipitation calculations require assumptions and the 80% assumption is also used by the Utah DWRe (Utah Division of Water Resources, 2010), 3) because of weather and soils, very little surface runoff from precipitation is observed on irrigated fields in Utah, and 4) precipitation is such a small fraction of ET that further detail would likely not change results.

The Utah Climate Center ET_{ref} estimate uses the ASCE standardized reference Penman-Monteith ET equation. To calculate the crop ET (ET_{crop}) we used procedures from Food and Agriculture Organization Irrigation and Drainage Paper 56 (FAO-56) and, when available, locally derived crop coefficients (Hill et al., 2011).

For the ΔSM variable we calculated the total available water (TAW) of the soil from the available water capacity (AWC), collected from the USDA's Web Soil Survey database, and a calculation of crop rooting depth. Then, using Table 22 from FAO-56, the management allowed depletion (MAD) was calculated (Allen et al., 1998).

The precipitation in Cache Valley in April and May of 2015 was 63.5 and 135 mm (2.50 and 5.30 in.) respectively, which was higher than the average April and May precipitation of 52.1 and 53.3 mm (2.05 and 2.10 in.) (Utah Climate Center, 2016). Therefore, we assumed the root zone depletion (D_r) at the beginning the time series was 0% and 25% of the TAW for annuals and perennials, respectively, because annuals are typically planted into a barren field where no ET for the year would have yet occurred, and perennials would likely have been evapotranspirating and depleting the soil moisture in spring before the beginning of the time series calculation. Note, an accurate estimate of initial depletion should take into context the precipitation of a particular year and when practical rely on actual soil moisture measurements.

Values and methods from Clemmens and Burt (1997) were used to calculate the accuracy in our time series calculation. The equations used and calculated accuracies are included in Appendix C in Pratt (2016).

2.2.3. Water use metrics

The water use metric typically most relevant to irrigators considers the amount of water needed to grow the crop (i.e. the beneficial and reasonable use) and the amount of water applied to the crop. Irrigation water applied in excess of what is required often means that resources (e.g. time, labor, and money) have been used unnecessarily, and in some cases yield has been compromised from loss of fertility via leaching and waterlogging. In Cache Valley, Utah, where leaching requirements are minimal due to low water salinity, the bulk of the water beneficially applied is for evapotranspiration. In this study we use the "beneficial consumed fraction" metric, which is ratio of irrigation water consumed by the crop to the total irrigation water applied. This metric avoids the use of the value-laden term "efficiency" and is adopted by the International Committee on Irrigation and Drainage (ICID) (Perry, 2011). The beneficial consumed fraction equation is shown in Eq. (2).

$$Beneficial\quad Consumed\quad Fraction = \frac{ET_{crop,\,irrigation}}{vol.\quad irrig.\quad water\ applied} \tag{2}$$

2.2.4. Application uniformity

A properly designed sprinkle system will attempt to achieve a balance between high application uniformity and low cost. Typically, the higher the uniformity, the more expensive the system. Using catch can data, we wrote a script in MATLAB to calculate field CU and generate a 3D plot of field application uniformity that takes into account sprinkler and lateral spacing and field edges. The script is included in Appendix D of Pratt (2016). With the CU values, the water distribution efficiency (DE_{pa}) was used to determine the percentage of the field over and under-irrigated using data from Keller and Bliesner (1995).

2.2.5. Scheduling method

After collecting the seasonal data, we gave each field two qualitative ratings regarding the irrigation scheduling method to compare trends between the GID and different scheduling methods. The first rating is of schedule interval which includes the ratings *fixed* (irrigations occurred at a fixed interval all season), *partially fixed* (irrigations occurred at a fixed interval for most of the season), *variable* (numerous irrigations occurred but at no identifiable interval), and *other* (only a couple of irrigations occurred at no identifiable interval). The second rating is the frequency of return flow occurrence and includes the ratings *RF every IRR* (return flows occurred on every irrigation), *RF early season* (return flows occurred at the beginning of the season only), *RF late season* (return flows occurred late in the season only), and *zero RF* (no return flow events occurred during the season).

2.2.6. Data analysis

With the irrigation metrics calculated, the trends between GID and field variables were explored using a variety of graphical methods.

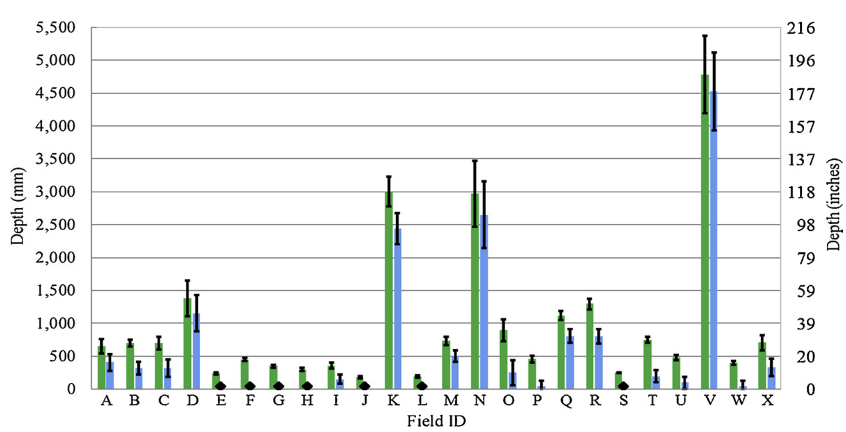

Fig. 2. Field gross irrigation depth and gross return flow. Black error bars represent the 95% confidence interval of each value. Diamonds indicate gross return flow was at or below the measurement error.

3. Results

3.1. Gross irrigation depth and gross return flows

The GID and gross return flows (GRF) (the seasonal total depth of return flow) for each field show the majority of fields applied less than 640 mm (25 in.) (Fig. 2). Three distinct outlier fields (K, N, and V) had GID and GRF significantly higher than the other fields. The majority of fields had some return flows, while seven fields had no return flows at all.

3.2. Case studies

In this section we present four cases to illustrate examples of good and poor irrigation practices and provide recommendations to improve these fields' irrigation configuration and management.

3.2.1. Case study 1 - Sprinkle irrigated pasture with good performance - Field W

Field W is a 0.38-hectare (0.93-acre) pasture of mixed grasses. The field is located in North Logan surrounded by other urban hay fields intermixed with new residential developments. The pasture is grazed by horses and cut and bailed three times a season. The water supply is a pressurized piped secondary system. The irrigator can irrigate whenever he chooses. The field is irrigated from two risers with 76 mm (3.0-inch O.D.) aluminum hand-move pipe and has a challenging geometry because of the long and narrow shape and resulting high perimeter to area ratio.

A time series plot of soil water balance for the season shows very few return flows (Fig. 3). Precipitation continually recharged the soil in May and irrigation did not begin until mid-June. The field received seven irrigations during the season, six of which applied around 50 mm (2 in.) of water, and one that applied nearly 100 mm (4 in.) of water. The calculated irrigation return flows only happened on two occasions in early July and late August, and the depth of these flows was minimal. Because no surface runoff or standing water was ever observed on this field, the return flows went to deep percolation. Additionally, the AW (red line) was kept well above the MAD (dashed grey line in Fig. 3). The cumulative irrigation depth was calculated to be 399 mm (15.7 in.), total return flows from irrigation of 43 mm (1.7 in.), and the change in soil moisture from irrigation was a positive 69 mm (2.7 in.). The irrigation management was very good, resulting in a beneficial consumed fraction of 0.8.

The 3D plot of the application uniformity at 3.0-meter (10-foot) intervals across the field shows that the field receives the most water in a strip down the middle, and that the south and east edges receive significantly less water than the rest of the field due to the lack of overlap that occurs at the field edge (Fig. 4). The CU and DU are 71.8% and 0.49 respectively, fairly good values for a field with a small area to perimeter ratio, yet still lower than recommended values. Distribution efficiency (DE_{pa}) analysis shows that 72% of the field receives more water than the 318 mm (12.5 in.) water requirement for net-ET while 28% of the field is under-irrigated (Fig. 5).

In summary this irrigator applied adequate but not excessive irrigation depths to avoid crop water stress, minimize return flows, and obtain a high beneficial consumed fraction. The soil moisture depletion was timed perfectly with the rain events so that all of the precipitation was utilized. However, this irrigator could have saved labor by adjusting the schedule, irrigating less frequently but for longer duration, thereby reducing the work to move sprinkler laterals. The field CU was low but decent considering the challenging field geometry. This was one of the best managed fields in the study.

3.2.2. Case study 2 - Drip irrigated vegetable field with good performance

Field L is a 1.02-hectare (2.51-acre) vegetable field using plastic mulch and 16 mm (5/8 in.) low flow drip tape on uniform topography. Detailed information on the drip tape is provided in Case Study 2 in Pratt (2016). The crops included tomatoes, sweet peppers, winter squash, and watermelons. A pump feeds the drip tape through a sand media filter, pressure regulator, and lay-flat hose manifold, and was run at the irrigator's discretion. The volume of water used for backflushing the filter was nominal compared with the total applied water, and therefore the backflush water was not subtracted from the applied water volume in the analysis. The drip tape laterals were 290 m (950 foot) and 171 m (560 foot) for different field sections. We recorded the flow rates and irrigation schedule with an electromagnetic datalogging flow meter, which was installed for the duration of the irrigation season. In the time series water balance we used an area-weighted average of the four crops for the depletion fraction, rooting depth, and crop coefficient.

Once the rooting depth was fully established in mid-July, the soil moisture closely followed the average MAD (Fig. 6). Note how the soil moisture does not oscillate much at all, indicating that the sum of irrigation and precipitation almost perfectly matched the crop ET, making the total water received by the crop nearly optimal. Although frequent irrigations are common with drip systems due to the smaller volume of soil receiving irrigation, the irrigations could have been at a lesser frequency but longer duration to reduce the time and labor required to turn the pump on and off. No return flow events occurred during the season, which led to a very high beneficial consumed fraction. The total applied irrigation depth was only 200 mm (7.7 in.) and the precipitation was 53 mm (2.1 in.). The beneficial consumed fraction was 1.0.

Drip system emission uniformity (EU) for the 171 m and 290 m drip tape runs was calculated to be 81% and 72% respectively. The 81% EU for the 171 m drip tape is above the minimum recommended value of 80% for line source tubing on uniform topography. The EU of the 290 m length however was significantly lower than ideal (Merriam and Keller,

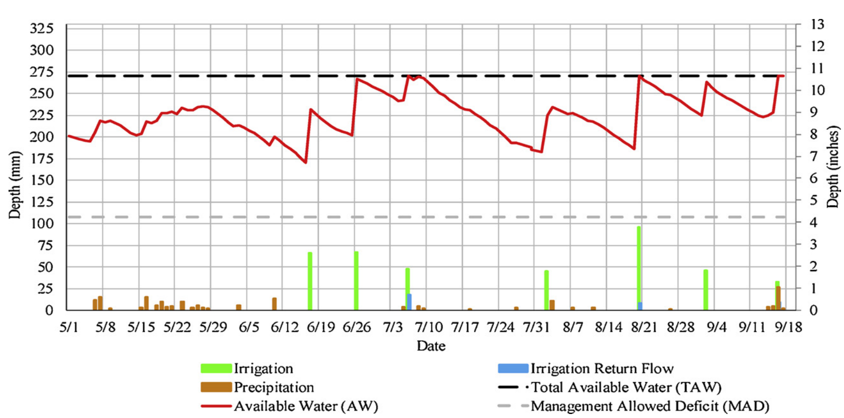

Fig. 3. Field W - Time series water balance.

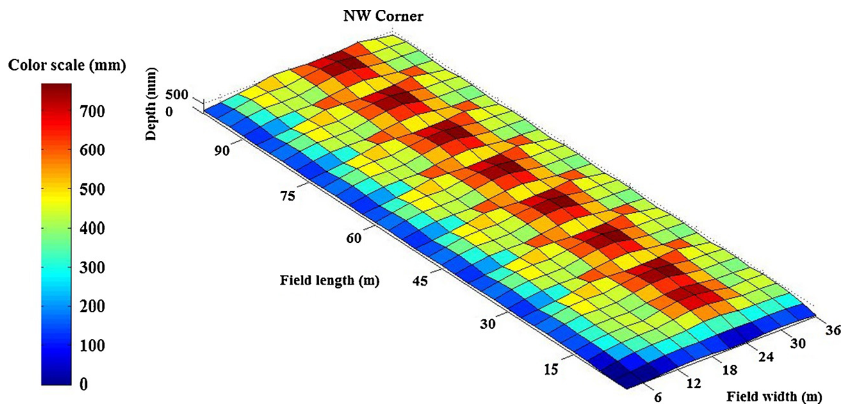

Fig. 4. Field W - 3D plot of sprinkler uniformity.

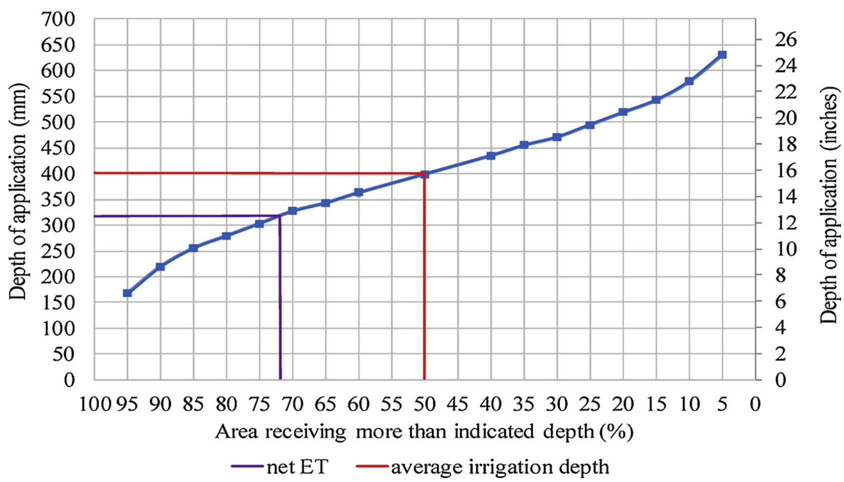

Fig. 5. Depth in different areas of field due to non-uniformity.

1978). To improve the EU of the 290 m runs, the irrigator could either 1) increase the size of the drip tubing from 16 mm to 22 mm (7/8 in.), 2) decrease the drip tube flow rate, or 3) run more lay-flat hose manifold to reduce the length of the 290 m run to 171 m or less. Increasing the tubing size is most likely the preferable option because the pump would operate at the same flow rate. According to the calculations both options 1 and 2 would increase the EU to 80%.

3.2.3. Case study 3 – Sprinkle irrigated garden with low beneficial consumed fraction

Field D is a 0.016-hectare (0.039-acre) large backyard garden and orchard surrounded by quickly growing urban development. The garden is irrigated with a fixed sprinkler system from an irrigation pump that draws water from an adjacent ditch. Seven sprinkler nozzles of mixed types are set at varying heights around the perimeter of the garden. The crops included densely planted mixed vegetables and half a dozen apple and pear trees. We used a 19 mm (3/4 in.) totalizer electromagnetic flow meter to measure the irrigation volume and took meter readings approximately every three weeks. Dividing the difference between each meter reading by the number of irrigation events in that time period gave the depth applied at each irrigation.

The time series plot (Fig. 7) shows that irrigation frequency was close to ideal before mid-July. However, the water depth of each irrigation application was high, and 75% or more of irrigations went to

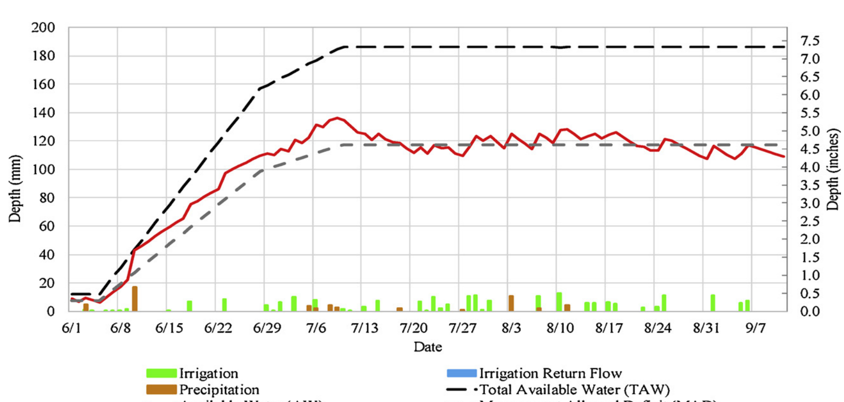

Fig. 6. Field L - Time series water balance.

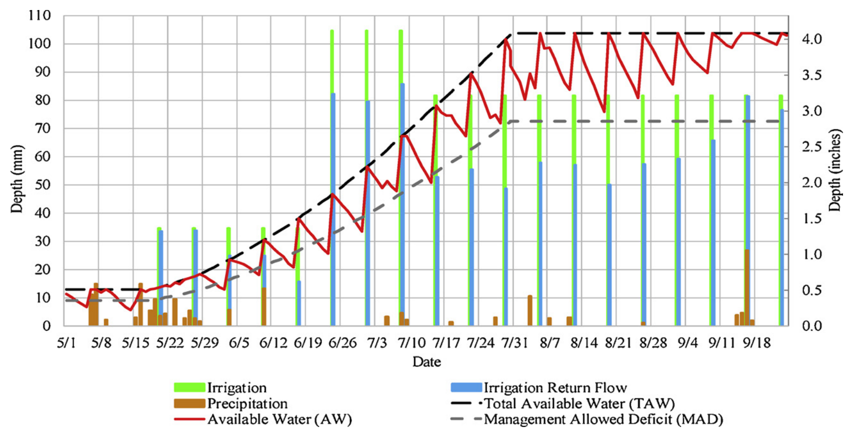

Fig. 7. Field D - Time series water balance.

deep percolation return flows. Two irrigations went almost entirely to return flow. The cumulative irrigation depth was calculated to be 1380 mm (54.4 in.), with irrigation return flows of 1040 mm (41.0 in.). These excessive applications led to a beneficial consumed fraction of only 0.25.

Using a catch can evaluation we determined the irrigation CU and DU of 66% and 0.41, respectively. The nozzles were in very poor shape, with two completely clogged, the spray of one immediately blocked by vegetation, and two rotating far outside of the garden and lawn area. The low uniformity may have been a part of the reason that this garden received so much water, because in order to adequately irrigate the dry spots the majority of the garden had to be excessively over-watered.

To improve irrigation in this garden the irrigator should improve the application uniformity by fixing clogged and improperly rotating nozzles as well as improve the irrigation scheduling by irrigating at the same frequency but a much shorter duration, especially early in the season when the root zone is shallow.

3.2.4. Case study 4 – Surface irrigated garden with low beneficial consumed fraction

Field V is a 0.076-hectare (0.19-acre) large backyard garden growing a wide variety of crops including mixed vegetables, grains, berries, cover crops, and fruit trees. The garden is surface irrigated via an open ditch secondary system. The main distribution channel in the garden is lined with plastic to reduce seepage losses. The irrigation flow rates were measured with an S-M flume designed by Samani and Magallanez (2000) and the irrigation schedule and staff gauge readings were recorded by the irrigator.

The vast majority of irrigations went directly to return flows (Fig. 8). The excessive return flows were likely due to sandy soils with high infiltration rates that make efficient flood irrigation challenging. The irrigation frequency for this field was very consistent - typically three times per week at every irrigation turn. Additionally, the soil moisture seldom approached even 50% of the MAD. Therefore, once the crops had reached full rooting depth (mid-August) the irrigation frequency could have been halved. Still, there were a couple of occasions in the summer where the soil moisture dropped slightly below the MAD. The total irrigation depth was the highest of all fields in the study at 4783 mm (188.3 in.), with calculated return flows of 4491 mm (176.8 in.), resulting in a beneficial consumed fraction of only 0.06. Because there was no observed surface runoff on the property the return flows went to deep percolation, and thus were not available to other users in the irrigation district.

Improving the beneficial consumed fraction early in the season would be very difficult with surface irrigation because of the frequent irrigations needed for seed germination in the sandy soil and the shallow root zone of young vegetable crops. If the irrigator wishes to save time and water during this period they should consider sprinkle irrigating (possibly with culinary water) shallow rooted crops until roots become more developed. Depending on how surface irrigation is controlled throughout the garden, deep rooted crops (e.g. trees, berries, and perennials) could still be surface irrigated. Once the full rooting zone of vegetables crops is developed, the irrigator could surface irrigate half as frequently and for less duration. To ensure adequate water distribution with a changed schedule, the rate of advance of the water towards the far side of the garden should be increased as much as possible by lining more of the distribution furrows with plastic sheeting, by installing more pipes and gates for better flow control, or by creating berms parallel to the water flow to allow higher flow rates over smaller areas.

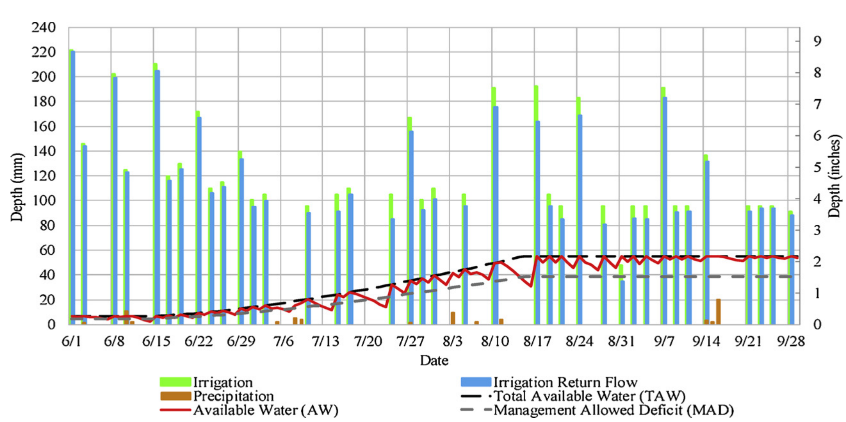

Fig. 8. Field V - Time series water balance.

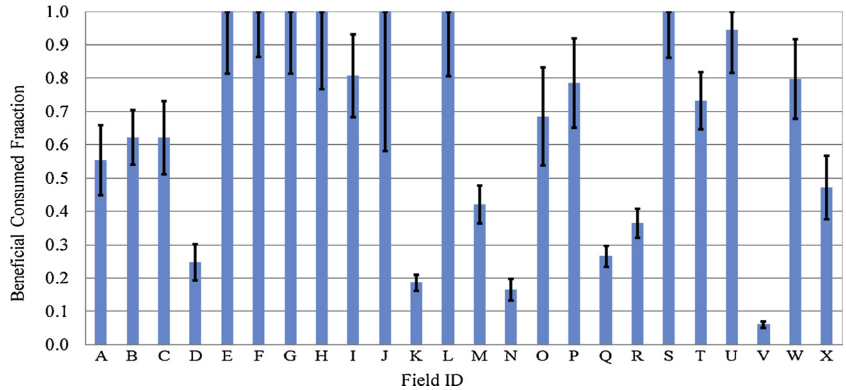

Fig. 9. Beneficial consumed fraction.

3.3. Summary observations

3.3.1. Beneficial consumed fraction

A bar chart of the beneficial consumed fraction for each field (Fig. 9) shows that seven of the fields had a calculated value of 1.0. Because an application uniformity of 100% is not possible, the fraction value of 1.0 results from under-irrigation that causes crop water stress and can be detrimental to yield. These irrigators should assess their application uniformity and consider applying more water to prevent yield loss.

A low beneficial consumed fraction, on the other hand, does not necessarily indicate a potential for water savings at the district or basin level. For example, Field K, a surface irrigated pasture, has a beneficial consumed fraction of 0.19, but the return flows go directly back into the canal via surface runoff. These return flows can be used by farmers located downstream on the canal. In contrast, return flows for Field N, a sprinkle irrigated field on a pumped system fed from a canal with a beneficial consumed fraction of 0.16, go to deep percolation. Thus, reducing the applied water is still a good target as the over irrigating results in high pumping costs and unnecessary leaching of nutrients.

3.3.2. Field size and gross irrigation depth

We hypothesized that small fields are more likely to be over irrigated than large fields, as small fields are easier to irrigate because they require less time and effort to do so. This hypothesis is supported by numerous studies around the globe (Speelman et al., 2008) which find farm scale to be a significant factor in total water use. To investigate this hypothesis we created a scatter chart of GID and GRF vs field size (Fig. 10). In addition to depths, the plot shows the distribution of field sizes in the study sample, with field sizes as small as 0.02 ha (0.04 acres) up to 4.974 ha (12.29 acres), with a slight concentration towards small fields. The black lines connecting the GID and GRF in Fig. 10 approximately represent net ET (ET minus precipitation minus the change in soil moisture, as calculated from the water balance in Eq. (1)). All black lines have a similar height and indicate that the net ET is similar across field sizes.

Note that two of the three fields with the highest GID were less than 0.08 ha (0.2 acres), and a third field was less than 1.6 ha (4.0 acres). Additionally, with the exception of two fields, all fields greater than 0.08 ha had GIDs less than 510 mm (20 in.) and calculated GRFs of zero. Therefore, the hypothesis that small fields are more likely to be over irrigated than large fields appears to have some validity. However, there are also a lot of small fields that do not over irrigate, indicating that there are other factors that contribute to over irrigating rather than field size alone.

3.3.3. Method and application uniformity vs gross irrigation depth

A four dimensional plot shows the relationship between GID and field size, irrigation method, and sprinkler application uniformity (Fig. 11). The dark green circles are sprinkle irrigated fields where a CU was calculated and the light green circles are fields where a CU was not calculated because the irrigators did not attempt to sprinkle uniformly due to the diversity of crops grown or an awkward field shape. The size of the circle represents the CU of the sprinkle system, with larger CUs having larger circles. The yellow triangles are the surface irrigated fields and the purple diamond is the drip irrigated field.

The plot shows that most larger fields used sprinkle irrigation. The variability of GID for the four surface irrigators (yellow triangles) was high. Two of the three outliers were surface irrigated but two surface

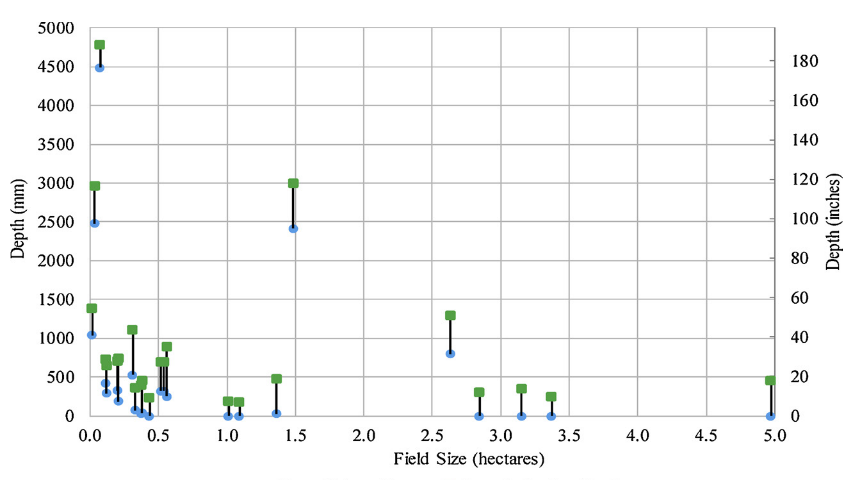

Fig. 10. Gross irrigation depth and gross return flow vs field size.

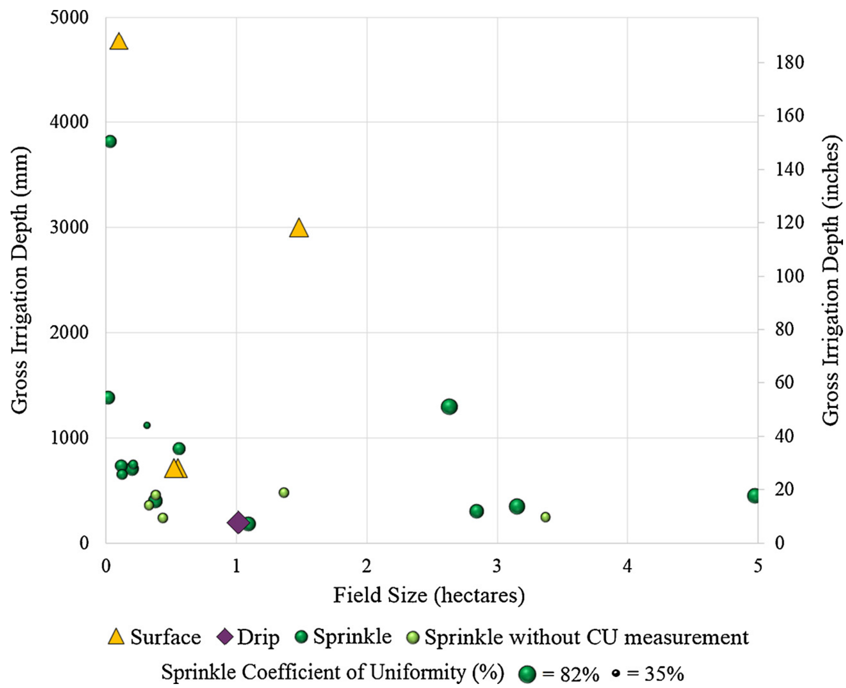

Fig. 11. Multi-variable plot of gross irrigation depth vs field size, irrigation method, and coefficient of uniformity for sprinkle irrigated fields.

irrigated fields had only approximately 700 mm (27.5 in.), performing better than many of the sprinkle irrigated fields, indicating that well managed surface irrigation can perform better than a poorly managed sprinkle system. The field with drip irrigation (purple diamond) had one of the lowest GIDs in the study.

In general, all sprinkle fields larger than 1.0-hectare (2.5 acres) had high CUs and low GIDs (indicated by large green circles on the lower right side of the plot), while fields smaller than 1.0-hectare had lower CUs and higher GIDs (indicated by smaller circles on the left side of the plot above 500 mm (19.7 in.) Almost all of the sprinkle fields had varying nozzle sizes throughout their systems and most of the fixed sprinkle fields had more than one clogged nozzle at the time of the evaluation. A more detailed discussion of the circumstances surrounding the irrigation of each plot is provided in Pratt (2016).

From the plot multiple trends are observed: 1) GID increases with decreasing field size and CU, 2) large fields are more likely to use sprinkle than surface irrigation, and 3) CU increases with increasing field size.

3.3.4. Scheduling and gross irrigation depth

Table 2 shows the two scheduling ratings for each field along with their respective GIDs and beneficial consumed fraction, ranked in decreasing order of GID. Two significant patterns are evident from the table. The fields at the top of the table with the highest GID and lowest beneficial consumed fraction received irrigations at fixed intervals. Return flows occurred on almost every irrigation throughout the season. These farmers likely did not know the depths of water they were applying, how much water their soil was capable of holding, or both. However, there were a few irrigators with fixed interval schedules that had zero return flows, so in these cases the fixed interval did not result in over irrigating. For the majority of fields without fixed interval schedules, farmers chose when to irrigate based on their judgement, and return flows were generally low. These results indicate that the role of irrigation scheduling and frequency is very significant in regards to GID and beneficial consumed fraction.

Table 2
Field gross irrigation depth, beneficial consumed fraction, schedule interval, and return flow frequency.

ID	Gross Irrigation Depth (GID) (mm)	Gross Irrigation Depth (GID) (in)	Beneficial Consumed Fraction	Schedule Interval	Return Flow (RF) frequency
V	4783	188.3	0.06	fixed	RF every IRR
K	3,002	118.2	0.19	fixed	RF every IRR
N	2,969	116.9	0.16	fixed	RF every IRR
D	1380	54.4	0.25	fixed	RF every IRR
R	1,300	51.1	0.36	fixed	RF every IRR
Q	1,120	44.0	0.27	fixed	RF every IRR
O	894	35.2	0.69	variable	RF early season
T	749	29.5	0.73	fixed	RF every IRR
M	734	28.9	0.42	fixed	RF every IRR
X	706	27.8	0.47	partially fixed	RF every IRR
B	699	27.5	0.62	fixed	RF every IRR
C	699	27.5	0.62	fixed	RF every IRR
A	655	25.8	0.55	fixed	RF every IRR
U	480	18.9	0.94	fixed	zero RF
P	457	18.0	0.79	partially fixed	NA
F	450	17.7	1.00	fixed	zero RF
W	399	15.7	0.80	partially fixed	zero RF
I	358	14.1	0.81	partially fixed	RF early season
G	348	13.7	1.00	fixed	zero RF
H	300	11.8	1.00	fixed	zero RF
S	250	9.7	1.00	variable	RF early season
E	240	9.4	1.00	partially fixed	NA
L	200	7.7	1.00	partially fixed	zero RF
J	180	7.2	1.00	other	zero RF

4. Discussion

The above relationships between the beneficial consumed fraction and GID and field size, irrigation method, application uniformity, and scheduling method provide important insights into what is actually occurring at the field level in urban and small farm irrigation practices.

Since there is very little prior work that has studied the irrigation practices of urban and small farmers, our discussion compares results to residential landscape practices and potential impacts to study participants, other urban and small farm irrigators with similar situations in the U.S., Extension programs, and the Utah DWRe.

4.1. Irrigators

The study results directly benefit the irrigators who took part in the study by providing them their own field's performance metrics (e.g. GID, GRF, CU, crop water stress, soil moisture management and timing of return flows) and customized recommendations for how they can improve their irrigation operations. Pratt (2016, Appendix F) presents analysis for the 20 other fields not included in the case studies in Section 3.2. From the 24-field sample, three areas of management stand out as needing improvement: 1) the knowledge of application rate and its importance in scheduling, 2) how to schedule irrigation frequency and duration, and 3) how to improve application uniformity. Although many educational resources exist in these areas, all study irrigators said they only used their own judgement. This is not surprising, as research shows that most growers make their irrigation decisions subjectively, based on their practical experience and observations (Knox et al., 2012), and that there often exists a default assumption that irrigation practices are already adequately efficient (Levidow et al., 2014). Thus, there are often weak perceived incentives to improve irrigation practices. Table 3 shows some of the actions and associated costs and benefits that could result from improved irrigation scheduling for each field in the study. The recommendations were developed by observing the time series water balance for each field and noting when in the season return flows or crop water stress occurred. The potential benefits include savings of water, pumping energy, and labor, reduced leaching, and improved yield.

4.2. Urban and small farm irrigators across the U.S

The circumstances of the fields in this study are not unique to Cache Valley, Utah, but are undoubtedly common across the U.S. Where irrigators find themselves in similar situations to the irrigators in this study (e.g. small field size, surface irrigation systems, poor sprinkle uniformity, or fixed irrigation schedule), they should focus their efforts on learning how to measure their application rate, schedule irrigations, and improve application uniformity. Doing so has the potential to bring them similar benefits as those described in Table 3.

4.3. Extension

Extension can benefit greatly from our findings by understanding the link between water use and irrigation management on urban and small farms. Training and educational efforts should focus on the three main areas of management needing improvement: 1) the measurement of application rates, 2) how to properly schedule irrigations, and 3) how to improve application uniformity.

Our results confirm the findings of Levidow et al. (2014) in that most irrigators will not improve their irrigation practices unless they understand the direct correlation between good irrigation management and savings in money, time, and yield. This begins with knowing how to

Table 3
Recommended schedule changes and relative costs and benefits.

Recommended schedule changes and associated costs and benefits.

ID	Recommended Schedule Change	On-farm Water Savings per Year (cubic meters)	On-farm Water Savings per Year (Acre-feet)	Relative Costs & Benefits
A	Discontinue use of 1 of the irrigation systems	360	0.29	Reduced manual labor, reduced leaching
B	Reduce duration 50%	1,720	1.39	50% of hrs saved, reduced leaching
C	Reduce duration 50%	1,650	1.34	50% of hrs saved, reduced leaching
D	Reduce duration 75%	170	0.13	75% less pumping costs, reduced leaching
E	Increase duration 25%	0	0.00	25% more pumping costs, slightly increased yield
F	Increase duration 20%	0	0.00	20% more pumping costs, slightly increased yield
G	Begin irrigating 2 weeks earlier in season, increase duration 25%	0	0.00	25% more pumping costs, increased yield
H	Begin irrigating 2 weeks earlier in season, increase duration 25%	0	0.00	Significantly more labor, increased yield
I	Increase duration 50% starting mid-July	250	0.20	50% more pumping costs, increased yield
J	Begin irrigating 1 month earlier, add 1 irrigation late season, increase irrigation duration 25%	0	0.00	100% more labor, increased yield
K	Reduce frequency 50%, reduce duration early season by 75%	NA	NA	50% of irrigation days saved, reduced leaching
L	Reduce frequency 50%, increase duration 125%	0	0.00	50% of irrigation days saved
M	Increase frequency 25%, reduce duration 50%	500	0.41	25% more irrigation days, slightly increased yield, reduced leaching
N	Reduce frequency 50%, reduce duration 75%	830	0.67	50% of irrigation days saved, reduced leaching
O	Reduce frequency 50%, reduce duration 100% starting mid-July	1,410	1.15	50% of irrigation days saved, reduced leaching
P	Reduce frequency 50%, increase duration 50% starting mid-July	140	0.11	10 irrigation days saved
Q	Reduce frequency 50%, increase duration 50% starting mid-July	2,450	1.98	6 irrigation days saved
R	Begin irrigating 1 month earlier, reduce duration 50%	2,106	17.07	Increased yield, increased labor early season, 50% of hours saved starting mid-July, reduced leaching
S	Reduce frequency 50%, increase duration 100% starting mid-June	0	0.00	Slightly increased yield
T	Reduce duration 20%	380	0.31	20% of hours saved, reduced leaching
U	Reduce frequency 75%, increase duration 300% starting mid-June	390	0.31	50% of irrigation days saved
V	Reduce frequency 50%, reduced duration 50% starting mid-June	3,410	2.77	50% of irrigation days saved, 50% of hours saved
W	Reduce frequency 50%, increase duration 100%	130	0.11	50% of irrigation days saved
X	Reduce frequency 50%, increase duration 50%	650	0.53	50% of irrigation days saved

measure their flow rate. Technology and cost does not need to be an impediment. For drip and sprinkle systems, flow measurement could be as simple as conducting a volumetric test with a hose, bucket and stopwatch. For surface systems, use the float method with a staff gauge. These methods would be a vast improvement over no measurements. Second, irrigators should use basic irrigation scheduling methods. At present, the easiest scheduling tool for use in Utah is Washington State University's mobile phone application "Irrigation Scheduler", which uses a series of weather networks that cover a large portion of the western U.S. and Canada, including northern Utah (Washington State University, 2016). This simple tool allows the irrigator to input field location, soil type, and crop type, and helps estimate the ideal irrigation schedule. Another option for consideration is weekly emails or web postings of water use for various crops and planting dates. Extension programs should promote the use of these or other similar scheduling tools in education efforts, keeping in mind that tools must be fast, reliable, and easy to use to find widespread use. Lastly, irrigators should be aware of their field application uniformity, and how poor uniformity means that either 1) some areas of the field are under-watered (reducing yield) while other areas of the field are over-watered (leaching fertility) or 2) crop water requirements of the entire field are met but significant volumes of water still go directly to return flows, also wasting resources. Although improving sprinkler uniformities can be constrained by field shape and size, labor and equipment costs, and system layout, encouraging simple low-cost measures such as nozzle maintenance (e.g. cleaning clogged nozzles, repairing nozzle arc and rotation, and replacing worn nozzles and gaskets), and the use of standardized and uniform nozzles may have the most effective results.

4.4. Utah Division of Water Resources conservation efforts

This study also benefits the Utah DWRe by providing valuable insights that can improve statewide water use estimation and conservation efforts. Specifically, DWRe programs should highlight the important role of irrigation management (measurement, scheduling, and application uniformity) and target urban farmers with small fields and unmetered secondary water sources that are more prone to over irrigate compared to farmers with large fields or metered sources, as also found in Speelman et al. (2008). Additionally, DWRe should partner with Extension to deliver programs as urban and small farm irrigators are likely already familiar with Extension.

The crop type most likely to occur in residential landscapes is mixed gardens. Comparing area-weighted average irrigation depth for the *Garden* category in this study of 493 mm (19.4 in.) to Utah landscape (primarily turfgrass) values of 826 mm (32.5 in.) (Utah Division of Water Resources, 2010) suggests DWRe can promote urban agriculture as an alternative to conventional landscaping. Such promotion can save water in the M&I sector while building community, improving nutrition, and promoting local food security. Additionally, this promotion would reduce fall over watering of turfgrass which is the season when residents fail to adjust irrigation timers to respond to reduced ET and urban water supplies are most scarce (Utah Division of Water Resources, 2010). Unlike landscape irrigation, our study results show that if urban and small farmers over irrigate, they do so in early season or over the entire season, but never just in fall.

5. Conclusion

Urban and small farming is growing yet relatively little is known about the sector's water use practices. We conducted comprehensive season long evaluations of 24 urban and small farm fields in Cache Valley, Utah. We measured applied irrigation depths and gathered time series data to calculate the changing soil moisture and the depth and timing of return flows throughout the season. For sprinkle systems we conducted catch can tests to calculate the CU.

Results showed that large fields generally have lower GID and higher CU than small fields. We also found that surface systems are more likely to have excessive GID than sprinkle systems, although well managed surface irrigation systems can outperform poorly managed sprinkle systems. Lastly, scheduling played a big role in GID: fields irrigating on a *fixed* interval schedule applied more water than fields irrigating with a *partially fixed*, *variable*, or *other* interval. The majority of the excess irrigation went directly to deep percolation, and occurred either early season or all season long. These timings contrast with residential landscapes where excess irrigation often occurs late in the season.

Three of the 24 fields had extremely high irrigation depths. Four case studies identified two fields with good management and two fields with poor management. These results illustrate the variability of irrigation circumstances and practices and the effect of scheduling (including irrigation duration and interval) and application uniformity on total water use and beneficial consumed fraction.

Study results can help participating urban and small farm irrigators and irrigators with similar situations in other areas. These users can improve by learning 1) low cost methods to measure application rates, 2) proper irrigation scheduling, and 3) improving application uniformity. Extension and Utah DWRe water conservation efforts should prioritize programs that teach irrigators techniques for improving management in these areas, and consider promoting small gardens over conventional turfgrass landscapes for urban water conservation.

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