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Uncertainties in leaching assessment in micro-irrigated fields using water balance approach

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ABSTRACT

Leaching is an important aspect of irrigation water management, as it must be minimal to save available irrigation water resources, prevent shallow groundwater tables, and reduce nutrient loadings to the groundwater. However, at the same time, leaching should be sufficient to maintain root zone salinity levels below the threshold to prevent yield reduction. Therefore, monitoring leaching is the key component in evaluation and optimization of irrigation water management practices. Water balance (WB) is a common approach used to estimate leaching in agricultural fields and was applied in this study to assess field-scale leaching and the associated uncertainties for an almond orchard under drip and micro-sprinkler irrigation systems. In this study, we showed that change is soil water storage (ΔS) is highly influenced by the extent of monitoring depth, the location and number of monitoring points. Local measurement of WB parameters showed that leaching is highly variable across the field, thereby introducing considerable uncertainty on estimated leaching using WB approach. It was also shown that unknown input of water through fog interception added to the complexity of closing water balance at field scale.

1. Introduction

Increase in human population and consequently the increase in demand for food as well as the limitation in expansion of agricultural land all indicate the need for increase in efficiency of crop production (Smith et al., 2010; Tilman et al., 2011; Assouline et al., 2015). The competition between urban, industrial, and agricultural areas for the limited water resources n one hand, and irrigated agricultural lands (which cover 20% of cultivated lands) producing 40% global food production(WWAP, 2009) on the other hand show that there is a continuous need for improving irrigation efficiency, especially in arid and semi-arid regions. Quality of irrigation water is an additional factor affecting irrigation and production efficiency due to the adverse effect of salinity buildup in the root-zone on crop production efficiency (Pitman and Läuchli, 2002). Therefore, in order to maintain an efficient and sustainable crop production, leaching fraction needs to be applied to leach the excess of salt out of the root zone which in turn adversely affect the irrigation efficiency. The amount of water that leaves the root zone toward the deeper soil profile is defined as leaching.

Leaching is an undeniable part of irrigated agricultural practices, since salt accumulation in the root zone adversely affects crop growth and yield, especially for salt- sensitive perennial trees like almond (Grieve et al., 2012). An optimum irrigation management practice must account for the leaching requirement, LR, defined as the minimum amount of water required to pass through the root zone in order to keep the root zone salinity level below a threshold value, which depends on the quality of irrigation water and crop salt tolerance value. However, the increasing concerns of groundwater pollution with agriculture being recognized as the main source of this environmental threat, suggest that the leaching fraction of irrigation water must be largely minimized to reduce nutrient loadings to groundwater. Therefore, there is a trade-off between agricultural production and environmental sustainability, requiring special attention to improve irrigation water management practices.

Leaching is affected by complex interactions between irrigation (the amount of applied water compared to evapotranspiration, irrigation method and frequency, uniformity in water application), plant response (root growth, distribution and uptake pattern) and soil type, and cannot be easily estimated. Therefore, in order to evaluate the current irrigation management strategies and to determine optimum irrigation management methods which satisfy both aforementioned aspects of sustainable agricultural practices, it is essential to monitor leaching of

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Nomenclature

CU	Coefficient of Uniformity
CV	Coefficient of Variation
DB	Drip Irrigation Block
DT	Drip Irrigated Heavily Monitored Tree
ET	Evapotranspiration
ET_a	Actual Evapotranspiration
ET_a^F	Field Scale Actual Evapotranspiration
ET_a^T	Tree Scale Actual Evapotranspiration
ET_c	Crop Evapotranspiration
ET_o	Reference Evapotranspiration
FB	Micro-sprinkler Irrigation Bock
FT	Micro-sprinkler Irrigated Heavily Monitored Tree
IW	Irrigation Water
IW^F	Field Average Irrigation Water
IW^T	Individual Tree's Irrigation Water
K_c	Crop coefficient for ET
K_s	Hydraulic conductivity
L	Leaching
P	Precipitation
SWS	Soil Water Storage
WB	Water Balance
ΔS	Change in Soil Water Storage
ρ_b	Bulk Density

water with associated solutes such as salts and nitrates.

Among the different methodologies for estimating the leaching below the root zone, the water balance (WB) is the most common approach (Thornthwaite and Mather, 1955; Xu and Singh, 1998). In the water balance approach, leaching (L) is computed from water inputs and outputs, in addition to changes in soil water storage, and is typically applied to large spatial (field) and temporal (days to weeks) scales. Despite that the WB is a common approach to estimate leaching, it was reported by Hanson et al. (2008) and Hanson et al. (2009) that the field-scale WB is not an appropriate approach to estimate leaching in drip irrigation. They found that spatially variable soil wetting patterns in drip irrigation cause localized leaching below the drip-line, whereas leaching values of near zero would be computed using the field scale WB approach.

Lafond et al. (2014) compared the leaching by both the WB and Darcy law (DL) approaches, using the measured drainage with a lysimeter as a benchmark. Using soil matric potential measurements from tensiometer pairs installed at the 30 and 60 cm soil depths, they determined that DL calculations over-estimated leaching of up to three orders of magnitude, while it was within the same order of magnitude using the WB approach. Cunnew and Edraki (2008) compared three approaches of water balance, DL, and field capacity to estimate leaching below the root zone. Their study showed that estimated leaching using DL and field capacity was correlated with irrigation and precipitation events, and the magnitude of the leaching rate increased as the soil water content increased. They also concluded that leaching rates estimated from water balance approach were unrealistic, since it resulted in negative leaching rates (upward flow) throughout the monitoring period. Qassim et al. (2008) used the WB to estimate the weekly leaching below the 40 cm soil depth of irrigated pasture. Greenwood et al. (2009) applied a slight revised version of WB equation to estimate the leaching in different forage species, where they assumed leaching occurs when the soil water content exceeded a certain threshold value. Lafond et al. (2014) compared the leaching calculated by WB approach with the measured drainage from a lysimeter as a benchmark and showed that the WB-based leaching was within the same order of magnitude of what was measured from lysimeter drainage. Barros et al. (2011) conducted a long-term WB experiment for flood irrigated field at watershed scale to evaluate associated errors and suggested that the WB can be improved by reducing the uncertainty in actual evapotranspiration, ET_a.

In this study we used the WB approach to estimate leaching under two micro-irrigation systems in an almond orchard at both field and tree scales. The objective of this study was to (a) evaluate the implication of the water balance approach for leaching assessment in micro-irrigated orchards, and (b) analyze the measured uncertainties and to provide insights into the causes of these uncertainties.

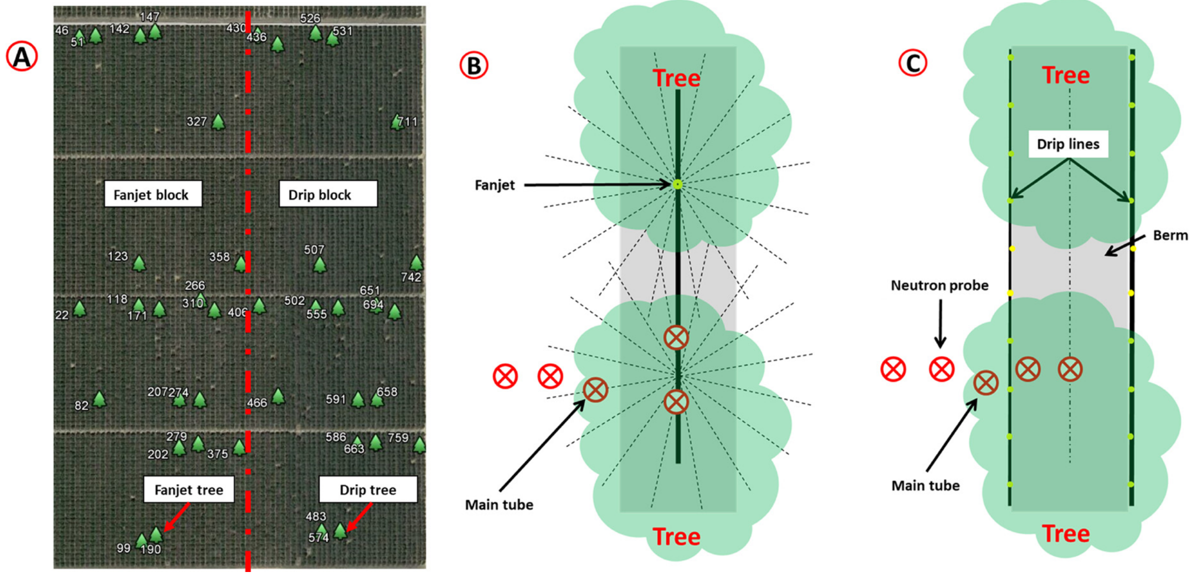

Fig. 1. A schematic top view of neutron probe access tubes in (A) DT and (B) FT. The red crossed circles denote the approximate location for neutron probe access tubes. The main tube represents the approximate location of neutron probe assess tube of all monitored trees in DB and FB (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

2. Materials and methods

2.1. Site description, evapotranspiration (ET) and precipitation (P)

A multi-year field experiment was carried out in one of the almond orchards of Wonderful Pistachios & Almonds (formerly known as Paramount Farm) in Belridge, CA, from February 2009 to December 2012. The orchard was stablished in 1999 (Muhammad et al., 2015) where almond trees were planted 6.4 m apart on top of 40 cm high and 200 cm wide berms along the rows which were spaced 7.3 m apart (Fig. 1).

The 44 ha orchard (550 m by 800 m) was divided into two irrigation blocks of drip (DB) and fanjet or micro-sprinkler (FB) in order to evaluate the leaching of water under these two micro-irrigation systems. The orchard is located at 35°30'22.76"N and 119°40'3.34"W at about 2.2 km from the CIMIS[1] station#146. The 14-years (1999–2012) average annual precipitation (P) is 129 mm, while the long-term average annual reference evapotranspiration, ET_o, is 1,481 mm which indicates the need for irrigation to grow crops in this area.

Fig. 2 shows the monthly P, ET, and IW for four years from Jan. 2009 to Dec. 2012. Whereas P was obtained from CIMIS station, the field average actual evapotranspiration, ET_a, was estimated from an on-site Eddy Covariance tower (Baldocchi et al., 1988; Shapland et al., 2013). Crop evapotranspiration, ET_c, was also calculated by multiplying ET_o with the almond crop coefficient, K_c, proposed by Sanden et al. (2012).

We note here that $ET_a \leq ET_c$ and under a non-stressed conditions ET_a is expected to be equal to ET_c. However, comparison of ET_a^F and ET_c in Fig. 2, shows that ET_a^F is generally higher than the ET_c. Whereas the higher ET_a^F in summer was justified by higher K_c values, we hypothesize that mid-day evaporation of intercepted morning-fog by tree branches during the fall and winter resulted in overestimation of evapotranspiration (Personal communication with Richard Snyder, Biometeorologist at UCDavis) during the fall and winter period. Therefore, the field scale evapotranspiration was adjusted (adj- ET_a^F) such that the orchard ET during the late fall and winter was assumed to be equal to ET_c. This adjustment resulted in reducing the ET for this period, thereby accounting for the effect of fog on overestimation of ET.

Couvreur et al., (2016) used spatiotemporal information of soil water storage, Stem Water Potential, and Photosynthetically Active Radiation to downscale the field scale ET data (ET_a^F) obtained from Eddy Covariance tower and estimated tree scale ET (ET_a^T) for each monitored tree across this same studied orchard. Therefore, ET_a were available at both field (ET_a^F) and tree (ET_a^T) scales. We note here that, similar to the assumption in adj-ET_a^F, it was assumed that the ET of each individual tree in late fall and winter is equal to ET_c and thus the adjusted ET_a^T is called adj-ET_a^T.

2.2. Soil water content and irrigation monitoring

In order to determine the variability of water balance across the orchard, a total of 40 trees (20 trees in each irrigation block) were selected randomly to monitor the applied irrigation water (IW), and soil profile water storage (SWS) from 01/27/ 2009 to 11/20/2012. We note here that only 30 trees were monitored for year of 2009. The ending monitoring date for the purpose of closing annual water balance were 02/16/2010, 1/12/2011, 2/17/2012, and 11/20/2012.

Irrigation- Each tree in FB was irrigated by two micro-sprinklers with nominal flow rates of 40 l h^{-1}, while two drip-lines, each with 10 emitters of 4 l h^{-1} flowrate were used to irrigate tree in DB (Fig. 1). Micro-sprinklers were located on the berm and 150 cm away from the tree trunk at each side, while the two drip lines were laid out about 0.8–1 m away from the tree trunk along the berm on each side of the rows. Irrigation was scheduled on a weekly basis with the duration of 24 h and occasional irrigation events of 48 h long. While a flowmeter at pump station was used to measure the applied water at field scale, for IW^F, we used small flow meters (SeaMetrics,[2] MTR200) to measure the amounts of local applied irrigation water for each of the monitored trees, IW^T, thereby evaluating uniformity of applied water across two irrigation blocks.

Soil water content- Whereas each of the 20 trees in the DB and FB treatments were equipped with a single neutron probe (Highnett and Evett, 2002) access tube down to the 270 cm soil depth, one tree from each block (DT and FT) were instrumented with four additional neutron probe access tubes for the purpose of monitoring the spatial variation of soil water content within the tree root zone. Fig. 1 shows the arrangement of the neutron probe access tubes around the DT and FT trees. The location of the single access tube relative to the tree trunk, marked as main tube in Fig.1, was kept constant for all monitored trees. Soil water content was monitored on weekly basis prior to each irrigation event at soil depths of 30, 60, 90, 120, 150, 180, 210, 240, and 270 cm. No soil moisture measurements were taken during the winter. Neutron probe count ratios were converted to volumetric soil water content using an in-situ calibration curve (Fig. 3).

In order to obtain a more representative soil water storage for each tree at field scale, the soil water content in DT and FT trees was used to develop a calibration equation, where the soil water content using the single (i.e., main) access tube measurements was correlated to the average soil water content using the 5-tube setup (Fig. 1).

2.3. Soil profile characterization

Among the most important information derived from soil profile characterization is an evaluation of the presence of soil layers and the textural/hydraulic properties of each individual layer across the soil profiles. For that purpose, a total of 80 undisturbed soil samples were collected at different depths down to 3 m from each of the DT and FT tree locations. There were between 3 to 5 samples for each depth. These samples were 6 cm tall with diameter of about 8 cm (sampled either using manual core sampler or hydraulic Giddings), from which saturated hydraulic conductivity and soil textural properties, and dry bulk density were measured.

In addition to these soil samples which were taken to evaluate the soil profile heterogeneity at the tree scale, a total of 360 undisturbed soil samples (one sample at each 30-cm depth interval down to 2.7 m, from each of the 40 monitored trees) were collected and analyzed for soil textural properties using hydrometer method and bulk density, thereby evaluating soil profile heterogeneity across the DB and FB treatments of the experiment.

2.4. Leaching

Leaching (L) can be determined from the soil water balance (Eq. (1)), using measurements of applied irrigation water (IW), precipitation (P), actual evapotranspiration (ET_a), and changes in soil water storage (ΔS) to a specific soil depth below the rooting zone. As the depth of the soil water storage measurements increases, we expect the estimated leaching to be more accurate, as it would increasingly account for local upward capillary rise caused by root water uptake. Thus, from periodic measurements of ΔS prior to each irrigation and corresponding data of IW, P, and ET_a, the leaching (L) can be computed from:

$$L = IW + P - ET_a - \Delta S \tag{1}$$

with measurement unit of depth of water (cm). Volume of applied water was divided by the area occupied by each tree yielding the

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[1] California Irrigation Management System (http://www.cimis.water.ca.gov/Default.aspx)

[2] http://www.seametrics.com/

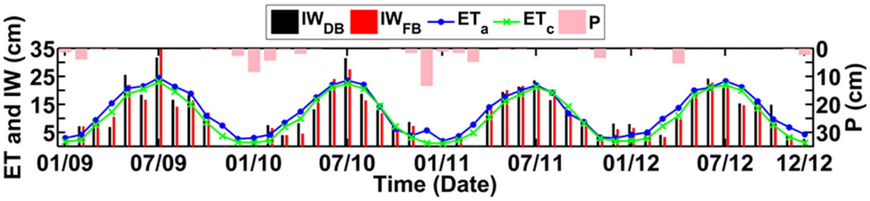

Fig. 2. Monthly values of P, ET_c, ET_a^F, and IW for four years from Jan 2009 to Dec. 2012.

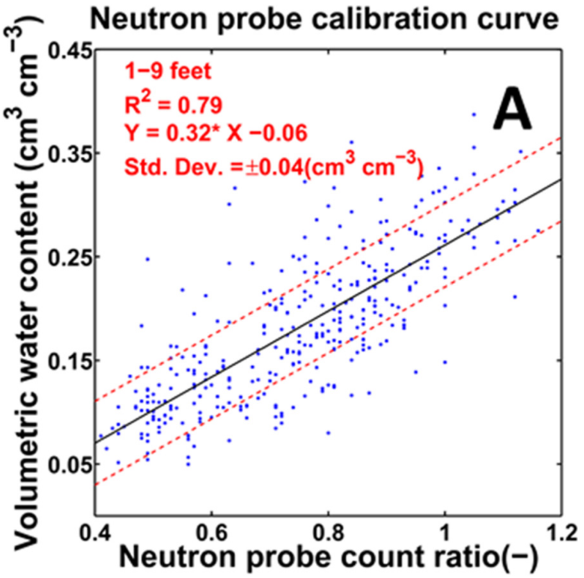

Fig. 3. Neutron probe calibration curve (black line) with corresponding uncertainty band defined by standard deviation (red dash-line) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

equivalent depth of applied irrigation water, IW. Whereas P was assumed to be uniform across the field, ΔS was measured at the tree scale. Couvreur et al. (2016) used spatiotemporal information of SWS, Stem Water Potential, and Photosynthetically Active Radiation to downscale the field scale ET data (ET_a^F) obtained from Eddy Covariance tower and estimated tree scale ET (ET_a^T) for each monitored tree across this studied orchard. Therefore, similar to IW, ET_a was available at both field (ET_a^F) and tree (ET_a^T) scales.

2.5. Uncertainty determination

In order to determine all possible scenarios for estimation of ΔS at tree scale, we used the combination rule as follow:

$$C(n,\,r) = \frac{n\,!}{r\,!\,(n-r)\,!}, \tag{2}$$

where *C(n,r)* shows the number of possible scenarios, *n* is total number of monitoring locations (i.e., 5) and *r* represents the selected number of monitoring locations ranging from one to five. For example, there are 10 different scenarios for selecting three (r) out of five (n) monitoring locations.

Eq. (2) was also used to determine all possible scenarios for estimation of leaching at irrigation block scale where *n* is total number of monitoring locations (i.e., 20) and *r* represents the selected number of monitoring locations ranging from one to 20. We note here that leaching values of all possible scenarios were subtracted from field average leaching (calculated using all 20 monitoring points), thereby calculating the difference between leaching values and the average as the range of uncertainty.

3. Results and discussions

3.1. Soil textural and hydraulic properties

According to USDA-NCSS Web Soil Survey, the soil profile of the study site was a mixture of Milhan sandy loam, Kimberlina fine sandy

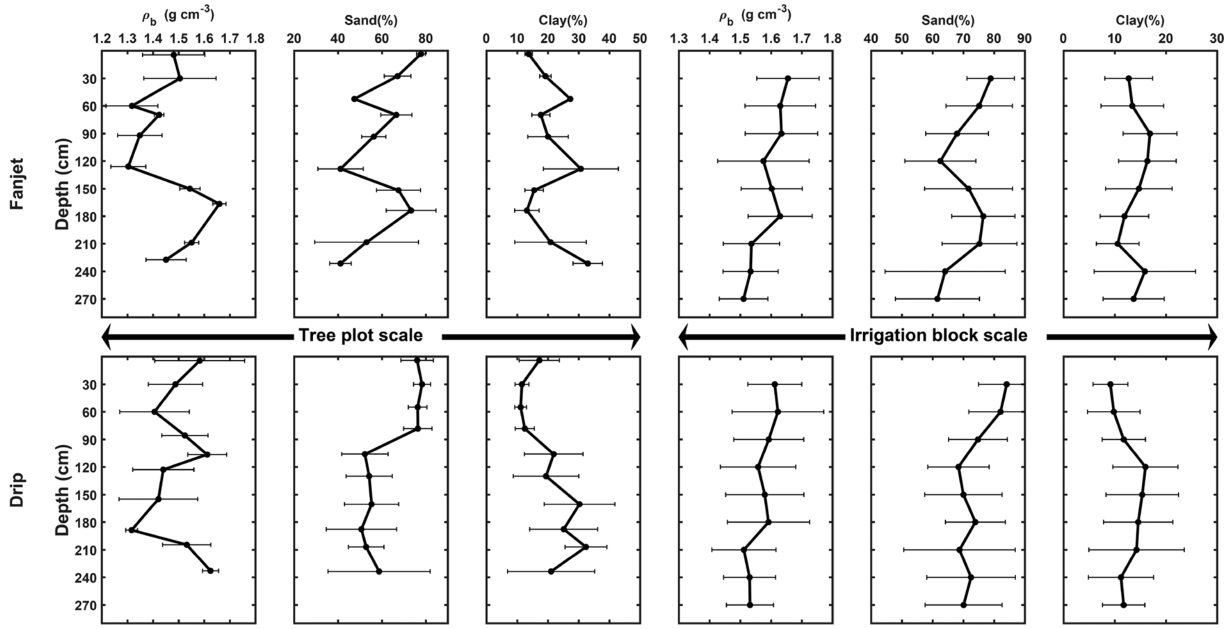

Fig. 4. Mean (tick line) and standard deviation (error bar) of dry bulk density and sand and clay contents as a function of soil depth in drip and micro-sprinkler sites at both tree and irrigation block scales.

loam, and Panoche clay loam. Fig. 4 shows the physical (sand, clay, and ρ_b) properties of soil profile at both tree and irrigation block scales.

At tree scale, bulk density varied by depth ranging from 1.3 to 1.65 g/cm3. The top 100 cm soil layer in DT was mostly sandy with distinct clay layers at depth of 180 cm in DT and depths 120 and 240 cm in FT. Coefficient of variation, CV, for bulk density decreased with depth from 8 to 10% to about 2–4%. However, it showed a general increasing trend for both sand and clay content where it increased from 5 to 10% to about 50%. Similar layering pattern was observed at irrigation block scale. The average bulk density showed a slight decrease with depth ranging from 1.65 to 1.5 g/cm3. The coefficient of variations for different depths were similar and ranged from 5 to 8%. Coefficient of variation for sand content varied between 10–20% while it was between 40–50% for clay content.

As is shown by analysis coefficient of variation, CV, there was large uncertainty in presence and depth intervals of identified soil layers within and between irrigation blocks and as a result, in soil profile water storage since soil profile water storage is closely related to soil textural properties and bulk density.

3.2. *Uncertainty in estimated leaching*

3.2.1. *Tree scale*

Fig. 5 shows the effect of number and location of monitoring points as well as the extent of monitoring depth in estimation of ΔS and thus in leaching. In contrast to the common perception that the change in soil moisture at deeper soil profile is minimal, Fig. 5 shows that ΔS values change as monitored depth of soil profile increases. In DT, for monitoring depth of 120 cm, the ΔS was 2.4, 1.7, -4, and -13 cm for years of 2009, 2010, 2011, and 2012, respectively. As the monitoring depth increased to 270, the ΔS was 3.9, 5.4, 8, and -14.5 cm for years of 2009, 2010, 2011, and 2012, respectively. The ΔS value was as follows for FT for years of 2009, 2010, 2011, and 2012. It was, respectively, 4.8, 5.2, 0.6, and -10.3 cm for monitoring depth of 120 cm and 6.2, 9.3, 5.9, and -14.8 cm for monitoring depth of 270 cm. We believe that the change ΔS value is an indication of the extent of wetting front due to localized applied water through micro-irrigation system, which emphasizes the potential uncertainties introduced by selection of monitoring depth. The response of ΔS values to the change in monitoring depth varies from one year to another suggesting that they are affected by changes in either or combination of irrigation management, plant water demand, and both the timing and amount of precipitation. In all monitoring years, the absolute value of ΔS increased as the depth of soil profile increased. It should be noted that the monitoring year of 2012 was shorter than others such that the last monitoring date was occurred before the winter rainfall (Section 3.2) when the soil profile is at its driest condition. Therefore, the ΔS sign is expected to be negative and the expected increase in absolute value of ΔS as the increase in monitoring depth results in a decreasing (more negative) trend.

It is also shown that decreasing the number of monitoring locations results in increasing the uncertainty range for estimation of ΔS. For example, the uncertainty around the average ΔS (i.e., using all five access tubes) in FT for monitoring depth of 270 cm in 2009 increased from 1.3 to 5.3 cm as the monitoring locations (i.e., number of access tubes) decreased from four to one. This increase in uncertainty was from 1.2, 2, and 4.4 cm to 4.8, 8.2, and 17.7 cm for years of 2010, 2011, and 2012, respectively. Similarly, decreasing the number of monitoring locations from four to one resulted in increase in uncertainty range for estimation of ΔS in DT. This increase in uncertainty was from 1.5, 1.6, 2.2, and 2.1 cm to 5.9, 6.5, 9, and 8.6 cm for years of 2009, 2010, 2011, and 2012, respectively.

The use of WB approach is based upon the assumption that all components (i.e., L, IW, P, ET_a, and ΔS) of WB equation are uniform across and thus representative of the study area. However, the results presented above shows that it is not a fair assumption even at tree scale. Localized water application through micro-irrigation system results in non-uniformity in water application around a tree. In addition to the non-uniformity in water application, heterogeneity in soil properties and layering as shown in Fig. 4 promotes non-uniform distribution and redistribution of water within the soil profile. Therefore, the total number of monitoring points, their locations and the extent of monitoring depth plays an important role in the degree of uncertainty in estimated ΔS.

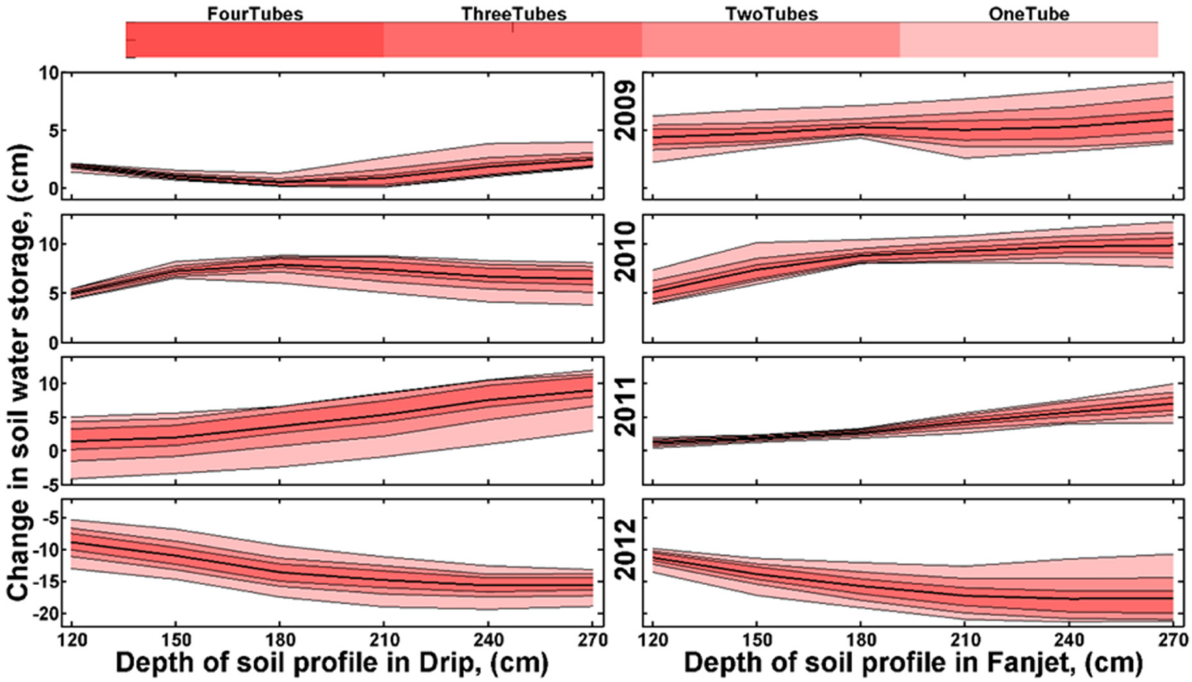

Fig. 5. The effect of number and location of monitoring points and the extent of monitoring depth in estimation of ΔS. Thick black line shows the ΔS calculated using all five access tubes. The shaded area represents the uncertainty range in estimation of ΔS (Y axis) for selected monitoring depth (X axis). Different colors of the shaded area represent the effect of number of monitoring locations per tree on the uncertainty range.

3.2.2. Field scale

Correlations between single tube and average of five tube water contents were determined using linear regression equation. Slops of regression line were 0.83, 0.79, 0.78, 0.70, 0.72, 0.96, 0.86, 0.56, 1.02 for drip and 0.36, 0.37, 0.47, 0.86, 0.83, 0.92, 0.78, 0.75, 0.94 for micro-sprinkler for depths 30, 60, 90, 120, 150, 180, 210, 240, 270 cm, respectively. It shows that (except depth 270 cm in micro-sprinkler). The intercepts of regression lines are all positive expect for depth 270 cm in micro-sprinkler (= - 0.01 $cm^3 cm^{-3}$) and depth 120 cm in drip (= - 0.02 $cm^3 cm^{-3}$). The positive intercept and the slope of smaller than one shows that using data from single access tube results in an underestimation of soil water storage when soil is dry and an underestimation of soil water storage when soil is wet. The soil water measured in all 19 single-access tube equipped trees in irrigation block was adjusted using the calibration equations presented in Fig. 6. We distinguished between the DB and FB treatments, as water application distributions were different for the two treatments.

The P value was assumed to be uniform across the orchard in water balance equation (Eq. 1). The monthly values of P show that the majority of precipitation occurs during the winter when almond trees are in dormancy. Despite its small amount in comparison to the annual water demand, it plays a major role in increasing the soil water storage and thus in water balance during the winter. It is also shown that the significant reduction in P during fall 2011, winter 2012, and fall 2012 was compensated by irrigation.

Unlike P, the amount of IW was measured at both field scale, IW^F, and locally using flowmeters installed for each of the monitored trees, IW^T. The annual IW^F values for years of 2009, 2010, 2011, and 2012 were 136.63, 118.16, 128.4, and 125.47 cm, respectively. The uniformity of irrigation across the orchard was considerably high with CU of 96%. Fig. 7 shows the annual IW^T as well as the annual average and standard deviation for DB and FB during monitoring period of 2009–2012. The annual average IW values were 139.62, 130.82, 142.56, and 126.78 for DB and 141.05, 124.45, 136.29, and 120.13 for FB for years of 2009, 2010, 2011, and 2012, respectively. The coefficients of variation, CV, were 3.1, 4.9, 6.1, and 6.4% for DB and 4.2, 5.1, 4.8, 2.8% for FB for years of 2009, 2010, 2011, and 2012, respectively. Comparison of IW between DB and FB shows that the annual average values of IW in DB are slightly higher than those of in FB.

T the spatial variation in ET is expected to contribute to the uncertainties associated with estimation of leaching at each monitoring point. Fig. 8 shows the annual adj-ET_a^T for each of the monitoring trees in each of the four years of 2009–2012 in DB and FB. Similar to IW, the average adj-ET_a^T in DB is higher than that of in FB. Despite similar trend observed between average adj-ET_a^T and IW for DB and FB, it should be noted that this similarity is not necessarily valid for all individual trees. For example, in 2011 at tree#17 both adj-ET_a^T and IW in DB are higher than those of in FB whereas it is the opposite at tree#16. Furthermore, it adds to the complexity where comparison of adj-ET_a^T between DB and FB does not follow the same trend as IW. For example, in 2010 at tree#11 in DB the adj-ET_a^T is higher while the IW is lower than those of in FB, whereas it is the opposite at tree#8, which would result in considerable difference in either soil water storage or leaching or both between these trees.

Table 1 shows the effect of local measurements of WB equation components on the estimated field average leaching in DB and FB for each year from 2009 to 2012. It shows leaching values for three different scenarios where 1- the only locally measured parameter is ΔS and other components of WB equation (ET, P, and IW) were assumed to be uniform across the irrigation blocks, 2- locally measured parameters were ΔS and IW, and 3- locally measured parameters were ΔS, IW, and ET. Similar to first scenario, other components of WB equation in scenarios #2 and #3 were assumed to be uniform across the irrigation blocks. In scenario #1, the field average leaching values are -1.73, 0.58, 0.04, 4.99 cm for DB and -8.22, -0.27, 0.94, 7.04 cm for FB for years of 2009, 2010, 2011, and 2012, respectively. Leaching values are generally small especially for years of 2010 and 2011. The addition of IW^T in scenario#2 resulted in higher estimation of leaching values (except for FB in 2012) especially in DB for years of 2010 and 2011 in which the leaching values increased from 0.58 and 0.04 cm to 13.24 and 14.2 cm, respectively. The difference in the magnitude of changes from scenario #1 to #2 between different years is due to the difference in average of IW^T in DB and FB and IW^F.

Fig. 9 shows the effect of number of monitoring points across the field (to estimate ΔS) as well as their associated local IW and ET in estimation of leaching in DB and FB. The X axis shows the number of monitoring locations and Y axis shows the ranges of uncertainty around the estimated average leaching (see Table 1 for average leaching values). Different colors of the shaded area from dark to light red represent scenarios of #1, #2, and #3, respectively. For example, in Fig. 9, the dark red shaded area for DB in 2009 shows that if only one monitoring location was used in scenario, depending on the location of monitoring point the estimated leaching could be from 5.7 cm below up to 11.1 cm above the average value listed in Table 1. In other words, the range of uncertainty (the difference between maximum and minimum) is 16.8 cm. It is shown that the increase in the number of locally-measured components of the water balance, increases the uncertainty range for estimation of leaching. This range increases to 24.8 and 54.5 cm in scenarios #2 and #3, respectively.

The number of monitoring locations also affect the uncertainty range such that the range of uncertainty decreases as the number of monitoring point increases. While the number of monitoring locations is usually more than one, in rare cases the number of monitoring points exceeds five which is a favored minimum number of data points for the purpose of statistical analysis. The range of uncertainties in case of five monitoring locations in scenario #1 are 9.5, 8.6, 3.3, and 9.5 cm for DB and 4.7, 4.4, 5.1, and 8.3 cm for DB for years of 2009, 2010, 2011, and 2012, respectively. These ranges increase to 20, 16.4, 17, and 11.6 cm for DB and 11.2, 14.2, 16.95, and 16.6 for FB in scenario #2 and to 28.1, 23.7, 19.4, and 26.26 cm for DB and 13.3, 20.6, 21.6, and 20.8 cm for FB.

The results of using five monitoring locations to estimate leaching

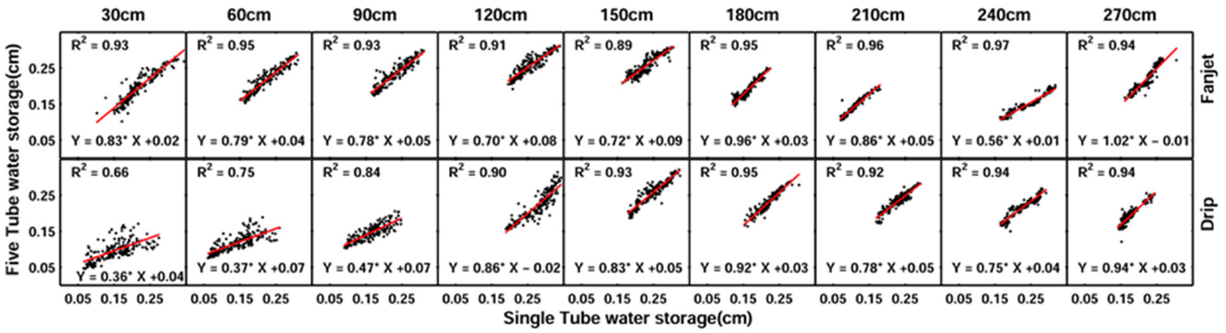

Fig. 6. Correlation between area-averaged soil moisture using single probe and 5-probes setup at different depths in FT and DT locations.

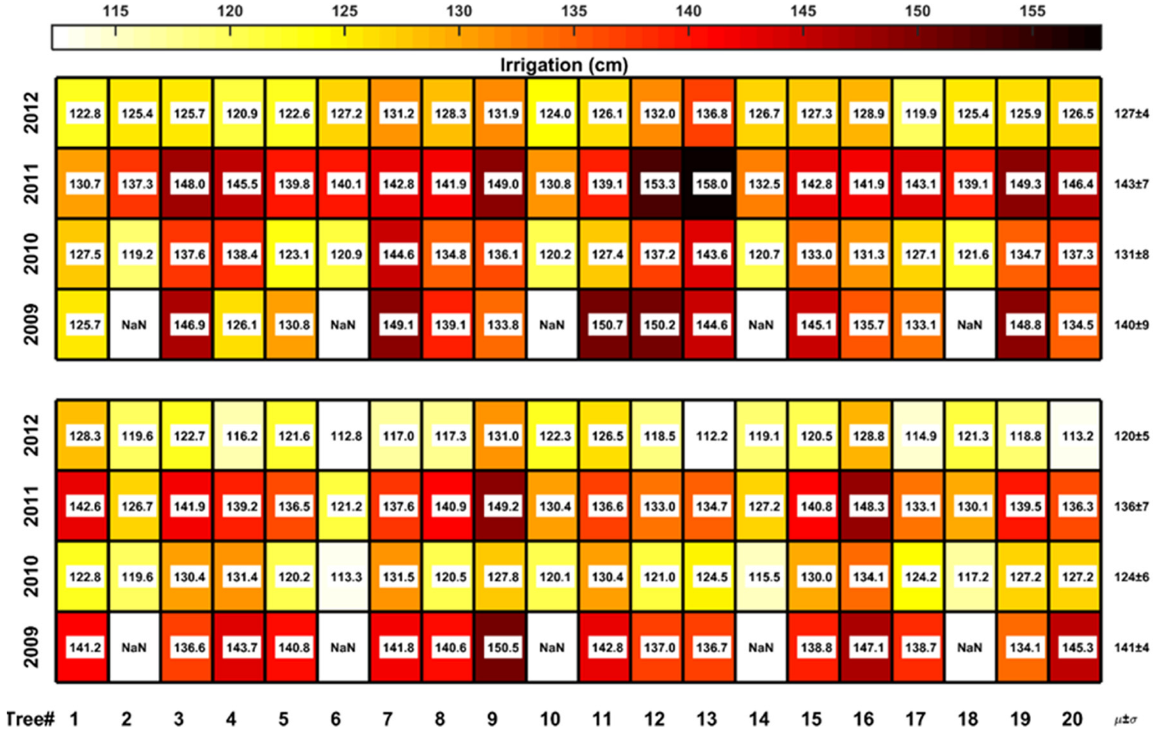

Fig. 7. Annual values of IW for each of the monitoring trees in drip and micro-sprinkler irrigation blocks during monitoring period of 2009–2012. Data on the right side shows the annual average and standard deviation of IW of each irrigation block for each year. Soil moisture was not monitored for trees #2, 6, 10, 14, and 18 in 2009.

show an average uncertainty ranges of 7.7 and 5.6 cm for DB and DF, respectively. These values are for scenario #1 and are the results of heterogeneity in soil properties and layering. Adding the effect of non-uniformity in IW in scenario #2 increases the uncertainty ranges to 16.3 and 14.7 cm. Scenario #3 introduces the effect of non-uniformity in plant water uptake (i.e., ET_a^T) which results in additional increases in uncertainty range to 24.4 and 19.1 cm for DB and DF, respectively. Therefore, the number of monitoring points and their location in the

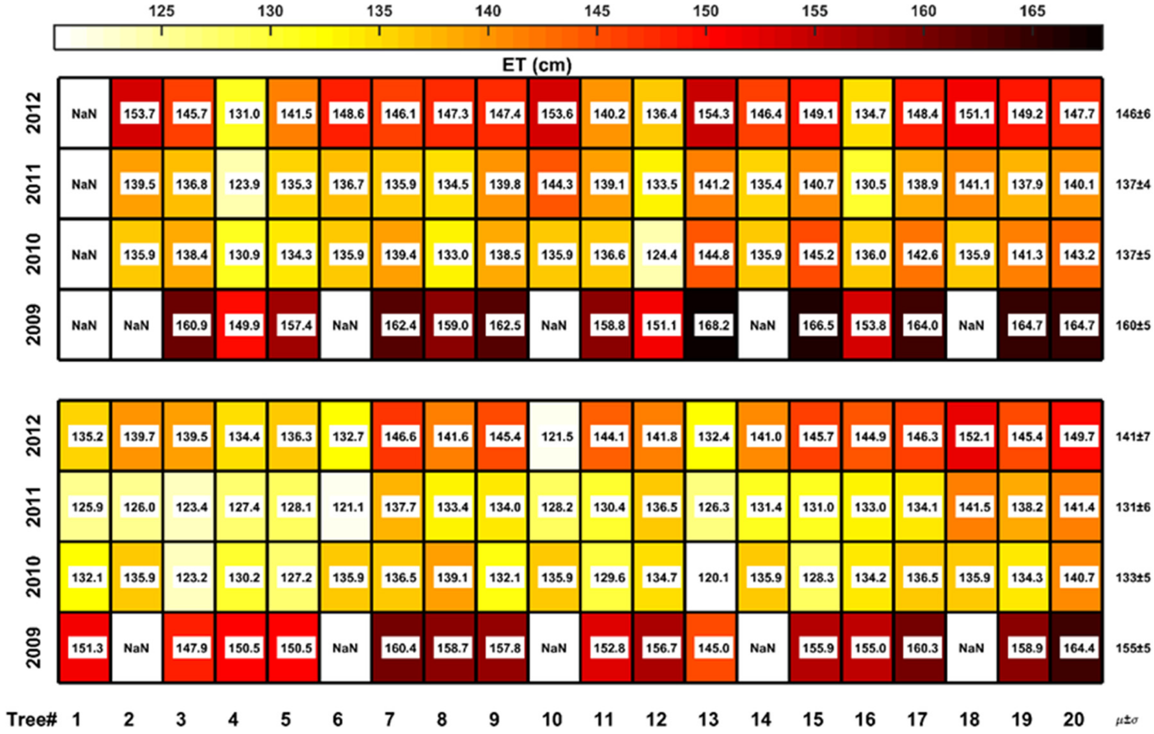

Fig. 8. Annual values of ET for each of the monitoring trees (adj-ET_a^T) in drip and micro-sprinkler irrigation blocks during monitoring period of 2009–2012. Data on the right side shows the annual average and standard deviation of ET of each irrigation block for each year. Soil moisture was not monitored for trees #2, 6, 10, 14, and 18 in 2009. The adj-ET_a^T was not determined for Tree #1 in DB.

Table 1
Average of annual leaching (cm) estimated under drip and micro-sprinkler irrigation blocks using only 1- ΔS, 2- ΔS and IW, and 3- ΔS, IW, and ET as the locally measured parameters.

		2009	2010	2011	2012
Drip	Local ΔS	−1.73	0.58	0.04	4.99
	Local ΔS + IW	1.26	13.24	14.2	6.3
	Local ΔS + IW + ET	0.5	11.7	10.5	4
Micro-sprinkler	Local ΔS	−8.22	−0.27	0.94	7.04
	Local ΔS + IW	−3.8	6.02	8.83	1.7
	Local ΔS + IW + ET	−1.24	7.63	10.76	−0.2

field for calculation of ΔS as well as their associated local IW and ET are key factors affecting the estimation of leaching at field scale.

4. Summary and conclusion

The leaching below the root zone of an almond orchard was studied at spatial scales of irrigation block and tree using the general soil water balance approach (WB). The study area was divided into two irrigation blocks of drip and micro-sprinkler (micro-sprayer) or fanjet irrigation systems. Textural properties of a 300 cm soil profile were evaluated at each of the 40 monitoring locations. The annual P, ET, IW, and ΔS for 40 monitoring locations for period of February 2009 to December 2012 were analyzed and the corresponding annual leaching using the WB approach were estimated.

The soil heterogeneity of this study site at both tree and block scales was shown to be a major contributor to the uncertainty in estimation of ΔS and as a result leaching. It was shown that ΔS is highly influenced by the extent of monitoring depth, the location and number of monitoring points at both tree and irrigation block scales. At irrigation block scale, the effect of locally-measured IW and estimated ET on the spatial variation of leaching was evaluated and it was shown that using local values increase the uncertainty of estimated leaching.

We conclude that 1) ΔS plays a significant role in estimation of leaching and thus should not be considered as negligible, even on annual basis in areas where winter rainfall is limited and soil profile is not brought to the field capacity during the winter, 2) there is large uncertainty in estimation of ΔS in micro-irrigation systems due to the localized water application and non-uniform re-distribution of water in the soil and it highly depend upon the irrigation management, soil properties, and number, location, and extended depth of monitoring point, and 3) the assumption of uniform ET at field scale introduces large uncertainty in estimated leaching which may vary between different fields and crop type, and suggest employing other techniques such as remote sensing to quantify the field scale variation of ET.

We emphasize here that variables such as soil heterogeneity and layering, non-uniformity of water application, interception of rainfall by tree canopy, variation in canopy size as well as root distribution, and heterogenous preferential flow path contribute to the complexity of uncertainty in leaching such that it is very difficult, if not impossible, to precisely evaluate it at both tree and irrigation block scales. We note here that the purpose of this study was neither to undermine the applicability of WB approach in estimation of leaching nor to present a precise estimation of its uncertainty. The purpose of this study was to present one of the possible scenarios of uncertainty in leaching estimated through Water Balance approach and more importantly to emphasize the need for acknowledging the existence of these uncertainties when using this approach to estimate leaching. It is especially important when the uncertainty (noise) in field-scale leaching dominate its temporal variation (signal). We also note that the overestimation of leaching results in unjustified change in irrigation management to reduce the loss of water, thereby introducing stress to plant and/or salt accumulation in the root zone. In case of the underestimation of leaching, it results in unjustified change in irrigation management to avoid stress to plant and/or salt accumulation in the root zone, thereby losing water and also leaching nutrient below the root zone.

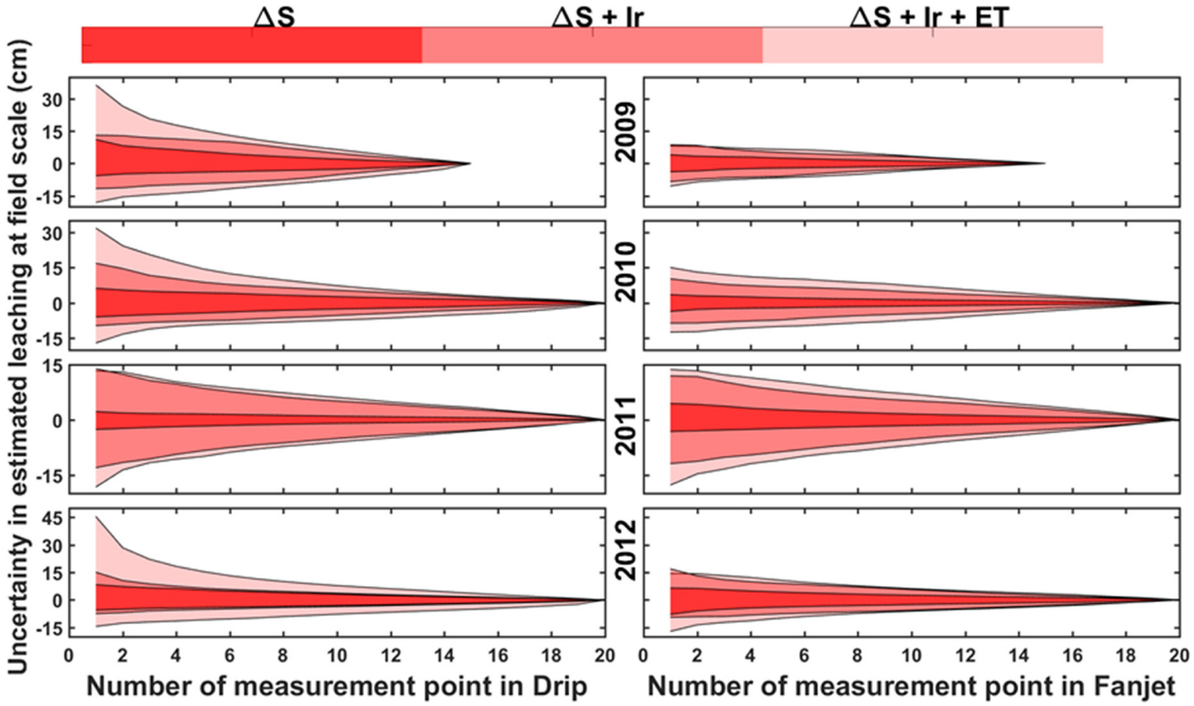

Fig. 9. The effect of number and location of monitoring points across drip and micro-sprinkler irrigation blocks and their associated local IW and ET in estimation of leaching below 270-cm deep soil profile. The shaded area shows the uncertainty range around the average in estimation of leaching (Y axis) for number of monitoring locations (X axis). Different colors of the shaded area from dark to light red represent different scenarios of estimated leaching using only 1- ΔS (dark red), 2- ΔS and IW(red), and 3- ΔS, IW, and ET (light red) as the locally measured parameters (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

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References

Assouline, S., Russo, D., Silber, A., Or, D., 2015. Balancing water scarcity and quality for sustainable irrigated agriculture. Water Resour. Res. 51, 3419–3436.

Baldocchi, D.D., Hincks, B.B., Meyers, T.P., 1988. Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods. Ecology 69, 1331–1340.

Barros, R., Isidoro, D., Aragüés, R., 2011. Long-term water balances in La violada irrigation district (Spain): I. Sequential assessment and minimization of closing errors. Agric. Water Manage. 102, 35–45.

Couvreur, V., Kandelous, M.M., Sanden, B.L., Lampinen, B.D., Hopmans, J.W., 2016. Downscaling transpiration rate from field to tree scale agric. For. Meteorol. 221 (2016), 71–77.

Cunnew, K., Edraki, M., 2008. Estimation of root zone drainage from a chardonnay vineyard - a comparison of methods. In: In: Goodwin, I., Oconnell, M.G. (Eds.), Proceedings of the Fifth International Symposium on Irrigation of Horticultural Crops Vol 1. International Society Horticultural Science, Leuven, pp. 209–215.

Greenwood, K.L., Lawson, A.R., Kelly, K.B., 2009. The water balance of irrigated forages in northern Victoria, Australia. Agric. Water Manage. 96, 847–858.

Grieve, C.M., Grattan, S.R., Maas, E.V., 2012. Plant Salt Tolerance. American Society of Civil Engineers.

Hanson, B., Hopmans, J.W., Šimůnek, J., 2008. Leaching with subsurface drip irrigation under saline, shallow groundwater conditions. Vadose Zone J. 7, 810–818.

Hanson, B.R., May, D.E., Simunek, J., Hopmans, J.W., Hutmacher, R.B., 2009. Drip irrigation provides the salinity control needed for profitable irrigation of tomatoes in the San Joaquin Valley. California Agric. 63.

Highnett, C., Evett, S.R., 2002. 3.1.3.10 neutron thremalization. In: Dane, J.H., Topp, C.G. (Eds.), Methods of Soil Analysis: Part 4 Physical Methods. Soil Science Society of America, Madison, WI, pp. 501–521.

Lafond, J.A., Éliane, B.P., Caron, J., Guillaume, T.R., 2014. Evaluating fluxes in histosols for water management in lettuce: a comparison of mass balance, evapotranspiration and lysimeter methods. Agric. Water Manage. 135, 73–83.

Pitman, M., Läuchli, A., 2002. Global impact of salinity and agricultural ecosystems. In: Läuchli, A., Lüttge, U. (Eds.), Salinity: Environment - Plants - Molecules. Springer, Netherlands, pp. 3–20.

Qassim, A., Dunin, F., Bethune, M., 2008. Water balance of center pivot irrigated pasture in northern Victoria, Australia. Agric. Water Manage. 95, 566–574.

Sanden, B., Brown, P., Snyder, R., 2012. New insights on Water management in almonds. Amer. Soc. Agron. Calif. Chap. Division of Agriculture and Natural Resources. University of California, Davis, pp. 88–93.

Shapland, T.M., McElrone, A.J., Paw, U.K.T., Snyder, R.L., 2013. A turnkey data logger program for field-scale energy flux density measurements using eddy covariance and surface renewal. Ital. J. Agrometeorol. 18, 5–16.

Smith, P., Gregory, P.J., van Vuuren, D., Obersteiner, M., Havlík, P., Rounsevell, M., Woods, J., Stehfest, E., Bellarby, J., 2010. Competition for land. Philos. Trans. R. Soc. Lond. B: Biol. Sci. 365, 2941–2957.

Thornthwaite, C.W., Mather, J.R., 1955. The Water Balance. Publications in Climatology, pp. 86.

Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences 108, 20260–20264.

WWAP, 2009. United Nations World Water Development Report 3: Water in a Changing World. World Water Assessment Programme), Paris/London.

Xu, C.Y., Singh, V.P., 1998. A review on monthly Water balance models for Water resources investigations. Water Resour. Manage. 12, 20–50.