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Simplified Forms of Deep Percolation Estimation Method below the Crop Root Zone for Silt-Loam Soils

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Deep percolation (DP) is an important variable in hydrologic cycle and water balance analyses. It also is important when quantifying crop water use (evapotranspiration), irrigation requirements (IR), recharge analyses, nutrient and micronutrient movement in the soil profile and below the crop root zone, and other analyses. Depending on several factors, DP can occur from irrigated or rainfed fields. Despite its importance, DP is a very difficult variable to measure or quantify. In most cases, this variable is assumed to be negligible or zero in practice because of difficulties in quantifying it. Similar to surface runoff, when DP is assumed to be negligible or zero, any error or uncertainty in DP could be lumped into the ET category and/or IR calculations. The result can be erroneous ET and IR estimates. This Extension Circular provides a simplified method to estimate DP that can provide reasonable estimates for practical applications.

In simplest terms, DP can be defined as the amount of soil-water that percolates below the crop's effective root zone. A schematic representation of DP and other influencing factors is presented in *Figure 1*. In some cases, the terms DP, vertical drainage, and seepage (or deep seepage) are used interchangeably. The amount of water undergoing deep percolation below the crop root zone depends on many factors, including soil physical characteristics; irrigation management and irrigation method; surface residue cover; precipitation pattern (amount, timing, intensity, and duration); field slope; soil-water status before the precipitation and/or irrigation event occurs; soil management (tillage) practices; and other factors.

Coarse-textured soils (e.g., sandy, sandy loam soils) usually have high infiltration rates, which can result in

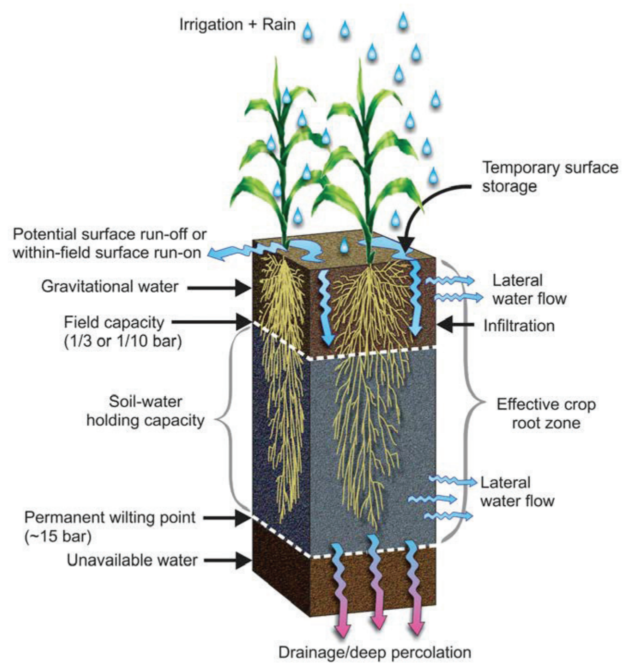

Figure 1. Schematic representation of effective crop root-zone depths and factors that affect deep percolation.

higher DP compared with fine-textured soils under the same amount of irrigation and/or precipitation. Deep percolation is, in general, more of a concern in humid and subhumid climates due to the greater amount of precipitation as well as lower evaporation and evapotranspiration rates from the soil surface compared with arid and semiarid climates where the potential for DP is usually lower.

The method of irrigation can have substantial impact on DP. Subsurface drip and center pivot irrigation methods

Table 1. Generalized Effective Crop Root-Zone Depths for Select Agronomic Crops.

Crop	Average Effective Root-Zone Depth (ft)	Crop	Average Effective Root-Zone Depth (ft)
Alfalfa for Hay	3–6	Red Clover	1.5
Alfalfa for Seed	3–10	Rice	1.5–3
Barley	2.5–5	Rye	2–3
Bluegrass	1.5	Snap beans	1.5
Bromegrass	2	Soybean	3
Canola	3–5	Spring Wheat	2.5–5
Cotton	3–4	Sudangrass	2
Dry Bean	2.5–3	Sugarbeet	3
Field Corn	4	Sunflower	2.5–5
Grain Sorghum	3–6	Sweet Clover	2
Green Bean	1.5–2.5	Sweet Corn	2–3
Millet	2	Sweet Sorghum	3–6
Oats	2.5–5	Turnips	1.5
Potatoes	1.5–2	Vineyard	3–6
Pumpkins	2	Watermelon	2
Radish	0.5	Winter Wheat	2–3
Rapeseed	3–5		

result in substantially lower DP compared with surface irrigation methods due to the mechanics and nature of the surface (gravity) irrigation. Eliminating the occurrence of DP with any irrigation method is almost physically impossible and/or economically unfeasible. However, a properly designed and operated irrigation method with correct irrigation, soil, and crop management practices can help to minimize DP.

By definition, the amount of DP is also a function of a crop's effective root depth. Thus, a good knowledge of the effective root-zone depth is needed for accurate determination of DP. In general, the amount of DP for deep-rooted crops (e.g., corn, sorghum) is lower than for short-rooted crops. Effective crop root-zone depths for some of the agronomic crops are provided in *Table 1* (USDA-NRCS, 2005; FAO-56, 1998; FAO-24, 1977). These values are generalized for different soils and can change with soil, crop, water, and other management practices. For some of the crops, the average values from FAO-56, FAO-24, USDA-NRCS (2005), and local knowledge have been used in *Table 1*.

Simplified Method for Estimating Deep Percolation

Estimating DP, in most cases, is not a straightforward process and options are limited for estimating this variable. As is the case with surface runoff, the existing methods to estimate DP are complex and require parameters, variables, and/or coefficients that are difficult to gather. In a research setting, it may be possible to measure or quantify the variables and parameters that are used to quantify DP. However, they can be very difficult to obtain by practitioners in practical applications, which can make the application of DP estimation procedures less applicable in practice. Therefore, a simplified method is needed to quantify DP to increase the likelihood of taking this variable into account when conducting soil-water balance analyses in practical applications.

The author has been conducting extensive field research experiments using center pivot and subsurface drip irrigation systems to measure ET, irrigation requirements, hydrologic balances, and related variables for many cropping and natural systems in different parts of Nebraska for 13 years, from 2004 to 2016. Over the years, DP amounts have also been quantified for different cropping systems under center pivot and subsurface drip irrigated fields. Using these long-term datasets, a simplified method was developed to estimate DP.

To develop this method, DP values from various field research projects conducted since 2004 were estimated by a daily soil-water balance approach using a computer program written in Microsoft Visual Basic (Bryant et al., 1992). The inputs to the computer program are weather variables (including air temperature, incoming shortwave irradiance, relative humidity, wind speed, and precipitation) on a daily time step, irrigation dates and amounts, and water content in the soil profile at crop emergence and at the end of the season. Inputs also include crop- and site-specific information such as planting date, crop maturity date, soil parameters, and maximum crop rooting depth (Bryant et al., 1992; Payero et al., 2009; Irmak, 2015a and b). In the simplified DP estimation method development, DP values quantified from different cropping systems over the years were correlated to the total amount of water (growing season precipitation + irrigation) supplied to the center pivot and subsurface drip irrigated fields.

Deep Percolation from Combined Center Pivot and Subsurface Drip Irrigated Fields

The relationship between precipitation + irrigation versus DP amounts for a Hastings silt-loam soil at Clay Center, Nebraska, is presented in *Figure 2*, in which the data from center pivot and subsurface drip irrigated cropping systems are combined. In *Figures 3* and *4*, data were separated for center pivot and subsurface drip irrigated fields individually. The author has been conducting research of the center pivot irrigation system on 40 acres, primarily with corn and soybean, from 2004 to 2016. The subsurface drip irrigation system-1 (SDI-1; 34 acres) and subsurface drip irrigation system-2 (SDI-2; 11 acres) were researched with corn, soybean, and winter wheat from 2004 to 2016. *Figures 2*, *3*, and *4* present the relationships in English units and *Figures 5*, *6*, and *7* present the same data and relationships in standard (metric) units.

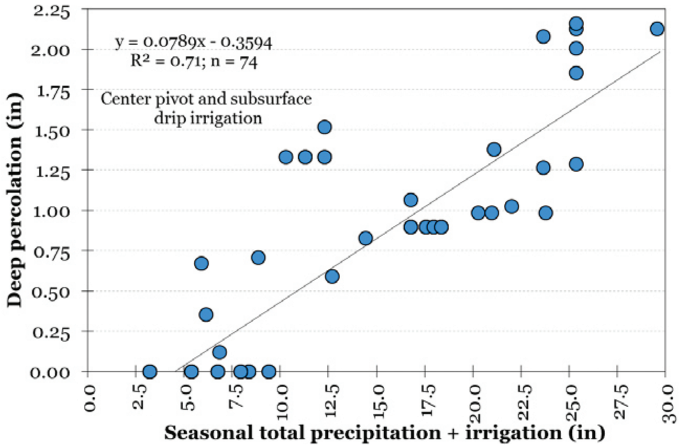

Figure 2. Relationship (in English units) between deep percolation (DP) below the crop root zone and growing season precipitation + irrigation. The relationship is developed from long-term data measured for row crops (e.g., corn, soybean, winter wheat) under silt-loam soils at Clay Center, Nebraska, from 2004 to 2016.

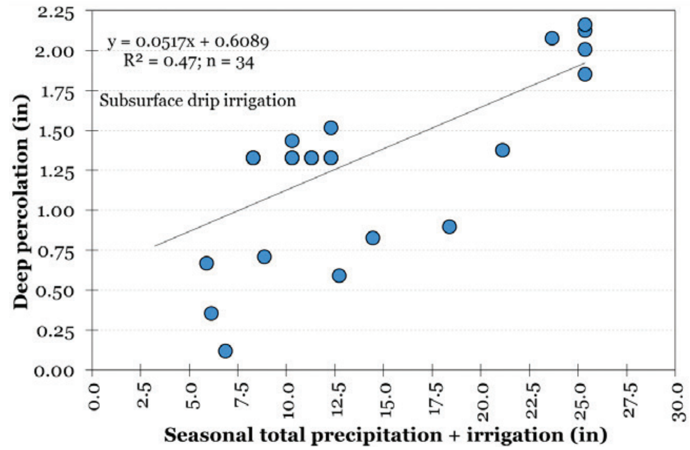

Figure 3. Relationship (in English units) between deep percolation (DP) below the crop root zone and growing season precipitation + irrigation for subsurface drip irrigated row crops. The relationship is developed from long-term data measured for row crops (e.g., corn, soybean, winter wheat) under silt-loam soils at Clay Center, Nebraska, from 2004 to 2016.

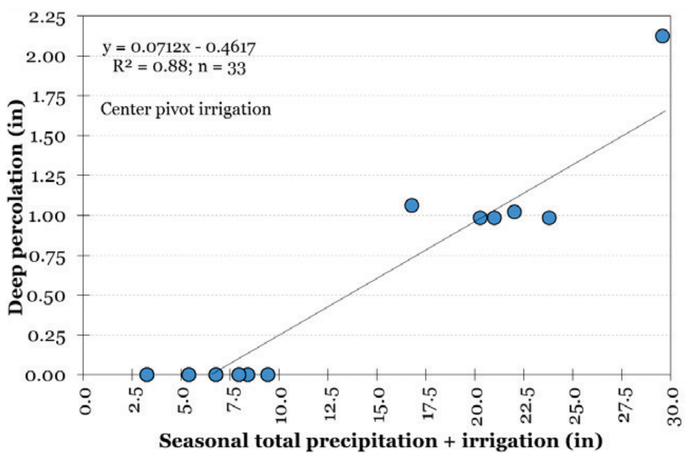

Figure 4. Relationship (in English units) between deep percolation (DP) below the crop root zone and growing season precipitation + irrigation for center pivot irrigated row crops. The relationship is developed from long-term data measured for row crops (e.g., corn, soybean) under silt-loam soils at Clay Center, Nebraska, from 2005 to 2016.

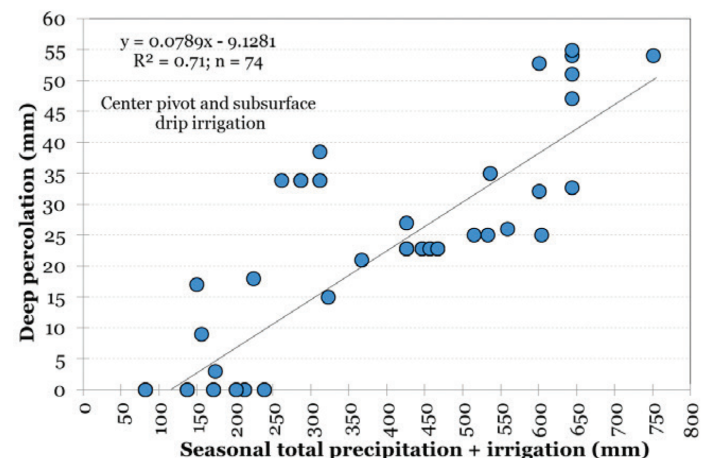

Figure 5. Relationship (in metric units) between deep percolation (DP) below the crop root zone and growing season precipitation + irrigation. The relationship is developed from long-term data measured for row crops (e.g., corn, soybean, winter wheat) under silt-loam soils at Clay Center, Nebraska, from 2004 to 2016.

The combined center pivot and subsurface drip irrigation data presented in *Figure 2* signifies a strong correlation between precipitation + irrigation and DP with a coefficient of determination (R^2) of 0.71. This indicates that 71 percent of the variability in DP was explained by precipitation + irrigation amounts alone for these experimental conditions. Deep percolation increased linearly with the increase in precipitation + irrigation. There is some scatter in the distribution of the data, but overall, the relationship presented in *Figure 2* [DP = 0.0789•(P+IR)–0.3594; DP = amount of deep percolation below the crop root zone in inches; P = precipitation in inches; IR = irrigation amount applied in inches] is strong and can be very useful to estimate average DP only as a function of precipitation + irrigation. Depending on the precipitation timing and amount, as well as the irrigation water applied to different treatments and cropping systems over the years, DP showed variation for the same amount of water supplied as expected (*Figure 2*).

For some of the precipitation + irrigation amounts, DP occurred, but for some other cases, DP did not occur for the same or similar amount of water supplied. This is due to several reasons, including initial soil moisture in the crop root zone just before and at the time of irrigation and/or precipitation, the treatment's irrigation level, precipitation and/or

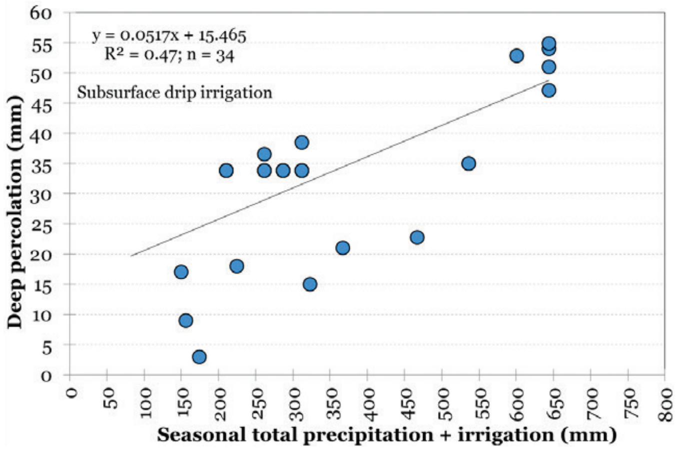

Figure 6. Relationship (in metric units) between deep percolation (DP) below the crop root zone and growing season precipitation + irrigation for subsurface drip irrigated row crops. The relationship is developed from long-term data measured for row crops (e.g., corn, soybean, winter wheat) under silt-loam soils at Clay Center, Nebraska, from 2004 to 2016.

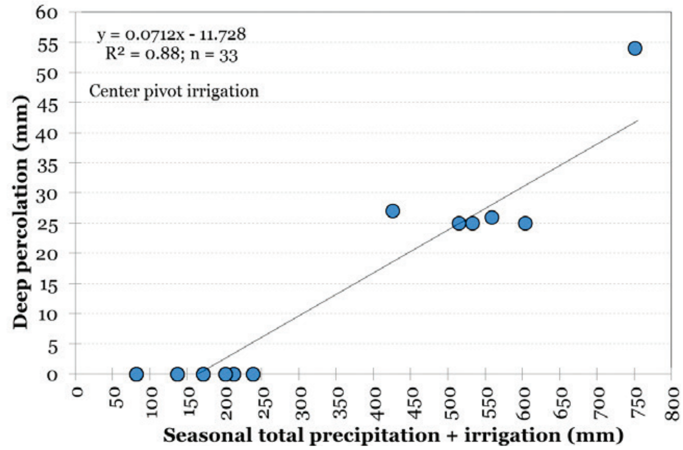

Figure 7. Relationship (in metric units) between deep percolation (DP) below the crop root zone and growing season precipitation + irrigation for center pivot irrigated row crops. The relationship is developed from long-term data measured for row crops (e.g., corn, soybean) under silt-loam soils at Clay Center, Nebraska, from 2005 to 2016.

irrigation timing, duration, and intensity during the growing season, the irrigation method and other factors that resulted in different DP amounts for the same or similar precipitation + irrigation amounts.

Deep Percolation from Only Subsurface Drip and Center Pivot Irrigated Fields

The correlation between precipitation + irrigation versus DP for only subsurface drip irrigated fields (*Figure 3*) is marginal ($R^2 = 0.47$). This is because there are several cases where very small and large DP amounts were observed for similar precipitation + irrigation amounts. This is likely due to the aforementioned reasons, primarily related to the treatment effect and differences. For example, for 12.7 inches of precipitation + the irrigation amount, variations of DP values of 0.60, 1.3, and 1.5 inches were observed.

While the number of observations in *Figure 3* is rather high (n = 34), all the data points are not visible because many data points with different precipitation + irrigation amounts had the same or very similar DP values, and all these data points fell on top of each other as one data point. The equation developed in *Figure 3* [DP = 0.0517•(P+IR) + 0.6089; DP = amount of DP in inches; P = precipitation in inches; IR = irrigation amount in inches)] could be used for estimating DP specifically from subsurface drip irrigated fields for practical purposes.

When the relationship between DP and precipitation + irrigation for only center pivot irrigation systems is considered, the relationship is also very strong (*Figure 4*) with an R^2 of 0.88 with 33 data points. There is some scatter in the distribution of the data, but this is expected because of different treatments with the same or similar precipitation + irrigation amounts. This results in different DP values for the same or different precipitation + irrigation amounts. Consequently, there were similar DP amounts quantified from 2004 to 2016 under different cropping systems, treatments, and years that had different irrigation levels and different precipitation timing, intensity, duration, and amounts. The amount of DP ranged from 0 to 2.1 inches and the amount of precipitation + irrigation ranged from 3.2 to about 30 inches. The equation developed in *Figure 4* [DP = 0.0712•(P+IR)–0.4617; DP = amount of deep percolation below the crop root zone in inches; P = precipitation in inches; IR = irrigation amount in inches] could be used for estimating DP specifically from center pivot irrigated fields for practical purposes.

Since subsurface drip and center pivot are two different irrigation methods, the amount of DP expected from these two fields can vary due to several reasons and that causes scatter in the data in *Figure 2*. One of the reasons is the surface soil wetness. With center pivot irrigation the entire soil surface is wetted during an irrigation event, whereas the topsoil (approximately top 6–8 inches) in the subsurface drip irrigated field remains very dry even during and after an irrigation event (in the absence of precipitation). Thus, for the same irrigation and/or precipitation amount, the amount of water that can be stored in the soil profile is different. This results in different DP amounts between the two different irrigation methods under the same or similar total amount of water supplied.

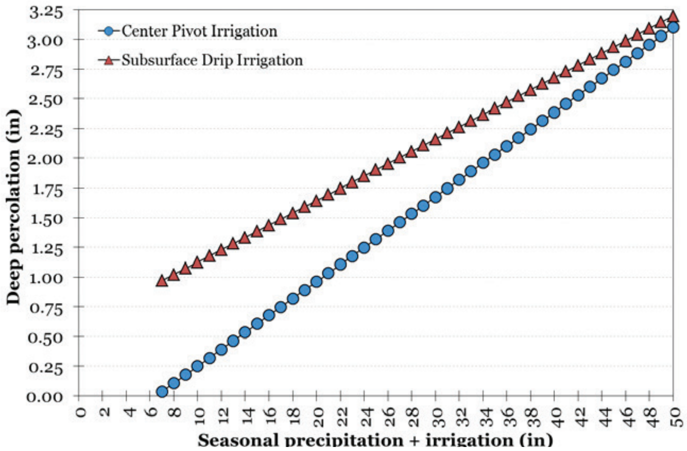

Figure 8. Comparison of deep percolation (DP) below the crop root zone (in English units) between subsurface drip and center pivot irrigated fields. The equations presented in *Figure 3* for subsurface drip and *Figure 4* for center pivot irrigation systems were solved for different amounts of precipitation + irrigation to estimate DP.

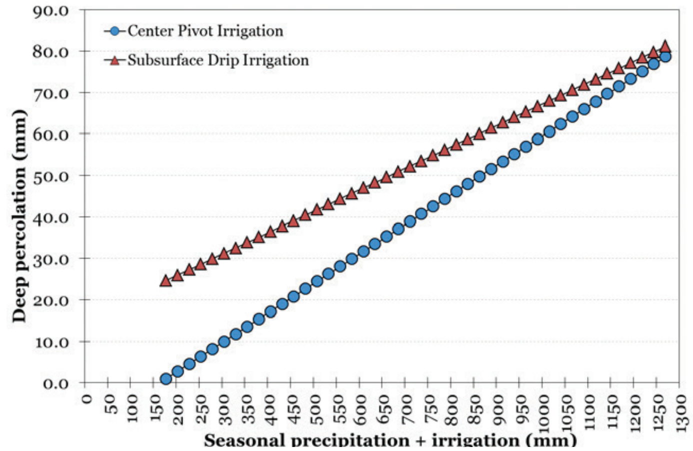

Figure 9. Comparison of deep percolation (DP) below the crop root zone (in standard metric units) between subsurface drip and center pivot irrigated fields. The equations presented in *Figure 3* for subsurface drip and *Figure 4* for center pivot irrigation systems were solved for different amounts of precipitation + irrigation to estimate DP.

Comparison of Deep Percolation from Center Pivot versus Subsurface Drip Irrigated Fields

Because the topsoil is not wetted with the subsurface drip irrigation system, about 8 inches of the top soil layer remains dry (except when it rains) that can hold water before water moves downward and potentially contributes to DP. Hasting silt-loam soil can hold about 2.2–2.3 inches of water per foot of soil layer. Thus, the top 8-inch soil layer can hold about 1.5 inches of soil-water before it moves downward.

In center pivot irrigation, the soil profile is wetted from the top. With subsurface drip irrigation, the drip laterals (tapes) are usually installed from 12 to 14 inches below the soil surface (installation depth depends heavily on soil textural characteristics and soil physical properties). This can be beneficial for reducing surface runoff from subsurface drip irrigated fields. The drip tapes might contribute to increased deep percolation with the subsurface drip irrigation compared with center pivot.

To further evaluate the potential DP amount differences between the two, equations were developed for subsurface drip irrigation only (*Figure 3*) and center pivot only (*Figure 4*). The equations were solved for estimating DP amounts for every 1 inch increase in precipitation + irrigation amounts. These results are presented in *Figure 8* (in English units). The same data and relationship are presented in metric units in *Figure 9*.

For the same precipitation + irrigation amounts, the subsurface drip irrigation had greater DP than the center pivot system for several reasons. For example, for 24 inches of precipitation + irrigation, the DP values were 1.25 and 1.85 inches (0.60 in difference) for the center pivot and subsurface drip irrigation systems, respectively. At a higher precipitation + irrigation range, the difference in DP between the two systems gets smaller. For example, when the precipitation + irrigation amount was increased to 34 inches, the DP values were 1.95 and 2.30 inches (0.35 inch difference) for the center pivot and subsurface drip irrigation, respectively. For the entire precipitation + irrigation range (from zero to 50 inches), the DP is, on average, about 0.50 inch greater in the subsurface drip irrigated fields than in the center pivot fields.

While subsurface drip irrigation resulted in slightly greater DP than the center pivot system, this would not be the case at all times. The lower DP values with center pivot irrigation, compared with the subsurface drip method for the same or similar precipitation + irrigation amounts, are partially due to the center pivot DP data, which were collected during dry, wet, and average years.

In contrast, most of the subsurface drip irrigated field data were collected during very wet years (2007, 2008, 2011, and 2014), resulting in greater DP. For example, the growing season precipitation amounts alone were 26, 26.9, 17.4, and 22.7 inches during the 2007, 2008, 2011, and 2014 growing seasons of April 15 to October 15, respectively. If the precipitation + irrigation versus DP relationship for the subsurface drip irrigated field had been developed for dry, average, and wet years (as was the case for the center pivot field), the amount of DP for the same or similar precipitation + irrigation amounts would have been expected to be similar between the two irrigation methods.

Another reason the subsurface drip irrigation DP values are greater than those in the center pivot fields is that the drip tapes were installed 14 inches deep in the soil profile, which may have resulted in a greater DP amount in the subsurface drip irrigation fields compared with the center pivot fields for the same or similar precipitation + irrigation amount. When irrigation is applied in the center pivot fields, the soil-water has to move through the top 12- to 14-inch soil layer to contribute to DP. However, when irrigation is applied in the subsurface drip irrigation fields, the soil-water does not need to move through that top layer, and this may result in slightly greater DP in these fields. However, overall results indicate that the DP amount from both methods is not substantially different for the same or similar precipitation + irrigation amounts.

Summary

The data and relationships presented in this publication were developed for typical corn, soybean, and winter wheat cropping systems grown under silt-loam soils in a 30-inch row spacing (10-inch row spacing for winter wheat) with a 0–1.5 percent field slope. The typical growing season total irrigation application amount with the center pivot ranged from zero for rainfed treatments to 1.25–1.40 inches per revolution for fully irrigated treatments on a five-day or weekly basis. The irrigation application for the subsurface drip system ranged from zero for rainfed treatments to 1.00–1.25 inches per week for fully irrigated treatments.

The simplified DP method indicated that under the environments studied during long-term research at Clay Center very little difference exists in deep percolation between subsurface drip irrigation and center pivot irrigation. On average, the DP was only 0.5 inches more for the subsurface drip irrigation system for 0 to 50 inches of precipitation plus irrigation range. The DP data for both irrigation systems represent dry, average, and wet years encountered from 2004 to 2016. However, for the SDI precipitation + irrigation versus data, most of the data points were quantified during very wet years (2007, 2008, 2011, and 2014). This resulted in greater DP than might be observed under normal and dry years. Years 2007, 2008, 2011, and 2014 were some of the wettest growing seasons in recent historical records at Clay Center.

While the relationships developed and presented in this study do not explicitly account for other variables that affect DP, during the quantification of DP values in various research projects from which the datasets were used to develop these relationships, the other DP influencing variables were accounted for. Thus, the relationships developed in this study implicitly account for other DP influencing variables.

The precipitation + irrigation versus DP relationships presented in this publication represent typical row crop production systems. These relationships can be used as simplified methods to estimate DP for center pivot and subsurface drip irrigated row crops (corn, soybean, winter wheat) with a typical crop root-zone depth of 3 to 4 feet for silt-loam soils. While these relationships do not account for other variables that influence DP, they can be useful tools in practice as they do not use complex formulas and/or approaches and do not require additional variables or parameters that can be very difficult to obtain to estimate DP. Significant attention to soil, crop, and irrigation management practices, soil type, as well as climatic conditions, must be taken into account when the data presented and the simplified method developed in this study are extrapolated or used beyond their boundaries to estimate DP.

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