Optimizing Overhead Irrigation Droplet Size for Six Mississippi Soils

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Abstract: Optimizing overhead irrigation practices will ensure that water loss is minimized, and each unit of water is used most effectively by the crop. In order to optimize overhead irrigation setup, a study was conducted over two years in Mississippi to quantify the optimal overhead irrigation duration and intensity for six soil types commonly found in row-crop production regions in the state. Each soil type was transferred to containers and measured for total water infiltration and water infiltration over time using a two-nozzle rainfall simulator in a track sprayer. The rainfall simulator was calibrated to apply 2.1 mm of water per minute. The rainfall simulator ran on a 2.4 m track for 90 s, with 3.2 mm total water applied during that time. After the 90 s overhead irrigation event, each container was undisturbed for 150 s and assessed for irrigation penetration through the soil profile. Commercially available irrigation nozzles were measured for droplet size spectrum. Results showed that across soil type, organic matter was the primary factor affecting water infiltration through the profile, followed by soil texture. Irrigation nozzle volumetric median droplet sizes ranged from 327 µm to 904 µm. The results will improve overhead irrigation setup in Mississippi, improving irrigation water use efficiency and reducing losses from soil erosion over the application of water and reduced crop yield.

Keywords: water use efficiency; droplet size spectrum; water infiltration

1. Introduction

Improving water use efficiency is a critical long-term goal for production agriculture in the Mid-Southern United States. In 2017, Mississippi had 734,322 hectares under irrigation, a 10% increase in total irrigated hectares from the 2012 U.S. Census of Agriculture [1]. Mississippi has 82% of its irrigated hectares under furrow irrigation, 17.5% under sprinkler irrigation, and 0.5% under drip or other low-flow micro irrigation methods [2]. Furrow irrigation is less uniform compared to overhead irrigation (center-pivot or lateral systems) [3–6]. Given that 82% of irrigated hectares in Mississippi are under furrow irrigation, this represents a significant potential for reduced water application efficiency. Recent evidence suggests that groundwater, especially in the Mississippi River Valley Alluvial Aquifer, is being withdrawn at an unsustainable rate [7,8].

The implication of improved water application and water use efficiency can lead to improved yields. Corn (Zea mays L.) yield has been shown to increase with improved crop water use efficiency and irrigation events [9]. Designing irrigation systems to apply optimized water volumes will drastically
improve corn yield [10]. Shifting from a lower water efficiency system like furrow irrigation will reduce total water applied, improve crop yield, and improve the long-term sustainability of the system. Beyond improving water use efficiency, shifting from furrow irrigation to overhead irrigation will dramatically reduce soil erosion. Soil erosion reduces productivity of agricultural land both in the short and long-term as well as overall land value [11]. Selecting the optimal sprinkler nozzle type for overhead irrigation systems can also improve the ability of water droplets to infiltrate through the soil profile.

As the kinetic energy decreases per droplet, water infiltration into the soil profile prior to ponding is greater [12]. The physical properties of a surface have a significant effect on the ability of the impacting droplet to deposit, bounce, or shatter, thereby repeating the deposit, bounce, or shatter process [13–15]. The size of the impacting droplet and surface physical properties will influence droplet deposition behavior [13,16]. Deposition surfaces of soils differ in wettability, which further affect the spreading and retention of a droplet [16]. Selecting a sprinkler to deliver optimal water deposition for a given soil type can prevent losses due to erosion or evaporation [17–19]. Water droplet impacts on the soil surface can dislodge soil particles and result in a significant amount of kinetic energy released upon impact, up to 289 kPa [20]. Impaction on the soil surface occurs with all depositing droplets, but impaction cratering is a more useful measurement than droplet splash [21]. The force from impacting water droplets can dislodge soil aggregates and initiate soil erosion [22–27]. Soil aggregate dissolution, induced by soil internal forces, dislodges small particles, which leads to the necessary components for splash erosion to occur [28]. Splash erosion is defined as soil aggregates breaking up into smaller particles [24,29]. Once soil aggregates breakdown, infiltration rate reduces due to crust formation on the surface and soil pore clogging, which leads to surface runoff produced by soil and water transport [19,30–36].

Measuring the droplet distribution size of sprays for pesticide application is a common practice in agriculture [37,38]. Droplet size measurements for pesticide applications are made using various real-time measurements [39], including laser diffraction [40], phase-doppler interferometry [41], or droplet image analysis [42]. Measuring droplet size distributions of sprinklers and nozzles used in overhead irrigation has been studied in previous research, but not using any one of the above methods commonly used to measure pesticide sprays [43–47]. In order to better understand the effect that sprinkler selection has on optimizing an overhead irrigation setup in Mississippi, the following objectives were to: (I) Determine the optimal overhead irrigation duration for six common soil types found in row-crop production regions in Mississippi, (II) determine the optimal overhead irrigation intensity (defined as unit of water per unit of time) for six Mississippi soil types, and (III) use a droplet image analysis system in the field to quantify the droplet spectrum for five sprinkler types that are commercially available in Mississippi. Objectives were designed in order to best provide recommendations to growers in the state for optimizing their overhead irrigation setup to minimize water loss and soil erosion and maximize irrigation water use efficiency and yield.

2. Materials and Methods

2.1. Soil Type Selection

Studies were conducted from 2018–2020 to determine the optimal overhead irrigation duration and intensity of commonly found soil types in row-crop production areas in Mississippi. Three soil types from the Delta region and three soil types from the Hills region of Mississippi were studied. The Delta region is an 18-county region along the Mississippi River back toward the east, an area with high-fertility soils and intense cropping. The three soil types selected were Commerce Silt Loam (fine-silty, mixed, super-active, nonacid, thermic Fluvaquentic Endoaquepts), Dubbs Silt Loam (fine-silty, mixed, active, thermic Typic Hapludalfs), and Sharkey Clay (very-fine, smectitic, thermic Chromic Epiaquerts) [47]. All three soil types were collected at the Delta Research and Extension Center in Stoneville, MS. The three other soil types were collected from the Hills region of the state,
an area of the state east of the Delta region, which comprises most of the rest of the state. Soils selected from this region were the Brooksville Silty Clay (fine, smectitic, thermic Aquic Hapluderts), Leeper Silty Clay Loam (fine, smectitic, nonacid, thermic Vertic Epiaquepts), and the Marietta Fine Sandy Loam (fine-loamy, siliceous, active, thermic Fluvaquentic Eutrudepts) [48]. The Brooksville Silty Clay soil type was collected at the Black Belt Experiment Station in Brooksville, MS, and the Leeper and Marietta soils were collected at the Roddy Foil Plant Science Research Center, in Starkville, MS. Soils were collected from fields used for row-crop production at each of the locations described. Soils from the top 50 cm were collected in two 70 L containers per soil type on August 1, 2018, for the three Delta soil types and on August 3, 2018, for the three soil types in the Hills. Each soil type was sent to the Mississippi State University Soil Testing Lab (MSUSTL) for characterization, which is shown in Table 1. Soils were analyzed for percent organic matter using the Mississippi State Soil Testing Laboratory standards, which utilize the DeBolt procedure, where organic matter is estimated by measurement of oxidized carbon [49]. MSUSTL analyzes P, K, Ca, Mg, and Zn using standard procedures as described by Lancaster, Rasberry, and Mehlich [50–52]. MSUSTL determines pH by dissolving soil in a water suspension and measuring the soil solution with a benchtop pH meter.

| Soil Type          | USDA Soil Texture | Organic Matter | pH    | P  | K   | Ca  | Mg   | Zn  |
|--------------------|-------------------|----------------|-------|----|-----|-----|------|-----|
| Delta Soils        |                    |                |       |    |     |     |      |     |
| Commerce Silt Loam | Medium             | 1.7            | 6.0   | 190| 523 | 4353| 883  | 3.93|
| Dubbs Silt Loam    | Medium             | 2.6            | 7.0   | 248| 840 | 8299| 1915 | 5.28|
| Sharkey Clay       | Fine               | 2.1            | 7.4   | 122| 664 | 12,433| 3752 | 2.47|
| Hills Soils        |                    |                |       |    |     |     |      |     |
| Brooksville Silty Clay | Fine            | 2.6            | 5.1   | 86 | 347 | 9424 | 172  | 1.12|
| Leeper Silty Clay Loam | Moderately Fine  | 1.8            | 6.2   | 203| 497 | 3563| 177  | 1.12|
| Marietta Fine Sandy Loam | Moderately Coarse | 1.5           | 5.4   | 131| 120 | 1545| 72   | 1.68|

2.2. Overhead Irrigation Duration Study

A study to measure the optimal overhead irrigation event was conducted between October 22 and 23, 2018. Six different soil types (Table 1) were transferred to 15 L plastic containers, which measured 41 cm × 29 cm × 17 cm. The base of each container was drilled with 50 mm × 4 mm holes to allow for drainage during the overhead irrigation duration study. Containers were filled to a 15 cm depth of each soil type to ensure water infiltration into the profile could be measured, but not so much soil where it would run off of the container once water was added. Prior to transferring to the 15 L containers, soils were agitated (turned over four times) and moistened to field capacity, which was determined by estimating soil moisture by feel and appearance. Each soil type was watered in two separate containers with four replications per soil type, totaling eight experimental units per soil type (Figure 1). Overhead irrigation was applied using a research track sprayer equipped with a rainfall simulator (Series IV, DeVries Manufacturing, Hollandale, MN, USA). The rainfall simulator ran on a 2.4 m track back and forth until the 90 s overhead irrigation event finished (Figure 1). The rainfall simulator was equipped with a two-nozzle boom at 50 cm spacing with UR 11010 nozzles (Wilger Inc., Lexington, TN, USA) calibrated to apply 2.1 mm of water per minute. Containers were watered in 90 s increments, with 3.2 mm of total water applied during that time. After the 90 s overhead irrigation event, each container was undisturbed for 150 s and checked to assess irrigation penetration through the soil profile. Irrigation penetration was assessed by taking a core of soil in the center of the soil container. If the core did not saturate at any depth, the soil was placed back into the container and the rainfall simulation continued until saturation was achieved at the 15 cm depth. Saturation was determined when soil sampled at the 15 cm depth was squeezed and free water was released.
Figure 1. (a) DeVries Series IV Research Track Sprayer equipped with a rainfall simulator. The simulator is equipped with a two-nozzle boom with Wilger UR 11010 nozzles. (b) The overhead irrigation event over two containers of Leeper Silty Clay Loam in the Irrigation Duration Study.

2.3. Overhead Irrigation Intensity Study

A study to measure the time it takes for an overhead irrigation event to percolate through the soil profile was conducted on October 24–25, 2018. As with the irrigation duration study, each soil type was placed into 15 L containers with two containers per soil type per irrigation event with four replications, totaling eight experimental units (Figure 1). The irrigation intensity was determined by calculating the time it took for 3.2 mm of water to percolate down into the soil.

2.4. Irrigation Nozzle Droplet Measurement Study

A study to quantify the droplet sizes produced across an array of overhead irrigation nozzles (sprinklers) was conducted on November 26, 2019, and January 15, 2020. An overhead sprinkler system was set up to allow each sprinkler applied through a 36-size nozzle at 69 kPa. A water pump (Simer 2825SS-10 GPM stainless steel portable transfer pump, Pentair, Delavan, WI, USA) was used to increase flow to the system to achieve the 69 kPa pressure. Sprinklers selected for measurement were widely available from local retailers. Sprinklers selected for testing were: Rotator Multi-Trajectory Orange; Spinner-Purple; Accelerator Gold; Sprayhead Brown, and Sprayhead Orange (Nelson 3030 Series with 3NV 36 size nozzle, Nelson Irrigation Company, Walla Walla, WA, USA) (Figure 2). Each sprinkler was analyzed using a particle/droplet image analysis (PDIA) system (VisiSize P15, Oxford Lasers, Didcot, UK) to measure the volumetric droplet size spectrum (Figure 3).

The volumetric droplet size spectrum parameters selected for data collection were the $D_{0.1}$, $D_{0.5}$, $D_{0.9}$, the maximum droplet size, the relative span, and the sphericity of each droplet. The $D_{0.1}$, $D_{0.5}$, and $D_{0.9}$ are the droplet diameters at which respective fractions of 0.1, 0.5, and 0.9 of the spray volumes are contained in smaller droplets [38,42]. The RS measures the evenness of the spray pattern [38] and is calculated using the following equation:

$$RS = \frac{D_{0.9} - D_{0.1}}{D_{0.5}}$$  \hspace{1cm} (1)
2.5. Statistical Analyses

Overhead irrigation duration and intensity study data were subjected to linear modeling and ANOVA using the agricolae package in RStudio (Version 1.2.1335). Prior to ANOVA, normality of data was statistically and visually inspected using the Shapiro–Wilks test, stem and leaf plotting, and Normal Q-Q plotting. Data was also inspected for homogeneity of variance using Barlett and Fligner-Killeen tests. Once model fit was ensured, ANOVA results were interpreted. Means were separated using Fisher’s protected least significant difference (α = 0.05), where significance was observed. Sprinkler droplet size data were not subjected to statistical analyses, a common practice with respect to droplet size data analysis [37,38,42].

Figure 2. Irrigation sprinklers used in this study. (a) Accelerator Gold, (b) Rotator Multi-Trajectory Orange (top view), (c) Rotator Multi-Trajectory Orange (side view), (d) Spinner Purple, (e) Sprayhead Brown, (f) Sprayhead Orange, (g) 3030NV. Series Sprinkler Body with 36-size nozzle.

Figure 3. (a) Oxford P15 measuring the spray droplet spectrum in the field. (b) Droplet atomization occurring as recorded by the Oxford P15.

Droplet size measurements were replicated three times and run for 120 s with a minimum of 200 droplets measured for each replication. The VisiSize P15 was positioned on the ground and away from the centers of the sprinklers to measure the streams through the system (Figure 3). This varied as much as 1 m to 3 m from the center of the sprinkler.

(1)
3. Results and Discussion

3.1. Overhead Irrigation Duration Study Results

Overhead irrigation duration was significant ($P < 0.001$) for all soil types, where the Dubbs Silt Loam held the most water and the Commerce Silt Loam held the lowest at 22.23 mm and 15.88 mm, respectively (Table 2). Sharkey Clay had the second highest total irrigation at 21.4 mm, but this was not statistically lower than the Dubbs Silt Loam. The other soils in order: Brooksville Silty Clay, Leeper Silty Clay Loam, and Marietta Fine Sandy Loam had total irrigation observed at 19.85 mm, 19.05 mm, and 18.26 mm, respectively (Table 2). Soil organic matter (OM) had a significant effect on optimal irrigation duration, as the two lowest organic matter soils the Marietta Fine Sandy Loam and the Commerce Silt Loam resulted in the lowest total irrigation water applied. The three greatest total irrigation durations were all from soils with greater than 2.0% OM. Organic matter had a greater effect on irrigation duration than soil texture class based on these six soil types. These results are consistent with previous research, which showed that organic matter was the most crucial factor influencing water infiltration through the soil profile, followed by soil texture [53,54]. Soil taxonomy can also explain the results with relation to total irrigation duration. The three lowest irrigation duration soils prior to ponding were all Inceptisols (Leeper, Marietta, and Commerce). The next two were both Vertisols (Brooksville and Sharkey), and the highest water holding capacity soil was the only Alfisol (Dubbs). Soil taxonomy and soil organic matter were significant factors influencing irrigation duration, which is consistent with other studies that took soil taxonomy into account [30].

| Soil Type                  | Optimal Irrigation Duration | Optimal Irrigation Intensity |
|----------------------------|------------------------------|------------------------------|
| **Delta Soils**            |                              |                              |
| Commerce Silt Loam         | 15.88 d                      | 153                          |
| Dubbs Silt Loam            | 22.23 a                      | 138                          |
| Sharkey Clay               | 21.43 ab                     | 134                          |
| **Hills Soils**            |                              |                              |
| Brooksville Silty Clay     | 19.85 bc                     | 140                          |
| Leeper Silty Clay Loam     | 19.05 c                      | 138                          |
| Marietta Fine Sandy Loam   | 18.26 c                      | 156                          |

Different letters indicate statistical separation using Fisher’s protected least significant difference ($\alpha = 0.05$). Overhead irrigation intensity did not result in a difference across soil types.

3.2. Overhead Irrigation Intensity Study Results

No differences were observed among the soil types on the time it took for 3.2 mm to percolate into the soil profile ($P = 0.1577$). This could be due, in part, to the low irrigation event measured in this study, as the lowest total irrigation measured in the irrigation duration study was still five-times this value at 15.88 mm. Overhead irrigation intensities ranged from 134 s for Sharkey Clay to 156 s for Marietta Fine Sandy Loam (Table 2). Though no differences were observed in this study, it was still necessary, as optimizing irrigation setup involves understanding how quickly water infiltrates the soil profile. The longest time it took in this study was observed for the Marietta Fine Sandy Loam, which had a considerable crusting and sealing off on the top 2 cm of the soil profile, causing water to runoff rather than infiltrate (Figure 4). The sealing off may be due to the coarser soil texture as observed in other studies [32].
Figure 4. (a) Marietta Fine Sandy Loam where crusting has occurred. This soil type though appearing saturated on the surface would be dry even 5 cm down into the profile. (b) Marietta Fine Sandy Loam side view showing water infiltration for the irrigation intensity study.

3.3. Irrigation Sprinkler Droplet Sizing Results

All droplet spectrum parameter results spanned a wide swath of droplet sizes (159 µm to 1467 µm). The Rotator had three distinctive streams and were measured separately. Two of the Rotator streams (S1 and S3) resulted in similar droplet measurement spectrum components (Table 3). The S2 stream for the Rotator was like both S1 and S3 for the \( D_{v0.1} \), but produced a much larger \( D_{v0.5} \), \( D_{v0.9} \), and maximum droplet size. The Rotator S2 produced the largest droplet size of any sprinkler (1467 µm), with Sprayhead Brown producing the smallest (159 µm) (Table 3). The maximum droplet size produced by each sprinkler was near to the \( D_{v0.9} \) produced for all sprinklers. The greatest sphericity was recorded with the Spinner and the lowest sphericity was recorded by Rotator S2 (Table 3). These two sprinklers produced similar droplet sizes, but had divergent relative spans. This is not surprising, as a tighter RS shows a droplet spectrum with fewer outlying droplets which may explain a higher sphericity. As sprays with lower sphericity falls toward the soil surface, they will likely have greater movement, elongation, and a greater effect from physical forces. The RS is a useful dimensionless number which is based on the \( D_{v0.1} \), \( D_{v0.5} \), and \( D_{v0.9} \). The RS measures the evenness of the spray pattern [38], as the closer to 1.00 the RS is, the tighter the “bell-curve” of the droplet sizes produced in the spectrum are. The need for greater sphericity among droplets in an irrigation event will help to improve repeatability of optimizing the setup.

| Sprinkler        | \( D_{v0.1} \) | \( D_{v0.5} \) | \( D_{v0.9} \) | Maximum Droplet Size | RS \(^2\) | Sphericity |
|------------------|----------------|----------------|----------------|----------------------|----------|------------|
| Accelerator      | 237            | 757            | 1152           | 1156                 | 1.22     | 90.7       |
| Rotator S1 \(^1\) | 214            | 506            | 1072           | 1084                 | 1.51     | 90.7       |
| Rotator S2       | 243            | 904            | 1467           | 1514                 | 1.43     | 89.0       |
| Rotator S3       | 186            | 482            | 847            | 867                  | 1.39     | 89.3       |
| Spinner          | 324            | 897            | 1117           | 1117                 | 0.88     | 91.7       |
| Sprayhead Brown  | 159            | 346            | 726            | 741                  | 1.64     | 90.0       |
| Sprayhead Orange | 179            | 327            | 601            | 638                  | 1.26     | 91.3       |

\(^1\) The rotator nozzle produces three distinct streams, so each of the three were measured separately. This was achieved by moving the Oxford P15 to capture each of the three respective streams. \(^2\) The RS measures the evenness of the spray pattern and is calculated using the following equation: \( RS = (D_{v0.9} - D_{v0.1})/D_{v0.5} \).

4. Conclusions

Optimizing irrigation is beneficial for a row-crop production system but can be costly if not properly set up—and even more so if improperly set up for a given soil texture. An improper irrigation
setup can result in over or under application of water, which is detrimental to crop yield [9–11,16–18]. Understanding the optimal irrigation intensity and duration, as well as the size of droplets produced by an array of commercially available irrigation sprinkler types, will provide significant knowledge to improving overall irrigation setup. Any crop type will benefit from optimized irrigation setup, but lacking knowledge of implications of soil type and sprinkler droplet size will invariably result in poor setup given that missing data piece. Furthermore, by overapplying water, the grower spends money to pump water that does not help his or her crop, which is costly to the overall bottom line for the grower [9,10]. By understanding optimal irrigation duration and irrigation intensity for soil textures across the state or region, any irrigation system can be tailored using these results to achieve maximum yield and minimize runoff. It is also a matter of environmental stewardship to apply only the necessary amount of water needed for a given soil texture. Recent drought years have brought the issue of water stewardship to the forefront of growers’ minds in Mississippi, but this issue is something that affects not only growers, but surrounding communities as well.

Given the information about the irrigation sprinkler droplet size spectrum, optimizing an irrigation setup can be accomplished beyond just ensuring that the desired water volume is achieved. Selecting an irrigation sprinkler type that produces a droplet size most appropriate for a given soil type will result in greater water infiltration, reduced runoff, and a greater return on investment for growers [20–26]. Using the six soil types from this study and the irrigation sprinkler droplet size data, developing optimized irrigation settings can be achieved. For a soil type with a reduced water holding capacity due to crusting like the Marietta Fine Sandy Loam, using a sprinkler that produces a smaller droplet size like the Sprayhead Brown or Orange would be optimal (Figure 4). Smaller droplets have less kinetic energy, resulting in reduced soil impaction, which will lessen the effect of crusting and increase water infiltration [25,27,30]. For a soil type like Sharkey Clay or Dubbs Silt Loam, any of the sprinkler types would be optimal, though something with a greater variety of droplet sizes like the Rotator Multi-Trajectory Orange would be recommended given its variety of stream sizes, which would be well suited for any soil type. Sprayhead Orange sprinklers would be well suited for most soil types given its relative span (RS) nearest to one of any of the sprinklers tested (Table 3). Irrigation sprinklers can produce droplet size spectra that span from Coarse to Ultra-Coarse using standard sizes developed for particle size classification by the American Society of Agricultural and Biological Engineers (ASABE) and the American National Standards Institute (ANSI) standard S572.2 [42,55]. The values presented in Table 3, as measured by the Oxford P15, are only volumetric measurements at certain points in the droplet size spectrum and are not exact values produced by each sprinkler. No irrigation sprinkler produces a mono-sized droplet spectrum. Therefore, using the $D_{v0.5}$ provides a median for which half of the volume of the droplets produced are above and half are below that value. By utilizing sprinkler droplet size, overhead irrigation systems can be further finetuned beyond the ability to apply precise amounts of water in specific places in the field. Applying precision irrigation volumes in a droplet size spectrum that is most suited for a given soil type will ensure improved stewardship of water resources and a greater irrigation efficiency.

Results from this study will help to optimize irrigation setup to ensure that water is applied in the most uniform and effective method. Although not every soil type was tested, the soils selected will provide a baseline to begin to make more informed irrigation decisions this growing season and beyond, with additional soil types to be tested in future studies. Results from this study can also be used outside of the state or region, as soil classification can easily be determined for any field, and irrigation sprinkler nozzles like the ones tested in this study are commercially available worldwide. Total irrigation water duration and intensity was shown to have a greater correlation to soil organic matter than soil texture, which should help growers to assess their irrigation water needs based on soil test results in the off-season. Improving water use efficiency is crucial, even in a part of the U.S. like Mississippi, which has rarely lacked for water in recent years. Optimizing irrigation duration and intensity will result in a greater stewardship of water resources in the Mid-South.
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