Impact of Drip Irrigation on Plant Root Development and Biotic and Abiotic Aspects of Soil

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Introduction

Drip irrigation is widely used in water scarce agricultural systems and has been described as the "dominant mode of micro-irrigation in India" (Bhattacharya et al., 2024). Touted for its water use efficiency, optimizing crop yield, and overall sustainability that makes growing plants in the desert a feasible project, drip irrigation is often considered a superior irrigation method to others (Mebrahtu & Tamiru, 2018). In a study comparing furrow versus drip irrigation, it was found that for certain crops, drip irrigation had a yield four times that of furrow irrigation (Al-Haddad, 2014). Furrow irrigation involves narrow, half-pipe like troughs that run alongside crops. These troughs are strategically placed to cover the entire field of crops. The downside is that water percolates too deep in the soil or evaporates (Al-Haddad, 2014). Crops also received inconsistent watering and showed signs of strain during boom and bust cycles of drought, with a study highlighting that crop growth is negatively impacted with variable water cycles (Cousins, 2020). Drip irrigation, therefore, has become renowned for supplying minimal and consistent water directly to the root zone of crops to combat these issues, while also maximizing crop yields (Al-Haddad, 2014). However, the belief that drip irrigation is an engineering success and saves water is accurate, but incomplete. Biological factors that arise as a consequence of the altered environment from drip irrigation are at present largely unappreciated. Drip irrigation creates a wetting zone around the roots, which is the intended purpose and the primary mechanism that creates the incredible water efficiency in this irrigation system. The wetting zone is consistent and its pattern is able to be accurately modeled and predicted in simulation (Liu, 2015).

In natural environments, plants are exposed to variable sources of water, such as rainfall. Plants have evolved resilience and become adaptive in response to the variability of natural water availability. Drip irrigation eliminates this variability and provides the constant wetting zone as discussed. This consistency includes a tradeoff. Although it is sustainable watering, it is a reduction in the heterogeneity of the natural environment in which the plants and other biological organisms evolved. This concept is supported by the semi-arid Chilean shrub, which shows that exposure to naturally variable water promotes adaptive traits that become diminished under consistent watering conditions (Lázaro-Nogal et al., 2015).

About the Author

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Dominykas Vaiciulis is a graduate of the University of Missouri - Columbia, where he earned his Bachelor of Science in Biological Sciences, a minor in Chemistry, and a certificate in Neuroscience. His curiosity about plant physiology led him to investigate how biological systems adapt to environmental change, particularly the effects of irrigation practices. Beyond plant physiology, Dominykas' interests include clinical medicine and improving healthcare through science communication. He plans to pursue a career as a physician while continuing to contribute to scientific research.

This review on drip irrigation was completed in collaboration with fellow undergraduates Theo Krummel and Cole Arnold.

This review examines how the consistent watering provided by drip irrigation reshapes plant root architecture, soil microbiome, and plant resilience, providing evidence that while drip irrigation substantially increases water use efficiency and crop productivity, it does so with potential tradeoffs in ecological resilience that must be considered when implementing this system.

Wetting Zones as a Selective Pressure

Lazarovitch (2007) found that the shape and size of the wetted area was not correlated with soil type or time, lowering the bounds of which the predictability of wetting zone consistency can be applied. The local wetted zone also creates environments where certain microbes thrive better than others, particularly microbes that are anaerobic and have greater survivability in these consistently moist, oxygen limited environments (Das, 2025). Over time, certain microbes named plant-growth-promoting microbes (PGPMs) have become an active member of supporting plant growth via regulation of soil nutrients and microbiome (Das, 2025). This is an evolutionary example of how shaping of the microbiome in the soil that crops are grown in has altered the fitness of a crop (Ansabayeva et al., 2025). In a consistent and predictable wetting zone that alters root structure and microbiome of the soil, drip irrigation is an active selective pressure on crop fitness. It not only enhances sustainability, but can also be used as an evolutionary tool with the way that it manipulates the ecological dynamics of agriculture. This introduces a key tradeoff between efficiency versus resilience. Delivery systems for irrigating crops may be optimized for crop yield, but a reduction in the ability for a plant to respond to other environmental stressors outside of water could lead to larger, ecological effects.

Root Architecture Under Drip Irrigation

One effect that the wetted area resulting from drip irrigation can have on roots is the depth to which the roots penetrate the soil. Along with affecting the root length, drip irrigation has a very distinct effect on the number of roots and mass of root tissue (Ma, et al., 2013). Roots may stay at a shallower depth around the wetted area and continue to accumulate new lateral roots and mass in this area when compared to non-drip irrigated roots. In a study done on Jujube trees, a type of Chinese date tree, the maximum root depth of drip irrigated trees that had been growing for 12 years was 5 meters. In contrast, the maximum root depth for a stand of 12 year old trees which had not received drip irrigation was 10 meters (Ma et al., 2013). This study was conducted in Mizhi County, Shaanxi Province, an arid region where the average precipitation for a year during the course of the research was 33.3mm. The maximum rain penetration was 2 meters into the soil (Ma et al., 2013). Non drip irrigated trees are adapted to a range of environments and so deep root penetration helps with drought tolerance. This deep root penetration allows for the trees to find water deep in the ground to supplement the sparse instances of precipitation (Ma et al., 2013). Therefore the fact that the drip irrigated trees had half the root depth is a significant difference and shows that the consistent wetted zone affects plant anatomy dramatically.

Root growth and architecture differences were also seen in winter wheat (Ma et al., 2022). When wheat was irrigated and fertilized by flooding and surface application root depth extended farther than surface drip irrigation and subsurface drip irrigation. However, the density of roots was higher at a shallower depth for flood irrigated wheat. Dissimilar to the previously mentioned Jujubee tree, winter wheat is not adapted to send down deep roots to find water during periods of drought (Ma et al., 2022). Drip irrigated wheat had more root density at depths of 40-80cm than surface drip irrigated wheat. Ma and colleagues (2022) found that the drip irrigated wheat also had significantly higher root density than flood irrigated wheat at the latest growth stages. These differences in depth and density also affected root activity, measured as water uptake over time. Between 0-20 cm of depth subsurface irrigated wheat had the lowest root activity of the three irrigation methods; however, after 20cm, subsurface irrigated wheat has higher root activity than surface drip irrigated and surface flood irrigated wheat. Both arid- and non-arid-adapted plants have significant changes to root growth and architecture as a result of the type of irrigation used. Though in both cases the wetted area does have a significant impact on the density and depth of the roots (Ma et al., 2022).

In a study done on apple trees drip irrigation also produced a difference in the root growth and architecture. Though the amount of water applied had the greatest effect on the root structure (Sokalska et al., 2009), the presence of the drip irrigation alone was not the sole determining factor. Three groups of apple trees growing in a climate that received an average total precipitation of 372mm were grown receiving no drip irrigation, intense drip irrigation, and economical drip irrigation. The drip irrigation was also applied to only the north side of the trees. The investigators found that under intense irrigation the tree roots spread the most asymmetrically with more roots growing on the south side of the tree. And while roots were found at all depths across the three treatments, only the control group had roots with a diameter greater than 3mm at a depth of 100cm (Sokalska et al., 2009). These results showed that depending on the level of irrigation roots will not only congregate around the wetted area but at high levels of irrigation will also disproportionately branch out into the non-irrigated side of the tree.

Soil Microbiomes Under Drip Irrigation

Another notable effect of drip irrigation is a change in composition of soil (Wang et al., 2023). Along with the use of fertilizers, soil microbiomes are important for sustaining nutrient levels that promote plant growth. Drip irrigation appears to act as a selective pressure on the microbes present in the soil (Wang et al., 2024). Abiotic factors like salinity and heavy metal content are also important to consider for plant health and human health (Guo et al., 2023; Lu et al., 2016), thus drip irrigation not only affects the structure of the plant and the soil microbiome, but also the composition of the soil (Guo et al., 2023).

Drip irrigation has been found to have a strong impact on the microbe biodiversity of the soil environment in which it is operating (Wang et al., 2023; Zhang et al., 2023). Whether impact is beneficial or detrimental varies based on several factors. For example, drip irrigation systems that utilize reclaimed water were found to lead to an increase in soil salinity within the first 0-60cm layer compared with tap water (Qiu et al., 2022). Higher salinity is a major concern in agriculture because salt accumulation can degrade soil conditions and interfere with nutrient transformations important for crop production (Guo et al., 2023). Some drip irrigation systems utilize a water solution that consists of reclaimed water with a low content of chlorine introduced as a maintenance/disinfection step (Song et al., 2019), and it was found that systems that use this practice reduced microbial growth and reproduction in the soil environment (Qiu et al., 2022). However, there were cases in which drip irrigation had net positive effects on the microbial environment in which it was functioning (Wang et al., 2024). In this case, it was observed that the timing/amount of irrigation changed the composition of beneficial bacteria present. An increase in irrigation during the period from the big trumpet stage to tasseling (crop growth stage intervals of maize plants) significantly increased the Chao index (richness of soil bacteria index) of soil bacteria by 2.95% relative to the control (Wang et al., 2024). This change in microbe diversity led to an increase in nutrient availability, especially for potassium. It should be noted that during other timing intervals, some microbial groups were eliminated by the treatments and that the favorable response only occurred during the one timing period. These results are likely only significant and replicable in these specific plants (maize) and more studies will need to be done to determine the specific intervals to water plants for beneficial microbe growth in other crops. In a separate study, it was observed that soil irrigated with saline water over a period of 11 years had major changes in bacteria composition, as well as salinity, soil water content, and nutrients (Guo et al., 2023). Over time gene expression in the bacteria also changed: expression of genes associated with nitrogen fixation, denitrification, and dissimilatory nitrate reduction increased, while genes associated with nitrate/nitrite transport and nitrification decreased. These changes made nitrogen availability less favorable for the plant overall under saline irrigation, because nitrate declined and nitrification was suppressed, even though N fixation was increased (Guo et al., 2023). Together these documented changes in microbe diversity and function provide strong evidence that drip irrigation systems can function as environmental selective pressures in the microecosystem in which they are applied.

Several studies where either reclaimed water or saline water was employed, found that salination of the soil increased. (Wang et al., 2023; Guo et al., 2023; Lu et al., 2016). Reclaimed water is commonly used in agriculture to preserve natural freshwater, and also for its higher nitrogen content, but as we have seen can lead to changes in the soil over long periods of time (Guo et al., 2023).

Soil salinity as previously stated in this paper can be a major concern, but drip irrigation actually has a much higher desalination rate than regular flood irrigation (18.46%-22.94% vs 5.32% respectively) (Wang et al., 2023). Drip irrigation also keeps soil water distribution (and therefore salt and nutrient distribution) much more uniform than flood irrigation, which in comparison over time damages soil structure and leads to uneven water infiltration (Wang et al., 2023). This means that drip irrigation makes saline water a viable option for agriculture in areas where there are no other options, so long as the proper measures are taken to maintain the soil.

Drip irrigation also has been found to reduce stress on plants that are grown in soil contaminated with heavy metals (Zhang et al., 2023). In a study of soybeans with drip irrigation and flood irrigation in soil with high heavy metal content, it was found that drip irrigation reduced Cd, Pb, and Cr(VI) concentrations in the root zone by 34.88%, 31.35%, and 34.20% respectively (Zhang et al., 2023). This was good for the soil, but it was found that higher amounts of heavy metals had ended up inside of the soybean plant. This wasn't purely a negative though, upon examination Zhang et al. (2023) found that the majority of the metals stayed in the roots with low concentrations ending up in the seeds of the plant.

Conclusions

Here we show that there is much more to consider than just crop production and water efficiency when utilizing drip irrigation. Over time, major changes to microbial biodiversity and soil composition (including salinity of the soil, and heavy metal accumulation) can be affected with use of drip irrigation. Drip irrigation is a key technological advance in agriculture (Wu et al., 2020). Without drip irrigation sustained high production agriculture in arid areas may not be possible. At the very least it would not be as efficient and would take much longer to establish and become productive and profitable. But drip irrigation has drawbacks that may be overlooked due to the success it has provided in water use efficiency and crop yields. Substantial changes have been documented to occur to the structure and function of plants roots when drip irrigation is used. Adding complexity to this issue, these changes vary among different plant types, but they may not necessarily harm the plant if it can still grow under conditions where it otherwise could not survive without drip irrigation. If methods change at a crop field or orchard it is important to keep in mind that the roots of these plants have previously grown under different specific conditions, and if these conditions are not maintained the plant may fail to produce to the same level, or produce at all. Drip irrigation also creates a selective pressure on the soil microbiome and the microbes present in the soil have a big impact on the health and productivity of the plant.

These effects don't occur in isolation, rather they're all part of an interconnected system in which drip irrigation affects the growth, and development of plants. The formation of stabilized wetting zones concentrates water and nutrients which affects the overall density and architecture of the root structure (Ma et al., 2022). The same wetting zones provide sizable influence on the soil microbiome, which is further fortified due to the clustered, shallow roots. In turn, nutrient cycling is impacted by these microbial and plant changes (Lattacher et al., 2025). What this means for environmental resilience in plants under drip irrigation conditions is the formation of a feedback loop as a result of the co-adaptation between root systems and soil microbiome. As a result, this dependence, which presumably no longer tolerates non-drip irrigation watering patterns, is rendered vulnerable to environmental challenges.

Ultimately, drip irrigation should not be viewed solely as an efficient water delivery system, but also as a selective pressure that reshapes plant root systems and the microbiomes of the soil the plant occupies. While the efficiency and sustainability of drip irrigation is unparalleled (Mebrahtu & Tamiru, 2018), it comes with this hidden tradeoff: Reduced biodiversity and ecological resilience. Acknowledging these hidden costs of efficiency is crucial towards making better environmental decisions with furthering agricultural innovation.

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