Agronomic and Economic Assessment of Aerating Drip Irrigation Water

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Abstract. *Injecting air into the crop root zone has been a goal of farmers since the dawn of agriculture, initially driving advances in tillage—and, ironically, no-till farming—and now fostering new advances in subsurface drip irrigation (SDI) practices. In this paper, we review the potential agronomic and economic benefits associated with the implementation of irrigation system involving aeration of the water delivered to the root zone via SDI. The importance of oxygen is acknowledged for many of the chemical reactions that take place in the root zone, such as nitrification, that result in the conversion of nutrients into plant-available forms. In contrast, a shortage of oxygen leads to denitrification and the gaseous loss of N to the atmosphere in the form of nitrous oxide, nitric oxide and, ultimately, free nitrogen. While many approaches have been adopted for delivering oxygen via the irrigation water, the system with the venturi injection technology appears to be most efficient. Findings from on-going applied research, combined with assessment of the economic benefits from commercial growers adopting the venturi technology indicate that there is also a biological shift in the soil microbial population due to aerated drip irrigation water. Future steps should explore the impact of these microbial shifts on the gaseous emissions and nitrate/nitrite/ammonia/ammonium ratios within the soil under aerated and non-aerated regimes. In addition to the environmental effects of aerating drip irrigation water, further documentation of the impacts of AirJection® on crop yield, quality, health, and profitability will also be important in stimulating adoption of the practice.*

Note: AirJection® is a registered trademark of Mazzei Injector Company

Keywords: Sub-surface drip irrigation, greenhouse gases, soil health, AirJection, nitrous oxide, venturi injection, aerating drip irrigation water.

Introduction

Injecting air into the crop root zone has been a goal of farmers since the dawn of agriculture, initially driving advances in tillage—and, ironically, no-till farming—and now fostering new advances in subsurface drip irrigation (SDI) practices (Ayars et al., 2015). Aerating subsurface drip irrigation water has been demonstrated to improve crop yield, quality, and profitability (Bhattari et al., 2004, 2005 &

2006; Goorahoo et al., 2001 & 2008). More recent research by Goorahoo et al. (2016) indicated that soil treated with aerated drip irrigation water can cause a beneficial shift in microbial populations, suggesting the possibility of significant improvements in nutrient use efficiency and nutrient availability, as well as reductions in groundwater pollution and the release of greenhouse gases from cropland.

Healthy soils teem with life, much of which depends upon aerobic conditions—earthworms, insects and beneficial microbes all thrive in the presence of air (Wolf, 1999). Growing recognition of the role of biology in the transformation and exchange of nutrients in the root zone helps underscore the importance of a healthy aerobic microbial community in the soil.

Oxygen is also critical for many of the chemical reactions that take place in the root zone, such as nitrification, that result in the conversion of nutrients into plant-available forms. In contrast, a shortage of oxygen leads to denitrification and the gaseous loss of N to the atmosphere in the form of nitrous oxide, nitric oxide and, ultimately, free nitrogen (US EPA, 2018).

Soils that lack adequate subsurface air—heavy clays, compacted soils and saline soils, for instance, or water-saturated soils that have "drowned out"—illustrate the importance of air in healthy plant development.

Growing Importance

In 1941, William D. Durell wrote in *Plant Physiology*, "It has long been recognized among plant physiologists that the air relations of roots have an extremely important bearing on both the vegetative and reproductive phases of plant growth." A study of suitable oxygen carriers, which could be applied as fertilizer and which would release oxygen slowly to the soil during the growing season, may be worthwhile," he added.

Aerating the soil may be even more worthwhile than ever in light of the challenges that today's farmers face. A global soil health crisis rages that includes dramatic reductions in soil organic matter, loss of structure from excessive tillage, salination, and acidification in many areas. Water challenges range from scarcity to the pollution of surface water and ground water with excess nutrients. And air pollution that includes nitrous oxide, nitric oxide and ammonia from agricultural sources puts farmers under significant pressure from their bankers, regulators, environmental activists, and neighbors (Park et al., 2012).

A recent study by Almaraz et al. (2018) of the University of California, Davis estimated that fertilized agricultural soils in California account for 20 to 32 percent of the state's NOx emissions. The U.S. EPA Inventory of U.S. Greenhouse Gas Sources and Sinks: 1990-2016 (2018) estimates agricultural soil management (US-EPA, 2018) causes 77 percent of the country's NOx emissions. The agricultural community is contesting these assertions, but the findings have focused the ire of environmentalists on farmers in California and nationwide and added weight to the argument that reducing the production of NOx caused by farming would be a significant step forward in improving air quality.

Mechanical Attempts at Aeration

The desire to aerate agricultural soils goes back to the era of the very first plows, pulled by ancient oxen to rip farmland, create porosity, and introduce air at least into the seed zone. The advent of moldboard plows in the 19th century turned over several inches of soil at a time, opening heavy northern European and North American soils to seeding—and to the atmosphere.

In recent decades, many farmers have sought to reduce the direct costs of tillage, including diesel, machinery, and labor, by reducing tillage passes or using lighter or more advanced, lower-disturbance equipment. There is also an increasing recognition of the externalities caused by tillage, such as the loss of soil organic matter, increased erosion, the development of impermeable plow pans beneath the level of tillage, and the destruction of natural soil structure—many of which, ironically, reduce the amount of air in many soils, at least over the long term.

Changes in irrigation practices are creating changes in soil management. According to Ayars, et. al. (2015), low-volume irrigation accounted for nearly 40 percent of California's irrigated acreage in 2010, the result of a steady rise since the early 1990s. Within that low-volume category, permanent subsurface irrigation accounts for a significant share of acreage, particularly in certain crops including tomatoes and tree crops.

The growing adoption of permanent subsurface irrigation lines and bedding practices that permit reduced-tillage management are contributing to more precise crop and soil management. (Yuan et al., 2018). They also create demand and opportunity for aeration via drip irrigation water.

Complex Aeration Systems

Subsurface drip lines provide a welcome and ideally positioned delivery system for air into the root zone, and several innovators have explored systems to exploit that pathway. One approach reads as if it were lifted straight from W.D. Durell's wish-list—the injection of hydrogen peroxide into the soil. Hydrogen peroxide is an extremely powerful oxidant. Mixed with water, it forms hydroxyl (OH) radicals that are highly reactive.

However, as a tool for injecting oxygen into the soil, hydrogen peroxide is somewhat worrisome. A key concern is the storage and handling of a highly reactive compound. On a biological level, hydrogen peroxide's role as a potent disinfectant in water treatment hints at the devastation it may cause to soil biota in the treated soil—microbes that play vital roles in the conversion and transport of nutrients to crop roots—and to roots themselves. And, because hydroxyl radicals are so reactive that they are very short-lived, Durell's ideal of a slow-release oxidizer is not realized by hydrogen peroxide.

Another logical approach was the employment of compressors to pump air into irrigation water. However, forcing air has proved to be an expensive approach due to energy, and equipment and maintenance costs required. Inadequate mixing of the forced air with the irrigation water makes it difficult to control the amount of air delivered and to keep it in the root zone.

Super microbubble generating systems, which create air bubbles less than three microns in size, have been demonstrated to be more effective than compressed air in improving photosynthesis in treated crops. However, the equipment and energy costs are high, so treated areas must be small, limiting the technology's effectiveness in field crops.

Venturi Injection Technology

The most efficient and effective aeration technology is the use of venturi injectors, which apply the Bernoulli principle to incorporate air into a moving stream of water (Goorahoo et al., 2001). The injector is a precisely engineered instrument in which the flow of irrigation water is constricted in a conical chamber, then allowed to expand again. The change in available space creates a corresponding change in pressure within the stream; as it expands into the outlet chamber, the flow creates a low-pressure zone that draws air into the stream through a suction inlet and entrains or dissolves it into the water. Because the injection and mixing is driven by the force of the water passing through the injector, the system requires no additional energy and operates with minimal head loss.

Turbulence created within the system allows well-designed venturi injectors to be highly efficient at dissolving oxygen into the stream. A study of venturi injectors in aerating drip irrigation water by Maestre-Valero and Martinez-Alvarez (2010) in Agricultural Water Management, demonstrated that venturi nozzles brought dissolved oxygen levels to 80.6 percent saturation—close to the saturation point. "The installation of the venturi air injector in the pipeline supplied a great quantity of extra dissolved oxygen and air bubbles to the water," they wrote.

Venturi injectors have been studied extensively in the 200 years since their development. In recent decades, they have been employed in systems ranging from wastewater treatment to fuel injection, and their efficacy in aerating, oxygenating or ozonating water is thoroughly proven. In 1996, Mazzei Injector Company of Bakersfield, California, began experimenting with the use of venturi injectors to aerate subsurface drip irrigation water. In 2000, the company brought its early AirJection® system to the Center for Irrigation Technology (CIT) at California State University- Fresno (Fresno State) for academic trials and validation. That year saw a pilot study on peppers. In 2001, Mazzei was awarded its first AirJection patent, and the company and university began field trials. Since 2003, the company and university researchers have tested the AirJection system in honeydew, cantaloupe, tomato, bell pepper, sweet corn, broccoli, and strawberry fields in California. Additional testing of the concept has been conducted by university researchers in Australia, Spain, Egypt, Italy, Japan, and China. Large-scale commercialization of AirJection began in 2005 and continues today.

Significant Benefits

Research by Fresno State and other academic institutions has demonstrated a wide range of benefits of aeration of subsurface drip irrigation water. In cooperation with the Fresno State research team, one major San Joaquin Valley farm compared 1,500 acres outfitted with an AirJection system against rows with conventional buried drip tape for eight years. They recorded a 23-percent average increase in yield in cantaloupes, as well as yield increases in honeydew, sweet corn, and peppers. The yield boost in cantaloupes ranged from 12 to 34 percent over the study period.

In other trials, tomato yields increased by 21 percent in normal soils and 38 percent in saline soil as a result of aerated subsurface irrigation water. Watermelon yields have been demonstrated to nearly double, while soluble solids increased by 4 percent. Studies in broccoli recorded increases in root mass, root size, and canopy among plants treated with aerated drip irrigation water. Aeration resulted in root dry weight increases of 12 percent in broccoli and 16 percent in sweet corn compared to crops irrigated with non-aerated water.

Profitability is also very positively impacted by aeration. In the California cantaloupe study, applying aerated drip water on all their cantaloupe acres would have penciled out to a total of 1.3 million more boxes and added net return of more than $3.7 million over the 8-year study period.

Significantly, the added yield required no additional irrigation water, increasing water use efficiency (WUE) by 23 percent on the aerated acres. In an era in which it is vital to create "more crop per drop" and more output per kilowatt of energy, such efficiencies will be increasingly valued. The beneficial effects of drip irrigation water aeration are likely to be observed in heavy or poorly structured saline soils, where crop stress, reduced macropore space, and low-oxygen conditions make the effects of introducing air to the root zone even more dramatic.

Biological Shifts

Recent replicated blind trials by Goorahoo and Josue Somano Monroy of Fresno State and Adrian Unc and Crystal McCall of Memorial University of Newfoundland indicate that aerating subsurface drip irrigation water can have significant impacts on the diversity of the soil microbial community (Goorahoo et al., 2016). The team used a PowerSoil extraction kit and PCR DNA analysis to assess the presence and proportion of genes in soil samples, discerning among genes from nifH, amoA and Archea—which are active in ammonia oxidation—and genes involved in nitrite or nitrate reductase processes, including narG, napA, nirK, nirS, and nosZ. The study explored the ratios among Archaea and the various bacteria in the samples.

Maintaining a balance of microbes that favor nitrification over denitrification is extremely important to creating an environment for good nutrient use efficiency (NUE), as well as for minimizing air pollution and the emission of greenhouse gases and smog precursors. Soils with adequate air, proper pH, and adequate moisture provide an environment conducive to increased nitrification and ammonification. In healthy soils, microbes Nitrosomonas and other microbes convert ammonia to nitrite, then Nitrobacter and other biota transform the nitrite into nitrate, which plants can use. The process requires two steps and microorganisms from up to four genera to complete. A shortage of oxygen increases denitrification, in which Pseudomonas, Bacillus, and Thiobacillus microbes reduce nitrate into nitrous oxides, nitric oxide, and ultimately into gaseous N2, all of which can volatilize into the atmosphere, depleting the soil of valuable nitrogen. While N2 is benign, nitrous and nitric oxides are harmful to the environment.

In the Goorahoo et al. (2016) study, the distribution of the tested genes within the microbial populations was very distinct among the aerated and non-aerated treatments. AirJection had a clear selective impact on the distribution of the tested genes among the population, and it may thus be hypothesized that total diversity also changed. Moreover, bacteria dominance in the samples treated with AirJection indicates a likely shift to more luxurious growth conditions.

The nature of the shift is extremely important. The microbial populations in the aerated treatments favored beneficial bacteria that convert ammonia and ammonium into plant-available nitrate, while the non-aerated treatments leaned toward higher proportions of reducing bacteria. That suggests that aeration can result in lower NOx production and increased availability of nitrate in the root zone, enhancing nutrient use efficiency while also reducing the release of NOx, NO and N_2 to the atmosphere.

Next Steps

There are two main avenues for future studies of aerating subsurface drip irrigation water. Deeper exploration of the makeup of microbial populations under aerated and non-aerated regimens is warranted, as is detailed investigation of the gaseous emissions and ratios among nitrate, nitrite, ammonia and ammonium within the soil under both types of treatment.

In addition to the environmental effects of aerating drip irrigation water, further documentation of the impacts of AirJection on crop yield, quality, health, and profitability will also be important in stimulating adoption of the practice.

Crop consultants and the irrigation industry can be extremely helpful in establishing demonstration and research plots for AirJection systems. With the growth in adoption of aeration technology and increased documentation of its effects on gaseous emissions and water pollution potential, it should be possible to attract the interest and support of agencies such as: the California Air Resources Board (CARB), the Greenhouse Gas Reduction Fund (SWEEP), California Healthy Soils Initiative, and the US Department of Agriculture's Environmental Quality Improvement Program (EQIP) to provide support for a technology that delivers important benefits to farmers while providing increasingly vital environmental services to society.

References

Almaraz, M., Bai, E., Wang, C., Trousdell, J., Conley, S., Faloona, I., & Houlton, B. Z. 2018. Agriculture is a major source of NOx pollution in California. Science advances, 4(1), eaao3477.

Ayars, J.E., A. Fulton and B. Taylor. 2015. Subsurface drip irrigation in California—Here to stay? Agricultural Water Management. 157: 39-47.

Bhattarai S.P., S. Huber, and D.J. Midmore. 2004. Aerated subsurface irrigation water gives growth and yield benefits to zucchini, vegetable soybean and cotton in heavy clay soils. Ann. Appl. Biol. 144: 285-298.

Bhattarai S.P., L. Pendergast, D. J. Midmore. 2006 Root aeration improves yield and water use efficiency of tomato in heavy clay and saline soils. Scientia Horticulturae. 108: 278-288.

Bhattarai S.P., N. Su, and D.J. Midmore. 2005. Oxygation unlocks yield potentials of crops in oxygen limited soil environments. Advances in Agronomy. 88: 313-377.

Durell, W.D. 1941. The effect of aeration on growth of the tomato in nutrient solution. Plant Physiology. 16(2): 327-341.

Goorahoo D., A. Unc, C. McCall, J. Samano-Monroy, F. Cassel Sharma, T. Thao, G. Seepersad. 2016. AirJection irrigation mitigates denitrification and leaching. Proceedings of the Irrigation Association Conference. 6 December 2016.

Goorahoo D., G. Carstensen and A. Mazzei. 2001. A pilot study on the impact of air injected into water delivered through subsurface drip irrigation tape on the growth and yield of bell peppers. California Agricultural Technology Institute (CATI) Publication # 010201.

Goorahoo D., D. Adhikari, D. Zoldoske, F. Cassel S., A. Mazzei, and R. Fanucchi. 2008. Potential for AirJection® Irrigation in strawberry production. pp 152-155 In: Takeda, F., D.T.Handley, and E.B. Poling (ed.). Proc. 2007 N. American Strawberry Symposium. North American Strawberry Growers Association, Kemptville, ON Canada.

Maestre-Valero J. and V. Martínez-Alvarez. 2010. Effects of drip irrigation systems on the recovery of dissolved oxygen on hypoxic water. Agricultural Water Management. 97. 1806-1812.

Park S., P. Croteau, K.A. Boering, D.M. Etheridge, D. Ferretti, P.J. Fraser, K-R Kim, P.B. Krummel, R.L. Langenfelds, T.D. van Ommen, L.P. Steele and C.M. Trudinger. 2012. Trends and seasonal cycles in the isotopic composition of nitrous oxide since 1940. Nature Geoscience. Vol. 5. April 2012.

US- EPA. 2018. Inventory of U.S. greenhouse gas sources and sinks 1990-2016. EPA 430-R-18-003. U.S. Environmental Protection Agency. 2018 Downloaded via https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

Wolf B. 1999. The Fertile Triangle. Chapter 1 in "The Interrelationship of Air, Water, and Nutrients in Maximizing Soil Productivity". Haworth Press, Inc. New York, (1999).

L. Yuan, N. Wenquan, W. Jingwei, X. Jian, Z. Mingzhi, L. Kangyong. 2016. Review on advances of AirJection irrigation. International Journal of Agricultural and Biological Engineering. Vol. 9, No. 2. 1-10.