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Soil Moisture Retention on the High Plains of North America via Compost Amendments: A Longitudinal Field Study

Wright Jerome[1], Kenner Scott[2], Lingwall Bret[3]

[1]Civil and Environmental Engineering (Retired), Rapid City, South Dakota, USA
[2]Department Head of Civil and Environmental Engineering (Retired), South Dakota Mines, Rapid City, South Dakota, USA
[3]Department of Civil and Environmental Engineering, South Dakota Mines, Rapid City, South Dakota, USA
Email: jerrywright47@gmail.com, Scott.Kenner@sdsmt.edu, Bret.Lingwall@sdsmt.edu

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Abstract

Water is a finite but vital resource, and the volume of water used in arid and semi-arid regions must be managed to its fullest and best use. Irrigation water is approximately 37% of the total water used in the United States by volume annually. Thus, this area of water use is critical for local and national water conservation. Irrigation is primarily used to increase soil water content above that which precipitation can supply. Soil structure and associated effects on drainage and evapotranspiration, however, largely control soil water content, no matter the amount of applied water. Therefore, improving soil structure to hold more water decreases the amount of water needed for irrigation, which frees that water for other uses. In this paper, organic compost amendments are studied to determine the change in soil structure and accompanying improvements in soil water content over a 4-year period. A uniform field site was selected for this research in the high plains of South Dakota, where irrigation water was available for crop growth. The test site was divided into two equal area fields; one without compost and a field with compost amendments added to 20 cm depth. Compost was incorporated into the treated field at rates of 5% and 10% by weight. Both fields received the same tillage, seed, fertilizer, weather and irrigation. Weekly to monthly in-situ water content measurements from both fields were recorded at the surface and the depths of 20, 40 and 60 cm from 2017 to 2020. Precipitation and applied irrigation water were recorded at the site. No irrigation occurred in 2019 and 2020, and moisture content was dependent on natural precipitation in those years. Results of water content and soil structure show significant differences in the water contents of the soils with the compost amendments compared to baseline, with higher compost content resulting in higher water contents without the soil becoming over-saturated. These results were consistent at all depths and across all growing seasons. This work demonstrates the efficacy of compost soil amendments in regulating soil moisture, which has profound impacts on crop yields, topsoil erosion losses, carbon sequestration, and water conservation.

Keywords

Water Content, Compost, Amended Soil, Soil Structure

1. Introduction

A finite quantity of usable quality freshwater water is available in any area of the world. This finite quantity is set by the balance of nature in the hydrologic cycle, while a host of other factors influence the quality of that water. How the quantity of water is used and managed to its fullest and optimal use is through best management practices. Methods of allocating water are sensitive to physical, social, institutional and political settings, making it necessary to design water allocation mechanisms accordingly [1]. This is especially true for high-quality water suitable for potable municipal use [2]. However, water as a resource is unpredictable and variable in even the best and most stable of times both in terms of quantity and quality. The unpredictable nature of water as a resource is increasing due to climate-system warming, as shown for many rivers and basins such as the Colorado River [3]. As snowpack disruptions decrease the available water resources in major river systems and aquifers in the central and western United States, additional pressure is placed on those resources by the demands of irrigation to feed a growing domestic population. Issues of water conservation have long been associated with the arid western US, west of the Rocky Mountains. However, recent degradation of aquifers in the semi-arid central US has placed more stress on surface water supplies, and municipalities and farmers are increasingly forced to turn to lower quality water sources east of the Rocky Mountains [4] [5].

Table 1 shows current water use in the United States. Dieter [6] showed that the largest single use of water in the US is irrigation to increase soil moisture for agricultural purposes. Recent attention to large decreases in riverine flows across the United States in the summer driven by increased populations competing with agriculture has highlighted the importance of increasing soil moisture to decrease irrigation demands [7]. Indeed, irrigation pressures on water supplies in summer months are having significant impacts on aquatic species throughout the western half of the United States. **Table 2** reinforces the issue of water allocation, while bringing more specificity to the different usage sectors across the United States and regionally.

Given that agriculture is the primary non-recoverable usage of water in the United States, it is sensible to focus efforts on water conservation and optimization on this segment of the US economy. Large monocropping operations and

Table 1. Categories of water use in the United States [6].

Consumption Category	Approximate Usage (%)
Public Water Supply	12%
Irrigation	37%
Aquaculture	2%
Mining	1%
Domestic	1%
Livestock	1%
Industrial	5%
Thermo-electric power	41%
Total	100%

Note: Thermo-electric power generation shown in Table 1 utilizes water for power plant cooling in a pass through versus a consumption basis. In Table 2, thermo-electric power usage represents water consumed.

Table 2. Categories of total water use in the United States [6] [7].

Sector Usage	Conterminous United States		17 Western States		Colorado River Basin	
	Consumption (10^6 m^3/yr.)	% of total	Consumption (10^6 m^3/yr.)	% of total	Consumption (10^6 m^3/yr.)	% of total
Domestic	9468	8	5239	7	891	13
Commercial and industrial	14,466	12	4298	5	319	4
Thermoelectric	4481	4	1248	1	254	4
Irrigation of hay and haylage	24,167	20	23,938	28	3819	53
Irrigation of Cotton	7287	6	5667	7	744	11
Irrigation of grain crops and silages	33,531	28	26,041	30	601	8
Irrigation of non-grain food crops	25,562	21	17,091	20	474	7
Livestock watering	2519	2	1379	2	53	1
Mining	50	0	21	0	2	0
Total	121,530	100	84,922	100	7187	100

high-density cattle operations are gaining footprint across the United States each year. "Dramatic changes in livestock production have occurred over the past two decades. The trend in swine, poultry, and cattle operations has been toward fewer but increasingly larger operations." [8]. Livestock (1% of total water) and irrigation (37% of total water) have been shown to be large consumers of water [6]. Large agricultural operations may require more irrigation as the technologies involved in monocropping and high-density cattle deplete soil health and decrease the soil's ability to retain moisture. "In agro-ecosystems, the soil health can change due to anthropogenic activities, such as preferred cropping practices and intensive land-use management, which can further impact soil functions"

[9]. Recent work by Richter *et al.* [7] has shown that depletion of river flows exceeding 75% can be attributed to irrigation from July to September of each year in years 2001 to 2015, while in the driest 10 years of the period 1961 to 2015 the number of waters with 75% depletion or more from July to September increases significantly.

Irrigation is driven by the need to maintain soil moisture contents above the wilting point to maintain sufficient vegetated growth so that successful crops can be harvested and brought to market (or, in the case of alfalfa, stored for winter use) [10]. Soil moisture contents are controlled through several mechanisms including drainage and evapotranspiration [11]. For optimal crops, the soil must retain sufficient moisture such that the plant-available water is sufficient, yet not so much water that root rot and disease set in [12]. These mechanisms of drainage and evapotranspiration are in turn controlled through the structure of the soil, its mineral composition, and organic contents [13]. The mineral composition is difficult to control, and sandy soils drain well, but retain little water, while clayey soils drain poorly and can retain large amounts of water. However, in clayey soils, much of that retained water is not plant available [14] [15]. Soil structure is a complex concept relating to relative compaction, degree of dispersion of mineral particles, and the grain size distribution of the mineral particles. This structure can be redone through tillage or compaction, but the effects of tillage can be easily undone through natural or anthropogenic means [16]. Soil organic content has a dual role in maintaining soil structure, while also balancing a soil's ability to both drain and retain water [17]. Thus, soil compost amendments applied via a tillage or surface application can have powerful influences on soil moisture contents across long time scales.

Soil moisture conservation can be achieved via utilizing waste currently being landfilled by composting it for use as a soil amendment [18] [19]. Compost utilized as an amendment to the soil structure improves soil health and structure for better water infiltration, storage, availability, and conservation [18] [20] [21]. Wright [22] demonstrated that, by observing soil moisture in soils during an extended dry period, soil moisture in soils with compost amendments added via tillage retained significantly higher moisture than the soils that had not received compost incorporation. This finding indicates that soil moisture conservation can be substantial. Therefore, when agencies and planners are considering how to conserve water, soil water content stabilization can provide potential savings through reduced irrigation demands. The use of compost for soil water content remediation provides a market for compost which supports the development of composting as a viable municipal solid waste (MSW) management option.

2. Background of Compost

Solid waste became a significant issue in the United States in the late 1980s. The Islip Garbage Barge in 1987, medical waste washing upon New York shores (1987-88), and the cry against landfills, created sensitivity to landfilling and forced a new approach to solid waste management. The Environmental Protection Agency (EPA), through the Resource Conservation Act, related research, policies and statutes, developed the hierarchy of solid waste to include, reduction, re-use, recycling, incineration, composting and landfilling. EPA [23] states the waste composition and weights/volumes of solid waste generated by the United States and **Table 3** and **Table 4** show a summary of how the United States manages it solid waste and portion of the solid waste stream that is compostable.

Yard trimmings, food waste, paper and cardboard are compostable and constitute 55.4% of the total solid waste stream. MSW composting based upon the figures in **Table 4**, allows communities to obtain a 50% reduction in tonnage being landfilled by composting the organic fraction of solid waste. Properly processed compost is a high-grade product from what was a waste.

Treatment of sanitary waste water produces bio-solids. Biosolids need to be managed in a safe and responsible manner. Historically waste water plants have land applied their biosolids or landfilled them. Land application of bio-solids creates a long-term liability because of long-term residuals, potential remediation and required monitoring. Transportation and application costs, along with regulatory required record keeping, testing, and long-term monitoring creates long term expense and liability for land application of biosolids. The EPA does allow the use of biosolids in composting if the process meets or exceeds their

Table 3. Management of MSW in the United States in 2012 [23].

Management Type	Approximate Usage (%)
Recovery (Including composting)	34.5%
Combustion/Waste to Energy	11.7%
Discarded (Landfilled)	53.8%
Total	100.0%

Table 4. Total municipal solid waste generation by material in 2012 [23].

MSW Source	Approximate Generation (%)
Food waste	14.5%
Yard Waste	13.5%
Paper & cardboard	27.4%
Glass	4.6%
Metals	8.9%
Plastics	12.7%
Rubber, leather, textiles	8.7%
Wood	6.3%
Other	3.4%
Total	100.0%

requirements and testing proves compliance with their regulations. When the biosolid compost meets requirements for pathogen kill and the compost does not exceed allowances for heavy metals, the compost becomes a Class A compost. Class A compost can be applied to any agricultural process without further testing. Compost is the end product obtained through the processing of two wastes into a usable and safe product [24].

Compost is a stable source of humus-like material for soil texture. The effects of compost on soil properties include improved structure (texture) and greater water holding capacity. Compost increases porosity, reduces bulk density, increases gas exchange and water permeability and water-holding capacity of a soil. The soil amended with compost will improve soil aggregation and the root zone environment [18]. "While there is not a consensus on exactly how to measure soil quality, there is little disagreement that organic matter content gives soils many of their desirable properties." [25] In Hudson's research soil, organic matter is important determinant of available water content because, on a volume basis, it is a significant component. One to six percent organic matter, by weight, is equivalent to approximately 5% to 25% by volume [21]. One of the cheapest forms of conservation is soil amendment with compost, which can cut summer irrigation demands in half [26]. Soil health is a combination of physical, chemical and biological properties that impact the function and productivity of the soil with several of these characteristics directly impacting the economics [27].

Three terms related to the water budget and soil health are field capacity (FC), wilting point (WP) and available water (AW) [28]. Compost increases water holding capacity and total porosity [19]. Increased water holding capacity increases the available water content. Compost addition is more effective than tilling by reducing the soil strength and compaction and increasing soil infiltration [29]. What is evident from research is that water holding capacity is greatly increased by adding organic matter to soil [30]. Research by Curtis and Claassen [31] showed that incorporation of yard waste compost decreased soil bulk density compared to non-tilled treatment, and the compost treatment increased soil carbon, nitrogen contents and plant available water. The use of mulch and soil conditioners has shown to improve efficiency of water use by reducing evaporation, improving water infiltration and storage, and reducing deep drainage [32]. Gufta and Larson [33] studied how particle size and particle size distribution contribute to porosity and water retention in the context of soil organic amendments.

With the benefits of composting solid waste and biosolids, creating a larger market for the compost is needed. A viable and desirable method for cities to utilize compost is in the conservation of their water with the goal of attaining sustainability. Several questions persist, however. Will the cost of transportation, application, and incorporation of compost require financial assistance? Will the economic gain from compost utilization, water conservation, improved soil health and expected higher crop yields pay for the investment of amending irrigated soils with compost? Will a realistic valuation of water help justify community investment in the use of compost? Municipalities may see the utilization of compost within their boundaries on lawns, golf courses, parks, etc. The result would be a significant reduction in the use of water for irrigation. Records from the City of Rapid City, South Dakota show that approximately 35% of their water production is for irrigation purposes [34]. On a national level, 42% of the fresh water used in the United States is used for irrigation [6]. The high percentage of water going to irrigation justifies evaluating compost as a potential for conservation. The potential conservation of irrigation water is addressed and recommended throughout this research.

A dollar value of water is vital for determining the cost-basis effectiveness and efficiency of compost as a soil moisture conservation measure to reduce irrigation demands and thus reduce the need to allocate water resources to irrigation. Each water producing utility determines its rate for sale of water based upon the cost of acquisition, treatment, distribution, delivery and collection of said water. The value of treated water is traditionally based upon what it costs to acquire, treat, and deliver. In South Dakota, the production and delivery cost of water is in the range of $0.004 per gallon [22]. The value of water to the community's economic activity is a basis for determining the local retail value of water. The cost of production and delivery of water does not show the water's value, only its cost. The economic activity created because water is available, is presented as a more realistic and true value of water. How precious our water supply is to us will determine its value. Wright [22] (2018) showed that when economic costs, cultural costs, and direct costs are all considered for South Dakota, that the value of water can range from $0.001 to $0.79 per gallon, with a best-estimate of $0.71 per gallon.

This research was initiated to determine if a soil is amended with compost, will there be a significant savings of irrigation water with equal or better crop production (effectiveness and efficiency)? Given the retail value and total economic value of water, will the value of water encourage meaningful conservation and protection of local water resources? Will the cost savings in water value, be sufficient for local cities to invest in the development of composting municipal solid waste?

"*Essentially, all life depends on the soil…There can be no life without soil and no soil without life; they have evolved together.*" (Charles E. Kellogg, USDA Yearbook of Agriculture, 1938, as noted in U.S. Compost Council 2013) [35].

3. Methods and Means

A site located immediately northwest of the Water Reclamation Facility (WRF) of the City of Rapid City, South Dakota was selected for this field study. The WRF owns a large field occasionally used by neighboring farmers for grazing on its premises that is adjacent to Rapid Creek, the largest local watercourse. The field was not leased for grazing at the time of the study. Relatively flat, with neighboring facilities and good access, the site was ideal for this study. Initial flow and pressure of the city supplied water source at WRF showed the ability to support an 800 series Rainbird radial sprinkler for an estimated radius of 75-foot (22.9-m) radius. Two fields, 150 feet × 150 feet (45.7 m), were developed with five-foot setbacks and a 10-foot (3.05-m) center of non-disturbed soil. A single Rainbird 800 series sprinkler was centrally located in each field for irrigation. Figure 1 shows the location and layout of the test site and WRF adjacent to Rapid Creek.

On May 25, 2017, soil samples and density of in situ soil were taken by American Engineering and Testing using a Troxler 3430 Moisture-Density Gauge. The average soil density was found to be 92.4 pcf (1.5 g/cm^3) over the top 8-inches (0.2-m) [n = 10, min = 90 pcf, max = 94 pcf] prior to any mechanical work including tillage. Soil samples were taken and sent to the North Dakota State University Soils Lab for a mechanical and chemical analysis, including pH, conductivity, and organic matter content. The surface soil was found to be a silty loam as per the NDSU soil report of June 12, 2017. On May 26, 2017, using the Guideline to texture (soil) by feel, USDA NRCS [36], a soil sample from the site was analyzed in accordance to the USDA NRCS process and the soil was determined to be silt-loam.

The NRCS Web Soil survey, defines the soil at the research site as Ow, Owanka clay loam, with the profile of clay loam being 60 inches (1.524 m) thick [(USGS, 2016) (Web Soil Survey, 10/23/17, pg. 1 of 2, Map Unit Description: Owanka clay loam – Custer and Pennington Counties Area, Prairie Parts, South Dakota)]. The National Resource and Conservation Service – United States Department of Agriculture [37] assisted in site evaluation by conducting two on site 45-inch (1.143-m) hydraulic soil testing probes. The Giddings Machine Company, Model GSRPS, hydraulic probe machine, with a 2-inch (50-mm) probe, was

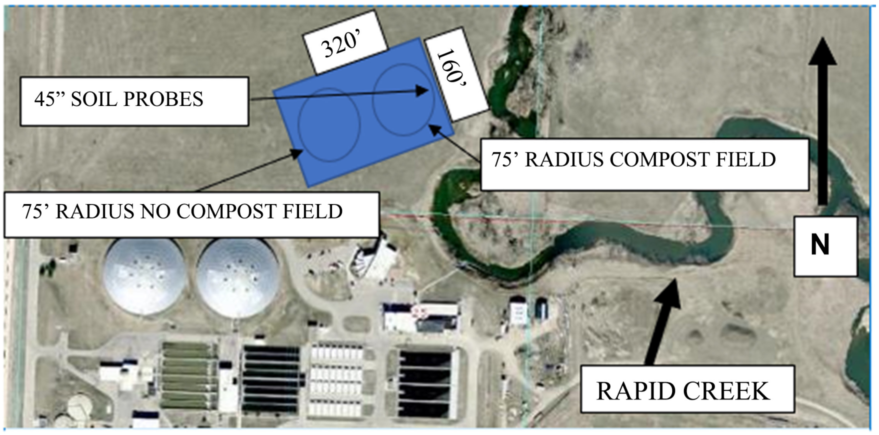

Figure 1. Research plots, no compost and compost, Rapid City Water Reclamation Facility, Rapid City, South Dakota, 2017-2019. Site layout and location map (Lat: 44 deg 1'27"N; Long 103 deg 5'50"W. Research plot orientated to 338 degrees NNW. Photo (Fugro Horizons of North America, Aerial Ortho Photograph, Rapid Map, 2015, latest aerial phot, still current).

used to acquire on site soil profiles. The insertion locations were at the south and north edges of the selected research site. The probes of the Shelby tube type were hydraulically pushed into the site soil approximately 45 inches (1.143 m) deep. The probes were withdrawn and studied by the NRCS USDA scientist and the primary project researcher. The NRCS field probe and review of the soil cores indicated a very uniform soil profile across the selected test site. The core samples indicated the site soil profile was uniform and very similar to the above mentioned NRCS Web Soil description.

Based on the wind rose data for the nearby Rapid City Regional Airport, the field data collection was aligned with the wind rose, approximately 20˚ west of north. Data collection was aligned at regular 10-ft (3.05-m) radial increments from the center of each field and at 45˚ increments from the zero-axis aligned with the wind rose. **Figure 2** shows the radial increments and angular increments for data collection.

Figure 3 and **Figure 4** show the fields before and during tillage operations. Fields were first worked with a spring tooth chisel plow that had a double gang

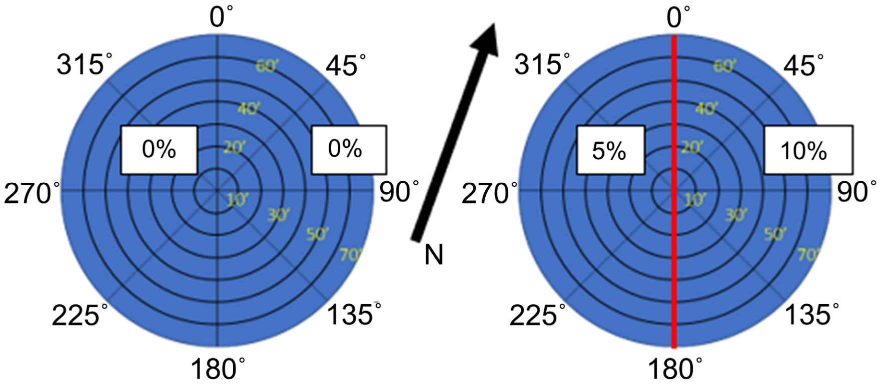

Figure 2. Data collection layout.

Figure 3. Tractor with chisel incorporating compost.

Figure 4. Tractor with disks blending soil and compost.

of chisels with the lead gang having 6 - 22-inch (150 - 560-mm) chisels at 18-inch (457-mm) on center and the second gang of chisels at 36-inch (914-mm) on center to initially incorporate compost. The fields were then disked to blend. The 12-ft (3.66-m) Miller Disk (SN1XR3405) tractor had two twelve-foot (3.66-m) gangs with 24-in (610-mm) disks 12-in (305-mm) on center. The 12-ft (3.66-m) disk had a cutting depth of 12-in (305-mm) measured in the field.

The south field (left field in Figure 1 and Figure 2) did not receive any compost. The north field (right field in Figure 1 and Figure 2) was divided in half, with the south half receiving 5% compost by weight and the north field receiving 10% compost by weight. The dividing line between the 5% and 10% was the 0 and 180-degree line. Compost was added to a depth of 8-in (203-mm) below ground surface. The total tonnage of compost for the 5% plot was 18.5 tons, while the 10% compost plot had 37 tons of compost applied. These masses of compost correlate to a uniform thickness of 1-in (25.4-mm) in the 5% area and 2-in (50.8-mm) in the 10% area of compost spread on the field surface and incorporated to 8-in (203-mm).

Compost was provided by the City of Rapid City. The compost applied was 1/2-in minus (9.5-mm) material and was composed of yard waste, municipal solid waste and bio-solids. The compost applied to this site met all federal requirements and was tested for compost quality.

After compost amendment, the fields were seeded with a cover crop. Cover crops were grown to 1) reduce erosion, and 2) simulate more realistic conditions of agriculture/landscaping so that evapotranspiration soil moisture losses were realistic. The seeding mix for cover crop vegetation consisted of fairway crested wheatgrass, side oats grama, ryegrasses (both annual and perennial) and Eureka II hard fescue. The same seed mixture went to both the no-compost field and the compost field at equal rates by weight (50 lb. [22.7 kg] each field). One hundred pounds of 18-46-0 fertilizer was equally distributed with 50 lb. (22.7 kg) applied to each field. Each field received equal machine work with two passes east west and one pass at 90 degrees of the east west work during seeding. There was overlapping in doing the passes. The soil was mixed as well as it could with the extreme dry soil conditions at the time of incorporation.

When the soil was initially worked, it was too dry for successful cover crop germination. A rain a few days after the planting moistened the soil and the soil was re-disked on June 20, 2017. Each field received a double disking from east to west, then cross disked. Soil conditions significantly improved and regular irrigation via sprinkler was applied once each week unless rainfall pre-empted the need for irrigation to keep the no-compost untreated field soil water content at or above the wilt point. To protect the plants in the study plots irrigation occurred at an estimated wilt point of 20 percent moisture. The wilting point is the amount of water per unit weight or per unit bulk volume in the soil, expressed in percentage, that is held so tightly by the soil matrix that roots cannot absorb this water and plant will wilt [28] [38]. The wilting point for a clay loam typical of this site is estimated at 20% [38].

In 2017, 15 irrigation events occurred. In 2018 only 3 irrigation events occurred. The drought of 2017 required irrigation to occur roughly once a week. Irrigation water was applied on Monday or Tuesday, as Thursday was the moisture content data collection day. Literature suggested a three-day infiltration period between irrigation and moisture content readings so as to estimate field capacity. The time of irrigation occurred in the early morning and completed by late morning to minimize wind and solar influence and disturbance. Initially, irrigation occurred one sprinkler at a time to maximize the radius of water applied. After observing operations on different days, wind speed and direction presented different applications to the two fields; both sprinklers were then operated at the same time so as to minimize any differences caused by the weather.

The drought conditions of 2017 limited the growth of the cover crop, as irrigation rates were designed to supplement normal rainfall for the Rapid City area rather than be the sole source of water (as is typical for agriculture in the region). On September 9, 2017, the site was lightly disked and reseeded. The applied seed type and amount was the same used in June. Fall rains in early September produced significant fall germination. The grass cover in the spring of 2018 was most adequate and spring moisture brought bountiful cover for the 2018 growing season. Precipitation in 2019 was in excess of normal and the fields were at or near field capacity, requiring no irrigation in 2019. 2020 was a dry year with annual precipitation approximately 3 inches (7.6-cm) below normal.

In 2017, 2018 and 2019, weekly data collection included measured precipitation, irrigation events, water content at 0 - 8 in (0 - 203 mm), 8 - 16 in (203 - 406 mm) and 16 - 24 in (406 - 609 mm) depths. In 2020, the data collection occurred once a month, with the data collected in the same procedure. Precipitation was measured by both a weather station on site, and a NOAA weather station at the nearby City airport approximately 3 km northeast of the research site. Surface soil moisture contents at 0 to 8-in (0 to 203-mm) depth were taken at each 45-degree quadrant, at 10-foot (3.05 m) intervals, with seven intervals, out to 70 ft (21.3 m). Moisture content readings were also taken for soil depths of 0 - 8 in (0 - 203 mm), 8 - 16 in (203 - 406 mm) and 16 - 24 in (406 - 609 mm) depths at on-site wells. There were six well nests in the no compost field and six well nests in the compost field. Locations were at the 45, 90, 135, 225, 270, and 315-degree quadrants at a radius of 30 feet (9.14 m).

The Hydro Sense II moisture instrument, from Campbell Scientific Inc., was used and found to be a reliable and an easy-to-use portable device for measuring volumetric water content of soil. The instrument allowed accurate moisture content without disturbing the field's soil structure. Moisture content readings were taken for the No Compost, 5% Compost and 10% Compost fields with minimal or no effect to the field's physical integrity. The water content in the top 8 inches of soil, the deeper wells and in situ soils were taken on a weekly schedule, with some intermittent points taken to observe field conditions. Separate soil samples were taken with moisture content being established by ASTM Method D-2216-90 that verified the instrument as being accurate and within the manufacturer's +/− 3% stated tolerance. Figure 5 shows the wells and the Hydro Sense II moisture content instrument.

4. Results and Findings

All water content data is in volumetric water content basis. **Volumetric** moisture content readings were taken in 2017, 2018, 2019 and 2020 and are presented in Tables 5-8 and Figures 6-9 averaged from all readings on the noted date. The presented data shows the change in volumetric water content over the season on a comparative basis of compost content, precipitation and time. After twenty-one

Figure 5. Hydro sense II moisture instrument and monitoring wells.

Table 5. 2017 Average moisture contents for 0 - 8 in (0 - 203 mm) depth by compost amounts.

Date	0%	5%	10%
06/19/17	31.8%	32.4%	29.5%
07/10/17	34.2%	35.2%	33.9%
07/11/17	40.1%	40.8%	35.8%
07/21/17	38.5%	43.8%	43.9%
07/24/17	33.7%	40.4%	40.4%
07/27/17	30.5%	34.7%	39.5%
08/03/17	22.0%	33.8%	37.4%
08/10/17	15.2%	23.7%	26.5%
08/17/17	39.8%	43.3%	50.1%
08/24/17	33.2%	38.5%	46.6%
08/29/17	29.5%	33.5%	43.3%
08/31/17	27.3%	32.1%	39.5%
09/05/17	20.9%	24.8%	34.6%
09/07/17	29.0%	33.6%	43.9%
09/14/17	28.9%	31.2%	41.5%
09/19/17	24.6%	32.4%	39.6%
09/21/17	23.7%	28.6%	36.3%
09/28/17	27.2%	31.1%	31.1%
10/05/17	29.3%	37.4%	43.5%
10/12/17	28.8%	33.0%	40.0%
10/24/17	20.6%	26.2%	34.4%
Yearly	28.98%	33.83%	38.63%

Table 6. 2018 average moisture contents for 0 - 8 in (0 - 203 mm) depth by compost amounts.

Date	0%	5%	10%	Date	0%	5%	10%
04/20/18	34.0%	33.8%	39.2%	07/18/08	40.5%	42.4%	40.9%
04/26/18	29.5%	32.4%	38.1%	07/26/18	31.9%	34.4%	36.4%
05/03/18	32.6%	36.4%	41.2%	08/02/18	26.6%	26.1%	28.9%
05/09/18	25.3%	24.7%	31.8%	08/09/18	20.2%	18.6%	20.9%
05/17/18	22.9%	27.5%	30.6%	08/13/18	19.5%	18.4%	20.2%
05/24/18	31.4%	37.1%	40.7%	08/16/18	32.7%	33.3%	35.1%
05/31/18	41.2%	44.6%	47.5%	08/23/18	23.9%	20.4%	23.5%
06/07/18	20.0%	20.7%	24.9%	08/30/18	16.4%	15.5%	17.2%
06/11/18	16.9%	18.6%	20.7%	09/06/18	22.4%	17.9%	18.3%
06/14/18	16.1%	24.2%	26.6%	09/13/18	18.8%	17.8%	19.1%

Continued

06/21/18	40.5%	42.2%	44.2%	09/20/18	21.9%	21.7%	20.8%
06/22/18	39.4%	42.3%	43.6%	09/27/18	20.6%	22.5%	22.7%
06/28/18	38.0%	39.9%	42.3%	10/04/18	20.7%	20.1%	21.4%
07/05/18	34.7%	32.8%	38.3%	10/11/18	28.2%	27.5%	29.8%
07/11/18	29.7%	25.8%	35.9%	10/18/18	28.0%	32.0%	31.8%
07/18/18	40.5%	42.4%	40.9%	10/25/18	19.8%	20.1%	21.3%
				Yearly	27.2%	28.1%	30.8%

Table 7. 2019 average moisture contents for 0 - 8 in (0 - 203 mm) depth by compost amounts.

Date	0%	5%	10%	Date	0%	5%	10%
04/19/19	33.2%	33.9%	33.9%	07/17/19	43.8%	45.6%	44.2%
04/25/19	37.3%	37.8%	38.2%	07/25/19	40.4%	42.9%	43.0%
05/03/19	39.6%	40.5%	40.6%	08/02/19	41.8%	38.9%	42.1%
05/10/19	41.1%	40.4%	40.6%	08/08/19	34.6%	34.3%	34.0%
05/16/19	35.2%	35.4%	36.0%	08/16/19	44.5%	46.3%	46.3%
05/24/19	42.6%	44.1%	43.9%	08/21/19	40.5%	37.6%	40.5%
05/30/19	41.7%	42.9%	43.7%	08/30/19	36.8%	35.6%	36.0%
06/06/19	40.6%	41.7%	40.2%	09/06/19	27.3%	31.7%	32.9%
06/13/19	32.9%	30.4%	31.2%	09/13/19	40.8%	40.5%	40.7%
06/19/19	28.4%	27.9%	25.5%	09/20/19	32.8%	32.0%	31.8%
06/26/19	33.0%	32.0%	33.1%	09/26/19	32.3%	35.1%	28.7%
07/08/19	42.0%	41.3%	39.5%	10/02/19	41.7%	39.3%	40.9%
07/11/19	41.1%	40.6%	41.3%	10/08/19	34.7%	34.9%	31.9%
07/17/19	43.8%	45.6%	44.2%	10/18/19	36.4%	36.1%	34.9%
				Yearly	37.7%	37.8%	37.6%

Table 8. 2020 average moisture contents for 0 - 8 in (0 - 203 mm) depth by compost amounts.

Date	No Compost Field	5% Compost Field	10% Compost Field
04/22/20	38.6%	37.3%	38.9%
05/17/20	42.5%	42.0%	43.2%
06/15/20	23.9%	21.8%	23.8%
07/14/20	30.3%	30.0%	32.4%
08/15/20	15.3%	13.6%	16.9%
09/15/20	28.3%	26.4%	25.3%
10/15/20	16.9%	13.4%	13.7%
Average	27.9%	26.3%	27.8%

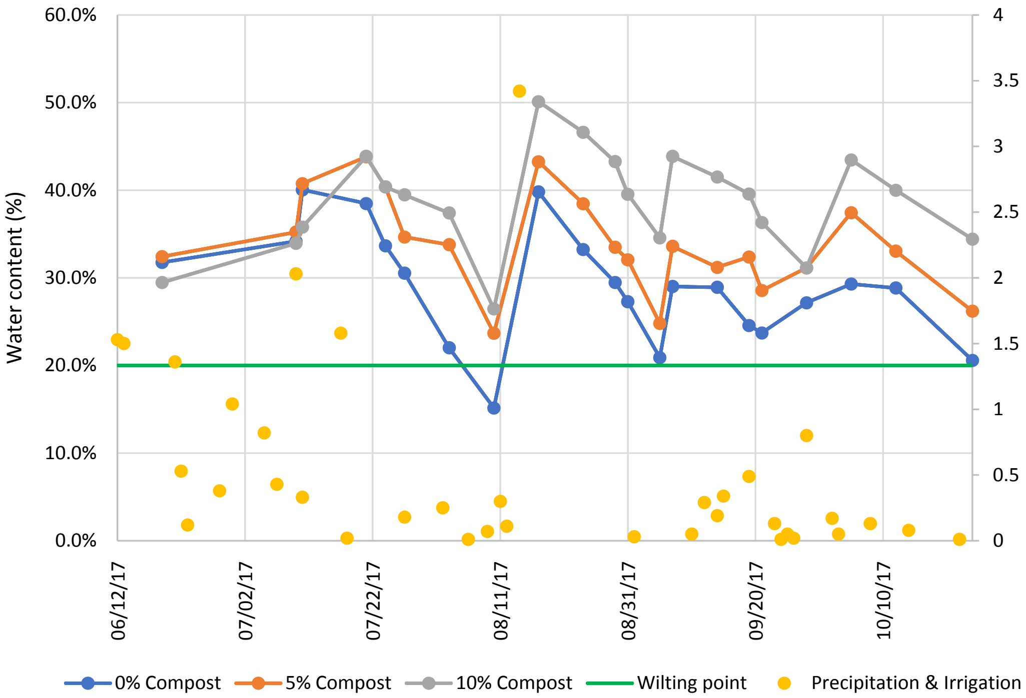

Figure 6. 2017 moisture content trends at 0 - 8 in (0 - 203 mm) depth.

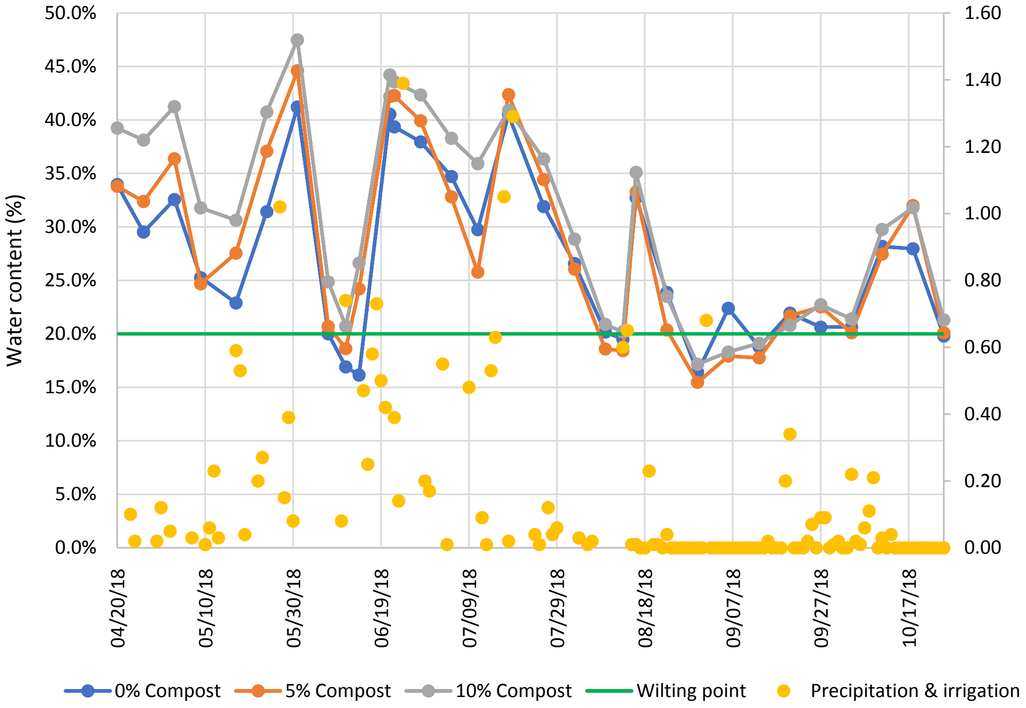

Figure 7. 2018 moisture content trends for 0 - 8 in (0 - 203 mm) depth.

sets of data, from June 19, 2017 through September 28, 2017, the average water content for each field, categorized by no compost, 5%, and 10% and the average field moisture at 0 to 8 inch-depth (0 to 203-mm) is presented in **Table 5** and graphed at **Figure 6**. The average water content for each field, categorized by no

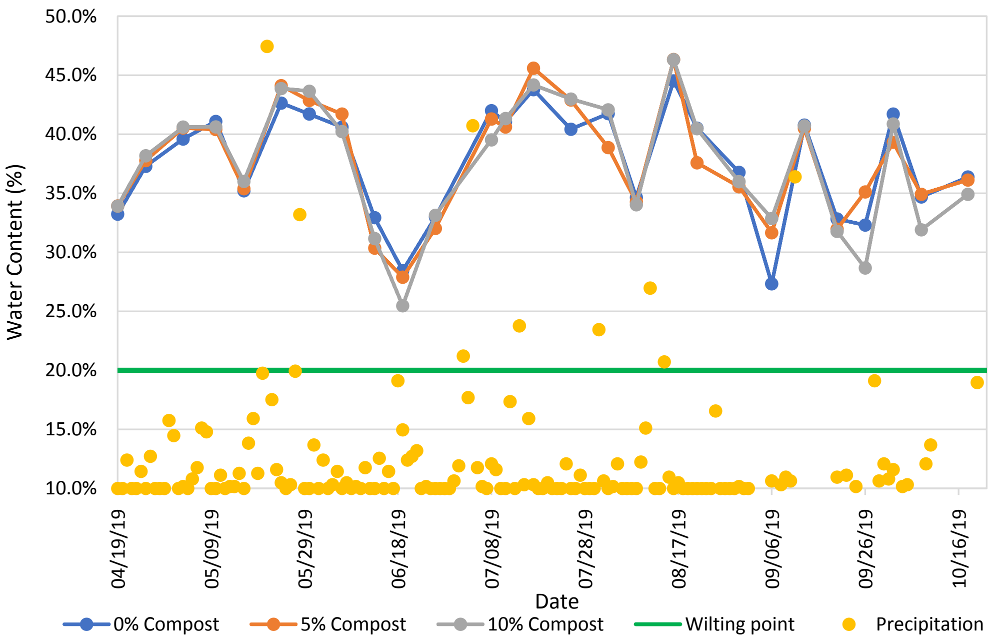

Figure 8. 2019 moisture content trends for 0 - 8 in (0 - 203 mm) depth.

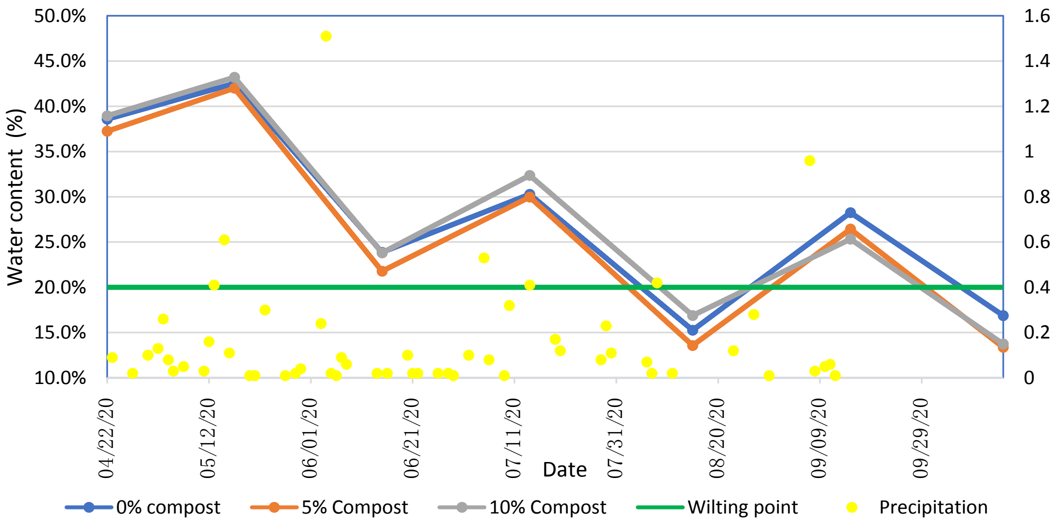

Figure 9. 2020 moisture content trends for 0 - 8 in (0 - 203 mm) depth.

compost, 5%, and 10% the average field moisture at 0 to 8 inches (0 - 203 mm) depth for the 2018 data collection season is presented in Table 6 and graphed in Figure 7, while the results for the 2019 data collection season is presented in Table 7 and graphed in Figure 8. The 2020 data collection season (April through October) is presented in Table 8 and graphed in Figure 9.

While it is useful to examine the differences between fields in the upper surficial root zone, there are also benefits for examining the water content differences by field and year at lower depths. Therefore, moisture readings for the depths of 8 inches (203 mm) to 16 inches and 16 inches (406 mm) to 24 inches (809 mm) are now compared. Note that the deeper intervals were not measured in 2017.

2018 moisture contents in the 8-in (203 mm), 16-in (406 mm) and 24-in (809 mm) depth of soils was measured and averaged and are shown in **Table 9**, while **Table 10** and **Table 11** present 2019 and 2020 data. Graphical Comparison for 2018 to 2020 at deeper depths is presented in **Figures 10-15**. The shallow data can be found in the preceding **Figures 7-9**.

Table 9. 2018 average moisture content by date, soil and depth.

Data for Chart											
0 to 8”				8 to 16”				16 - 24”			
Date	0%	5%	10%	Date	0%	5%	10%	Date	0%	5%	10%
04/20/18	33.1	32.9	37.0	04/20/18	26.3	20.8	41.4	04/20/18	23.8	19.3	36.7
04/26/18	29.0	31.9	40.2	04/26/18	25.7	20.4	42.2	04/26/18	24.7	18.6	38.0
05/03/18	32.3	40.0	40.6	05/03/18	33.7	29.5	45.8	05/03/18	27.8	27.4	41.5
05/09/18	24.4	27.6	34.7	05/09/18	31.9	28.6	42.7	05/09/18	26.5	24.9	40.0
05/17/18	22.7	30.2	30.2	05/17/18	31.4	29.2	41.6	05/17/18	26.7	25.9	39.8
05/24/18	28.9	37.7	42.3	05/24/18	24.5	29.8	44.2	05/24/18	23.6	27.1	41.3
05/31/18	41.3	46.7	46.5	05/31/18	32.5	36.4	46.0	05/31/18	23.0	32.2	45.3
06/07/18	19.1	26.3	29.0	06/07/18	33.3	27.2	39.2	06/07/18	21.2	26.1	42.5
06/14/18	26.9	34.6	36.2	06/14/18	23.4	27.2	38.8	06/14/18	22.7	28.5	40.7
06/22/18	39.9	43.1	45.2	06/22/18	43.4	45.5	52.0	06/22/18	35.1	35.2	50.5
06/28/18	38.7	40.5	42.0	06/28/18	44.1	45.6	49.1	06/28/18	40.3	44.4	53.1
07/05/18	36.9	41.4	41.8	07/05/18	41.1	43.9	49.0	07/05/18	38.6	41.2	52.5
07/11/18	30.7	34.8	36.6	07/11/18	39.0	43.1	45.1	07/11/18	36.6	38.9	49.4
07/19/18	41.8	42.5	43.1	07/19/18	42.3	45.0	47.6	07/19/18	37.4	36.4	53.6
07/26/18	32.8	38.2	36.5	07/26/18	42.9	43.1	47.1	07/26/18	39.5	43.4	51.8
08/02/18	25.3	30.0	31.1	08/02/18	40.3	39.1	46.1	08/02/18	37.3	40.6	51.2
08/09/18	19.6	22.3	22.3	08/09/18	32.6	33.0	39.7	08/09/18	31.4	30.0	46.5
08/16/18	33.9	37.3	36.4	08/16/18	30.0	34.3	42.4	08/16/18	28.6	34.6	46.5
08/23/18	22.6	29.1	26.4	08/23/18	28.2	28.1	37.8	08/23/18	23.6	28.9	44.2
08/30/18	17.5	18.2	19.5	08/30/18	25.3	24.0	31.6	08/30/18	22.3	28.2	42.9
09/06/18	18.6	18.2	20.2	09/06/18	23.1	25.7	34.0	09/06/18	20.5	22.6	39.5
09/13/18	18.3	18.9	19.5	09/13/18	22.4	24.9	30.0	09/13/18	20.8	18.8	42.1
09/20/18	19.7	26.1	20.2	09/20/18	18.8	20.4	28.2	09/20/18	15.8	16.9	40.2
09/27/18	18.2	20.9	22.2	09/27/18	17.7	21.0	26.2	09/27/18	17.9	21.6	37.9
10/04/18	21.6	19.9	22.2	10/04/18	16.4	18.1	19.8	10/04/18	16.3	18.0	33.7
10/11/18	26.8	22.1	24.7	10/11/18	17.2	19.9	21.8	10/11/18	16.2	17.1	31.3
10/18/18	0.0	0.0	0.0	10/18/18	0.0	0.0	0.0	10/18/18	0.0	0.0	0.0
10/25/18	0.0	0.0	0.0	10/25/18	0.0	0.0	0.0	10/25/18	0.0	0.0	0.0

Table 10. 2019 average moisture content by date, field and depth.

Date	No Compost Field			5% Compost Field			10% Compost Field		
	0 - 8”	8 - 16”	16 - 24”	0 - 8”	8 - 16”	16 - 24”	0 - 8”	8 - 16”	16 - 24”
04/19/19	33.5	40.5	36.3	33.4	38.4	37.2	35.3	42.0	43.7
04/25/19	37.0	42.1	37.2	38.4	42.2	40.8	39.7	43.0	45.9
05/03/19	38.2	40.1	36.5	38.3	40.9	38.5	40.4	41.1	45.1
05/10/19	43.0	41.5	36.5	40.2	40.8	39.9	38.1	43.7	46.0
05/16/19	35.4	39.5	37.4	37.0	43.0	38.0	38.1	43.6	46.0
05/24/19	42.4	44.1	40.3	44.4	42.8	40.8	42.7	43.6	47.1
05/30/19	41.0	43.8	41.1	43.3	43.7	43.6	43.7	46.0	47.0
06/06/19	40.8	43.6	37.8	41.4	47.0	42.9	41.5	44.7	48.8
06/13/19	33.8	43.8	41.1	30.9	41.7	42.2	29.4	42.3	47.3
06/19/19	29.4	41.0	37.7	29.9	40.3	40.5	23.8	37.2	40.3
06/26/19	33.6	40.3	39.6	34.3	40.7	40.7	37.5	39.1	44.2
07/08/19	41.4	44.6	41.8	43.5	45.2	43.0	39.1	44.9	48.1
07/11/19	43.7	43.1	43.7	41.7	44.1	47.2	41.8	43.5	44.5
07/17/19	46.0	45.5	41.6	47.2	45.5	44.9	43.4	42.8	48.7
07/25/19	43.9	45.7	42.5	40.8	42.7	50.3	45.6	45.4	48.3
08/02/19	44.4	42.6	42.5	42.9	42.0	46.0	41.4	38.4	49.2
08/08/19	40.0	43.8	38.8	37.3	40.3	39.9	33.9	32.3	48.4
08/16/19	46.0	45.4	43.0	46.7	47.5	44.8	49.4	46.8	52.0
08/21/19	39.9	45.9	40.9	38.9	46.1	48.1	41.1	47.3	48.9
08/30/19	38.3	45.5	42.9	37.5	41.0	41.4	35.9	39.7	46.9
09/06/19	33.6	44.9	41.2	30.8	38.2	50.5	31.2	41.4	43.8
09/13/19	43.4	40.9	39.6	43.1	41.1	39.6	40.8	42.7	46.9
09/20/19	34.0	40.4	32.5	32.8	37.6	36.8	28.9	36.7	42.9
10/02/19	33.5	37.1	35.0	34.4	35.1	37.3	26.5	35.7	44.5
10/08/19	37.2	34.6	29.6	34.1	28.8	32.0	35.4	31.5	32.7
10/18/19	38.8	35.7	29.8	35.9	36.1	33.9	36.1	32.1	34.8

Table 11. 2020 average - observed moisture content by date, soil and depth.

Date	0 - 8” Depth		
	NC	5%	10%
04/22/20	39.7	39.2	40.3
05/16/20	42.7	43.0	45.9
06/15/20	26.5	22.4	27.1
07/14/20	32.1	29.5	32.7
08/15/20	15.2	15.4	16.0
09/13/20	28.2	26.8	22.3
10/15/20	16.1	11.9	13.3
Date	**8 - 16” Depth**		
	NC	5%	10%
04/22/20	40.5	38.2	40.7

Continued

05/16/20	40.4	43.7	44.9
06/15/20	34.8	33.9	37.4
07/14/20	25.2	31.2	34.9
08/15/20	19.3	17.2	33.8
09/13/20	20.8	23.1	27.0
10/15/20	18.5	20.6	21.2
Date	16 - 24” Depth		
	NC	5%	10%
04/22/20	35.0	36.2	43.8
05/16/20	39.1	40.4	46.4
06/15/20	31.6	32.0	44.3
07/14/20	24.1	27.6	42.1
08/15/20	15.4	13.4	33.8
09/13/20	14.9	20.5	30.7
10/15/20	14.5	16.4	25.6

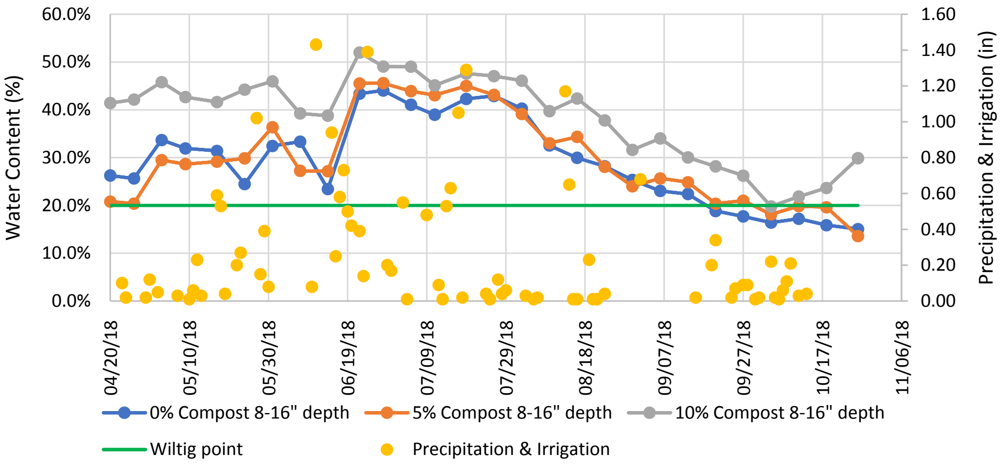

Figure 10. 2018 moisture content trends for 8 - 16 in (203 - 406 mm).

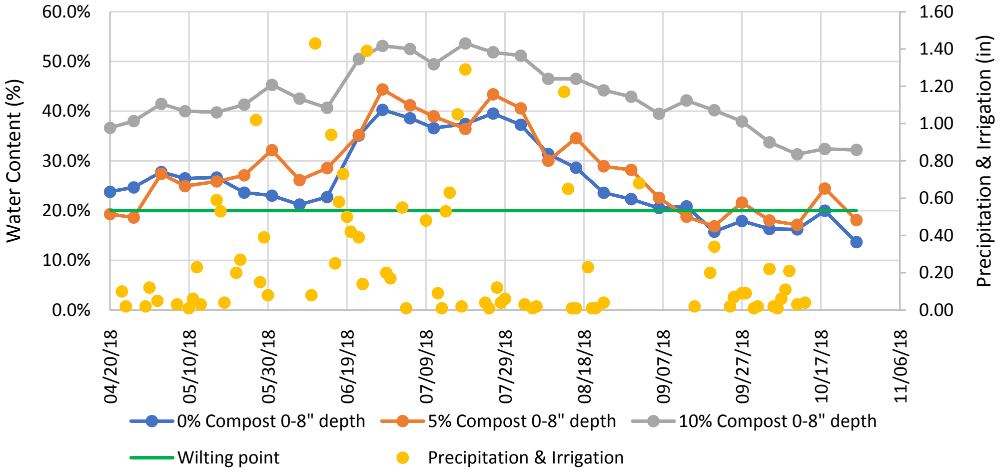

Figure 11. 2018 moisture content trends for 16 - 24 in (406 - 809 mm).

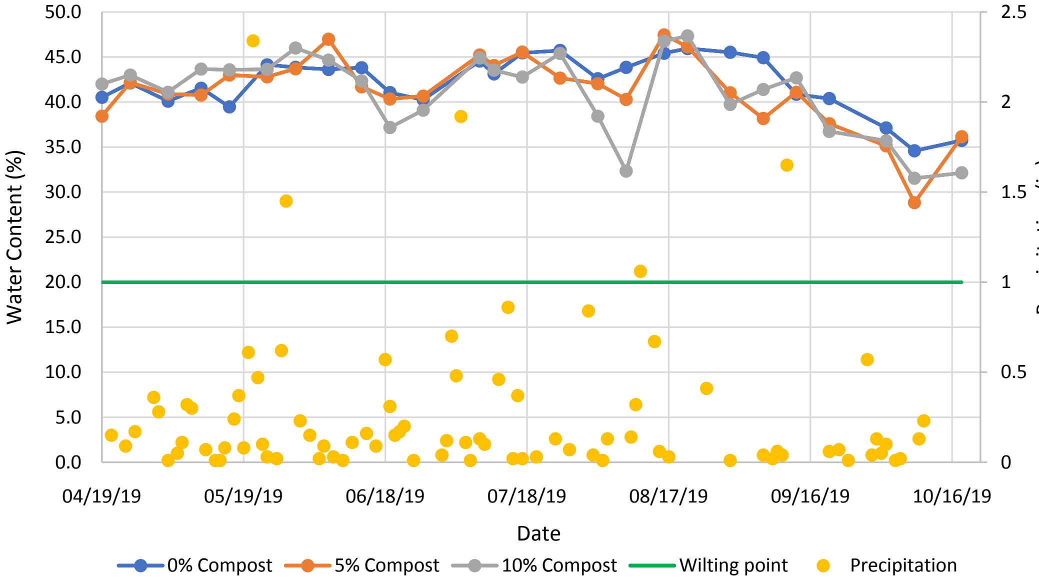

Figure 12. 2019 moisture content trends for 8 - 16 in (203 - 406 mm).

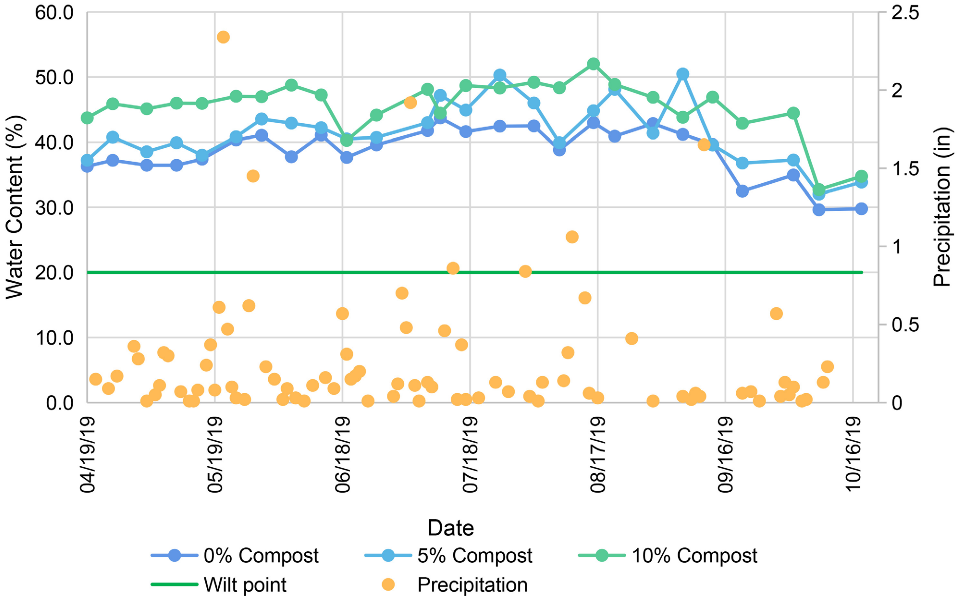

Figure 13. 2019 moisture content trends for 16 - 24 in (406 - 609 mm).

In 2017 and 2018, in the mid-July through mid-August time frame, the fields were allowed to dry down to see how the different soils, with and without compost, maintained their field moisture content. Table 12 summarizes the findings and Figure 16 and Figure 17 demonstrate how the soil that had received incorporated compost retained adequate moisture for the entire data period. In 2017, no compost soil did not maintain adequate moisture. In a drought period the savings could be critical in having a crop. With an approximate field capacity of 40% and a wilt point of 20%, the results over a 30-day period showed considerable differences. Table 13 shows the amount of water applied to the fields by natural precipitation and irrigation.

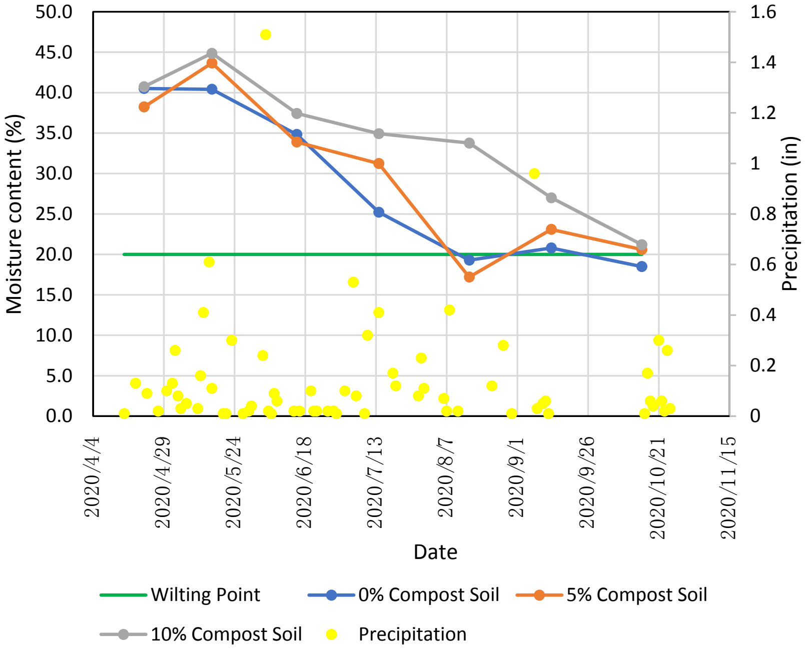

Figure 14. 2020 moisture content trends for 8 - 16 in (203 - 406 mm).

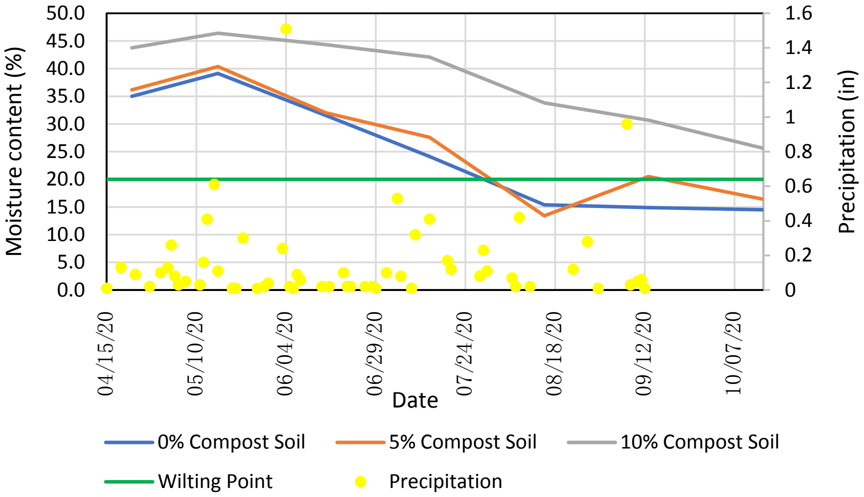

Figure 15. 2020 moisture content trends for 16 - 24 in (406 - 609 mm).

Table 12. Volumetric moisture content—dry down period.

Field	Date	Water Content	Date	Water Content
No Compost	7/21/17	41.7%	8/10/17	13.2%
10% Compost	7/21/17	50.2%	8/10/17	31.6%
No Compost	7/18/18	43.2%	8/9/18	19.3%
10% Compost	7/18/18	42.2%	8/9/18	22.3%
No Compost	7/17/19	43.8%	8/16/19	44.5%
10% Compost	7/17/19	44.6%	8/16/19	45.9%
No Compost	7/14/20	29.9%	8/15/20	15.2%
10% Compost	7/14/20	31.1%	8/15/20	14.9%

Table 13. Water to fields by year.

Year	Precipitation	Irrigation No Compost	Irrigation Compost
2017	12.84"	6.61"	6.02"
2018	18.84"	1.81"	1.73"
2019	27.06"	0.00"	0.00"
2020	12.86"	0.00"	0.00"

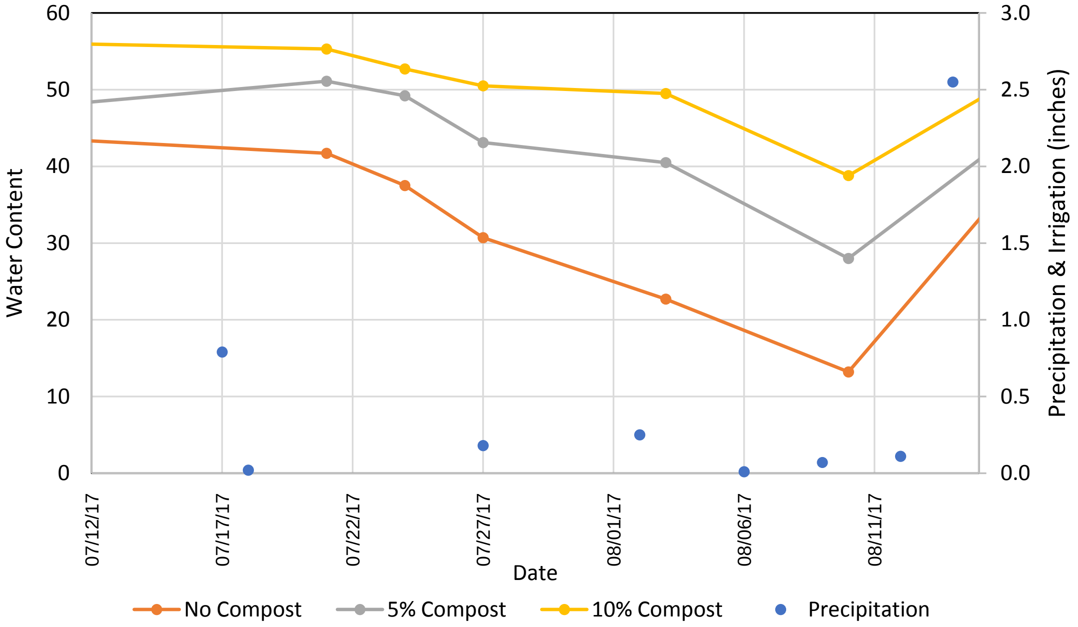

Figure 16. 2017 volumetric moisture content 0 - 8 in (0 - 203 mm) depth during 30-day dry down.

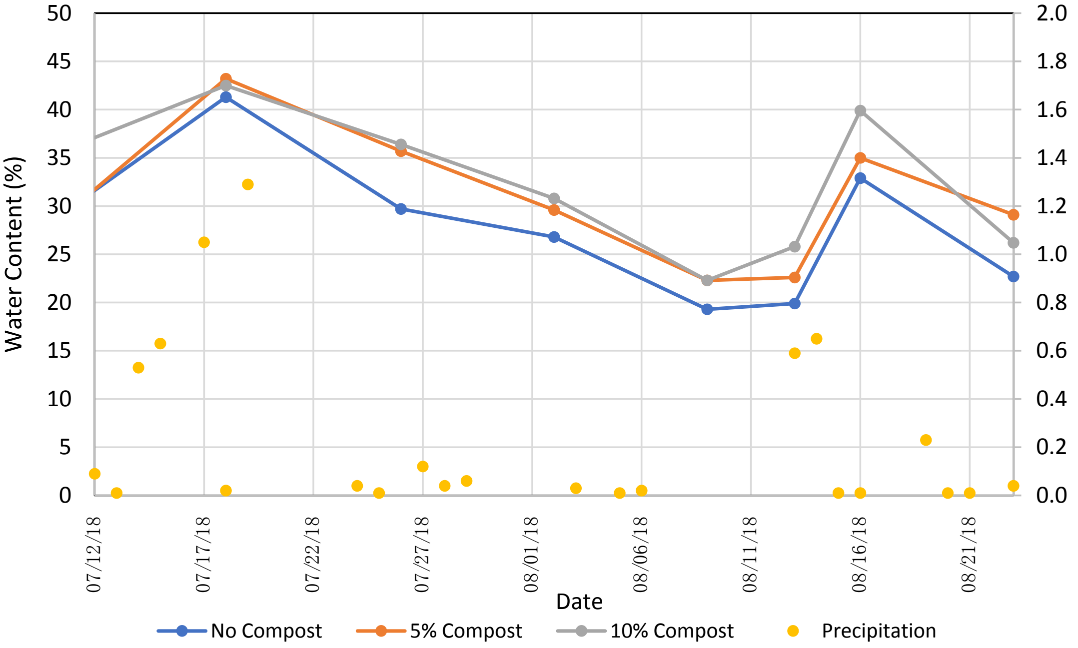

Figure 17. 2018 volumetric moisture content 0 - 8 in (0 - 203 mm) depth during 30-day dry down.

The comparison of moistures by soil at the 0 - 8 in (0 - 203 mm) depth in Table 14 shows that even in the wet year of 2018, the composted soil retained more moisture than the no compost soil. More remarkably is the moisture retained in 2017 where the moisture received by the no compost and compost fields was the same, there was a significant difference in moisture content as the dry down period proceeded. On August 10, 2017, the moisture content in the no compost soil was at 13.2% and the moisture content in the compost field was 31.6%.

5. Discussion

The design of this experiment established one variable and that being the soil being amended with compost or not. The soil amended with compost received 5% or 10% by weight amended into the in-situ soil. All three soil types, no compost, 5% compost, and 10% compost received the same amounts of seed, fertilizer, and machine mixing. Precipitation was assumed as equal with the fields adjoining. Extra irrigation water, approximately 0.6-in (15-mm) of water, was applied to the no compost field in August of 2017 as that field soil reached the wilt point. The weekly moisture content readings for 2017 were taken over the period of June 19, 2017 through October 24, 2017. The weekly moisture content readings for 2018 were taken over the period of April 20, 2018 through October 26, 2018. The weekly moisture content readings for 2019 were taken over the period of April 19, 2019 through October 18, 2019. The weekly moisture content readings for 2020 were taken over the period of April 22, 2020 through October 15, 2020. Throughout both of 2017 and 2018 years of observation, the soils containing compost retained more moisture than the non-compost soil. With record precipitation occurring in 2019, the 0 - 8 in (0 - 203 mm) soil depth in all three

Table 14. Moisture differences by year using average volumetric moisture content at 0 - 8 in (0 - 203 mm) depth.

Year	Field	Average % Moisture	Difference
2017	No Compost	29.0%	NA
	5% Compost	33.8%	+4.9%
	10% Compost	38.6%	+9.7%
2018	No Compost	27.2%	NA
	5% Compost	28.1%	+0.9%
	10% Compost	30.8%	+3.6%
2019	No Compost	37.7%	NA
	5% Compost	37.8%	+0.0%
	10% Compost	37.6%	+0.0%
2020	No Compost	26.9%	NA
	5% Compost	27.3%	+1.5%
	10% Compost	27.3%	+1.5%

fields was approximately equal. With precipitation significantly reduced in 2020, the 0 - 8 in (0 - 203 mm) soil depth in all three fields was approximately equal. Deeper soil moistures, however, were different in the three soils.

Results show water content benefits and higher crop yields from the use of compost. The benefits are derived by the fields improved total soil carbon, biomass, and moisture to provide a combined increase in crop yield. In addition to higher crop fields, weed infestation was significantly different between fields. The visual health and vitality of the plants appeared much higher in the 10% soil area when compared to the no compost or the 5% soil area. Although not a formal part of this study, it is noted that the no compost field had an approximate 25% infestation of buffalo bur weeds where the compost fields show a minimal amount of infestation estimated at 1% - 2%. **Figure 18** and **Figure 19** show comparisons of crop yields and weed infestations.

Figure 18. No compost field, approximately 25% weed Infestation, July 2018.

Figure 19. 10% compost field, minimal weed, very heavy grass, July 2018.

In order to discuss the benefits of compost amendments to soils for agricultural and residential use, it is useful to quantify the benefits by placing a dollar value on the amount of water conserved by amending soils with compost. The value of water is difficult to define. Efforts to define the value of water have found the cost per gallon but not a stated value. The cost per gallon of water production and delivery was found to be: $0.024 in Atlanta, Georgia, $0.012 in New York City, $0.004 in Cape Town, South Africa [39], and an average of $0.005 in Rapid City, South Dakota [22]. In this paper, the value of water is developed for the Rapid City South Dakota area. With the value of water developed, the benefits of soil compost amendments are calculated by evaluating the reduction of irrigation water needed for comparable crops. In developing the value of water for the Rapid City South Dakota area, the direct costs for water production and transportation are compared with the retail value of water and the economic activity enabled by a water supply. The analysis of retail value and economic impact using retail sales and city sales tax revenue showed that water is valued at an average of $0.72 per gallon in the Rapid City area [22]. With the value of water established, the benefits of compost amendments are shown.

In this research, moisture applied to the non-compost fields and the compost field was the same. The field data shows that the amount of water content in the soils observed varied and the higher the percentage equated to higher water content. **Table 15** summarizes water value based upon water content for 2017 and 2018.

With compost incorporation estimated at $2770/acre for 5% and $5266 per acre for 10%, water needs a value based upon "economic" activity to justify investment in compost incorporation. Using the 0% to 10% moisture content, the savings in water value based upon retail activity at $0.71 per gallon at an average of $10,268 per year, would take a year to amortize without interest. The savings in water production and delivery cost at $0.005 per gallon at an average of $72 per year, would take close to 75 years to amortize without interest.

Table 15. Value of water saved.

Year	Average moisture	Change 0 - 8-inch depth	Gallons of water	Water value at $0.005/gallon City Cost	Water value at $0.71/gallon Sales Tax Value
2017					
0%	28.98%	0.00%	0	0	0
5%	33.83%	+4.85%	10,588	$52.94	$7517
10%	38.63%	+9.65%	21,066	$105.33	$14,957
2018					
0%	27.20%	0.00%	0	0	0
5%	28.10%	0.90%	1965	$9.82	$1395
10%	30.8%	3.60%	7859	$39.29	$5580

6. Conclusions

If water has a significant value to a community, region, state or nation, amending irrigated soil with compost, with a minimum of 5% to an ideal of 10% by weight, is a means of conserving water and assisting to attain sustainability. Compost utilization, because of the transportation and product cost, will necessitate a subsidy from the water beneficiary. The water utility and not the agricultural producer will likely be the subsidizer. Utilization of compost in an urban area, with irrigated green space, can reduce the estimated 35% of its water production for irrigation by the use of compost in residential and commercial projects, public works projects, and in the irrigation of their parks, golf courses, and other landscaped public spaces.

Water has significant value and its conservation and protection must be a high priority in a community. The dollar value can be determined by operational costs or as an economic necessity. The cost of production appears to create a low value of water. When the economic activity of a community is used to calculate water value, the value is significantly higher. Without water in quantity and quality, a community's economic existence is threatened. Sizable amounts of irrigation water can be conserved by building and maintaining healthy soils.

Review of water content data from 2017, 2018, and 2019, the addition of compost to the soils studied increased the soils' ability to retain moisture, infiltrate water from irrigation and or precipitation, and improves infiltration of water to deeper soils in the 16" to 24" depth. Water availability to root systems was significantly improved. Increased organic content from the compost amendments allowed the soils to remain moist in dry times, and to dry better in high precipitation times.

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Conflicts of Interest

The authors declare no conflicts of interest.

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