Review of the Quantitative Tradeoffs of Using Organic Residuals in Arid Agriculture

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved June 2020 by the
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ARIZONA STATE UNIVERSITY

August 2020

ABSTRACT

Water reuse and nutrient recovery are long-standing strategies employed in agricultural systems. This is especially true in dry climates where water is scarce, and soils do not commonly contain the nutrients or organic matter to sustain natural crop growth. Agriculture accounts for approximately 70% of all freshwater withdrawals globally. This essential sector of society therefore plays an important role in ensuring water sources are maintained and that the food system can remain resilient to dwindling water resources. The purpose of this research is to quantify the benefits of organic residuals and reclaimed water use in agriculture in arid environments through the development of a systematic review and case study. Data from the systematic review was extracted to be applied to a case study identifying the viability and benefits of organic residuals on arid agriculture. Results show that the organic residuals investigated do have quantitative benefits to agriculture such as improving soil health, reducing the need for conventional fertilizers, and reducing irrigation needs from freshwater sources. Some studies found reclaimed water sources to be of better quality than local freshwater sources due to environmental factors. Biosolids and manure are the most concentrated of the organic residuals, providing nutrient inputs and enhancing long-term soil health. A conceptual model is presented to demonstrate the quantitative benefits of using a reclaimed water source in Pinal County, Arizona on a hypothetical crop of cotton. A goal of the model is to take implied nutrient inputs from reclaimed water sources and quantify them against standard practice of using irrigated groundwater and conventional fertilizers on agricultural operations. Pinal County is an important case study area where farmers are facing cuts to their water resources amid a prolonged drought in the Colorado River Basin. The model shows that a reclaimed water source would be able to offset all freshwater and conventional fertilizer use, but salinity in reclaimed water sources would force a need for additional irrigation in the form of a large leaching fraction. This review combined with the case study demonstrate the potential for nutrient and water reuse, while highlighting potential barriers to address.

DEDICATION

This thesis is dedicated to my wife Katherine Krukowski who has been there with me through the rigorous process of pursuing my masters and always helped me along with immense patience, love, and encouragement. I would also like to dedicate this work to my dad, Anthony Inzerillo, who saw such potential in me and encouraged me to pursue a life in engineering to create a better world.

ACKNOWLEDGMENTS

First, I would like to thank my advisor, Dr. Rebecca Muenich, for her excellent mentorship, patience, kindness, and assistance. Her faith in me from the beginning, expertise, and educational philosophy helped me excel in my studies and my research. I would also like to thank the rest of my dissertation committee Clinton Williams, Dr. Kerry Hamilton, and Dr. Peter Fox for their insight and guidance. A special thanks to everyone in the Muenich lab group for their friendship and support through this process. The lab group has been a memorable experience and one I won't forget. Being around so many great minds was invigorating and inspiring. I wish everybody I have had the pleasure of getting to know a great future ahead of them. Finally, I would like to thank the funding for my research provided by the USDA National Institute of Food and Agriculture, Capacity Building Projects for Non-Land Grant Colleges of Agriculture project 1017146, grant number 2018-70001-28751.

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CHAPTER 1

INTRODUCTION

Background

Reuse of organic residual material such as reclaimed water, biosolids, manure, and other materials has been common in agricultural operations for centuries. Organic residuals are materials from human activities that can be recycled for use in crop agriculture or other purposes. These materials typically have high nutrient content that can aid crop growth and soil health (Arabi et al., 2016). Contemporarily, their use has become much more important given issues of climate change, resource scarcity, population growth, and dwindling water resources (Beekman, 1998). Scarcity of resources will be exacerbated by a growing human population. This is especially a concern in arid environments where water is already scarce, and soils are typically non-arable without intervention. Agriculture has been essential to the development of societies the world over. Globalization has brought with it an era of ever-increasing connectivity of people, goods, and markets. This shift has consequently wedged a significant distance between people and food. It has also drastically changed the methods in which food is grown. The world is moving away from local food that once created the basis for sustained food security for communities and towards much larger, centralized operations (Allen & Wilson, 2008). Climate change is severely complicating the issue of food security by affecting crop yields, access to water, and access to food (Newton et al., 2011). More commonly used inorganic fertilizers require large energy inputs which further exacerbate climate issues (Snyder et al., 2009) and also lead to increased nutrient pollution in water bodies (Bastida et al., 2017; Rahman & Zheng, 2018). Greater climate variability has also led to increased desertification (Mbow et al., 2017). Therefore, it is important that agriculture operations in arid environments should seek new, sustainable ways to grow food to increase food security (Qadir et al., 2007). Using organic residuals on arid agricultural land can bring a multi-faceted fix to the burgeoning problem of food insecurity by relieving pressure off traditional water sources, allowing for monetary savings to farmers and society at large, reducing negative environmental impacts like discharge of sewage and the overuse of inorganic fertilizers, and improving soil conditions on croplands (Friedler, 2001; Arabi et al., 2016; Jaramillo & Restrepo, 2017).

Reclaimed water holds much promise to be a widely available recycled agricultural resource. Reclaimed water is plentiful since any water that arrives at a wastewater treatment plant can be recycled to some degree. This is especially true since there are currently technologies available to treat water to varying degrees of quality (Zurita & White, 2014). Reclaimed water contains significant concentrations of nutrients that can aid in crop growth and soil quality such as nitrogen, phosphorus, potassium, and carbon in the form of organic matter. Although some caution should be exercised when using reclaimed water sources because many sources may also contain high levels of harmful microorganisms, salts, and heavy metals (Chen et al., 2013). Usually, regulations are in place to require reclaimed water sources to be treated to a certain degree in order to mitigate the above risks (Jaramillo & Restrepo, 2017). Reclaimed water also reduces pressure on freshwater sources by supplanting new freshwater withdrawals as an irrigation source. If properly managed, reclaimed water may be able to offset some amount of conventional fertilizer use and freshwater irrigation requirements (Dordas et al., 2008).

Biosolids are used across the world as a viable option to fertilize land. Biosolids are a product of the wastewater treatment process. They are the solid portion of wastewater typically created from adsorption and settling processes, which can ultimately be dewatered to a more transportable and applicable form. High in organic matter, biosolids have a high potential to bolster soil health by increasing soil aggregation, water holding capacity, soil microbial communities, and the availability of nutrients for crop growth (Sullivan et al., 2015).

Organic residual use is particularly important in arid environments where soils have low or no organic matter content. Organic matter in soils typically correlates with precipitation and surrounding flora in the environment. Arid environments have low precipitation and sparse vegetation. Studies have found consistent vegetative ground cover in arid environments significantly increases overall soil organic matter, which produces a positive feedback relationship leading to a healthier soil (Arabi et al., 2016). Organic matter promotes soil aggregation and soil microbial health, which allows for essential nutrients to be cycled from fertilizers. Thus, the efficient use of organic residuals in arid land agriculture could be highly beneficial.

Thesis Objective

There have been previous systematic reviews of organic residual use and its associated benefits and risks. These papers have paved the way in collecting detailed information about organic residual use. However, usually similar systematic reviews focus on one material only. Further, they draw research from around the world, without considering climatic regions. I have created a systematic review that collects, reviews, and describes existing studies completed to understand organic residual use in agriculture; specifically, the use of reclaimed water, biosolids, and manure. This review is centered on semi-arid and arid environments because these environments face increasing climatic pressures.

I also completed a case study on cotton farming in Pinal County, Arizona to see if a hypothetical reclaimed water source would be a significantly viable option to reduce fertilizer and freshwater use in the area. This was done in the hopes to identify sustainable options for agriculture in semi-arid and arid environments, an area of the world where one third of the population lives (United Nations).

Approach

A systematic review was chosen to amalgamate existing research in the field of organic residual application impacts on soil quality, crop growth and more. This type of review originates in the medical field where it is common and imperative to have many repeatable studies about procedures and pharmaceuticals to prevent harm to the public (Methley et al., 2014). Given the multitude of effects organic residuals can have on an agricultural operation and the difficulty in separating only one aspectual effect from other effects, a systematic review was chosen to complete this research (Grant et al., 2009). This systematic review takes a more holistic approach that gathers research from around the world relating to organic residual use and their effect on soils and crops. The results of this review can be a resource to promote further research into organic residual use to conserve resources.

Eligibility criteria was established to produce directed and compelling research. An adjusted PICO (population, intervention, comparison, outcome) term list was created and is as follows:

PICO List

P

Soil Quality or Soil Conditions
Plant Growth
Nutrient Availability or Nutrient Uptake
Water Resources
Water Availability
1 or 2 or 3 or 4 or 5

I

Reclaimed Water or Recycled Water or Wastewater
Manure
Biosolids
Application
Soil Amendment
Fertilizer
Nitrogen
Phosphorus
Potassium
Organic Matter or Organic Carbon
1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10

C

Groundwater
Irrigation
Treated Water
Inorganic Fertilizer or Industrial Fertilizers or Conventional Fertilizers
1 or 2 or 3 or 4

O

Benefits
Water Holding Capacity
Hydraulic Conductivity
Nutrient Load
Plant Available
Nitrogen
Phosphorus
Potassium
Carbon
Magnesium
Calcium
Salinity
Reduce
Increase
Control
1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 or 12 or 13 or 14 or 15 or 16 or 17

Although the PICO tool is usually utilized in medical research, it was adjusted for the purposes of this paper to produce an organized path to gather research of interest (Methley et al., 2014). Years considered for review were from 2004 to 2020 to keep studies more relevant in their findings and in the hopes to prevent conflicting results when newer findings made older research invalid. Language chosen to gather research was reduced to English, which could significantly affect the amount of relevant studies available for review given organic residual research is pursued globally. Even with this limitation, many studies from non-English-speaking countries were published in English. A total of 126 studies were paired down to 58 relevant studies included in this review.

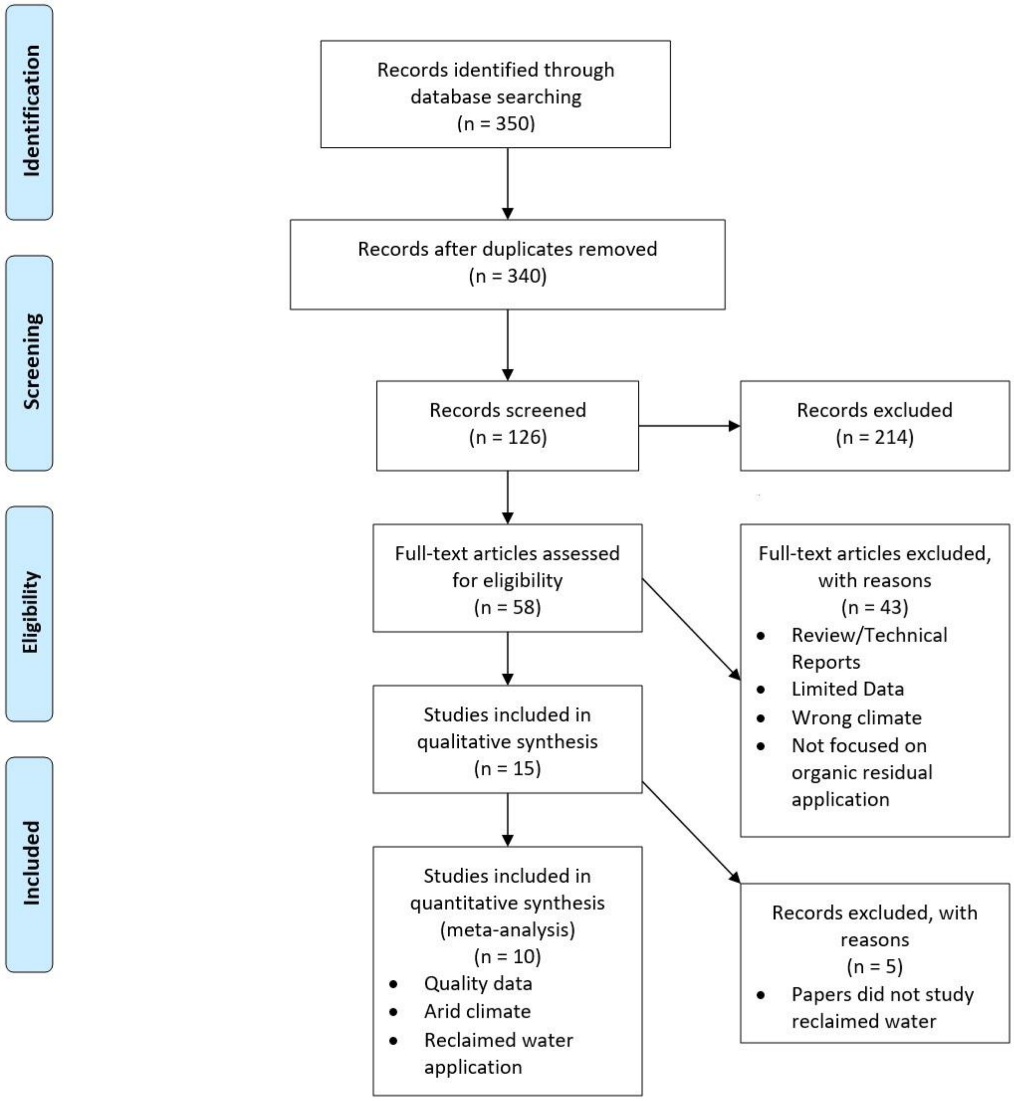


Figure 1: PRISMA diagram displaying how studies were included in this review

The number of studies reviewed was 350 after initial searches and an initial literature review was written. Then, studies were excluded for relevance, which in this case was defined by research determining the effects of organic residuals on agriculture or plant growth. Next, studies that were not located in semi-arid or arid environments were excluded. At this point, there were 58 studies that were used for the systematic review. Technical reports, papers with limited or too specific data, and sociological studies were removed as well. The final step in research selection determined whether the last pool of papers studied reclaimed water application as opposed to other organic residual mediums and materials. This last pool of 10 studies were included in the case study in chapter two.

A case study investigating the effectiveness of a hypothetical reclaimed water source on Pinal County, Arizona cotton farms was then conducted. A new set of criteria was chosen to refer to and design a hypothetical reclaimed water source that would be appropriate for this agricultural setting. The purpose of this exercise is to find out if a reclaimed water source could offset freshwater use and conventional fertilizer use. Studies were paired down once again from the previous 58 studies using some extra criteria: study directly dealt with organic residual application, occurred in semi-arid or arid climates, and needed to have consistent and quality data for quantifying benefits. Studies also needed control scenarios that were compared to organic residual application. When applicable, control data, application data, and ultimate effects on crop growth or soil quality were extracted. In addition, a few studies compared multiple organic residual materials. Data was extracted from these studies as well. Considering the new criteria, 15 studies went through a thorough data extraction process: 11 reclaimed water studies and 4 biosolids studies. Data points collected were as follows: area of study, climate, soil description, crop cover, time frame, water management, fertilizer additions, type of control, type of application, type of effect, type of additional application (if applicable), pH, N, P, Na, Ca, organic matter, electrical conductivity, land temperature, and average evapotranspiration rates. pH, N, P, Na, Ca, organic matter, electrical conductivity of control, application, other application, and/or results were recorded from the perspective of concentrations in reclaimed water. Units of N, P, Na, Ca, and organic matter were converted to a consistent unit of mg kg^{-1} to enable comparisons. Electrical conductivity was standardized to a unit of dS m^{-1}. A synthetic reclaimed water source was created by average the extra data points of each parameter into one usable data point to analyze the effects of organic matter, electrical conductivity, nitrogen, and phosphorus inputs on all cotton cropland in Pinal County, Arizona. This was done in to quantify net benefits of using a reclaimed water source as the one developed for the case study.

CHAPTER 2

SYSTEMATIC REVIEW OF ORGANIC RESIDUAL USE

Introduction

As some essential agricultural resources dwindle, research into organic residuals promotes the recycling of nutrient rich materials and the reduction of reliance on some energy intensive materials. This study presents a review of existing research on organic residual use from across the world. An effort was made to focus on semi-arid and arid environments, although important research is being done across many different climates and research settings.

With a focus on semi-arid and arid environments, it is helpful to understand the state of soils in these climates. Arid climates are defined by soils that contain little to no organic matter, which means arid soils cannot support sustained agricultural operations without intervention (Nettleson & Peterson, 1983).

Throughout this review, many studies were conducted by growing different kinds of crops, which expose different intentions set out to further research in the field of organic residuals. Research that grew crops like corn, wheat, and barley grown with organic residuals picked edible crops that are some of the most widespread crops around the world (Delibecak & Ongun, 2015; Koenig et al., 2011). Other research looked at the growth of niche local crops like lemon grass and Jatropha curcas; the former being used for its herbal properties and the latter being studied for use as a biofuel (Lal et al., 2013;

Dorta-Santos et al., 2014). Four studies investigated organic residual applications with fruit crops such as grapes, citrus, and nectarines (Paranychianakis et al., 2004; Bastida et al., 2017; Vivaldi et al., 2017). Crop studies typically measured protein content, yield, biomass, chlorophyll, and other parameters.

Macronutrients are described briefly below in order to synthesize what happens with organic residual application as it relates to soil quality and crop growth, in addition to other potential benefits and risks:

Nitrogen

Nitrogen is a limiting nutrient that is typically needed in higher rates when compared to other nutrients like phosphorus or potassium. Nitrogen deficiencies cause lower levels of protein in crops, yellowing leaves, and stunted growth. Excessive nitrogen in crops can also cause excessive vegetative growth that reduces effective grain yields and delays maturity of the crop (Johnson et al., 2005). Organic residuals contain high levels of nitrogen primarily in the form of organic nitrogen. Conventional nitrogen fertilizers are usually composed of inorganic forms of nitrogen like ammonia created through an energy intensive process called the Haber-Bosch process, which fixes nitrogen from the air with methane. The production of every ton of ammonia causes a release of 2-3 tons of carbon dioxide, so reusing available organic materials can reduce greenhouse gas emissions (Bicer et al., 2017). Organic residuals readily contain high levels of organic nitrogen that can then be processed by soil microbial communities into inorganic forms of nitrogen like nitrate and ammonium during the process known as mineralization and nitrification (Johnson et al., 2005). These inorganic forms are the most soluble making them easy for crop uptake but are also prone to leaching into the environment. Leaching nitrate into the environment is a particularly significant problem leading to eutrophication of waterways and lower oxygen fixation when ingested by humans (Walsh et al., 2012). With efficient organic residual use and proper application timing, there can be improved use of nitrogen for crops without significant issues leading to leaching of nitrates and reducing the need for conventional fertilizers that release excess carbon dioxide into the environment.

Phosphorus

Phosphorus is another limiting nutrient for plant growth. Most phosphorus used as an input in agriculture comes from the mining of phosphate rock. Unlike nitrogen, phosphorus requirements for plant growth are lower and come in forms that are not soluble. When it comes to organic residuals, phosphorus is typically tied up in organic matter and not readily available for plant growth. Plant-available phosphorus is broken down by enzymes in the soils and plant roots at a slower pace when compared with steps involved in the nitrogen cycle (Sullivan et al., 2015). Phosphorus aids in root development and overall plant growth (Abdolzadeh et al., 2010). Data collection included later in this review demonstrated that it is found in significant quantities in organic residual material but may not be consistent enough to completely supplant conventional phosphorus fertilizer. Some studies included in the review used organic residuals that could completely replace the use of conventional phosphorus fertilizer (Boudjabi et al., 2008; Delibecak & Ongun, 2015). This would reduce pressure to mine, process and transport more phosphate rock, which unlike nitrogen, is a limited resource. However, phosphorus is typically needed at lower rates and is utilized more slowly (Pierrou, 1976).

Organic Matter

Organic matter is enormously important to soil quality and consequently crop growth. Organic matter is described as organic carbon, soil organic carbon, soil organic matter, and others in the research reviewed below. It may be the most important organic residual constituent when dealing with agriculture in semi-arid and arid environments because arid soils do not naturally have the moisture content and vegetation to promote the breakdown of organic matter into soils (Nettleson & Peterson, 1983). Organic matter contains vegetative material, biomass, detritus, and humus. The more complex materials like vegetative material, biomass, and detritus are the most nutrient dense and break down over time providing additional nitrogen, phosphorus, potassium, and other nutrients for crop growth. Humus is the final product after all decomposition processes occur. It promotes soil structure, which then increases the ability of soils to hold onto important cations - known as cation exchange capacity. Overall, benefits of organic matter in soils are numerous: improved water infiltration that allows for more uptake of water by crops and less runoff; increased aeration that promotes nutrient cycling, especially pertaining to nitrogen; increased soil water holding capacity that can lead to less irrigation; reduction of clayey aggregates that allows for easier tilling and seed bed preparation; increased pH buffering capacity; and a healthy environment for microorganisms that increases nutrient cycling and decomposition processes (Fenton et al., 2008). Without organic matter, soils in drier environments could not sustain agricultural activities and soils in more nutrient rich areas would be hurt from over utilizing nutrients over many crop cycles. Therefore, locating and utilizing organic matter is imperative to successful agriculture. Organic residual material is a great source of organic matter and can be utilized well for improved soil quality on a large scale, especially with more solid forms of organic residuals like biosolids and manure.

Salt Content and pH of Soil

Salt content and pH are a few other important parameters to keep track of when applying organic residuals because of their interconnectedness with nutrient cycling and soil structure development. Excess salts can be very detrimental to plant growth and long-term soil health. Over time, excess salts can prevent crop growth all together. Two significant functions can occur with high salt content: high salinity causes excessive soil aggregation and creates an imbalance in the osmotic pressure between the soil and the plant making water absorption difficult for plants; high sodium levels lead to sodic conditions that disperse clay and destroy soil structure making infiltration of water and absorption of nutrients very difficult. Saline conditions are typically measured through electrical conductivity or the sodium adsorption ratio. Electrical conductivity measures total salts in soils including but not limited to nitrates, sodium chloride, sulfate, ammonia, and potassium. The sodium adsorption ratio (SAR) is the ratio of sodium to one half the square root of calcium and magnesium and is measured as:

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{+2} + Mg^{+2}}{2}}}$$

Figure 2: Formula for the sodium adsorption ratio

It is an important measure because sodium, calcium, and magnesium concentrations in soils interact with one another. High sodium concentrations cause disaggregation of soils, reduces hydraulic conductivity, and prevents nutrient cycling. High calcium and magnesium causes aggregation, consequently working against disaggregation processes from high sodium. It is important to know both electrical conductivity and sodium adsorption ratio because the former is a broader measure and can indicate high calcium, magnesium, nitrates, or other salts while the latter specifically determines sodium concentrations (Sonon et al., 2015).

Optimal pH is crucial to the cycling of nutrients in soils. Higher pH soils can create an environment where salts accumulate, which will damage soil health and reduce successful crop growth. Soil pH controls soil microbial communities and can influence the availability of nutrients. Soils in arid environments typically have high pH and therefore have commonly high salt content (Soil Quality Indicators: pH, 1998). Coupled with low organic matter content, semi-arid and arid soils are difficult to cultivate in their natural state and would benefit greatly from organic residual use.

Research into organic residual application in agricultural settings has uncovered significant benefits and risks to their use. This review focuses on two important organic residual materials: reclaimed water and biosolids. Although there are other organic residual materials, there is a wealth of research into reclaimed water and biosolids. As such, a review into organic residual use, benefits, and risks is important in order to streamline research goals of future researchers. When possible, this review specifically focused on studies in semi-arid and arid environments to focus on environments that would benefit the most from organic residual use.

Reclaimed Water

Reclaimed water sources may be the most important agronomic application for arid environments because it provides a dual benefit of irrigation water and nutrient inputs. Reclaimed water sources are water resources taken from the human water cycle, typically after wastewater treatment, to be reused in some way. There are many applications for reclaimed water other than agronomic applications such as streamflow replenishment, aquifer recharge, irrigation of public spaces, and recycled drinking water. This review will focus on reclaimed water used as an irrigation and nutrient source.

Reclaimed water is a product of the human component of the water cycle. It is a recycled water source treated to certain standards depending on geographic governing regulations, but the general terminology and treatment processes usually fall under three categories: primary, secondary, or tertiary treatment. Primary treatment involves screening of large objects, grit chamber settlement, and flow through a sedimentation tank. A significant portion of biosolids will settle in the sedimentation tank, which is discussed later in this review. Secondary treatment typically involves an activated sludge process where wastewater is aerated and inoculated with bacteria that breaks down most organic matter into inert by-products (Jaramillo & Restrepo, 2017). Tertiary treatment includes an array of treatment technologies such as different membrane filters, reverse osmosis systems, chemical disinfection, ozone, or UV exposure (Gerba & Pepper, 2019). After tertiary treatment, water quality is very high and can usually be released into the environment and eventually used again by a downstream user. Lal et al. (2013) was the only study reviewed that used a primary reclaimed water source. All others used secondary treated, tertiary treated, or both.

Reclaimed water studies occur around the world in varied climatic regions, but a majority came from semi-arid or arid climates. Of the papers reviewed, 9 were based in Asia, 10 were based in Europe, 7 were based in North America, and 3 in South America. Of those studies reviewed in Asia, 5 were in the Middle East. Of those studies reviewed in Europe, all 10 were from semi-arid regions: 7 were from Spain, 2 were from Italy, and 1 was from Greece. 5 of the 7 studies based in North America were in semi-arid or arid regions. Considering there was also 1 semi-arid study picked from South America, 72.41% of the studies picked came out of semi-arid or arid climates, which shows the importance of research in the field of reclaimed water irrigation. The research volume shows that these countries and regions are trying to find other ways to sustain agriculture well into the future since water is a severe limiting factor in agriculture in drier climates.

Reclaimed water sources vary greatly in nutrient content between studies. Because nitrogen compounds are typically water soluble, they are commonly found in high rates in reclaimed water sources. From the data extracted, nitrogen concentrations range from 4.2-29.9 mg/L in reclaimed water sources (Morugan-Coronado et al., 2010; Alkhamisi et al., 2011). Depending on timing and crop requirements, nitrogen at those concentrations could replace conventional nitrogen fertilizers by a significant amount. Forms of nitrogen vary greatly between studies, but most are readily available for crop uptake, especially when paired with organic matter additions that come along with reclaimed water application (Dordas et al., 2008). Phosphorus was found to range from 3.77-29.06 mg/kg in the data that was extracted (Heidarpour et al., 2007; Vivaldi et al., 2017). Again, if managed properly phosphorus content in reclaimed water could significantly reduce the need for conventional fertilizers. Organic matter ranged from 2,300-3,800 mg/kg (Dorta-Santos et al., 2014). Water source electrical conductivity ranged from 0.02-24.1 dS/m (Morugan-Coronado, 2010; Dorta-Santos et al., 2014). However, the maximum value of 24.1 was an extreme outlier. Most electrical conductivity values were within bounds to allow proper crop growth. pH ranged from

7.3-8.7. Similarly, 8.7 was an extreme (Dorta-Santos et al., 2014). At a pH of 8.7, nutrient uptake and microbial activity would be diminished. Most values for pH were within range to support crop growth (Soil Quality Indicators: pH, 1998).

Biosolids

Biosolids are nutrient dense organic residuals produced from the wastewater treatment process. They are usually collected during primary or secondary wastewater treatment using sedimentation tanks. Commonly, biosolid materials are dewatered in order to be transported and applied with ease making them an appealing organic residual material. Biosolids are very high in organic matter content, making this organic residual material a great candidate to increase water holding capacity of soils (Artiola, 2006).

Through the selection process, not as many biosolid studies were included in the review compared to reclaimed water studies. A total of 13 studies were chosen: 1 from Africa, 1 from Australia, 2 from Asia, 3 from Europe, and 6 from North America. Studies that were in semi-arid to arid environments were uncommon. If a study was from an arid environment but done under lab or greenhouse conditions, then these studies were not sorted by climate characteristics. Of the 13 studies, only 3 were in semi-arid or arid environments.

Although less data was available in the biosolids studies, what was available shows the density of nutrients contained in sources of biosolids. Nitrogen concentrations ranged from 19.77-980 mg/kg (Koenig et al., 2011; Delibecak & Ongun, 2015).

Phosphorus concentrations ranged from 73.18-7000 mg/kg. Organic matter ranged from 15,400-28,200 mg/kg. Electrical conductivity was higher than that of reclaimed water studies, ranging from 3.62-5.8 dS/m, because of the dense nature of biosolids constituents (Boudjabi et al., 2008; Delibecak & Ongun, 2015).

Similar Studies

Research on reclaimed water agronomic applications is prevalent. Past researchers have gathered groups of studies for different purposes in ways that can be helpful to future studies. Some outline the general regulation framework set out by different international and national bodies like the Food and Agriculture Organization (FAO) run by the United Nations, the World Health Organization (WHO), and the United States Environmental Protection Agency (USEPA) (Jaramillo & Restrepo, 2017). Other reviews gathered information about the history of organic residual use, as well as benefits and risks of using this resource (Artiola, 2006; Jaramillo & Restrepo, 2017; Chen et al., 2013). The importance of using organic residuals in arid environments is mentioned in review material but not explored in depth in specific studies. When possible, this review focuses on studies in arid environments where organic residual applications can make the biggest difference.

Benefits of Organic Residual Use

46 studies of 58 discussed benefits involved with the use of organic residual materials. Organic residuals contain numerous benefits in agricultural settings, especially

in arid environments that have a lack of water resources and organic matter in soils. Organic residuals can aid successful agricultural operations to provide food and goods creating resilient food systems at many scales. Reusing organic residual material prevents these waste streams from entering the environment where concentrated nutrients and other constituents can harm ecosystems. If nothing else, reusing organic residual material creates a more circular economy where less is wasted overall (Vaneeckhaute et al., 2018). This review will mainly focus on organic residual benefits as they pertain to agricultural application such as nutrient inputs, organic matter, and crop productivity. Benefits associated with bolstering soil microbial populations and proper organic residual management are discussed briefly as well.

Nutrient Benefits

Nitrogen is one of the most important agricultural inputs. Proper nitrogen inputs in terms of timing, amount, and type of nitrogen affect all cropping systems to a large degree. One important aspect of nitrogen contained in organic residuals is the ability of the residual to promote nitrogen mineralization. Nitrogen is a part of the nitrogen cycle in which organic forms of nitrogen are converted to inorganic forms. Inorganic forms of nitrogen like nitrates and ammonium are readily available to plants. Biosolids typically have high concentrations of nitrogen and have been successfully applied to supply nitrogen for crop growth. Overall, 6 studies researched nitrogen mineralization, accumulation, or efficiency (Jin et al., 2011; Wuest & Gollany, 2013; Dordas et al., 2008;

Li et al., 2012; Rigby et al., 2016; Koenig et al., 2011). In one study between 8 other organic residual applications, biosolids contained the highest concentration of nitrogen (Wuest & Gollany, 2013). A positive relationship has been found between doses of biosolids and nitrogen mineralization rates (Jin et al., 2011). Given the high nitrogen contents in biosolids, management strategies should be created and executed to prevent excessive nitrogen concentrations in soil profiles. Reclaimed water has significant nitrogen concentrations as well, but much less when compared to biosolids. However, nitrogen is typically readily available in reclaimed water sources because it contains nitrogen nutrient compounds in their simplest forms such as nitrates or ammonia (Wafula et al., 2015). Reclaimed water sources can supply significant amounts of nitrogen even though reclaimed water sources are a much more diluted agronomic application (Dorta-Santos et al., 2014; Alkhamisi et al., 2011).

Phosphorus concentrations in organic residual materials are well-studied in agricultural settings. Biosolids contain significantly high concentrations of phosphorus, sometimes in excess of crop requirements. When biosolids are applied based on crop nitrogen needs, phosphorus applications can concentrate in excess in soils (Li et al., 2012). Reclaimed water sources can contain significant concentrations of phosphorus depending on location and treatment level (Heidarpour et al., 2007; Vivaldi et al., 2017; Elliot & Jaiswal, 2012). Phosphorus concentrations can completely replace conventional phosphorus fertilizer use when reclaimed water has concentrations of phosphorus at the

USEPA’s limit for secondary drinking water, 3-4 mg L^{-1} (Elliot & Jaiswal, 2012). Reclaimed water sources in arid environments have been found to contain significant phosphorus concentrations in plant-available form, making it easy for crops to uptake phosphorus from reclaimed water sources (Zohar et al., 2014). There is enough phosphorus to support crop growth even at low concentrations; although volume of irrigation water and timing are important indicators as to whether phosphorus in reclaimed water is readily available for crops (Elliot & Jaiswal, 2012).

In recent literature, 11 studies found that organic matter is one of the most important constituents in organic residual material. Organic matter accumulation provides soil aggregation. Soil aggregation in turn provides sites for nutrients to attach, which facilitates efficient nutrient uptake by crops. Studies measured organic matter using different metrics such as soil organic carbon or organic matter. Some found that increased organic matter promoted carbon and nitrogen mineralization (Jin et al., 2012; Morgan, 2011). Others found that increased organic matter increased microbial activity, biomass, and microbial resiliency in arid soils (Adrover et al., 2012; Morugan-Coronado, 2011). Adrover et al. (2012) found a strong correlation between organic matter content and nitrogen content in soils. This correlation may favor biosolids application since biosolids have a high concentration of organic matter. Morugan-Coronado et al. (2011) shows that promoting microbial communities with organic matter accumulation in semi-arid or arid environments makes microbial communities more resilient to temperature change.

Benefits to Crops

Most studies included in this review center around the effects of organic residual and reclaimed water use on a crop. Studies focused mainly on crop yield, but also on the crop quality, i.e., chlorophyll levels (Alkhamisi et al., 2011), leaf area (Boudjabi et al., 2008), leaf gas exchange (Paranychianakis et al., 2004), and above-ground biomass (Boudjabi et al., 2008), among other growth parameters.

Organic residual and reclaimed water sources typically have significant macronutrient concentrations that can be recycled and used by crops. Coupled with organic matter and proper irrigation management, reclaimed water can be a sustainable water source and nutrient input.

One study evaluating the effects of reclaimed water found that it produced corn crops that were taller, matured earlier, contained more chlorophyll, and had more yield. (Alkhamisi et al. 2011). Importantly, these results indicate that reclaimed water can facilitate successful agricultural operations in arid, food-insecure areas—presuming a reclaimed water source is available. Regions lacking sufficient water resources to successfully grow food can look to reclaimed water to either replace or increase the amount of irrigation water available.

Other studies evaluating biosolids found that its use increased yields and green vegetation, such as leaf-area index and above-ground biomass (Koenig et al., 2011; Boudjabi et al., 2008). Specifically, biosolids were found to promote carbon and nitrogen mineralization and increase organic matter and thus water-holding capacity the soil (Jin et al., 2011; Wuest & Gollany, 2013). Thus, much like the case with reclaimed water, the results of the studies analyzing the benefits of the use of biosolids indicate that biosolids facilitate successful agricultural operations in arid or semi-arid regions. This is especially true where water resources are limited. Studies indicate that regions lacking sufficient water resources can look to biosolids to decrease the amount of irrigation water necessary to grow healthy crops due to the fact that biosolids help soil retain water, allowing crops more time to uptake the limited water resource.

Notably, some studies found that the use of organic residuals increased green vegetation, but not yields. However, this was most likely due to incorrect timing or quantity of the organic residual on any given crop (Koenig et al., 2011). In order to promote soil health—and consequently crop health—while implementing organic residuals, Morugan-Coronado et al. (2011) and Mounzer et al. (2013) suggested increasing the dose of organic residuals but applying them more frequently with shorter irrigation events to pair.

Risks of Organic Residual Use

24 studies of 58 found discussed risks involved with the use of organic residual materials. Residual materials are derived from waste materials, which could contain unwanted concentrations of bacteria, nutrients, heavy metals, and other constituents. Studies showed that, unlike conventional fertilizers, organic residuals posed a greater risk

of misapplication to the detriment of soil quality and crop growth. Some studies discussed bacterial concentrations (Halalsheh et al., 2008; Negahban et al., 2012), heavy metals (Lal et al., 2013), and other toxic compound accumulation associated with reclaimed water sources (Chen et al., 2013 Xu et al., 2010).

Excess Nutrients

9 studies found that the use of organic residual materials poses a greater risk of excess accumulation of nutrients in soil—which quickly becomes dangerous to the health of crops, the environment, and human health. In particular, organic residual materials are very likely to cause salt and nitrate build up in soil profiles. Excess salt and nitrogen destroys soil structure, prevents nutrient uptake, and is likely to destroy crops, cause eutrophication in waterways, and even birth defects in humans (Heidarpour et al., 2007; Chen et al., 2013). However, at least two studies found that this risk can be mitigated with simple management techniques applied to the timing and quantity of reclaimed water application (Duan et al., 2010; Bastida et al., 2017).

Risks to Microbial Communities

Managing quantity and timing of reclaimed water irrigation affects soil microbial communities. Shorter and more frequent irrigation events promote microbial communities in a few ways. Managing irrigation in this way allows for a quick build up (wet cycle) and break down (dry cycle) of organic matter. During dry cycles, some of the microbial community will break down and continue nutrient cycling, providing nutrients to crops and the microbes left in the soil. A subsequent wet cycle will promote more resilient microbes in the soil, making the community stronger as a whole (Morugan-Coronado et al., 2011). If the reclaimed water source has a high electrical conductivity, it has been found that shorter and more frequent irrigation events can also create salt-resistant microbial populations.

Salinity Increases

Salinity may be the most important barrier to organic residual and reclaimed water use. This is especially true when organic residuals are applied to aridic soils that have a propensity for high salt content (Alkhamisi et al., 2011). 9 studies specifically outlined the effects of salinity accumulation in soils that can cause reductions in yield and damage to soil structure. However, many more studies at least mentioned concern for salinity build-up in soils. Depending on treatment, salts in reclaimed water sources can be low, which comes at the expense of lower overall nutrient contents. Treatment options will remove a wide variety of nutrients from harmful salts to essential plant nutrients. In addition, forms of nitrogen are salts and harm soil health and water quality when in excessive concentrations (Morugan-Coronado et al., 2011).

Heavy Metal Accumulation

Chen et al. (2013) highlights varied studies done by the authors and researchers around the world pertaining to the risks associated with reclaimed water sources. Heavy metal accumulations from metals such as As, Cd, Cu, Cr, Ni, Pb, and Zn and associated risks were found to be minimal and typically do not affect crop growth (Chen et al., 2013; Lal et al., 2013). For the sake of safety to human health and the environment, suggestions are made to properly manage concentrations of heavy metals especially when industrial sources are nearby agriculture and water sources (Chen et al., 2013).

Other Considerations

Important components of research into risks of biosolids and reclaimed water use should include contaminants of emerging concern. This field of research is expansive and most likely multi-generational in scope because there are a multitude of chemical components created by industry sources, it is challenging to keep up with these constituents' effects in the environment (Chen et al., 2013).

CHAPTER 3

CONCEPTUAL MODEL OF USING ORGANIC RESIDUALS IN AN ARID AGRICULTURAL SETTING

Introduction

Reclaimed water has been used for irrigating farmland for millennia. If harnessed properly, reclaimed water sources have the potential to be a truly renewable resource. Benefits of using reclaimed water for agriculture are numerous; from economic to environmental, reclaimed water can potentially help agricultural operations on many fronts. This is especially true in arid environments where water and other resources are scarce. There have been many studies demonstrating that using reclaimed water comes with benefits and risks that freshwater sources do not necessarily have (Adrover et al., 2012; Dorta-Santos et al., 2015; Morugan-Coronado et al., 2011). A high-level understanding of both the benefits and risks is important in making decisions whether to use such sources of water or not. A quantitative approach to understanding the benefits of reclaimed water, especially in arid agriculture, is lacking in the literature. This case study sets out a path to understanding water quality issues associated with using reclaimed water. The objectives for this project are to gain an understanding of the significant benefits of using reclaimed water and if those benefits can significantly reduce the amount of irrigation water needed for substantial crops in a desert agricultural system.

Pinal County, Arizona was chosen as a study area because it is in an arid environment, has an economy that heavily relies on agriculture, and has pressing issues of water allocation that will need to be addressed quickly if agriculture is to continue in this area. The newest Drought Contingency Plan for Colorado River water agreed upon between California, Nevada, Colorado, New Mexico, Utah, Wyoming, and Arizona contains water cuts for when Lake Mead goes below 1,075 feet in elevation (Arizona Discussions on Drought Contingency Planning, 2019). Pinal County water users are slated to be among the first users to have significant water cuts for a few reasons. Farmers in the county rely heavily on Central Arizona Project (CAP) water, which comes from Lake Mead (Hatcher, 2019) and Pinal farmers have some of the lowest water rights of all water users. The state of Arizona has had a mandate towards valuing residential and commercial water users over agricultural water users as the state’s agriculture industry has declined over time (Allhands, 2019). Unfortunately, these water cuts are viewed as imminent. There has been an increase in deep groundwater drilling to supplant the reduction of CAP water, which increases concerns of sustainable water use.

This case study hopes to reveal the benefits of using reclaimed water for irrigation for Pinal County farmers. Infrastructure to obtain reclaimed water sources may be lacking in the area, so lead time and funding to build reclamation and conveyance projects is likely to be a large obstacle to widespread reclaimed water irrigation. However, it is most important to understand whether such projects would be beneficial to the county in the first place. By examining 8 indicators in a synthetic RW profile, a significant analysis of water and nutrient savings was completed. Overall, this case study seeks to quantify the amount of water saved with organic matter accumulation in soils and the amount of N and P fertilizer than can be replaced with N and P accumulation all from a synthetic reclaimed water source rich in nutrients.

Methods

Initially, a land use map was created for Pinal County. All land uses in the county were displayed. Most agricultural operations are in the western part of the county. Cotton was chosen as an indicator crop for analysis for a few reasons. First, if recommendations were to be considered, cotton is a non-edible crop. Even though extensive and appropriate treatment options are available, there would be minimal concern for poor reclaimed water quality affecting public health. Second, cotton requires a great deal of water and would benefit greatly if irrigation could be reduced using reclaimed water sources or through beneficial effects of reclaimed water use (Frisvold, 2016). Finally, cotton is the second largest crop in acreage in Pinal County covering 89,007.2 acres or 14.18% of all the crop land in the county (USDA National Agricultural Statistics Service Cropland Data Layer, 2019) and as such is a very important crop to the local economy.

County	Crop	Acreage	Water Use (Acre-Feet Per Year)	Water Use (Acre-Feet Per Year)	Water Use (Gallons Per Year)
Pinal	Cotton (Upland)	89,007.2	4.5	400,532.4	130,513,860,299

Table 1: Cotton acreage and water usage in Pinal County, AZ

Land cover of Pinal County is shown below (Figure 3). Nearly all agriculture is located in the western portion of the county dominated by cotton (in red) and alfalfa (in pink).

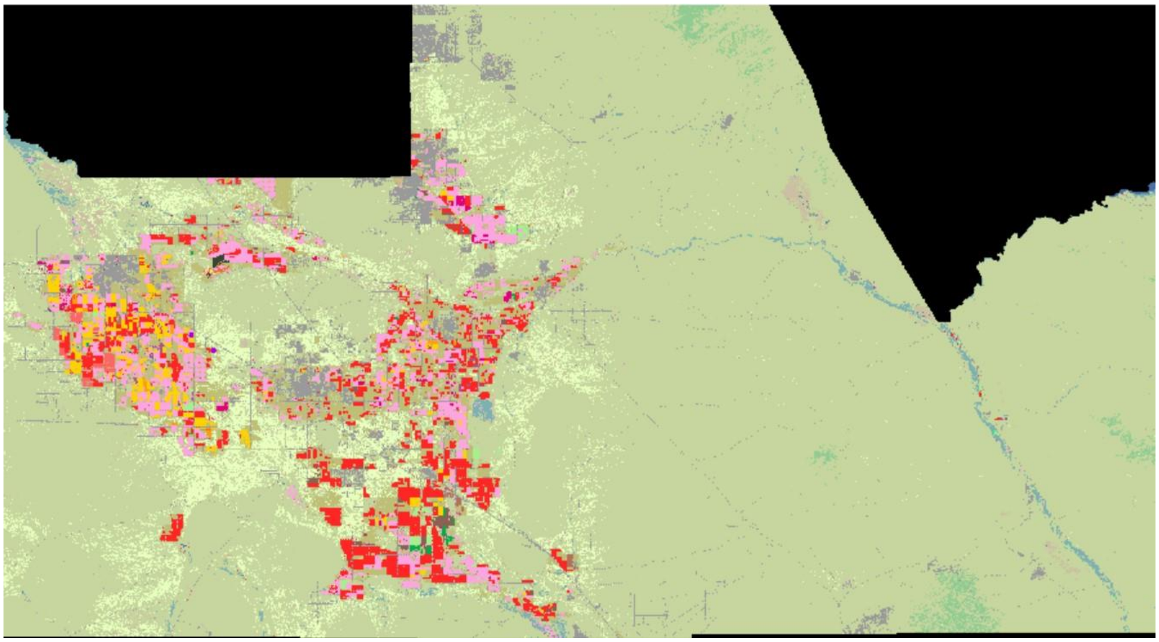


Figure 3: Land Cover map of Pinal County, AZ from USDA NASS CropScape Data Layer

A synthetic reclaimed water source was created for analysis by pulling data from nine different sources in order to obtain the water quality parameters for analysis (pH, total N, P, Na, Ca, Mg, organic matter, electrical conductivity, and sodium adsorption ratio (SAR)). N, P, Na, Ca, Mg, and organic matter are standardized to units of mg L^{-1}; Electrical conductivity is in units of dS m^{-1}. The water profile was created by averaging values from relevant studies (Lal et al., 2013; Morugan-Coronado et al., 2010; Adrover et al., 2012; Duan et al., 2010; Alkhamisi et al., 2011; Dorta-Santos et al., 2014; Heidarpour et al., 2007; Paranychianakis et al., 2004; Vivaldi et al., 2017). The origin of this data was from a systematic analysis of semi-arid and arid studies using reclaimed water applications. Data in these studies was consistent and thorough. Climates and soils were similar to Pinal County, though all the studies were located outside of the United States. The motivation to extract such data was to provide sources of reclaimed water of different treatments from arid environments. Many parameters extracted are above federal and state water quality regulations for reclaimed water use (Water Pollution Control, 2019). Therefore, this is a hypothetical exercise in providing additional nutrient and organic matter inputs by using a reclaimed water source. There has been research in decentralizing and treating different tiers of water quality for particular uses (Vaneekhaute et al., 2018). More research should be done in this field in order to fully take advantage of the benefits associated with reclaimed water use.

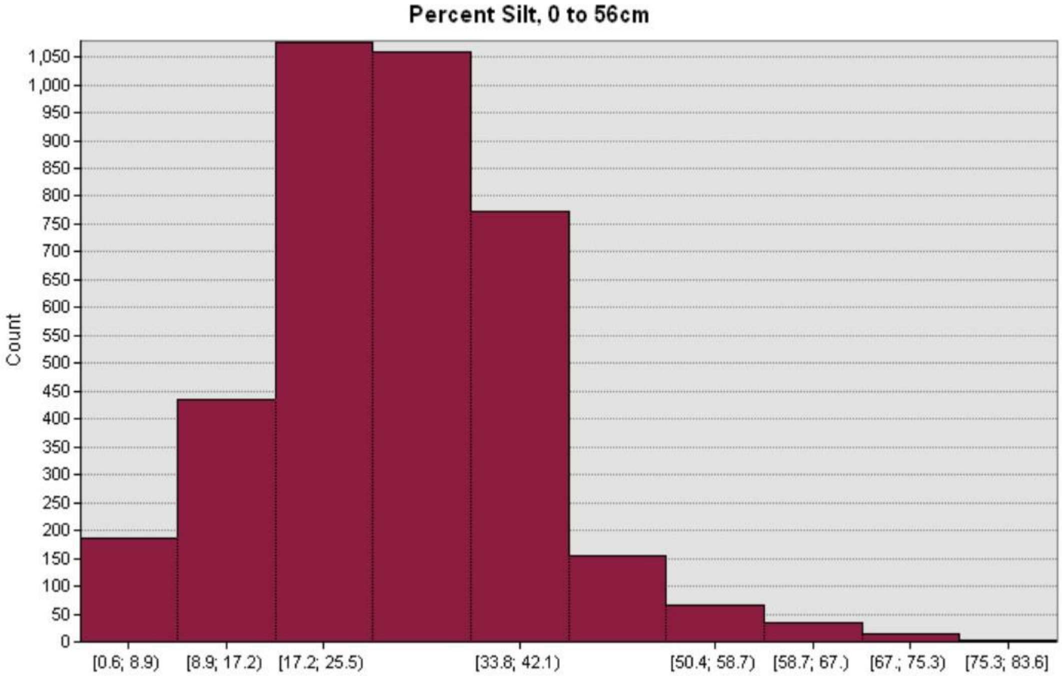
Available water capacity can typically range from 0-0.25 with a pure soil made up of only sand, silt, and clay (Soil Quality Resource Concerns: Available Water Capacity, 1998). With additional organic matter accumulation, available water capacity increases in a variety of ways depending on percentages of silt, clay, and sand. Electrical conductivity can range significantly. For this analysis, an electrical conductivity value of 2.25 dS/m from the aggregated data was used for the reclaimed water source. Organic matter in soils should range from 3-6% in agricultural soils in order to have a successful crop yield (Adrover et al., 2012; Granato et al., 1995; Fenton et al., 2008). Organic matter in the area of interest was much lower, indicating aridic soils with low nutrient content and low potential for soil aggregation. Through the review process, there was only one data point for organic matter content in a reclaimed water source, which was 3,200 mg kg^{-1} or 0.32% (Dorta-Santos et al., 2014). Optimally, available water capacity would increase to its known maximum value to obtain the most benefit for soils and crop growth. Therefore, the goal is to increase available water capacity as high as possible with reclaimed water application. The relationship between organic matter and available water capacity varies depending on the ratio between silt, clay, and sand. Sandy soils will see the highest benefit from increased organic matter applications (Minasny and McBratney, 2017). The relationship between organic matter and available water capacity in a sandy soil for this case study can be approximated be as follows:

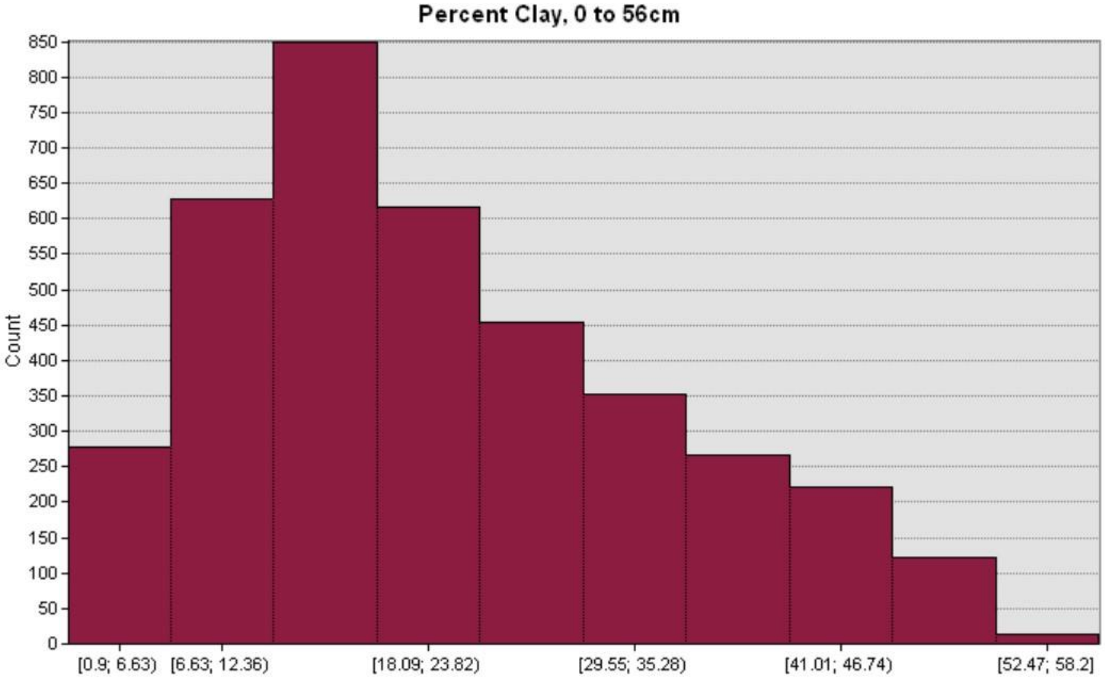
$$AWC_2 = AWC_1 + 1.13 * OM$$

(Minasny and McBratney, 2017).

Where AWC_2 is the available water capacity after supplemental organic matter, AWC_1 is the original available water capacity, and OM is organic matter. This relationship is derived from converted aggregated values from a recent meta-analysis looking at the relationship of organic matter application and available water capacity across a variety of soil types.

By observing histograms of silt, clay, and sand percentages, both silt and clay percentages exhibit a right-tailed distribution with many observations of low clay and silt percentages. Whereas the percent of sand across the county exhibits a curve akin to a normal distribution or a bimodal distribution with a spike in observations with a high sand percentage in the soil profile (Figure 4).


Percent Silt, 0 to 56cm
Count
1,050
1,000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
[0.6; 8.9)
[8.9; 17.2)
[17.2; 25.5)
[33.8; 42.1)
[50.4; 58.7)
[58.7; 67.)
[67.; 75.3)
[75.3; 83.6]


Percent Clay, 0 to 56cm
Count
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
[0.9; 6.63)
[6.63; 12.36)
[18.09; 23.82)
[29.55; 35.28)
[41.01; 46.74)
[52.47; 58.2]

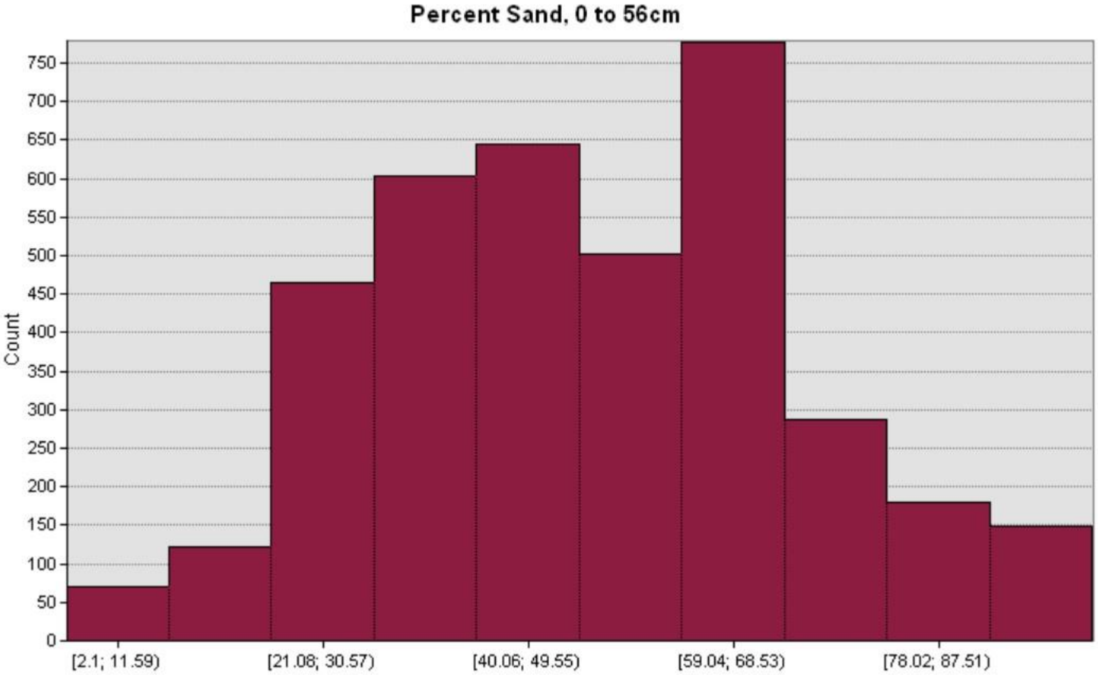


Figure 4 Histograms of silt, clay, and sand in Pinal County.

Sandy soils are conducive to high hydraulic conductivity. These soils also have low available water capacity and organic matter. Organic matter application will be most beneficial to sandy soils because the optimal soil type for crop growth is one that allows water in, but also optimally holds water in plant-available locations in the soil profile. In other words, sand allows water into the soil and a matrix of organic matter holds water in place so it can be used by plants instead of percolating down through a deep soil profile (Cates, 2020). Through analyzing soil data in the county, an available water capacity value of 0.15 was used for further analysis because it is the most common data point in the first 22 inches (approximately 56 centimeters) of soil. A 22-inch soil profile was used for analysis because most cotton roots develop approximately within the first 22 inches of soil (Ritchie et al., 2007). Therefore, it can be expected that:

$$(0.15\ inch*inch^{-1}) * (22\ inches) = \mathbf{3.30}\ \boldsymbol{inches\ of\ water\ in\ the\ soil\ profile}$$

Assuming no loss in the system, potential available water capacity is expected to be 0.51 if organic matter content is 0.32% in the synthetic reclaimed water source. By this estimate, available water capacity can increase by a factor of 3.4. It is unknown how long it would take for organic matter content to rise to accumulate in soils. However, Granato et al. (1995) showed that after 12 years of consistent reclaimed water application, organic matter content rose to 4.4. After a decade without reclaimed water application, organic matter content reduced to 3.9%. Other studies have shown some resiliency to organic matter content in soils especially when proper soil management techniques are used such as short and frequent irrigation events (Bastida et al., 2017; Jin et al., 2011). It is likely there will be losses due to conveyance, runoff, and evapotranspiration. Further field research should be done to test accurate organic matter build up in soils.

Results

With an increase in organic matter, available water capacity can potentially increase as follows:

$$(0.51\ inch\ inch^{-1}) * (22\ inches) = \mathbf{11.22}\ inches\ of\ water\ in\ the\ soil\ profile$$

Inches of water in the soil profile over the entire acreage of cotton in the county can be converted to acre-feet through a few important conversions:

$$1\ inch\ of\ water\ in\ the\ soil\ is\ 27{,}154\ gallons\ across\ 1\ acre\ (Manske)$$

$$3.30\ inches\ of\ water\ in\ the\ soil\ is\ 89{,}608.20\ gallons\ across\ 1\ acre$$

$$89{,}608.20\ gallons\ acre^{-1} over\ 87{,}007.2\ acres\ is\ 7{,}796{,}558{,}579.04\ gallons$$
$$or\ \boldsymbol{23{,}926.76\ acre-feet}$$

$$11.22\ inches\ of\ water\ in\ the\ soil\ is\ 304{,}667.88\ gallons\ across\ 1\ acre$$

$$304{,}667.88\ gallons\ acre^{-1} over\ 87{,}007.2\ acres\ is\ 26{,}508{,}299{,}168.74\ gallons$$
$$or\ \boldsymbol{81{,}351.00\ acre-feet}$$

$$Net\ soil\ water\ gain\ in\ cotton\ crop\ root\ zone: \mathbf{81{,}351 - 23{,}926.76}$$
$$= \boldsymbol{57{,}424.24\ acre-feet}$$

Referring to table 1, a crop of cotton needs an average of 4.5 acre-feet of water per year (Frisvold, 2016). Across Pinal County, that would be a total of 400,532.4 acre-feet of water for a season. Given an additional 57,424.24 acre-feet of water available in the soil after consistent reclaimed water irrigation, the total area of cotton crop could reduce water irrigation by volume by 14.34%. Although this is an ideal case, it is a useful exercise in understanding the effects of organic matter on available soil water capacity.

An analysis of reclaimed water electrical conductivity follows to add real world factors that would affect the full potential of organic matter additions to soils. An average electrical conductivity of 2.25 dS m^{-1} was previously determined from a systematic data analysis of studies on reclaimed water applications. Background electrical conductivity commonly ranges from approximately 0 to 1.92 dS m^{-1} in the first 22-inches of soil across Pinal County. In order to combat excessive salinity in soils, leaching fractions are used to flush salt through soil profiles (Ayers & Wescott, 1976). The salt tolerance threshold of cotton is 7.7 dS/m after which yields will diminish. Above 17 dS/m, a 50% reduction in yield can be expected (Ashraf, 2002). Therefore, to obtain a good yield with reclaimed water, 7.70 dS/m would be the maximum salt tolerance. The worst-case scenario would be having soils with an initial electrical conductivity of 1.92 dS m^{-1}. Therefore, a leaching fraction can be expected as the following:

$$LF = \frac{EC_{iw}}{EC_{dw}} = \frac{2.25 + 1.92}{7.70} = 0.54$$

Using the equation for leaching fraction where LF: leaching fraction, EC_{iw}: electrical conductivity of the irrigation water, and EC_{dw}: electrical conductivity of the drainage water, a leaching fraction of 0.54 was determined to keep salt content below the detrimental electrical conductivity threshold for cotton. Therefore, the amount of water needed to grow cotton crops in Pinal county to account for salinity is 54% more than if the reclaimed water did not have salt in it. In comparison, groundwater near the area of interest and Central Arizona Project water has been found to contain electrical conductivities around 0.01 – 0.02 dS m^{-1} (Brown & Caldwell, 2003). A leaching fraction of only 0.001 – 0.003 (0.1 – 0.3%) would be necessary, which is approximately a 99% reduction in leaching fraction water.

Total irrigation requirement using reclaimed water including leaching fraction:

$$400{,}532.4 \;\; acre\ feet^{-1} * 1.54 = 616{,}819.90\ acre\ feet^{-1}$$

Total irrigation requirement using groundwater or CAP water including leaching fraction:

$$400{,}532.4 \;\; acre\ feet^{-1} * 1.002 = 401{,}333.46\ acre\ feet^{-1}$$

Above is the total water requirements for all cotton crop acreage in Pinal County, Arizona over a growing season including leaching fraction using a reclaimed water source and using groundwater. By subtracting potential gains from addition water storage due to the organic matter-available water capacity relationship, the total irrigation requirement using reclaimed water will net at 559,395.66 acre $feet^{-1}$. That is an additional 158,062.20 acre $feet^{-1}$ compared to groundwater or CAP irrigation requirements. Therefore, when electrical conductivity is considered, reclaimed water will not produce a net water savings. However, increased organic matter includes a host of other benefits; mainly in producing soil aggregates that facilitate nutrient cycling in soils and crops. Further research can include effluent qualities and quantities found in wastewater treatment plants in Pinal County. This may glean additional guidance and more real-world applications of reclaimed water across the county.

Reclaimed water also contains significant nutrient benefits that may be able to offset conventional fertilizer use. Conventional fertilizers are energy-intensive and expensive. Production of conventional fertilizers significantly contributes to greenhouse gas emissions (Snyder et al., 2009). Sourcing a portion of nutrient inputs through reclaimed water use would be a sustainable solution to reducing reliance on conventional fertilizers. An analysis of nitrogen and phosphorus concentrations supplanting conventional fertilizers is a useful exercise to reducing conventional fertilizer requirements.

Nitrogen is an essential macronutrient required in healthy crop growth. Inorganic forms of nitrogen are readily available to crops and therefore concentrations of inorganic nitrogen are important to understand. Pounds per acre of nitrogen supplied by a reclaimed water source can be calculated as follows:

$$Pounds\ of\ N\ Per\ Acre = \ [ppm\ of\ NO_3 - N] * [inches\ of\ water\ applied] * [0.23]$$

In Arizona, a cotton crop needs about 4.5 acre-feet of water per season. Converting acre-feet to inches is as follows:

$$1\ inch\ of\ water\ in\ the\ soil\ is\ 27{,}154\ gallons\ across\ 1\ acre\ (Manske)$$

$$1\ acre - foot\ is\ 326{,}000\ gallons$$

$$4.5\ acre - feet\ is\ 1{,}467{,}000\ gallons$$

$$1{,}467{,}000\ gallons\ /\ 27{,}154\ gallons\ is\ 54.03\ inches$$

$$Parts\ Per\ Million\ of\ NO3 - N\ is\ 14.55\ (Table\ 2)$$

Therefore:

$$[14.55] * [54.03] * [0.23] = 180.81\ lbs\ acre^{-1}$$

Given a cotton crop typically needs 80-120 lbs acre^{-1} of N, this synthetic reclaimed water source could provide nitrogen in excess of 60-100 lbs acre^{-1}, which could cause issues of leaching nitrate into groundwater or agricultural runoff. Cotton is particularly susceptible to excess nitrogen as it will delay maturation of the crop (Hake et al., 1991). Another issue with this type of nitrogen application is timing. The amount of nitrogen needed for different stages of the cotton crop's life cycle is different over time. Luckily, most nitrogen application is needed in the younger stages of growth, which lines up with early irrigation as well (Stevens, 2019). Further field research could identify an optimal co-application of irrigation with reclaimed water along with appropriate timing and concentration of nitrogen.

Phosphorus is another essential macronutrient needed for proper crop growth. It is required in lower concentrations than nitrogen and is integral to root development and overall plant growth. Phosphorus concentrations were measured at 12.64 mg/kg, which is a 1:1 relationship with units of parts per million. Phosphorus as PO_4 can be roughly converted to pounds per acre-foot as follows (Tracy & Hefner, 2009):

$$Pounds\ Per\ Acre\ Foot\ of\ PO_4 = [\,ppm\ of\ PO_4 - P] * [2.7]$$

$$Pounds\ Per\ Acre\ Foot\ of\ PO_4 = [12.64] * [2.7] = 34.13\ lbs\ acre - foot^{-1}$$

Cotton crops across Pinal County will require 517,487.86 acre-feet of the synthetic reclaimed water source constructed for this case study including water savings from organic matter and a leaching fraction due to electrical conductivity. Therefore:

$$517{,}487.86\ acre - feet\ *\ 34.13\ lbs\ acre - foot^{-1} = 17{,}661{,}860.66\ lbs\ of\ PO_4$$

$$\frac{17{,}661{,}860.66\ lbs}{87{,}007.2\ acres\ of\ cotton} = 203\ lbs\ acre^{-1}\ of\ PO_4$$

Throughout the life cycle of a cotton crop, it has been suggested that 61 lbs acre^{-1} are needed for a successful crop. From this analysis, it was found that this reclaimed water source can provide over three times the necessary amount of phosphorus. Just like excess nitrogen, excess nitrogen can contaminate waterways and cause eutrophication processes. In addition, excess phosphorus can limit a crop’s ability to uptake micronutrients like iron and zinc. At such a high rate like in this case study, crop failure is possible.

Conclusion

Overall, the synthetic reclaimed water source created for this case study bolsters concerns of excess salinity and nutrient contents (Duan et al., 2010; Dorta-Santos et al., 2014). Regulations on reclaimed water are in place to prevent a lot of these risks posed by excess salts and nutrients in reclaimed water sources. Although the research exists, further studies can still be done to investigate utilization of a water source with high concentrations of nutrients while managing the risks, especially when it comes to timing and quantity. Reclaimed water sources such as the one outlined in this case study can be mixed with freshwater irrigation sources so conventional fertilizer use and pressure on freshwater sources can be reduced. Reclaimed water applications can be timed properly to provide appropriate nutrient concentrations at the right time in the life cycle of a crop. Considerations should be made to manage accumulation of nutrients in soils over time, especially in Arizona where the growing season can potential continue throughout the year due to favorable climatic growing conditions. If closely managed, reclaimed water in a desert environment can help to sustain successful agriculture.

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APPENDIX A

TABLES

Study	Location	Climate	Type of RW	Type of Irrigation
Lal et al., 2013	Karnal, India	BSh	Primary	Flood
Morugan-Coronado et al., 2010	Biar. ES	BSk	Secondary	Flood
Adrover et al., 2012	Mallorca, ES	BSk	Secondary	Drip
Duan et al., 2010	Littlefield, TX, US	BSk	Secondary	Drip
Alkhamisi et al., 2011	Rumais, OM	BWh	Secondary	Drip
Dorta-Santos et al., 2014	Fuerteventura, ES	Bwh	Secondary	Drip
Heidarpour et al., 2007	Isfahan, IR	BWk	Secondary	NA
Paranychianakis et al., 2004	Heraklion, GR	Csa	Secondary	Flood
Vivaldi et al., 2017	Trinitapoli, IT	Csa	Teritary / Lagoon / Secondary Wastewater	NA

Table 1: Data extracted from relevant studies in the systematic review

Study	pH	N	P	Na	Ca	Mg	OM	EC	SAR
Lal et al., 2013	8.2	18.00	4.300	NA	NA	NA	NA	1.300	4.6
Morugan-Coronado et al., 2010	7.6	34.00	5.800	220.5	59.31	52.60	NA	0.020	NA
Adrover et al., 2012	7.8	10.84	NA	NA	NA	NA	NA	2.32	NA
Duan et al., 2010	8.1	9.230	NA	117.0	52.00	24.00	NA	0.963	3.4
Alkhamisi et al., 2011	7.9	29.90	NA	75.00	32.31	15.00	NA	1.110	14
Dorta-Santos et al., 2014	8.5	10.40	25.53	270.7	21.50	12.90	3200	9.730	19
Heidarpour et al., 2007	7.3	21.77	3.770	155.3	49.23	25.40	NA	1.430	5.4
Paranychianakis et al., 2004	7.5	5.700	10.70	247.0	39.10	9.300	NA	1.900	9.2
Vivaldi et al., 2017	7.6	1.540	25.75	126.9	83.11	21.56	NA	1.500	3.2
Synthetic Reclaimed Water Source	**7.8**	**14.55**	**12.64**	**173.2**	**48.08**	**22.97**	**3200**	**2.25**	**8.4**

Table 2: Nutrient data extracted from relevant studies in the systematic review