TITLE: Field comparison and crop production modeling of sweet corn and silage maize (*Zea mays* L.) with treated urban wastewater and fresh water

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ABSTRACT: In Australia, interest in wastewater reuse has grown. While wastewater can potentially offer a nutrient advantage over conventional irrigation, crop yield increases may be offset by effects of high salinity. Effects of wastewater irrigation on crop production and soil health were investigated in two ways: a field experiment addressing short-term effects and modeling longer-term impacts. The field experiment was established at the Shepparton Wastewater Treatment Plant in Shepparton, Victoria to compare effects of wastewater irrigation to conventional irrigation. Silage maize and sweet corn (*Zea mays* L.) were grown over the summer of 2012–2013 under the following flood irrigation treatments: wastewater and fresh water with and without fertilizer. Both harvests produced yields and qualities comparable to commercial farm standards and no significant differences were found between water types. Maize production with long-term wastewater irrigation at various salinities was modeled and no significant yield losses were observed after 50 years of simulated irrigation. Topsoil electroconductivity doubled after the field trial and simulation results predicted significant soil salt accumulation by factor of 2. Mean wastewater sodium absorption ratio of 4.52 and electroconductivity of 1.52 dS/m indicate potential for sodicity-related soil problems for long-term irrigation. Management of soil health may be necessary.

KEYWORDS: APSIM; Australia; crop production; irrigation; soil; wastewater

Introduction

Water scarcity and food production are among the greatest challenges currently facing humanity. Agriculture is the largest user of water globally (UN-Water 2006) and in Australia as well, where 54% of total water is used by the agricultural industry (ABS 2012). In light of the recent decade-long drought and growing concerns for future water availability, the Australian government has pursued many new wastewater reuse projects, including agricultural irrigation initiatives (Radcliffe 2010). The majority of these projects were established in the coastal capital cities, but interest is growing for wastewater reuse in inland regional cities. The wastewater treatment center at the regional city of Shepparton, Victoria, has long reused its treated wastewater for irrigating grazed pastures and forest plantings (GVW 2012), but the regional domestic water authority, Goulburn Valley Water (GVW), is interested in alternative higher value uses of water, such as irrigation of annual cash crops.

Using wastewater for irrigating annual crops and fodders can be advantageous for a number of reasons, including year-round reliability, decreased disposal costs, and pressure alleviation on other water sources (Hamilton et al. 2007, Raschid-Sally et al. 2005). Of most interest is the high nutrient content in wastewater. Many studies have reported yield increases from this additional fertilizing for crops such as eggplant, cauliflower, cabbage, and maize (AlNakshabandi et al. 1997, Hussain and Al-Saati 1999, Khan and Shaukat 2008, Kiziloglu et al. 2008). However, the relationship between nutrient supply, nutrient uptake, and crop yield is complicated by soil processes such as immobilization and leaching (Janssen et al. 2005). Furthermore, the concentration of nutrients in wastewater is highly variable and can even be excessive for crops, leading to overfertilization, reduction in crop size, and nutrient leaching (Baier and Fryer 1973, Hamilton et al. 2007, Tillman and Surapaneni 2002). In some cases, high nutrient concentrations can be toxic to crops. Boron, for example, is a micronutrient required only in small amounts (<500 g/ha) and there is only a small concentration range between plant deficiency and toxicity (Unkovich et al. 2006). Due to these processes, the subsequent impact on crops would depend heavily on the quality of the wastewater and soil health.

In addition to nutrient concerns, wastewater's potential benefits are further counterbalanced by potential salinity, sodicity, and heavy metal risks. Highly saline irrigation water can cause direct crop toxicity, nutrient activity suppression, and loss of yield in the short term (Munns and Tester 2008). In the long-term, salts can accumulate in the soil, leading to soil structural degradation. Since salinity in Australian soils is dominated by NaCl salts, management of salt build-up is inevitably linked to management of sodicity (Muyen et al. 2011). Wastewaters typically have high sodium concentrations relative to other cations, with sodium absorption ratios (SAR) ranging from 4.5 to 8.0 (Hamilton et al. 2007). Long-term irrigation with wastewater can potentially lead to a decline of soil physical properties in the form of clay dispersion, pore blockage, and reduced hydraulic conductivity (Halliwell et al. 2001, Muyen et al. 2011). Such soil structural deterioration depends on many factors, including the dynamic relationship between the soil exchangeable sodium percentage (ESP) and the electrolyte concentration of the soil solution, where sodicity-related dispersion can be offset by clay coagulation from high ion concentration in solution (Sumner 1993). Heavy metals in wastewater have been observed to accumulate in soils and plants over long-term irrigation, in some cases causing health risks for humans or livestock consuming wastewater-irrigated crops (Ghosh et al. 2012, Khan et al. 2008). However, this type of accumulation may take decades or centuries to reach threshold concentration levels even when raw sewage—which typically contains markedly higher concentrations of heavy metals than treated effluent owing to precipitation in the treatment process (Goldstone et al. 1990, Karvelas et al. 2003, Lester 1983, Stephenson and Lester 1987, Toumi et al. 2000) is being used for irrigation (Hamilton et al. 2007, Xiong et al. 2001) and thus cannot be investigated effectively in a matter of a few years.

Despite the importance of wastewater irrigation as a potential solution to water scarcity issues, only a handful of field studies have thus far been conducted to compare the effects of wastewater and fresh irrigation water on crop production. With the complex relationship between wastewater quality, soil health, and crop production, Janssen et al (2005) called for more such comparative field studies to investigate wastewater agricultural irrigation. While comparative field studies can easily address short-term issues from wastewater nutrient loading and salinity on crop production, it takes considerably more resources and time to investigate effects of sodicity and heavy metals resulting from long-term wastewater irrigation, particularly because heavy metal accumulation is gradual (Assouline and Narkis 2013, Ghosh et al. 2012, Hussain et al. 2010, Khan et al. 2008, Levy 2011, Xiong et al. 2001). Modeling is a less resource-intensive technique to explore long-term wastewater irrigation issues and programs such as APSIM (Agricultural Production Systems Simulator) have been successfully utilized for such simulation purposes (Brennan et al. 2008, Paydar et al. 2005, Snow et al. 1999a, Snow et al. 1999b, van Opstal et al. 2012).

To address both ends of the spectrum, this study includes a field experiment focusing on the short-term impacts of wastewater irrigation on maize production (*Zea mays* L.), both in the form of sweet corn and silage maize, and a crop production model focusing on the long-term impacts. Maize is the world’s largest planted crop, with some 883 million tons produced globally, and is used for food, livestock feed, industrial use, and biofuel (Abbassian 2006, FAO 2012). Additionally, maize is locally used for silage and livestock feed in partial mixed rations in central and northern Victoria, where the dairy industry is a strong presence (GSCC and Coomes Consulting 2006, Harris 2011). This study will not focus on heavy metal accumulation because there are no prominent sources of heavy metals in the Shepparton wastewater system, indicating it would likely take centuries for metal accumulation in soil (Hamilton et al. 2007, Xiong et al. 2001). Instead, the modeling will investigate salinity issues and the possibility of yield decreases and salt accumulation.

The objectives of this study were:

a) to determine how wastewater irrigation affects crop yield and quality in comparison to conventional fresh water irrigation
b) to determine if wastewater-irrigated crops can meet commercial yield and quality standards
c) to assess risk of long-term saline wastewater irrigation on soil salt accumulation
d) to determine the effect of long-term saline wastewater irrigation on crop yield

Materials and methods

Field trial

Experimental Site

The study was conducted on virgin agricultural lands at Shepparton Wastewater Treatment Plant at Shepparton, northern Victoria, Australia (36°19'33.79"S, 145°22'52.56"E). No irrigation of any kind had occurred at the site before. The wastewater treatment plant handles municipal and industrial wastewater from the food processing companies in Shepparton, utilizing wastewater stabilization ponds for primary and secondary treatment. The climate of the area is characterized as semi-arid (Australian Bureau of Meteorology 2013). Further climate details are given in Table 1. The soil type at the Shepparton WTP site has been mapped and classified as Goulburn Loam (Skene and Poutsma 1962). Goulburn loam is described as red chromosol with a strong textural contrast between the fine sandy clay loam of the surface horizon and the medium clay of the subsoil horizon. Soil properties are described later in the paper. The water table depth is > 3 m (Goulburn Broken Catchment Management Authority 2012).

Experimental Design and Crops

Silage maize (cv. 36Y84 hybrid 104 CRM) and sweet corn (cv. Goldensweet Improved F1) were grown at the site together. A third crop, okra, was also grown at the site but due to complicating weed effects over the course of the study, results for this crop are not reported. The experimental design was a split-split-plot with six replicate blocks (Fig 1). Each block comprised four border-check irrigation bays with the following treatments: wastewater irrigation with fertilizer (WF), wastewater alone (W), fresh water with fertilizer (CF), and fresh water alone (C). Water treatment (W or C) was randomized to “double bays”, and then fertilizer (yes or no) was randomized to irrigation bays within double bays. Water was distributed to bays via irrigation pipes running down the middle of the site. Within each irrigation bay, crop species were randomized between three plots of 5 m by 7 m, separated by 3 m between plots.

Maize and sweet corn seeds were sown on November 13, 2012 into 6 rows per plot, with 70 cm between rows using a mini air seeder. Fertilizers were applied at sowing according to recommended dosages. The fertilizer rates for nitrogen, potassium, and phosphorus at sowing were: silage maize, 132 kg nitrogen/ha, 106 kg potassium/ha, 26.4 kg phosphorous/ha (Garcia n.d.) and sweet corn, 500 kg/ha of 12:12:17 (Limsey 2009). Seedlings were later thinned out to approximately 20 cm between plants in December. Atrazine post-emergent herbicide was applied 10 days after sowing.

Irrigation and Rainfall

Due to multiple crops with different water requirements within the same bay, irrigation was not based on crop specific evapotranspiration but was instead applied on average every five days using border-check irrigation, the dominant irrigation method in the region (Murray Dairy 2012). The commercial practice of the two-thirds rule, where flooding continued until the advance water front reaches two-thirds of the irrigation bay, was used with identical irrigation volumes applied to both fresh and wastewater bays, as measured by in-line flow meters. For both water types, a mean of 76 ± 12 m^3 water was applied per treatment per irrigation event and a mean interval ± standard deviation of 5.35 ± 1.92 days occurred between events. Sweet corn received a total of 2753 m^3 of water over 17 irrigation events and maize 3177 m^3 over 21 irrigation events (Table 1). With the exception of a considerable rainfall event of 385 m^3 in late February after the sweet corn harvest, there was negligible rainfall over the course of the study, with sweet corn receiving 93 m^3 and maize receiving 495 m^3 (Table 1). The mean rainfall in Shepparton from November to March 1996-2013 is 669 m^3 and the mean for February is158 m^3, so both crops received less than the mean rainfall for the growing season (Australian Bureau of Meteorology 2013).

Water Quality

Water samples were taken every two weeks for a total of seven sampling events during the growing season and analyzed for pH, N (nitrate, nitrite, ammonia, total N, total Kjeldahl N, total oxidized N), P, Na, K, Mg, Ca, B, five-day biochemical oxygen demand (BOD_5), *E. coli*, electroconductivity (EC), and sodium absorption ratio (SAR) by SGS Australia laboratories (Shepparton). Quality of both wastewater and fresh water was variable across the course of the study, but in general, wastewater tended to have higher nutrient concentrations and salinity than the fresh water (Table 2).

Soil Analysis

An electromagnetic survey was conducted on site prior to the start of the field trial using EM38-Mk2 with dual-frequency RTK GPS capability (Fig 2). Composite soil samples were collected from the site from 0–20 cm before sowing and at the end of harvest. Samples were oven dried, ground, and passed a through 2-mm sieve for chemical analysis. Soil samples were analyzed for pH by 1:5 0.01M $CaCl_2$ extraction (DPI Victoria 2011), EC by 1:5 water extraction (DPI Victoria 2011), available P by 0.5M $NaHCO_3$ (Schoenau and O’Halloran 2008), ammonia and nitrate N by 2.0M KCl extraction (Maynard et al. 2008), and metals by acid digestion with inductively coupled plasma atomic emission spectrometry (ICP-AES) (Hendershot et al. 2008, US EPA 1996).

Harvest Analysis

Sweet corn cobs were deemed mature when they reached a sugar content of BRIX 14–22% and harvested on February 19, 2013. All cobs within an area of 4 m by 4 m in the middle four rows of each plot were harvested by hand, with the outer two rows as buffer area. Total corn yield and cob count were determined per plot area and extrapolated to per-hectare yield based on the experimental planting density of 70 cm between rows and 20 cm between plants. Twenty corn cobs per plot were then selected with the aid of a random number chart for crop quality analysis. Sample corn cobs were weighed and measured for length and circumference. Sweetness was analyzed by BRIX pocket refractometer PAL-1 (Atago) and color by the Chroma Meter CR-400 (Konica Minolta). The five standard color parameters are lightness index (L^*), hue angle (h°), saturation index or chroma (C^*) and coordinates on the chromaticity diagram (a^* and b^*) (Little 1975). Lightness is measured on a scale of black = 0 to white = 100. Coordinates a^* corresponds to the horizontal axis from red-purple to bluish-green while b^* corresponds to the vertical axis of yellow and blue (McGuire 1992). Hue (red, green, yellow, blue, etc) is represented by an angle on the color wheel while chroma (saturation of color) is represented by the hypotenuse of the right triangle created by joining points (0, 0), (a*, 0), and (a*, b*). Hue angle and chroma are given as (Sharma 2003):

$$C^* = \sqrt{((a^*)^2 + (b^*)^2)} \qquad \text{Eq. 1}$$

$$h^\circ = \tan^{-1}(\frac{a^*}{b}) \qquad \text{Eq. 2}$$

Maize maturity was indicated by the milk line of the grain and overall plant health (Garcia n.d.). After the majority of the crop reached a milk line of 3 on a scale of 1–5, the maize crop was harvested by hand on March 8, 2013. All plants in an area of 4 m by 4 m within the middle four rows of each plot were harvested, with the outer two rows as buffer area. Total maize biomass was determined per plot area and extrapolated to per-hectare yield based on the experimental planting density of 70 cm between rows and 20 cm between plants. Eight maize plants were then randomly selected per plot for nutrient analysis. This was done by pinpointing two locations along each row and harvesting the nearest plant for a total of eight plants across four rows. Plants were dried at 60°C, ground to 1 mm, sieved, and sent to FeedTest (Agrifood Technology, Werribee, Victoria) for their near-infrared (NIR) silage package. Parameters analyzed included dry matter (DM), the amount of feed remaining after removal of water; partial DM, the amount of feed from the initial drying of wet samples; crude protein, the extent of silage protein content calculated by the amount of nitrogen found; acid detergent fiber (ADF), a measure of digestibility; neutral detergent fiber (NDF), a measurement of the plant cell wall make-up; dry matter digestibility (DMD), the quantity of organic matter and ash content; organic dry matter digestibility (DOMD), the quantity of only organic matter; and metabolizable energy, the predicted energy content from the feed (Kaiser and Piltz 2004).

Statistical analysis

GenStat 14th Edition was used for all statistical analyses. Analysis of variance (ANOVA) models were run on the crop data to test the main effects of water and fertilizer, and their interaction, as well as to determine crop density variability. Crop placement in first, middle, or last plot along the irrigation bay, referred to as plot position, was an unbalanced random factor in the design. To determine if plot position had a significant effect, linear mixed models (Patterson and Thompson 1971) were run on the crop data using a random effects model of double bay nested within block, and fixed effects of plot plus water by fertilizer. Additional ANOVA models were run on soil data before and after the study to determine effect of time and water type, as well as on soil moisture data. For all soil analyses, data from fertilized bays were compiled with data from non-fertilized bays with the same water treatment. Fisher's least significant difference (LSD) *post hoc* tests at the 0.05 level were applied to crop data to compare pairs of means. Unless otherwise stated, significance refers to a Type I error rate of 0.05.

Modeling of long term salinity effects using Agricultural Production Systems Simulator (APSIM)

Biophysical Model Description

This study utilized the APSIM v7.5 model (Keating et al. 2003) as the biophysical modeling framework. APSIM is an agricultural systems modeling environment that allows plug-in and pull-out of a range of modules to reflect various cropping systems. The modules most important to this study are the soil–water module APSIM-SWIM (Huth et al. 1996) and the crop growth module APSIM-Maize (Carberry and Abrecht 1991, Keating et al. 2003).

These modules are subsets of the full configuration of APSIM, which also simulates climate, nutrient balance, and farm management.

APSIM-SWIM is the APSIM version of the SWIM v3 (Soil Water Infiltration and Movement) (Huth et al. 2012) model for water and solute movement in soil. It provides an one-dimensional simulation of water fluxes based on a numerical solution to the Richards equation (Richards 1931) and the single-root analogue. Solute movement and uptake is calculated using a solution to the convection-dispersion equation. Detailed descriptions of the numerical methods used in solving the Richards equation and the convection-dispersion equation are provided by Verburg et al (1996). Since this module is one-dimensional, it does not consider lateral flow or horizontal heterogeneity, only vertical heterogeneity. No interaction or competition for exchange surfaces by solutes is considered. Field variability is captured within the lumped parameterization approach. Toxicity of solutes is not considered in this model, but it is assumed that the osmotic pressure dominates the salt impact on crop water intake (Paydar et al. 2005).

APSIM-Maize was developed from an earlier version called AUSIM-maize (Carberry and Abrecht 1991). The module uses the same physiological principles as other crop modules to capture resources and utilize them for growth, but all the parameters are specific to maize or maize cultivars.

Simulation Set-Up

The model was parameterized for the virgin agricultural lands at Shepparton Wastewater Treatment Plant (WTP) at Shepparton, northern Victoria, Australia (36°19'33.79"S, 145°22'52.56"E). Long term climate data for the site consisting of rainfall, radiation, temperature, and evaporation was obtained from SILO climate database (DSITIA 2014). The simulation ran between 1950 to 2000 for a total of 50 years for silage maize crop production. A reliable sweet corn model for APSIM compatible with SWIM3 has not been developed yet. The sowing occurred on November 1 each year of the simulation with the cultivar Pioneer_3153 at a density of 10 plants/m^2, a depth of 30 mm, and a distance of 750 mm between rows. The crop was fertilized once during sowing with 150 kg of urea N per hectare, as common practice for farmers growing fodder maize in the area (Garcia n.d.). No P or K nutrient modules were activated, meaning the model would simulate scenarios where P and K are not limiting. Modeled outputs included biomass, grain yield, grain protein percentage, soil EC, and soil Cl content.

Soil Parameters

Soil physical, chemical, and hydraulic properties used for modeling maize production was based on the soil surveys conducted by the Department of Primary Industries (Table 6) (DPI Victoria 2004, Skene and Poutsma 1962). Properties for deeper subsoils were based on the Department of Primary Industries' Victorian Soil Resources for GN26 soil pit in the Goulburn Broken area (Fig 3A-E) (DPI Victoria 2012).

Space weighting factors used in the Richard Equation for water flow and the advection-dispersion equation for solute flow of the SWIM module were both set to 0.5. The space weighting factors in SWIM can vary between 0.5 (central space weighting) and 1 (fully upstream space weighting) (Verburg et al. 1996). The central space weighting tends to give smaller numerical errors than fully upstream weighting (Ross 1990). All other SWIM parameters were left to default values.

Irrigation

APSIM was run on a daily time step and the irrigation interval in the model was set to 7 days if rainfall in the past day was less than 15 mm. The model applied irrigation on the first day of the cycle with no subsequent irrigation until the defined cycle length is completed.

APSIM does not directly model total dissolved salts (TDS) or EC of the irrigation water directly in its irrigation module. The only solutes modeled directly in the irrigation module are NO_3, NH_4, and Cl. Although Cl ion concentrations are available, Cl alone would not simulate the full salinity effects of the wastewater. To better model the salinity of the wastewater irrigation, this study converted the EC values of the wastewater to solute concentrations using scalar corrections, as done in other studies (Paydar et al. 2005, Snow et al. 1999a). The following relationship was used:

$$TDS = k \times EC \tag{1}$$

where TDS is total dissolved salts (mg/L), k is the scalar constant, and EC is the electroconductivity (μmho/cm). Evangelou (1998) found k to be 0.64 for waters dominated by Cl and since there is no published data for k for wastewaters, it was assumed that Cl would be the dominant ion in the wastewater. The conductances of common ions found in wastewater are in the same order of magnitude and very similar to Cl (APHA et al. 2013), so it was assumed that the other ions would behave similarly to Cl. Scenarios modeled in this study covered a range of irrigation water salinities representing variation of potential EC expected for the site. Based on the biophysical properties of the wastewater from the Shepparton WTP site listed in Table 2 (GVW 2011b), the following variations in EC were modeled: 0.0 dS/m, 0.8 dS/m, 1.0 dS/m, 1.5 dS/m, 2.0 dS/m, and 6.5 dS/m. These correspond to fresh water salinity, minimum wastewater salinity, mean wastewater salinity ± standard deviation, and maximum wastewater salinity. These irrigation salt concentrations were assumed to remain constant through the entirety of the simulation time. But in reality the salt concentrations would vary over time.

Statistical analysis

GenStat 14th Edition was used for all statistical analyses. ANOVAs were run on the APSIM data to determine if different salinities of wastewater irrigation had an effect.

Results

Experimental field trial

Soil health

Significant differences could be seen between wastewater and fresh-water bays over the study, even after only one season of wastewater irrigation. Comparisons for total P and Na revealed significant differences between wastewater and fresh water soil as well as between pre- and post-study, with higher concentrations in wastewater and pre-study (Table 3). Significant differences were also found for pH, EC, and Na with significant interactions between water type and time. The pre-study values were similar, but diverged post-study with higher pH, EC, and Na concentrations in wastewater. Significant differences were observed for Zn pre- and post-study, but the significant interaction between water type and time resulted in lower Zn concentrations post-study. No significant differences were seen for ammonia and Cu. Nitrate, Ca, K, Mg, and Mn concentrations differed only in pre- and post-study. The topographical survey results show that the site is very flat with a slight east-west ridge (along the axis of the “irrigation piping” shown in Figure 1), which we subsequently took advantage of when positioning the irrigation bays, which were laser-graded with a fall away from the ridge, where the irrigation pipes divided the blocks (Fig 2). The initial conductivity differed on the two sides of the ridge, with higher conductivity in the northern blocks (1-3) than in the southern blocks (4-6) (Fig 2).

Sweet corn

The study yielded a successful sweet corn harvest across all the treatments (Table 4). There was no significant difference in number of plants across the treatments, indicating no effect on crop yield and quality parameters from planting variability (ANOVA, $P > 0.05$).

All yields exceeded the average yield of 9.9 ton/ha for sweet corn fresh market production in Victoria (Beckingham 2007), but no significant differences were observed between water or fertilizer treatments (Table 4). Cob count and plant height were significantly affected by an interaction between water type and fertilizer (Table 4). In the absence of fertilizer, plant height and cob count tended to be larger for wastewater, while in the presence of fertilizer, it was the reverse. Cob weight, husk, length, and circumference were not significantly affected by water type or fertilizer.

Of the quality parameters, only three were significantly affected by the water type: chromaticity coordinate a^*, hue angle ($P < 0.01$), and BRIX sweetness measurement ($P < 0.05$) (Table 4). Chromaticity coordinate a^* and hue angle parameters show contrasting trends, however. Higher a^* values were seen in fresh water treatments (overall mean of 3.98 for fresh water and 3.37 for wastewater) but wastewater treatments produced higher hue angles (overall mean of 86.44 for wastewater and 85.73 for fresh water). While a^* and h^o values in WF and C are significantly different from each other, they were not different from values in CF or W. The hue angle, chroma, and lightness index results were similar to other post-harvest analyses on color characteristics for sweet corn *sh2* cultivars, indicating that the color of sweet corn from this study is within the normal range (Smyrniotaki 2011). BRIX sweetness was also significantly affected by fertilizer presence ($P < 0.01$) (Table 4). Overall, wastewater produced a significantly sweeter crop than fresh water (overall means of 15.60% and 15.16% respectively) and non-fertilized crops were significantly sweeter than fertilized ones (overall means of 15.85% and 14.90% respectively). However, all the treatments were within the normal BRIX sweetness range (14-22%) for *sh2* cultivars of sweet corn (Beckingham 2007). Sweetness from W and C crops was significantly greater than corn from CF, but sweetness of crop from WF showed no difference to the other treatments. All other sweet corn parameters show no differences among the treatments, with the exception of plant height, where pair-wise comparisons were inconsistent and could not be determined.

The experimental design was set up to account for spatial variability across the study. However, the potential for water logging was observed the last plots of some bays on some occasions, likely due to the prevailing south-easterly wind holding back drainage in Blocks 4, 5, and 6. Because this effect was unbalanced with respect to the location of the three crops, a linear mixed model was run to account for the plot position. The parameters significantly affected by plot position were fresh yield, cob length, husk, chromaticity coordinate B^*, and chroma, ($P < 0.05$), and plant height ($P < 0.001$) (Table 4). Use of the linear mixed model generally brought the means closer together in comparison to the general ANOVA model, but did not affect the significance of water type and fertilizer treatments.

Maize

Across the board, the study produced maize yields that were on the low end of the potential yield range for commercial farms (12–25 ton DM/ha) (Table 5), but all the quality parameters fall within the normal range for silage maize compared to season averages for Australian farmers (FeedTest 2013, Griffiths et al. 2004). As with the sweet corn, no significant differences between planting densities across treatments were found (ANOVA, $P > 0.05$), thus allowing for proper evaluation of treatment effects.

Water type did not have a significant effect on any of the maize parameters (Table 5). Contrastingly, fertilizer was a significant factor across all maize parameters ($P < 0.05$) except crude protein, acid detergent fiber, and partial dry matter. Maize height at the end of the season was not only significantly affected by fertilizer ($P < 0.001$), but also by a significant interaction between water type and fertilizer ($P < 0.01$) (Table 5). Similar to the sweet corn, maize was taller for wastewater in the absence of fertilizer, but the reverse held when fertilizer was present. The linear mixed model results show that height was also significantly affected by the plot position ($P < 0.001$), presumably indicating effects of drainage issues at the bottom of the south-facing irrigation bays. However, none of the other parameters were affected by the plot position (Table 5).

For the majority of the quality parameters, the experimental results either met or were comparably close to commercial standards for high-quality silage. The DM and crude protein target range for chopped maize silage is 33–38% and 4.5–8.5% respectively (Griffiths et al. 2004). All of the treatments produced silage harvests with mean DM and crude protein contents within this range (Table 5). Target ADF and NDF values around 25% and 32% correspond to higher energy and forage intake respectively (Kaiser and Piltz 2004). All the treatments resulted in ADF values that fall well within high-quality forage range. The experimental NDF values were higher than the ideal, but well below low-quality forage NDF of 72% (Table 5) (Kaiser and Piltz 2004). High-quality silage DMD and DOMD are around 76.7% and 72% respectively while low-quality silage DMD and DOMD are approximately 45.2% and 42% (Kaiser and Piltz 2004). The experimental DMD values are within the high quality target, but DOMD values are slightly lower than ideal. All the treatments produced maize with typical metabolizable energies (10–11 MJ/kg DM) (Griffiths et al. 2004).

With the exception of DM, moisture, partial DM, and plant height, all the pair-wise comparisons for maize parameters between the treatments were non-significant (Table 5).

Maize from CF had significantly greater DM and partial DM than maize from C by 5.5% and 6.05% respectively while C produced greater moisture levels than CF, but measurements from both CF and C were not distinct from W and WF. Maize heights from CF and WF were significantly greater than heights from C and W by 18.75 cm and 8.24 cm respectively.

Crop Production Modeling

No significant losses in yield, biomass, or grain protein percentage were determined after long-term wastewater irrigation (Table 7). There were no statistically significant yield losses across the different salinity treatments. There were statistical significances in the salt accumulation in the soil, with Cl concentrations up to 73651 kg/ha from irrigation with highly saline (6.5 dS/m) wastewater. The resulting soil EC at 50 cm was approximately twice the EC of the irrigation with fresh water for each treatment (Fig 4).

Discussion

This study investigated crop production from wastewater irrigation in two parts, an empirical field experiment and a modeling exercsie. This is one of the few field studies to investigate the impact of wastewater irrigation on sweet corn yield and quality. Overall, the experimental component showed that there was little difference in yield or quality from wastewater irrigation in comparison to fresh irrigation water for both sweet corn and silage maize. Both the sweet corn and maize harvests produced yields and qualities comparable to commercial farm standards and no significant differences were found between the water types. The modeling component showed that all differences in crop parameters were found statistically insignificant. Over the course of 50 years, soil EC at 50 cm concentrated by approximately a factor of 2 from the wastewater salinity.

Sweet Corn and Maize as Candidates for Wastewater Irrigation

Based on the experimental yields, sweet corn would be a good candidate for wastewater irrigation. There are several quality aspects that deserve further investigation however. From a sweet corn market perspective, the most important parameter is the sugar content (Evensen and Boyer 1986). Since overall wastewater produced a significantly sweeter crop than fresh water, this indicates a potential market advantage. However, sweetness is inversely correlated with cob size; smaller cobs have greater concentrations of sweetness. Before implementation of wastewater irrigation for sweet corn production is pursued, research should explore whether wastewater can produce sweeter yet not significantly smaller corn than fresh irrigation water.

Cob color and appearance are also considered important qualities of sweet corn, particularly for consumers (Beckingham 2007). There is anecdotal evidence for regional preferences between yellow and bicolour white-yellow sweet corn cultivars (Suslow and Cantwell 1997), but no scientific studies have looked into consumer preference for sweet corn color. Linking those preferences to quantitative measurements of hue angle and chromaticity coordinate a* may be interesting, particularly given wastewater irrigation produces crop with different color parameter measurements (Table 4).

The experimental results for silage maize are encouraging. Although the treatments produced lower digestibility and energy (Table 5), the magnitude of difference is only 5% and 15% respectively compared to the standards and all other parameters fell within high quality range. No discernible differences were seen for water type, and other studies on the effect of wastewater irrigation on silage maize yield and quality found that wastewater-irrigated maize was of satisfactory quality in comparison to conventionally grown maize (Marten et al. 1980, Tavassoli et al. 2010). There is a strong potential market for silage maize in the area. Shepparton is the center of one of Australia’s largest milk producing regions with

1,663 dairy farmers working in the Goulburn region, who collectively contribute 25% to the value of Victorian milk production (ABS 2008). Dairy is currently undergoing a shift from fully-irrigated grazed pasture system to water-efficient feed production systems where annual fodder and forage crops play an important part of the feed base (DPI Victoria and Dairy Australia 2011). Considering the potential demand, silage maize would be an excellent candidate for wastewater irrigation for Shepparton.

Feasibility of Crop Yield Increases

Although other studies had reported yield increases for maize from wastewater irrigation (Esmailiyan et al. 2008, Khan and Shaukat 2008, Mohammad and Ayadi 2004, VazquezMontiel et al. 1996), there may be several reasons why a yield increase was not seen here. Over the course of the trial, rainfall made up only 3.26% (93 m^3) of total water applied on the sweet corn plots with irrigation making up the remaining 96.74% (2753 m^3) (Table 1). Similarly, rainfall accounted for 13.47% (495 m^3) of total water applied to the maize plots and irrigation was the remaining 86.53% (3177 m^3). Not only did the crops experience a very challenging physical environment, but the climate also provided ideal conditions for full implementation of the irrigation treatments, with only one major rainfall event towards the end of the field season that only affected the maize crop and which equated to a single irrigation event in terms of volume. Outside of this major rainfall event, the average rainfall event only amounted to 10.85% (8 m^3) of a typical irrigation event (76 m^3).

In addition, the site soil and wastewater quality is poor in comparison to other places (Table 2, Table 3, Table 6). The wastewater in this study had lower concentrations of N and P than other studies (Esmailiyan et al. 2008, Khan and Shaukat 2008, Mohammad and Ayadi 2004, VazquezMontiel et al. 1996) and the nutrient levels may have been insufficient to cause an impact on yield or quality, as demonstrated by the lack of significant differences between treatments for most parameters (Table 4, Table 5). The high soil pH at the site may have also locked in nutrients deposited by the wastewater, limiting uptake by plants (Alam et al. 1999). Similar issues have occurred before at the site: GVW normally use the treated wastewater to irrigate pasture for sheep and have noticed cases of brittle bones in the sheep. Investigation into the issue pointed to high soil pH affecting nutrient bioavailability, thus preventing nutrient uptake by the sheep (GVW, personal communication). This may be the reason why the fertilizer application in the treatments failed to cause an impact on yield even though optimal nutrient ratios based on commercial practice were used. Subsequent research will need to investigate what amendments can be applied to the soil to counter the high soil pH and potentially increase plant bioavailable nutrients.

In a few of the studies that reported maize yield increases from wastewater irrigation, different irrigation methods were used, including drip irrigation (VazquezMontiel et al. 1996) and sprinkler irrigation (Tamoutsidis et al. 2009). Border check irrigation was chosen for this study because it is the prevalent irrigation method in the Goulburn Valley region (Murray Dairy 2012) and is widespread throughout the world (Brouwer et al. 2013). While surface irrigation methods have their advantages, such as low capital investment, there may be correlation between crop yields and irrigation method. A study that focused on the effect of wastewater irrigation method on maize yield found that subsurface drip and surface drip irrigation produced better yields than surface furrow irrigation (Hassanli et al. 2009). However, no significant yield difference was found between the wastewater and fresh irrigation water. Future studies should investigate whether different irrigation methods improve wastewater irrigation yields.

The experimental design and plot positions may have also affected crop yields. Sweet corn was influenced more by the plot position than maize, affecting important parameters such as yield and cob size (Table 4), but undoubtedly significant differences in height for maize could have affected the amount of biomass for harvest (Table 5). The magnitude of height difference was around 10% between maize grown in the outermost plots in comparison to maize grown in the first and middle plots (data not shown). Since the plot position was an unbalanced random factor in the experimental component of this study, the effects of poor drainage and other factors of plot position required a linear mixed model to determine their effect. In this case, maize yield had not been affected by plot, even with the height differences.

Short- and Long-term Impacts of Wastewater Salinity and Sodicity

Although the wastewater salinity was significantly higher than the fresh water's (Table 2), no immediate adverse effects of salinity were observed in the crops. Both the soil and wastewater experimental EC were still within the tolerable range for sweet corn and maize (Blaylock 1994, Evans 2006, Stevens et al. 2008). In the APSIM modeling however, maize yields decreased by 15.90% when salinity was at its maximum of 6.5 dS/m, but these losses were not statistically significant. The APSIM model only accounts for yield loss from osmotic pressure (Paydar et al. 2005), so it is possible that there would be additional yield loss from salt toxicity. However, given that the mean wastewater EC over long-term monitoring (Table 2) is 1.5 dS/m and the 75th percentile of wastewater EC is 1.7 dS/m, instances where wastewater EC goes above maize's salinity tolerance of 1.7-1.8 dS/m (Blaylock 1994, Evans 2006, USDA and NRCS 2013) will likely be infrequent. Thus based on the modeling and field trial results, there may be some maize yield losses, but they will likely be insignificant.

The APSIM modeling provided a one-dimensional look at soil salt accumulation from long-term wastewater irrigation if no interventions were made. The predicted soil EC from continual wastewater irrigation is twice that of the wastewater EC (Table 7). If these soil EC were interpreted as EC of saturated soil paste, irrigation with wastewater of EC 2.0 dS/m and 6.5 dS/m will result in saline soils, defined as soil with EC > 4.0 dS/m (Hamilton et al. 2007). Modeling sodicity effects was not possible in APSIM, but the wastewater SAR and EC values (Table 2) indicate possible sodium-related problems. Based on the relationship between the wastewater SAR and EC values as graphed in Stevens et al (2008), conditions at Shepparton are borderline between stable soil structure and possible sodicity problems. The possibility of soil problems would depend on rainfall and the soil structure (Mehanni and Repsys 1986, Surapaneni and Olsson 2002). Based on other field studies in the Shepparton area, wastewater-irrigated soils are prone to instability. A field study at Mooroopna, a town nearby Shepparton, found that after 10 years of irrigation with wastewater of EC 0.8-1.0 dS/m, the soil SAR had not increased above 3 for sodic soil, but the mechanically dispersed clay ranged from 17-39%, indicating instability due to mechanical stress (Surapaneni et al. 1998). Another study in Tatura found soil sodification occurred after 4 years of irrigation with waters of EC values greater than 0.8 dS/m (Burrow et al. 2002). Even after 1 year of maize irrigation with wastewater of EC 1.0 dS/m at Tatura, exchangeable sodium percentage (ESP) of the irrigation bays increased (Surapaneni and Olsson 2002).

Soil analyses of perennial pasture paddocks at the Shepparton Treatment Plant that have been continuously surface irrigated with wastewater for 8–28 years provide insight on appropriate management techniques for salinity and sodicity. The clay loam soils at the treatment plant have moderately elevated pH (6.6–8.7 for topsoil, 8.6–9 for subsoil) and salinity levels (0.08–0.68 dS/m for topsoil, 0.2–0.67 dS/m for subsoil) (GVW 2011a). The soil pH levels have generally risen slightly over the years, but the current soil salinity levels are believed to have reached equilibrium given the wastewater salinity levels, application rates, high soil clay content, and drainage. Similarly, the soil sodium levels in those paddocks are moderately elevated (0.77–6.48 meq Na/100 g), but have remained relatively constant over the years (GVW 2011a). The high soil clay content around Shepparton results in the potential for sodicity-related soil dispersion and temporary surface waterlogging, the latter of which is also brought on by the inherent characteristics of the site soils (GVW 2011a, Sumner 1993, Surapaneni et al. 1998). These trends indicate that continued wastewater irrigation for maize and sweet corn growth at the treatment plant would cause slight increases in soil salinity, pH, and sodicity, as well as the occasional waterlogging. These factors can be managed by regular gypsum applications, fertilizer and irrigation scheduling based on wastewater nutrient loading and plant demand, constant monitoring of soil health, and selection of plant species tolerant of waterlogging in a commercial setting (GVW 2011a). Maintaining an appropriate leaching fraction and an acceptable root zone salinity level is critical to controling risks from salinity and sodicity. The volume of water applied above the crop requirement will depend on the wastewater salinity level. Another approach is to use fresh water to flush the salts down to deeper soil levels (Surapaneni and Olsson 2002, Tillman and Surapaneni 2002).

Impacts of Wastewater Nutrients

The low nutrient concentrations in the Shepparton wastewater appeared to be insufficient for affecting crop yield or quality (Table 4, Table 5). The soil analyses showed that besides Na, no significant increases in nutrient concentration occurred in the wastewater bays compared to the fresh-water bays (Table 3). In fact, decreases in concentration were observed across both water types, likely due to plant uptake over the growing season. The low wastewater nutrient concentration is beneficial in the case of boron. While B is an essential element for plant growth, even presence in amounts appreciably greater than required can cause toxicity (Unkovich et al. 2006). Boron toxicity can affect almost all plants, but there is a wide range of tolerance among crops. Maize falls in the moderately tolerant crop category and is able to withstand B concentrations of 2.0–4.0 mg/L (Ayers and Westcot 1994), which is far above the concentration found in the wastewater here (Table 2). However, certain other crops such as peaches and plums are more sensitive and can only tolerate up to 0.5–0.75 mg/L (Ayers and Westcot 1994). Since those fruits are important crops grown in the Shepparton area, monitoring of B concentrations would be necessary if wastewater irrigation is to expand beyond maize.

The lack of nutrient accumulation in soils post-study is in line with long-term trends in the wastewater irrigated paddocks at the treatment plant (Table 2). Of all the macronutrients, K was the only one to gradually accumulate over the 8–28 years of irrigation (330–700 mg Skene K/kg); all other macronutrients were found at concentrations typical of intensively farmed soils (GVW 2011a). However, the nutrient uptake by maize or other crops is likely different to perennial pasture. If the land use is to be changed, modeling of soil nutrient levels should be undertaken to determine if nutrient availability will be limiting to crops and how much fertilizer should be applied.

Long-term Heavy Metal Concerns for Wastewater Irrigation

Heavy metal build up in wastewater-irrigated soils is a major public health and environmental concern. While the toxicity of heavy metals in soils is a complex phenomenon, governed not only by concentration but also by various conditions affecting bioavailability (Li et al. 2006, Xiong et al. 2004), indicative thresholds do exist, and it would be reasonable to state that it would typically take decades or even centuries for most heavy metals in treated wastewater to accumulate to problematic concentrations (Smith et al. 1996). There are two reasons for this. Firstly, accumulation of most water-borne heavy metals in soils is a very slow process. For example, a study of Cd, Cr, Cu, Ni, Pb, and Zn accumulation in soils at the Western Treatment Plant at Melbourne, Australia, showed that after 107 years of irrigation of pasture with *raw* industrial sewage, only concentrations of Cd and Zn just reached the plant toxicity thresholds (Ecological Investigation Levels) and all except Cr were well below the Human Investigation Levels appropriate for home-grown produce (separate thresholds do not exist for commercial production) (Hamilton et al. 2007, NRMMC et al. 2006, Xiong et al. 2001). Secondly, heavy metal removal, primarily through precipitation to sludge, is a highly effective process for most metals, regardless of treatment plant type (Goldstone et al. 1990, Karvelas et al. 2003, Lester 1983, Oliver and Cosgrove 1974, Stephenson and Lester 1987). For example, the study (Toumi et al. 2000) of a waste stabilization pond system and train similar to that at Shepparton demonstrated removal efficiencies of 91%, 92%, and 71% for Zn, Cu, and Pb respectively. Given both these considerations and the fact that there are no major industrial inputs of heavy metals into the Shepparton sewer (the cannery waste is relatively low in heavy metals in comparison to other industrial effluents), it is not surprising that no significant differences in soil concentrations of any of the surveyed metals in this study were observed between plots irrigated with wastewater and fresh water, and it would likely take a very long time for heavy metals to accumulate to appreciable levels and pose toxicity problems. The downward trend in soils concentrations (significant for Zn and Mn but not Cu) from pre- to post-irrigation for both fresh and wastewater is likely explained by the flushing of heavy metals from the soil. Therefore, irrigation with this effluent might initially result in a reduction in the concentrations of many heavy metals.

Regulation of Wastewater Reuse

While the results from the crop production show wastewater can be used for agricultural irrigation without immediate biophysical harm to crops, there are other aspects of reuse that need to be considered, such as public health risks. In Victoria, the Department of Health is responsible for managing public health concerns related to wastewater reuse. This government body regulates wastewater reuse schemes through the Environmental Protection

Agency’s *Guidelines for Environmental Management: Use of Reclaimed Water* (EPA Victoria 2003b). Agricultural irrigation of raw human food crops such as sweet corn is considered Class A water use, thus necessitating the application of the *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks*, which governs Class A reuse (EPA Victoria 2003a). For these Class A reuse schemes to be approved, they must undergo a rigorous assessment through the hazard analysis and critical control point framework (HACCP) and through techniques such as quantitative microbial risk assessment (QMRA) to ensure that the water is ‘fit for purpose’ for the particular reuse scheme (NRMMC et al. 2006). A probabilistic QMRA for norovirus risk was conducted for wastewater irrigation of vegetables in Shepparton and found that waste stabilization pond treatment alone did not have sufficient virus removal to meet the World Health Organization (WHO) threshold for acceptable level of risk for wastewater reuse, but addition of disinfection treatments provided acceptable results for consumption of cucumber (Mok et al. in press).

Conclusion

Combined, the field and modeling studies suggest that wastewater can be viably used as agricultural irrigation water with no significant crop yield or quality losses. Both sweet corn and silage maize have been shown to be suitable crop candidates for wastewater irrigation. However, long term wastewater irrigation will result in salt accumulation in soil and it will be important to monitor this to avoid possible problems with sodicity. This has crucial ramifications both locally for the Shepparton area, with the dairy industry’s high demand for forage crops, and globally. As climate change increases rainfall variability, wastewater irrigation for agriculture may increase in prevalence. Demonstrating there are no significant production risks from wastewater irrigation is important for sustaining crop production as well as for satisfying reuse regulations. Wastewater qualities and soil conditions will vary from location to location, thus it will be necessary to manage irrigation schemes based on the context of the site. Regular monitoring of soil health will also be essential to prevent potential salinity, sodicity, and heavy metal problems associated with long-term wastewater irrigation.

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Table 1: Climatic conditions and irrigation frequency during the study. Rainfall and evaporation data as collected at the Shepparton Wastewater Treatment Plant by GVW. Temperature data as collected at Shepparton Airport by the Australian Bureau of Metrology.

Time	**Irrigation**		**Rainfall**		**Pan Evaporation**	**Temperature**	
	Volume (m^3)	**Frequency (events)**	**Volume (m^3)**	**Frequency (events)**	**Total (m^3)**	**Min (C^o)**	**Max (C^o)**
November 14–30	300	2	6	2	369	6.1	39.8
December	779	5	58	5	750	9.2	39.0
January	1042	7	12	1	1041	8.9	42.2
February	914	6	418	6	707	10.5	39.2
March 1–8	142	1	0	0	149	9.6	34.5
Sweet Corn (Nov 14 – Feb 19)	2753	17	93	9	2637	6.1	42.2
Maize (Nov 14 – Mar 8)	3177	21	495	14	3016	6.1	42.2

Table 2: Characteristics of fresh and wastewater. Minimum, maximum, mean, and standard deviation values are reported. Monitoring data collected from selected maturation ponds by Goulburn Valley Water from 2007-2011 using standard laboratory methodology approved by NATA (GVW, 2011).

		EXPERIMENTAL FIELD TRIAL DATA						**GOULBURN VALLEY WATER MONITORING DATA**		
		Channel			**Wastewater**			**Wastewater**		
Parameter	**Units**	**Min**	**Mean ± SD**	**Max**	**Min**	**Mean ± SD**	**Max**	**Min**	**Mean ± SD**	**Max**
E. coli (Colilert)	MPN/100 mL	41.00	107.00 ± 60.70	230.00	63.00	967.57 ± 1557	4400	0.00	371.12 ± 2261	24000

pH	pH units	7.50	7.76 ± 0.13	7.90	9.30	9.96 ± 0.36	10.40	6.68	8.82 ± 0.57	10.63
EC	μS/cm	49.00	56.29 ± 3.86	59.00	1000	1142.86 ± 78.68	1200	863	1517.31 ± 413.78	6476
BOD_5	mg/L	<4	<4	<4	16.00	25.86 ± 5.40	32.00	4.00	20.34 ± 18.13	110
Total P	mg/L	0.03	0.06 ± 0.03	0.11	4.00	6.26 ± 1.39	8.10	2.20	5.16 ± 1.80	11.00
Nitrite-N	mg/L	0.003	0.01 ± 0.02	0.05	0.003	0.04 ± 0.08	0.20	0.003	0.16 ± 0.21	0.97
Nitrate-N	mg/L	0.003	0.12 ± 0.30	0.80	0.003	0.05 ± 0.05	0.15	0.005	0.88 ± 1.87	14.00
Ammonia-N	mg/L	0.005	0.13 ± 0.08	0.80	0.005	0.08 ± 0.13	0.35	0.005	1.70 ± 2.50	10.00
Total Oxidized N	mg/L	0.005	0.03 ± 0.02	0.06	0.02	0.11 ± 0.09	0.27	n/a	n/a	n/a
Total Kjeldahl N	mg/L	0.30	0.74 ± 0.38	1.40	6.30	12.71 ± 4.74	19.00	2.40	9.21 ± 3.79	27.00
Total N	mg/L	0.33	0.88 ± 0.39	1.40	6.40	12.73 ± 4.72	19.00	n/a	n/a	n/a
Ca	mg/L	2.60	2.81 ± 0.25	3.20	13.00	17.86 ± 4.30	24.00	25.00	39.59 ± 10.38	72.00
Mg	mg/L	2.10	2.33 ± 0.24	2.70	17.00	29.00 ± 11.97	46.00	42.00	79.98 ± 25.14	160.00
Na	mg/L	1.40	4.40 ± 1.54	6.60	36.00	186.57 ± 68.23	240.00	120.00	207.27 ± 67.59	480.00
K	mg/L	1.90	1.97 ± 0.83	3.80	38.0	65.29 ± 59.61	200.0	29.00	43.13 ± 9.78	81.00
B	mg/L	0.003	0.01 ± 0.003	0.011	0.098	13.68 ± 35.86	95.00	n/a	n/a	n/a
SAR	n/a	0.03	0.46 ± 0.15	0.65	1.49	6.47 ± 2.7	10.14	2.82	4.52 ± 1.09	7.55
TDS	mg/L	n/a	n/a	n/a	n/a	n/a	n/a	540.00	981.54 ± 277.79	2200
Suspended Solids	mg/L	n/a	n/a	n/a	n/a	n/a	n/a	4.00	55.03 ± 43.58	180.00

Table 3: Soil properties before and after the study. Means and *P*-values are reported.

Parameter	**Units**	**Fresh**		**Waste**			***P*-value**	
		Pre-Study	**Post-Study**	**Pre-Study**	**Post-Study**	**Water**	**Time**	**Interaction**
pH	pH units	5.25	5.43	5.26	5.92	0.01	<.001	<.001
EC	dS/m	0.12	0.08	0.12	0.25	<.001	<.001	<.001
Ammonia-N	mg/kg	45.7	45.3	46.4	46.6	0.79	0.96	0.90
Nitrate-N	mg/kg	13.6	4.74	16.2	5.61	0.08	<.001	0.48
Available P	mg/kg	13.9	8.40	14.6	11.9	0.02	<.001	0.13
Total Ca	mg/kg	1192	1106	1231	1090	0.80	<.001	0.35
Total Cu	mg/kg	20.2	15.4	14.1	13.0	0.40	0.17	0.64
Total K	mg/kg	6700	6131	6898	5902	0.87	<.001	0.07
Total Mg	mg/kg	2134	2037	2211	2008	0.69	0.004	0.27
Total Mn	mg/kg	426.7	394.9	446.7	379.4	0.92	<.001	0.06
Total Na	mg/kg	363.4	377.4	368.2	659.3	0.003	<.001	<.001
Total Zn	mg/kg	30.82	28.83	32.37	27.22	0.88	<.001	0.02

Table 4: Sweet corn yield and quality results. Fresh weight yields and cob counts were calculated for density of 70cm between rows and 20cm between seeds. Color was analyzed with a chroma meter and sweetness was measured by BRIX pocket refractometer. Means are labeled with letters signifying *post hoc* test comparisons, with the exception of plant height, where pair-wise comparisons were inconsistent, and *P*-values are reported. No plot *P*-value is reported for sweetness due to modelling inconsistencies.

		Treatment				***P*-Value**			
Parameter	**Units**	**C**	**W**	**CF**	**WF**	**Water**	**Fertilizer**	**Interaction**	**Plot**
Fresh Yield	t/ha	11.18^{a}	16.81^{a}	17.66^{a}	16.10^{a}	0.55	0.24	0.15	0.04
Cob Count	cob/ha	40870^{a}	61020^{a}	59250^{a}	53150^{a}	0.49	0.37	0.04	0.15
Cob Weight	g	196.33^{a}	192.39^{a}	207.94^{a}	193.32^{a}	0.34	0.66	0.70	0.09
Husk	g	75.31^{a}	68.94^{a}	79.40^{a}	80.54^{a}	0.65	0.22	0.55	0.05
Length	cm	19.52^{a}	18.97^{a}	19.93^{a}	19.15^{a}	0.11	0.57	0.82	0.05
Circumference	cm	14.66^{a}	14.66^{a}	15.03^{a}	14.47^{a}	0.23	0.76	0.37	0.20
Plant Height	cm	141.67	148.23	149.45	143.94	0.94	0.12	<.001	<.001
Sweetness	BRIX %	15.73^{b}	15.98^{b}	14.59^{a}	15.21^{ab}	0.05	0.01	0.56	N/A
Lightness	L^*	71.97^{a}	71.96^{a}	72.06^{a}	72.34^{a}	0.75	0.36	0.57	0.41
a^*	a^*	4.17^{b}	3.61^{ab}	3.78^{ab}	3.12^{a}	0.01	0.14	0.84	0.41
b^*	b^*	53.56^{a}	53.88^{a}	52.76^{a}	53.32^{a}	0.39	0.17	0.80	0.04
Chroma	C^*	53.75^{a}	54.02^{a}	52.92^{a}	53.44^{a}	0.44	0.16	0.80	0.05
Hue Angle	h^{o}	85.54^{a}	86.18^{ab}	85.92^{ab}	86.70^{b}	0.01	0.16	0.82	0.30

Table 5: Maize yield and quality results. Yields calculated for densities of 70cm between rows and 20cm between seeds. DM = dry matter; ADF = acid detergent fiber; NDF = neutral detergent fiber; DMD = dry matter digestibility; DOMD = organic dry matter digestibility. NIR silage quality analyses completed by FeedTest. Means are labelled with letters signifying *post hoc* test comparisons and *P*-values are reported.

		Treatment				***P*-Value**			
Parameter	**Units**	**C**	**W**	**CF**	**WF**	**Water**	**Fertilizer**	**Interaction**	**Plot**
Dry Yield	t DM/ha	10.30^{a}	11.71^{a}	13.95^{a}	13.24^{a}	0.74	0.03	0.32	0.16
DM	%	36.57^{a}	37.85^{ab}	42.07^{b}	38.68^{ab}	0.35	0.04	0.12	0.06
Moisture	%	63.43^{b}	62.15^{ab}	57.93^{a}	61.32^{ab}	0.35	0.04	0.12	0.06
Crude Protein	% of DM	6.75^{a}	6.88^{a}	7.03^{a}	7.37^{a}	0.56	0.20	0.73	0.07
ADF	% of DM	23.23^{a}	22.97^{a}	24.13^{a}	23.73^{a}	0.64	0.17	0.91	0.78
NDF	% of DM	46.57^{a}	45.95^{a}	47.58^{a}	47.73^{a}	0.82	0.03	0.49	0.56
DMD	% of DM	72.57^{a}	73.03^{a}	69.92^{a}	71.60^{a}	0.41	0.04	0.49	0.30
DOMD	% of DM	68.32^{a}	69.42^{a}	66.58^{a}	68.07^{a}	0.25	0.03	0.76	0.49
Metabolizable Energy	MJ/kg DM	10.93^{a}	11.05^{a}	10.65^{a}	10.83^{a}	0.33	0.02	0.72	0.28
Partial DM	%	39.15^{a}	41.00^{ab}	45.20^{b}	41.40^{ab}	0.52	0.07	0.10	0.09
Plant Height	cm	167.73^{a}	172.93^{a}	186.48^{b}	181.17^{b}	0.99	<.001	<.001	<.001

Table 6: Soil physical, chemical, and hydraulic properties for Goulburn Loam from DPI soil surveys (DPI, 2004). Mean and standard deviation reported.

Parameter		Unit	Horizon A (0 – 18cm)	Horizon B1 (19 – 33cm)
Soil physical properties	Bulk density	g/cm3	1.50 ± 0.12	1.64 ± 0.13
	Clay	%	17.7 ± 9.6	33.0 ± 13.1
	Silt	%	38.6 ± 5.7	37.2 ± 6.1
	Sand	%	43.7 ± 8.2	29.8 ± 11.0
	Organic matter	%	4.63 ± 0.79	2.17 ± 1.00
Soil chemical properties	EC	dS/cm	0.17 ± 0.18	0.13 ± 0.15
	pH (H_2O)	pH	6.4 ± 0.8	7.1 ± 0.4
	Ca	meq/100g	5.6 ± 1.4	5.7 ± 2.0
	Mg	meq/100g	3.1 ± 1.3	4.1 ± 1.4
	Na	meq/100g	0.8 ± 1.2	1.1 ± 1.1
	K	meq/100g	0.7 ± 0.4	0.6 ± 0.3
	ESP	%	6.3 ± 5.8	8.4 ± 6.2
Soil hydraulic properties	Saturated hydraulic conductivity	mm/hr	28.7 ± 15.2	3.77 ± 6.28
	Available water capacity	%	13.6 ± 6.67	14.9 ± 4.01
Volumetric water content	Matric suction at 0 kPa	%	41.8 ± 5.8	42.9 ± 4.9
	Matric suction at 10 kPa	%	38.6 ± 6.0	39.6 ± 6.1
	Matric suction at 60 kPa	%	35.5 ± 5.9	36.2 ± 7.7
	Matric suction at 1500 kPa	%	24.9 ± 5.2	24.8 ± 8.0

Table 7: Simulated maize yield, grain protein content, soil chloride, and soil EC at 50 cm; values presented are means over 50 years. Letters indicate significant differences.

Wastewater EC (dS/m)	Yield (kg/ha)	Biomass (kg/ha)	Grain Protein (%)	Cl (kg/ha)	Soil EC at 50cm (dS/m)
0.0	6111^{a}	14816^{a}	7.125^{a}	0^{a}	0.00^{a}
0.8	6035^{a}	14710^{a}	7.109^{a}	9670^{b}	1.74^{b}
1.0	6015^{a}	14683^{a}	7.103^{a}	12069^{c}	2.17^{b}
1.5	5960^{a}	14603^{a}	7.088^{a}	18048^{d}	3.26^{c}
2.0	5904^{a}	14506^{a}	7.077^{a}	24045^{e}	4.37^{d}
6.5	5139^{a}	13368^{a}	7.418^{a}	73651^{f}	14.29^{e}
P-Value	0.374	0.433	0.419	<0.001	<0.001

Fig 1 The experimental site design. Each plot was 5 m x 7 m with 3 m buffer between plots. Each irrigation bay was 5 m x 30 m separated by a 1 m check bank. Between blocks, there was a gap of 5 m, not including check banks. Results for okra production are not reported in this paper.

Fig 2 Electromagnetic conductivity and topography map. Survey was conducted by FarmingIT using RTK GPS and EM38-Mk2. Elevation is meters above sea level.

Fig 3 Soil properties from DPI Goulburn Loam GN26 soil pit (DPI, 2004). Properties include A) pH, B) salinity, C) sodicity, D) clay percentage, and E) coarse sand percentage.

Fig 4 Simulated impacts of long term waste water irrigation on soil EC