Science of the Total Environment 648 (2019) 116–124

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Effects of ferric sulfate and polyaluminum chloride coagulation enhanced treatment wetlands on *Typha* growth, soil and water chemistry

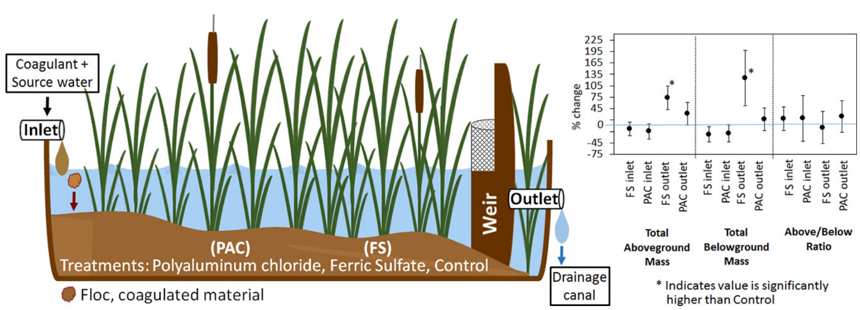
Yan Ling Liang [a,*], Tamara E.C. Kraus [b], Lucas C.R. Silva [a,d], Philip A.M. Bachand [c], Sandra M. Bachand [c], Timothy A. Doane [a], William R. Horwath [a]

[a] Department of Land, Air, and Water Resources, 1 Shields Avenue, University of California Davis, Davis, CA 95616, USA
[b] United States Geological Survey California Water Science Center, 6000 J Street Placer Hall, Sacramento, CA 95819, USA
[c] Bachand & Associates, 2023 Regis Dr., Davis, CA 95618, USA
[d] Environmental Studies Program, Department of Geography, Institute of Ecology & Evolution, University of Oregon, 1585 E 13th Ave, Eugene, OR 97403, USA

HIGHLIGHTS

- Coagulation treatment wetlands improve water quality and mitigate land subsidence.
- On-site coagulation did not result limit nutrient availability to Typha plants.
- Exposure to floc did not negatively affect Typha growth or mass accumulation.
- No toxicity signs observed in Typha exposed to floc during entire growing season.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 1 July 2018
Received in revised form 23 July 2018
Accepted 24 July 2018
Available online 25 July 2018

Editor: Frederic Coulon

Keywords:
Sacramento-San Joaquin Delta
Allometrics
Nutrient
Plant mass
Agricultural water treatment
Subsidence

ABSTRACT

Land surface subsidence is a concern in many deltas worldwide as it contributes to water quality degradation, loss of fertile land and increased potential for levee failure. As a possible solution to these concerns, on-site coagulation enhanced treatment wetlands (CETWs), coagulation water treatment followed by wetland passage serving as a settling basin, were implemented in a field-scale study located on a subsided island of the Sacramento-San Joaquin Delta in northern California under three treatments; coagulation with polyaluminum chloride (PAC), coagulation with ferric sulfate and an untreated control. Because CETWs offer a relatively novel solution for water quality improvement and subsidence reversal due to its low-infrastructure requirements and in-situ nature, effects from these systems remain uncharted and they may have adverse effects on plant biomass production that also contribute to sediment accretion. This study focuses on the effect CETWs had on the growth of *Typha spp.*; the dominant vegetation in the wetlands. Plant growth parameters and nutrient content were measured in conjunction with soil, pore water and surface water chemistry. Soil analysis indicated there was no intermixing of newly formed flocs and original soil material. Where there was significant deposition of floc, PAC treatment reduced phosphate concentrations and ferric sulfate treatment increased total Fe concentrations in surrounding water compared to the control. Results indicated coagulation treatments had no negative effects on *Typha* leaf nutrient content, *Typha* growth or allometric parameters. Additionally, no signs of plant toxicity such as necrosis, wilting or chlorosis were observed in any of the treatments. Overall, this study suggests that CETWs are viable treatment

Abbreviations: CETW, Coagulation enhanced treatment wetland; DOC, Dissolved organic carbon; FS, Used to indicate ferric sulfate treatment; PAC, Used to indicate polyaluminum chloride treatment.

* Corresponding author.
E-mail addresses: yanliang@ucdavis.edu (Y.L. Liang), tkraus@usgs.gov (T.E.C. Kraus), lsilva7@uoregon.edu (L.C.R. Silva), philip@bachandassociates.com (P.A.M. Bachand), sandra@bachandassociates.com (S.M. Bachand), tadoane@ucdavis.edu (T.A. Doane), wrhorwath@ucdavis.edu (W.R. Horwath).

https://doi.org/10.1016/j.scitotenv.2018.07.341

option for water quality improvement and sediment accretion while having no negative impact on the growth of *Typha* plants.

1. Introduction

Worldwide, many river deltas such as the Rhine-Meuse-Scheldt, Ganges and Mississippi deltas are threatened by land surface subsidence (Brown and Nicholls, 2015; Tessler et al., 2015; Törnqvist et al., 2008; Verhoeven and Setter, 2009). Many of these deltas provide valuable land for agriculture, recreation, wildlife habitat and ecosystem services (Clarkson et al., 2013; Costanza et al., 1997) and loss of these lands due to flooding would greatly impact millions of people and many other species (Edmonds et al., 2017; Syvitski, 2008). The Sacramento-San Joaquin Delta (Delta) located in northern California of the USA face similar threats resulting from significant subsidence due primarily to organic matter oxidation and physical compaction, with some regions now six meters below sea level (Deverel et al., 2016; Kraus et al., 2008; Stumpner et al., 2015). Increasing land subsidence has been associated with increased levee failure risk that can result in loss of valuable agricultural land due to flooding and temporarily or permanently unusable Delta water due to salt water intrusion (Delta Protection Commission, 2012; Mount et al., 2015; Mount and Twiss, 2005). Current practices in the Delta require extensive levee systems and constant pumping of water off these lands to maintain usability. Drainage water from these peat soils contains high levels of dissolved organic carbon (DOC) that can contribute to degraded water quality in the Delta waterways (Kraus et al., 2008). Of particular concern, DOC reacts to form carcinogenic disinfectant-by-products during chlorination for drinking water (Fleck et al., 2004; Fuji et al., 1998; Kraus et al., 2008) and poses a potential health risk for over 25 million California residents that use this source for drinking water (Lund et al., 2010; Lund, 2016).

Coagulation treatment for water quality improvement is commonly practiced in drinking water and wastewater treatment industries (Jiang, 2001), but its application in treatment wetlands and for treating agricultural drainage water are less studied and applied (Lindstrom and White, 2011; Malecki-Brown and White, 2009; Malecki-Brown et al., 2009; McCord and Heim, 2015). Coagulation enhanced treatment wetlands (CETWs), where treatment wetlands serve as a settling basin following coagulation treatment, is a potential solution that can improve the quality of water exported into the Delta waterways with the added benefit of rebuilding land elevation to combat subsidence (Bachand et al., submitted-a; Bachand et al., submitted-b; Hansen et al., 2018; Henneberry et al., 2016; Stumpner et al., 2018). In the water treatment industry, the behavior of water treatment residuals (i.e. flocs) is not often considered since the material is removed and disposed of in landfills (EPA, 2011), but due to the in-situ nature of CETWs it is necessary to gather information on the effects of flocs in these natural settings. Though CETWs may offer a relatively novel solution for water quality improvement and subsidence reversal due to its low infrastructure design and in-situ nature, it may have adverse effects on plant biomass production that also contribute to rebuilding land elevation. Of particular concern, coagulation has been shown to remove phosphorus, an essential plant nutrient (Qualls et al., 2009), and metal coagulants have been shown to hyper-accumulate in plants resulting in toxicity (Eid et al., 2012; Jacob and Otte, 2004; Zhong et al., 2009); these effects could potentially result in stunted plant growth and lower biomass production.

Wetlands in this study were dominated by *Typha spp*., an emergent wetland plant belonging to the Typhaceae family that exhibit fast growth (Byrd et al., 2014; Larkin et al., 2012; Miao et al., 2008) and has been used for contaminant remediation and carbon sequestration (Asaeda et al., 2010; Byrd et al., 2014; Kruzic and Kreissl, 2009; Sasikala et al., 2008; Zhong et al., 2009). Although a previous study showed no effect on *Typha* growth for up to 3 months in alum treated coagulation wetland systems (Malecki-Brown et al., 2010), implementation of such systems requires operation on an extended basis for cost effectiveness (Bachand and Bachand, Manuscript in preparation), therefore, it is necessary to assess *Typha* growth over longer periods.

In this study, we focused on the effect CETWs have on *Typha* growth, soil, pore water and surface water chemistry to evaluate the safety and viability of CETWs as an option for water treatment and sediment accretion. This study was conducted using on-site hybrid coagulation treatment wetlands receiving flocs produced by ferric sulfate or polyaluminum chloride coagulation in addition to untreated control wetlands. Plant growth parameters (allometrics, plant mass and leaf nutrient content), soil, pore water and surface water chemistry were measured to determine the effects of coagulation and produced flocs on plant, soil and water components.

2. Experimental methods

2.1. Study site

The study site was located on the southern part of Twitchell Island (Latitude: 38.099, Longitude: −121.656), a subsided island in the Sacramento-San Joaquin Delta of California, U.S.A. Historically a wetland, Twitchell Island was drained in the 1870s for agricultural purposes requiring the construction of levees and pumping stations to maintain arable lands and prevent re-flooding of the islands. Corn, alfalfa and rice are the primary crops grown on the island, but tomatoes, asparagus and potatoes have been grown in the past (Fleck et al., 2004). The soil on this island is Rindge mucky silt loam, classified as a Euic, thermic Typic Haplosaprists according to National Resources Conservation Services, and comprised of detrital material from historic wetland species *Schoenoplectus acutus* (Tules) and *Phragmites* (Miller and Fujii, 2010).

The study site comprised of nine treatment wetlands; each about 12.2 m wide, 36.6 m long and 0.4 m deep. Prior to flooding in June 2011, feldspar marker horizons were placed in each wetland to establish a baseline for the original soil layers (Fig. S1) (Stumpner et al., 2018; U.S. Department of the Interior, 2010). The wetlands vegetated naturally and were dominated mainly by *Typha* spp. comprised of *T. latifolia*, *T. angustifolia*, *T. domingensis* and their respective hybrids (Byrd et al., 2014; Miller and Fujii, 2010). Wetlands were flooded on July 1, 2011 to a depth of 40 ± 9 cm, with construction and testing of the coagulation systems during the following year. Coagulation was applied continuously from July 2012 to November 2013 (16 months) except for a 3-week period in October 2012 when the coagulation system was offline due to equipment failures. Three treatments were considered in which the source water was; (i) treated with polyaluminum chloride coagulant (PAC, Kemira PAX-XL19, Kemira Water Solutions, Inc.), (ii) treated with ferric sulfate coagulant ($Fe_3(SO_4)_3$, 60% Soln., Kemira Water Solutions, Inc.) and (iii) untreated (control). These are henceforth referred to as PAC, FS, and control treatments, respectively. A randomized block design was used to assign a treatment to each wetland, with 3 replicates per treatment (Bachand et al., submitted-a). This randomized design was used to account for any natural soil variability or gradients existing among the wetlands.

Coagulation application occurred by dosing into pipes carrying source water which consisted primarily of island drain water that was occasionally supplemented with San Joaquin river water when island drain water levels were low. Dosed coagulant, applied at rates to remove 60–80% of source water DOC concentrations, was immediately