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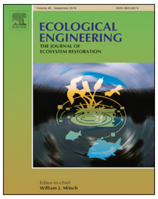

Biosolids as a marsh restoration amendment

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ABSTRACT

As concerns about sea-level rise mount, municipalities in coastal areas are looking to nature-based protection and adaptation. Oftentimes such projects are marsh creations or restorations, where areas of open water are filled with dredged material to an elevation where emergent vegetation can grow. We are investigating ways biosolids can be used as an amendment to dredged material to enhance project outcomes. Marsh mesocosms were constructed in San Francisco Bay and planted with native cordgrass, *Spartina foliosa*. Some mesocosms contained a subsurface layer of biosolids. Vegetation grown with biosolids had significantly increased number of new shoots, aboveground biomass, and belowground biomass. Vegetation with only dredged material had greater rooting depths but this result was not significant. By combining natural processes with human infrastructure, the application of biosolids for marsh creation is a sustainable practice.

1. Introduction

It is well established that salt marshes provide vital ecosystem services, such as assimilating nutrients, providing habitat, sequestering carbon, and attenuating wave action (Mitsch and Gosselink, 2007; Ouyang and Lee, 2014; Pinsky et al., 2013). There is great interest in rebuilding salt marshes in order to restore these functions, particularly as they pertain to coastal protection (Narayan et al., 2016 and references therein). These marsh restorations typically consist of raising the elevation of an area of open water to the point where emergent vegetation can take hold; this process requires a large input of sediment. Material dredged from waterways is most commonly used, and the reuse of this dredged material is encouraged by federal agencies (U.S. Environmental Protection Agency, 2007). Herein we propose and discuss another possible source of sediment, biosolids. Biosolids are the solids product of modern wastewater treatment and are ubiquitous in populated areas. Depending on their properties and the properties of the receiving waters, biosolids fit into one of three categories: 1) source of fill material; 2) beneficial amendment to other fill material; 3) harmful material not to be used. We investigate this second category, using biosolids as an amendment to dredged material.

1.1. Background

1.1.1. Marsh restoration and sediment amendments

Dredged material is one of the only sources of sediment suitable for marsh restoration projects and available in the quantities needed. Dredged material tends to have a high sand content, which aides the dewatering and consolidation processes but also causes the restored marsh soil to differ from established marshes (*e.g.* lower organic matter, lower water content, and higher bulk density (Armitage et al., 2014; Fearnley, 2008; Streever, 2000; Edwards and Proffitt, 2003; Feagin et al., 2009). As with most newly restored marshes, dredge-material marshes tend to have less belowground biomass (Tong et al., 2013; Armitage et al., 2014; Streever, 2000; Boyer et al., 2000). Streever (2000) performed a review of restorations and found no evidence that levels of organic matter in dredged-material marshes were increasing over time to reach levels of established marshes.

In order to improve performance of dredged-material marshes and accelerate restoration, sediment amendments ranging from compost to direct nutrient addition have been suggested and tested (Cain and Cohen, 2014; Kelley and Mendelssohn, 1995; Fearnley, 2008). Mimicking edaphic conditions of established marshes can help restore driving physical processes (Zedler, 2001). Increased nutrients can help overcome other stressors (eg. salinity (Cavalieri and Huang, 1979)). In southern California, rototilling kelp compost was found to significantly increase the height and stem density of *Spartina foliosa* (O'Brien and Zedler, 2006). Products like the Gulf Saver®Bag use compost in an effort to increase the survival of the vegetation transplants (Sullivan, 2010). Some biosolids-derived compost products are already being used in restorations (*e.g.* in a riparian wetlands (Sutton-Grier et al., 2009)).

1.1.2. Biosolids

The term "biosolids" was recognized by Water Environment

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Federation in 1991 in response to advances in treatment technology that produced material safe for reuse (Lu et al., 2012). The term "sludge" now typically refers to the solids portion of wastewater while undergoing treatment, but prior to 1991, it referred to the solids at any treatment stage. Biosolids are continuously produced in all populated areas. In 1998, approximately 6.2 million dry metric tons were produced in the U.S. (U.S. Environmental Protection Agency, 1999), and in California, 688,000 dry metric tons were produced in 2014 (California Association of Sanitation Agencies, 2015). These figures increase as the population increases. The composition of biosolids varies depending on the specific treatment processes (*e.g.* anaerobic digestion, chemical stabilization, composting) and waste streams being treated (*e.g.* industrial, residential). They characteristically contain organic matter and nutrients, as well as heavy metals. Land application of biosolids is guided by U.S. EPA regulations so that land owners can take advantage of the well-established soil-improving benefits of biosolids application, while preventing potentially harmful accumulation of contaminants (Lu et al., 2012; Garcia-Orenes et al., 2005; Tian et al., 2013).

1.1.3. Biosolids in salt marshes

Biosolids in wetlands are often thought of in the fresh water context, as there is extensive research on the use of wetlands to treat wastewater (*e.g.* Kadlec and Wallace, 2008). While that practice is beneficial and can be used in conjunction with restoration (*e.g.* freshwater assimilation wetlands (Day et al., 2004)), it is not our focus. We focus on the use of biosolids as part of the soil in salt marshes.

There are a few previous studies that have looked at the impact of biosolids in salt marshes. In the 1970s, I. Valiela, J.M. Teal, and coauthors sought to understand the potential consequences of sewage sludge contamination. They measured vegetation and nutrient responses to a bi-weekly broadcast of sewage sludge in a salt marsh in Massachusetts. They measured an increase in aboveground biomass (Valiela et al., 1975), decrease in root mass, and no effect on rhizomes (Valiela et al., 1976). Haines (1979) performed a similar experiment in Georgia, applying dried sewage sludge to a salt marsh, and found an increase in aboveground and belowground biomass. Vance et al. (2003) investigated the potential of converting sewage oxidation ponds to marshes. They found no statistical difference in final biomass between samples grown in 0% and 70% sewage sludge. This result was likely due to its aged nature, as the sewage sludge contained low concentrations of organic matter (about 2%).

Results from previous studies indicate that a biosolids amendment containing organic matter and nutrients could be beneficial to vegetation, especially at early stages of marsh development. This use of biosolids as an amendment in restoration projects provides an opportunity to connect human infrastructure and natural coastal processes. Inspired by this opportunity, we designed one possible implementation technique and tested it with mesocosms installed within a marsh. The implementation uses local constraints relevant for marsh restoration in San Francisco Bay.

2. Methods

2.1. Study site

The study site for the field experiments was Western Stege Marsh. It is a 0.04 km^2 tidally influenced salt marsh in Richmond, California, and is part of the San Francisco Bay estuary. The mean tidal range is 1.3 m, and the two dominant vegetation species are *Spartina foliosa* (Pacific cordgrass) in the low marsh and *Salicornia pacifica* (pickleweed) in the mid to high marsh (T.T.E. Inc, 2010).

2.2. Mesocosms

To study the effect of biosolids as an amendment, an array of marsh mesocosms was constructed (Fig. A.4). In-situ mesocosms are recommended for testing new restoration techniques (Callaway et al., 1997). This array consisted of 24 PVC pipes each with a 15 cm diameter that was open to the bottom sediment. The array of pipes was built into the bank of a tidal creek, adjacent to the marsh platform. The top of the pipes had an elevation even with the surrounding marsh, which was confirmed using a laser level. This design allowed for control of the pipe substrate while exposing the vegetation to natural conditions. It was inspired by "marsh organs," a well-documented design for measuring primary production of marsh vegetation (Morris, 2007).

Each pipe was filled with a specific substrate, described in Section 2.3, and planted with *S. foliosa* sourced from the surrounding marsh on December 22, 2015. The shock of transplanting vegetation from one environment to another is commonly damaging. Not all transplanted vegetation senesced and regrew new shoots, as expected. Pipes without alive shoots were replaced, and on June 16, 2016, all pipes had one alive stem at least 10 cm tall. Shoots were individually tracked over the course of multiple site visits, which allowed us to determine at the end of the experiment if shoots were old (*i.e.* transplanted from the marsh) or new growth (*i.e.* grew on its own). These are the definitions for 'new' and 'old' used herein. The entire array was wrapped in a plastic mesh to prevent herbivory. Two 4 mm holes were drilled 10 cm from the top of each pipe to allow some drainage.

2.3. Substrate

Since a typical rooting depth of *S. foliosa* is 30 cm (Callaway and Josselyn, 1992), the top 30 cm of each pipe was the focus of the experiment. From 30 cm to the ground (61.4 cm total), the pipes were filled with dredged material sourced from Martinez Harbor (Martinez, CA) or clean sand. A layer of burlap was used to denote the 30 cm mark.

Of the 24 pipes, 16 were control pipes. The top 30 cm of control pipes were filled with dredged material obtained from the Hamilton Wetlands Restoration Project site. This material was sourced from the Port of Oakland deepening project and began dewatering in 2008. We collected this material on December 15, 2015.[1]

The remaining 8 pipes contained the same dredged material as the controls plus an 8 cm layer of biosolids starting 12 cm beneath the surface (Fig. 1). The biosolids were obtained from the East Bay Municipal Utility District (EBMUD) Wastewater Treatment Plant on December 11, 2015. This facility produces Class B biosolids, which are used in agricultural fields and as daily cover in landfills. The biosolids had a soil-like consistency. Chemical properties of the biosolids at the facility were measured 11 days prior to and 18 days after our collection date as part of routine monitoring. These results are used for characterizing the biosolids used here because the tests show low monthly variability in the biosolids properties. These tests also revealed that the biosolids met the fecal coliform standards for Class A Biosolids (2015 annual maximum < 1000 MPN/g) (Code of Federal Regulations, 1999)).

Dredged Material Management Office (DMMO) is the regulating authority for the reuse and dumping of dredged material in San Francisco Bay. Only the biosolids' mercury concentration exceeded the set limits. Mercury in San Francisco Bay is more strictly regulated than in other water bodies because there is an elevated concentration from mining in the watersheds that feed the Bay (Davis et al., 2012). The concentration was approximately twice the set total maximum daily limit (TMDL) (San Francisco Estuary Institute, 2015; Freitas and Chakrabarti, 2015). Note, it was 57 times less than U.S. EPA land application limit (Code of Federal Regulations, 1999). When the 8 cm of biosolids is averaged with the 22 cm of dredged material, the resulting concentration was under the limit.

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[1] The results presented here are from the second trial of experiments. The first trial resulted in high mortality rates of vegetation in control pipes. Informed by this result, one of the original biosolids treatments was removed to have twice as many control pipes.