Navigating the Plastic Tide: Exploring Microplastic Pollution in the Sacramento-San Joaquin Delta

Thesis

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Bachelor of Science in Environmental Studies

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Abstract

The Sacramento-San Joaquin Delta stands as a vital link between California's inland urban and agricultural regions and the coastal expanse of the San Francisco Bay Estuary. Drastically altered since the Gold Rush of 1848, this ecosystem faces complex challenges, including climate change, urbanization, and pollution. The increasing presence of microplastic pollution in virtually all environments is becoming a widespread concern, extending its reach into important ecosystems like the Delta. Microplastics, originating from the breakdown of larger plastic items, constitute a substantial portion of global pollution. While marine plastic pollution receives considerable attention, the extent of terrestrial and freshwater plastic pollution, particularly in estuarine environments like the Delta, remains relatively understudied. These microplastics infiltrate estuarine ecosystems through various pathways, including agricultural activities, urban runoff, and wastewater discharges, presenting ecological, economic, and public health risks. This review aims to investigate the physical, chemical, and biological impacts of microplastics from agricultural activities on the Sacramento-San Joaquin Delta. By examining current knowledge, identifying gaps, and proposing future research directions, this review seeks to deepen our understanding of microplastic pollution in these critical ecosystems. This review aims to explore the implications of microplastics

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Dedication

I would like to dedicate this paper to my family, Chii, my Sutter family, my friends, and fellow classmates who have supported me before and during my undergraduate career. I'd also like to thank Brian, the best partner, who has learned so much about microplastics and agriculture from all of my ramblings. A special thank you to Billie and Ein, as always.

Acknowledgments

I would like to thank Dr. Reede, Dr. Titus, Dr. Fulton, and Dr. Stevens for giving me their time to help me refine my ideas for this research project and for everything else they and the rest of the Environmental Studies Department have taught me. I'd also like to thank Kirt Sandhu, Denise Wong, Dr. Hanley, and the rest of my cohort at the Department of Toxic Substances Control for their knowledge and guidance. I am especially grateful to Kathryn Meyer, my mentor, for her extensive support, insights, and patience. I'm so excited for what is to come. I also want to give my sincerest thanks to my thesis advisor Connor Rosenblatt for giving me advice on my academic and professional career, guiding me through this paper, and making learning such a joy.

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Introduction

In the dynamic landscape of California, the Sacramento-San Joaquin Delta, hereafter referred to as the Delta, stands as a pivotal nexus, intricately linking inland urban and agricultural regions to the coastal environment of the San Francisco Bay Estuary. The Delta, with its intricate network of channels, sloughs, and marshlands, supports a diverse network of biodiversity while also serving as the primary conduit for freshwater supply to the San Francisco Bay Estuary (Marineau & Wright, 2020). However, alongside its ecological importance, the Delta faces growing threats from various anthropogenic stressors including climate change, urban development, and pollution (Kraus-Polk & Fulton, 2020). Human activities have profoundly shaped this unique and complex ecosystem since the California Gold Rush in 1848 (Kraus-Polk and Fulton, 2020).

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One emerging concern is the pervasiveness of microplastic pollution, which through its growing concentration in the Delta, poses risks to those who depend on it. Microplastics are derived from larger pieces of plastic, a material used in virtually every industry due to their versatility, durability, and cost-effectiveness, making up a significant portion of global pollution (Rochman et al., 2022). The global input of plastic into our oceans is estimated to be around 11 million metric tons annually and is estimated to grow as the global population rises (COPC, 2022). Despite extensive research on marine plastic

Commented [RCJ4]: This is a really strong transition sentence! I think it would fit a little better as the first sentence of the next paragraph pollution, terrestrial and freshwater plastic pollution, especially in estuarine environments like the Delta, remains relatively understudied in comparison (Hitchcock & Mitrovic, 2019). Microplastics, in particular, are a growing concern due to their ability to persist for extended periods, their potential to accumulate harmful pollutants, and their permeability (Rochman et al., 2022). San Francisco Bay has been noted for having some of the highest microplastic concentrations compared to other regions worldwide (Sutton et al., 2019). The substantial presence of microplastics in the San Francisco Bay suggests a parallel trend of microplastic pollution within the Delta, which empties into the San Francisco Bay Estuary (Prata et al., 2019). Microplastics enter estuarine ecosystems through various pathways, including runoff from urban areas, industrial discharges, and agricultural activities posing ecological, economic, and public health risks to the Delta and its surrounding communities (Hitchcock & Mitrovic, 2019).

Understanding the dynamics of microplastic pollution in the Delta is essential for developing effective management and mitigation strategies (Rochman et al., 2022). This literature review aims to explore the impacts of microplastics originating from agricultural activities on the Sacramento-San Joaquin Delta and its connected counterpart. By examining the current state of knowledge, identifying gaps, and proposing future research directions, this review seeks to understand the complexities of microplastic pollution in these critical ecosystems and contribute to informed decision-making and management strategies. The structure of this review will encompass an exploration of the definition and classification of microplastics, sources and distribution patterns within estuarine environments, ecological significance and vulnerability of estuaries to pollution, as well as the specific impacts of microplastics on estuarine ecosystems, assessment methodologies, mitigation and management strategies, and future research directions leading to more effective conservation and stewardship of these invaluable natural resources.

Methods

The methods employed for this literature review involved a comprehensive search and synthesis of existing peer-reviewed publications, reports, and research articles related to microplastic pollution in estuarine environments, with a specific focus on the Sacramento-San Joaquin Delta and the San Francisco Bay Estuary. A systematic search was conducted across multiple academic databases provided by the Sac State Library, the CalEPA Library Services, and Google Scholar. The search was guided by a set of keywords including:

Microplastic	Plastic
Estuaries	Sacramento-San Joaquin Delta
Pollution	San Francisco Bay Estuary
Agriculture	Ecological Impacts
Contaminants of Concern	Policy
Mitigation	Toxicity
California	Impacts

To ensure the inclusion of the most recent and pertinent studies, the search was limited to peer-reviewed articles, scientific reports, and relevant literature published between 2014 and 2024. Government reports, policies, and websites were consulted to provide additional background information on the current policies in California regarding microplastics and pertinent information on Delta agriculture. The inclusion criteria aimed to capture a comprehensive range of literature addressing microplastic pollution in estuarine environments, with a particular emphasis on the unique characteristics and challenges faced by the Sacramento-San Joaquin Delta, and as an extension, the San Francisco Bay Estuary.

Understanding Microplastics

Plastics and Microplastics

Plastic is a versatile and ubiquitous material that is derived from synthetic polymers, which are long chains of molecules derived from petroleum or natural gas (Bucci & Rochman, 2022). These polymers can be molded into various shapes, sizes, and forms, giving rise to a vast array of plastic products with diverse functionalities. Low and high-density polyethylene (PE), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polystyrene (PS) make up approximately 90% of the global demand for synthetic plastic (Vermeiren et al., 2016). Because of its durability, affordability, and wide-ranging applications, plastic has become an integral part of modern society. From consumer products to industrial packaging, plastic serves a myriad of purposes, contributing to global economic development and technological advancement. However, the durability that makes plastic so valuable also lends to its persistence in the environment even after disposal (Miller et al., 2021). Plastic pollution that makes its way into the environment often degrades into smaller fragments known as microplastics.

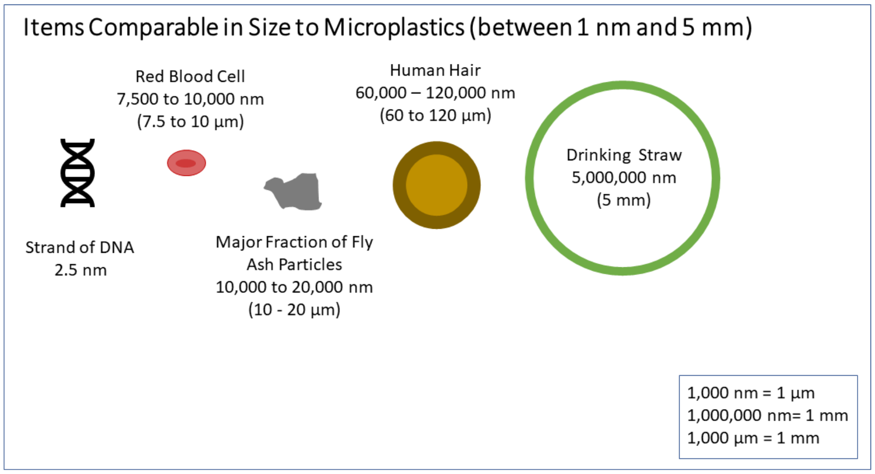

Figure 1: *Items comparable in size to microplastics. Retrieved from ITRC, 2023.*

Definition and Classification of Microplastics

Microplastics, as defined by the California State Water Resources Control Board (SWRCB, 2020), are three-dimensional solid plastic particles that are smaller than 5,000 micrometers (µm), or 5 millimeters, in length and have had chemical additives or other substances added to them (**Figure 1**) (SWRCB, 2020). The Department of Toxic Substances Control (DTSC, 2023) and other California state agencies have also adopted this definition as they also work to address the ever-growing issue that is microplastics (DTSC, 2023; OPC, 2022). This definition does not include naturally occurring polymers such as wool, silk, or cellulose (SWRCB, 2020). Microplastics can be classified into two categories based on their origin: primary and secondary. Primary microplastics are intentionally manufactured at small sizes for specific purposes, such as microbeads in cosmetics or nurdles used in plastic production (Li et al., 2016). Secondary microplastics form as a result of larger plastic items degrading into smaller fragments due to environmental factors like ultraviolet radiation, mechanical processes, or chemical processes (COPC, 2022). Microplastics exhibit diverse shapes, sizes, and compositions, depending on their sources and environmental conditions (COPC, 2022). Microplastics can be classified into morphological categories based on their commonly encountered forms which include granules, pellets, fibers, fragments, films, and foams (Dickey, 2022). Like their larger parts, microplastics threaten environments like the Delta due to their ubiquity, pervasiveness, and potential to accumulate harmful contaminants along with the chemical additives used in their production (Li et al., 2024).

Sources and Distribution of Microplastics in the Environment

Plastic, and therefore microplastics, can be found throughout the environment as a consequence of inadequate waste management practices (Li et al., 2024). While plastic is indeed beneficial in many industries, plastic waste and pollution has grown an alarming rate. As of 2015 only 9% of the 6,300 Mt, or 6,300 million metric tons, of plastic produced since the 1950’s had been recycled (Geyer et al., 2017). Landfills, industrial and municipal discharges, stormwater runoff, marine activities, atmospheric deposition, and land-based activities such as construction, landscaping, recreational activities, and agricultural practices contribute to the widespread distribution of plastic pollution in terrestrial and aquatic environments globally (Rochman et al., 2022). When plastics degrade in the environment due to factors such as sunlight exposure, mechanical abrasion, or microbial activity, they can release the chemical additives from their production phase into the surrounding environment (Hofmann et al., 2023). Due to their large surface area-to-volume ratio and hydrophobic nature, microplastics can effectively adsorb various organic and inorganic contaminants present in aquatic environments (Hofmann et al., 2023). These pollutants include heavy metals, pesticides, persistent organic pollutants, and other compounds, further complicating their environmental impact (Okeke et al., 2022). Because of the exponential rate at which we use plastic and our inadequate plastic waste management, the accumulation of microplastics and associated pollutants in the environment has become a pressing global issue with far-reaching implications for ecosystem health and the well-being of species everywhere (Li et al., 2024).

The Sacramento-San Joaquin Delta

Ecological Significance

Covering approximately 738,000 acres, or over 1,100 square miles, the Delta represents one of the largest estuarine systems in the United States (Delta Stewardship Council, 2020). The Delta is formed by the confluence of the Sacramento and San Joaquin Rivers before their waters continue to flow into the San Francisco Bay. Its unique geography includes a network of channels, sloughs, and islands, making it a complex and diverse ecosystem (Shuford et al., 2019). As the largest estuary on the west coast of North America, the Sacramento-San Joaquin Delta plays a multifaceted role in the state's ecological and socio-economic fabric. These transitional zones where freshwater and saltwater meet serve as vital habitats for diverse flora and fauna, acting as nurseries for juvenile fish, breeding grounds for migratory birds, and natural filtering systems for water quality (Bakir et al., 2021). This connection is of paramount importance, not only for the ecological health of these estuarine ecosystems but also for the sustainability of California's agricultural industry, which heavily relies on the freshwater flows from the Delta for irrigation (Shuford et al., 2019). California's increasing population and extensive urbanization underscore the critical role of the Delta in supplying freshwater for municipal, industrial, and recreational purposes, serving as a major component of the state's water supply infrastructure.

Ecologically, the Delta provides a critical habitat for a variety of plant and animal species. Its marshes, wetlands, and waterways provide vital breeding and feeding grounds for numerous fish, birds, and mammal species. The Delta plays a crucial role in supporting the Pacific Flyway, serving as a stopover for migratory birds during their journeys along the West Coast (Shuford et al., 2019). The Delta also serves as a cornerstone in California's water supply system, supporting vital water conveyance projects such as the State Water Project (SWP) and the Central Valley Project (CVP). The SWP transports water from the Sierra Nevada Mountains to users in Southern California, while the CVP provides water to farmers in the Central Valley and beyond (Kraus-Polk & Fulton, 2020). Both projects rely heavily on the Delta as a hub for water conveyance and distribution, highlighting its critical role in supplying water to agricultural, urban, and industrial users throughout the state (Marineau & Wright, 2015).

Delta Agriculture

California's Mediterranean climate, characterized by rainy, mild winters and dry summers, has provided many regions of the state with an ideal environment for a diverse range of crops to thrive. In the Delta, the combination of rich alluvial soils and the moderating influence of the nearby San Francisco Bay further enhances the region's agricultural productivity (Delta Stewardship Council, 2021). Before they were displaced, this region supported over 10,000 Coastal Miwok (Kraus-Polk & Fulton, 2020). The tidal marshes had rich soils and easy access to water, making the islands of the Delta and surrounding land appealing to settlers looking to farm in the 1850s (Delta Stewardship Council, 2021). Today, the Delta covers around 728,000 acres, encompassing approximately 1,100 square miles of land across several counties including Sacramento, San Joaquin, Solano, Contra Costa, and Yolo (Delta Stewardship Council, 2020). Of that land, over 500,000 acres are devoted to agriculture (Delta Stewardship Council, 2020). The agricultural sector in this region is diverse, cultivating over 70 types of crops ranging from staple grains like rice and corn to iconic California products such as tomatoes, almonds, and wine grapes (Delta Stewardship Council, 2021). These farms are characterized by a mix of large-scale commercial operations and family-owned farms, each contributing to the region's agricultural legacy (Delta Stewardship Council, 2021). However, alongside its economic contributions, agriculture in the Delta region also experiences unique challenges that may be influenced by climate change. Along with the expected difficulties in running a farm, Delta farmers also contend with irrigation and drainage issues, pumping costs, flood risks, and land subsidence. It is estimated that a combination of factors including wind erosion, the use of heavy equipment, and the oxidation of peat soils have caused land to subside as much as 25 feet (Delta Stewardship Council, 2021). Microplastic pollution is another emerging area of concern as more research highlights this as a growing problem (Lloret et al., 2021).

Vulnerability to microplastic pollution from agriculture

Due to their unique hydrological and sedimentary dynamics, deltas and other estuarine environments have the potential to accumulate plastic debris that is transported from upstream sources such as rivers, urban areas, and industrial sites making them critical research locations for studying microplastics (Dickey, 2022). However, the Delta faces numerous threats, including pollution from microplastics originating from various sources, including agricultural activities (Lloret et al, 2021). The extensive agricultural lands surrounding the Delta contribute to its pollution through runoff containing pesticides, fertilizers, and plastic debris (Vermeiren et al., 2016). The industrialization of agriculture brought about various technological advancements, including the increased use of plastic materials in farming practices (Tian et al., 2021). It is now common for plastic to be used for purposes such as mulching, drip irrigation systems, greenhouse coverings, controlled-release fertilizers, and packaging, accounting for around 2% of plastics used in agriculture worldwide (Jansen et al., 2019). These applications can contribute to higher crop yields and improved efficiency by conserving water, controlling weeds, regulating soil temperature, and protecting crops from pests and diseases (Tian et al., 2021). When these plastics degrade over time the resulting microplastics leach into the soil and surrounding waterways like the Sacramento or San Joaquin Rivers(Jansen et al., 2019). Microplastics carried by river currents can accumulate within the Delta's sediments, where they may persist and impact aquatic organisms (Karbalaei et al., 2018). The ingestion of microplastics by wildlife, including microscopic organisms such as plankton, can lead to bioaccumulation and the transfer of pollutants up the food chain (Coffin et al., 2022). As we continue to better understand the intricacies of microplastic pollution, it becomes more apparent that a deeper understanding of its impacts and the exploration of effective mitigation methods are imperative to better safeguard our ecosystems, water infrastructure, and personal health.

Microplastic Pollution from Agriculture

Plastic in Agriculture

Microplastics in agriculture represent a significant but often overlooked aspect of plastic pollution. Agricultural practices contribute to the release of microplastics into the environment through various routes, primarily due to the widespread use of plastic-based materials. The agriculture industry utilizes vast quantities of plastic materials including mulch films, irrigation systems, packaging, and agrochemical containers, among others (Jansen et al., 2019). PE, PP, PVC, and PET are plastics often used in agricultural applications because of their durability, flexibility, light weight, low cost, and ability to withstand exposure to the various chemicals used in agriculture (Krone, 2020, Abbasi 2024). These materials can degrade over time, releasing microplastics and adsorbed chemicals into soil and water systems. High-flow events such as intense rainfall or irrigation can result in rapid runoff across land surfaces. During these events, water can accumulate quickly and flow swiftly across fields carrying with it various pollutants, pesticides, sediments, and microplastics (Hitchcock & Mitrovic, 2019). Plastic mulch films, typically made of low-density PE, are commonly utilized in farming practices across North America at an average rate of 20 kg/ha, with reuse and recycling rates resting below 10% (Hofmann et al, 2023). These films serve essential functions such as weed suppression, soil moisture conservation, and the promotion of higher rates of nutrient uptake. However, their widespread use also poses a challenge as they are a significant source of microplastics in agricultural soils. (Hofmann et al., 2023). Additionally, biosolids recycled from sewage treatment plants, when applied to agricultural land, may introduce microplastics into the soil, which can then runoff into nearby water bodies during rainfall or irrigation events (Weber et al., 2022).

Microplastics from agriculture can originate as primary sources, directly introduced into the environment through agricultural activities, or as secondary sources, derived from the breakdown of larger plastic materials used in farming (Dickey, 2022). While the Delta region was naturally nutrient-rich with peat soil historically providing ample fertility, the depletion of these soil nutrients through intensive farming now often necessitates increased fertilizer inputs for agriculture. Controlled-release fertilizers (CRFs) offer a solution by reducing the quantity of fertilizer needed per unit area of cropland and minimizing the time spent in fertilization efforts (GESAMP, 2016; Hofmann et al., 2023). Although CRFs provide benefits such as cost reduction and decreased nutrient runoff levels into water systems they also introduce a new environmental concern in the form of microplastic contamination (GESAMP, 2016). The use of CRFs comes with a trade-off, as the polymer coatings used to encapsulate nutrients in CRFs can degrade over time, releasing microplastic particles into the soil and water systems (Hofmann et al., 2023). Therefore, while these fertilizers offer advantages for agriculture, it is essential to consider the potential environmental costs associated with microplastic contamination.

Pathways of Microplastic Transport from Agricultural Areas

The transportation of microplastics from agricultural lands into estuaries involves a complex journey through various pathways including surface runoff, erosion, and groundwater seepage (Bucci & Rochman, 2022). Modifications to the waterways since the 1850s, coupled with reduced inflow as a result of drought years or human decisions, can lead to the accumulation of pollutants from urban and agricultural runoff in certain areas of the Delta (Kraus-Polk & Fulton, 2020). Hydrological processes play a crucial role in the transport of macroplastics, which is plastic material larger than 5 mm, and microplastics from agricultural areas to water bodies such as estuaries (Lloret et al., 2021). These ecosystems function as a sink to plastic debris and host the transformation of macroplastics into microplastics (Yao et al., 2019). Coupled with high organic matter content and sediments, microplastics that end up in areas that experience slower water flows settle gradually not unlike clay (Dickey et al., 2022). Studies found that microplastics deposited in estuarine marshes were uniformly distributed across the estuary by natural hydrological processes suggesting the ocean may also be a contributing source beyond the immediate watershed (Dickey, 2022). However, this observation does not address the impact of water diversion practices from the Sacramento-San Joaquin Delta aimed at increasing freshwater flows and mitigating saltwater intrusion. Soil erosion, exacerbated by factors such as land use practices and weather conditions, can contribute to the dispersion of microplastics into adjacent land and water bodies (Karbalaei et al., 2018). Additionally, microplastics released into the soil can infiltrate groundwater sources, potentially contaminating drinking water supplies and aquatic ecosystems (Bucci & Rochman, 2022).

Future Challenges

The challenges faced by agriculture in the Delta region could potentially exacerbate microplastic pollution in several ways. Changes in land use, restricted water use, and climate change also play a role in the increase in microplastics in the Sacramento-San Joaquin Delta. Alterations in land use patterns, such as increased urbanization and shifts in agricultural practices, are expected to lead to greater runoff and erosion, thereby increasing the transport of microplastics from agricultural fields into water bodies like the Delta (Marinaeu & Wright, 2014). The types of agricultural practices employed, including tillage methods, irrigation techniques, and the use of plastic mulch, also impact the release of microplastics into the environment (Krone, 2020). The need for plastic mulch films to suppress weeds and conserve soil moisture may also rise with increased temperatures, further adding to microplastic pollution in agricultural soils (Broadhagen et al., 2016). Furthermore, the composition and properties of plastic materials used in agriculture, such as their durability and degradation rate, play a crucial role in determining the extent of microplastic pollution (Broadhagen et al., 2016).

Restrictions on water use may necessitate changes in irrigation methods. Increased irrigation demands due to warmer and drier summers may lead to greater use of plastic irrigation systems, which can contribute to the release of microplastics into soil and water systems as these materials degrade over time (Krone, 2020; UrJansen et al., 2019). Climate change-induced alterations in precipitation patterns, temperature, and hydrological cycles can further compound these issues by affecting soil erosion rates and altering the pathways through which microplastics are transported into aquatic environments (Hitchcock & Mitrovic, 2019).

Challenges such as land subsidence, which can result from factors like wind erosion, the oxidation of peat soils, and the use of more heavy equipment may contribute to the fragmentation of plastic materials used in agriculture and releasing microplastics into the environment (Delta Stewardship Council, 2021). Flood risks associated with climate change may lead to more frequent and intense flood events in the Delta region. During such events, plastic debris left in fields or improperly disposed of on agricultural lands can be carried by floodwaters into nearby water bodies, thereby increasing microplastic pollution (Bucci & Rochman, 2022). Addressing these factors requires a multifaceted approach that emphasizes sustainable agricultural practices, improved waste management strategies, and greater awareness of the environmental consequences of plastic pollution in the Delta region (Rochman et al., 2022).

Impacts of Microplastics on Estuarine Ecosystems

Microplastics in the Delta

As we navigate the complex web of challenges facing the Delta, it becomes increasingly clear that addressing these factors is not only critical for the region's ecological balance but is also essential for mitigating the pervasive threat of microplastic pollution. The San Francisco Bay Estuary, where the Delta flows into, was found to have significantly higher microplastic contamination compared to other urban waterbodies in North America (Prata et al., 2019). Similarly, there was a parallel trend of microplastic pollution found within the Delta (Rochman et al., 2022). Microplastic contamination in waterways often stems from sources such as stormwater runoff, agricultural runoff, and wastewater discharge (Sutton et al., 2016). After taking samples from waterbodies closely associated with these sources, researchers found that agricultural runoff was a significant pathway for microplastics to enter the aquatic ecosystem, followed by wastewater treatment effluent and urban stormwater runoff (Rochman et al., 2022). The concentration of fibers and fragments in waterbody samples collected in this study was observed to be significant, with smaller amounts of film, glassy fragments, and other morphologies present **(Figure 2)** (Rochman et al., 2022). The presence of fibers may suggest a potential linkage to the application of biosolids in agricultural fields, wherein synthetic textile residues from WWTP's can be inadvertently introduced into soil environments (Lloret et al., 2021). The abundance of fragments could be attributed to the mechanized process of tilling and plowing, which may dislodge and mechanically break down residual plastic materials previously utilized in agricultural operations (Karbalaei et al., 2018).

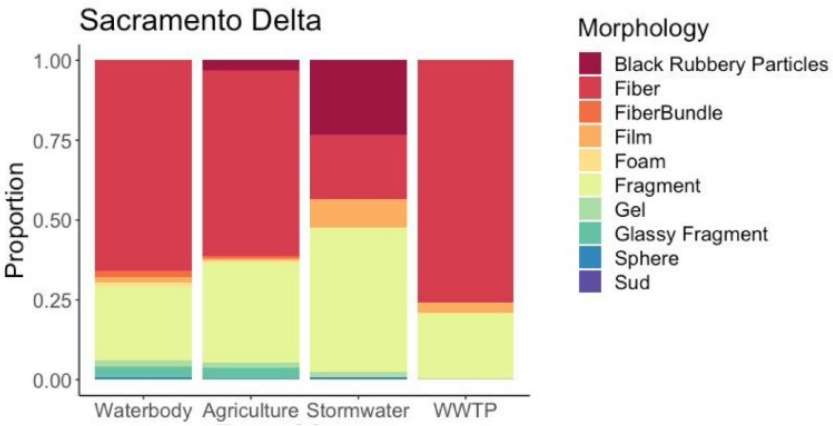

Figure 2: *Proportion of each morphology within each sample type for each pathway tested.*

Microplastic contamination within the Delta is subject to spatial and temporal variations, driven by factors including hydrodynamics, land utilization, and seasonal changes. These variables interact in complex ways, shaping the distribution and abundance of microplastics across different regions and time periods. Hydrodynamics, which encompass tidal currents and river flow patterns, play a fundamental role in the transport, dispersion, and deposition of sediments and microplastics originating from upstream sources (Marineau & Wright, 2014). Given the extensive historical human impact on the Delta and its surrounding agricultural landscapes and urbanized areas, the risk of heightened microplastic pollution is significant as estuary sediments are microplastic sinks (Lloret et al., 2021).

One of the challenges in addressing microplastic pollution in the Delta is that because this landscape has been heavily modified, pollutants are increasing in concentration due to reduced inflow (Kraus-Polk & Fulton, 2020). Microplastic concentrations vary depending on the proximity and intensity of these land uses and are an area that requires further study. Estuaries have been found to play a role in trapping plastic debris, affecting its distribution and transport between terrestrial and marine environments. Findings have suggested that in estuarine environments like the Delta, concentrations of macroplastics may be relatively low compared to microplastics, but they could still contribute significantly to the total plastic mass. This implies that while macroplastics might be less abundant, they may have a substantial impact on microplastic pollution (Yao et al., 2019).

Because the anthropogenic restructuring of the Delta has necessitated over 1,100 miles of levees to protect the islands within, channels with levees exhibit increased shear velocity, enhancing sediment transport capacity and potentially redistributing settled microplastics within (Marineau & Wright, 2015). In contrast, deep-water shipping channels within the Delta, subjected to annual maintenance dredging and constrained sediment supply, tend to exhibit low-velocity characteristics. While sediment disturbance may be less frequent in these channels, dredging activities can significantly disrupt sediment layers, potentially resuspending microplastics and influencing their transport dynamics (Marineau & Wright, 2015). Microplastics found in the Elkhorn Slough of California, an estuary also surrounded by agriculture, were found to be similar in size to coarse sediments found there. The distribution of both sediment and microplastic particles were found to behave, and settle, similarly (Dickey, 2022).

Physical Impacts

Investigations into Bay Area wastewater facilities, some of which release into the Delta, have implemented water conservation measures due to severe drought sometimes experienced by the region, which is further exacerbated by climate change. These measures potentially contribute to increased concentrations of microplastic particles found in the San Francisco Bay Estuary (Sutton et al., 2016). While some treatment plants successfully separate up to 99% of microplastics from wastewater, this means most microplastics remain within biosolids (Karbalaei et al., 2018). Consequently, because biosolids from WWTP's are often used as soil amendments on agricultural lands, the Delta faces an elevated risk of increased microplastic levels due to these combined factors. The application of biosolids to agricultural fields is a significant source of microplastic contamination for soil, potentially lasting decades (Weber et al., 2022). This is especially notable on agricultural lands that are regularly plowed, indicating mechanical breakdown is more responsible for plastic spread than slower processes like erosion (Weber et al., 2022). Waterways passing through urban centers accumulate additional microplastics from stormwater runoff, while wastewater treatment facilities may lack adequate filtration systems to remove these contaminants effectively (Hitchcock & Mitrovic, 2019). A comparison found that wastewater treatment plants (WWTP) with tertiary filtration did not have a noticeable effect on reducing the presence of microplastics in treated wastewater effluent, implying granular tertiary filtration may not be an effective method for controlling microplastic pollution in wastewater (Sutton et al., 2016).

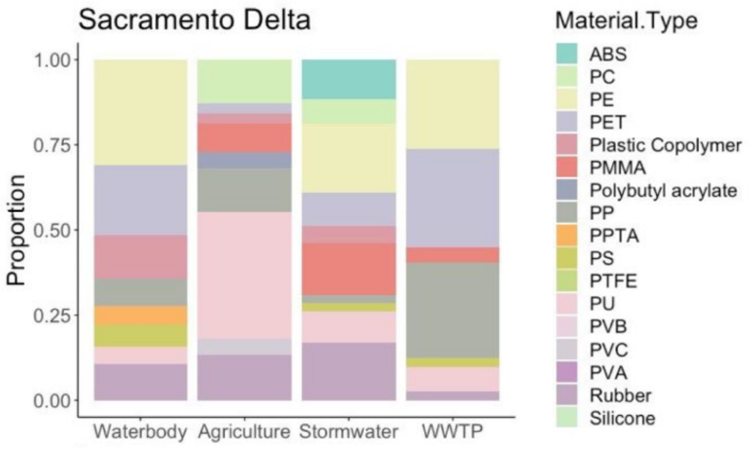

Figure 3: *Proportion of confirmed plastic-type within each sample type for each pathway tested. Highest concentrations from agriculture include polyurethane (PU), polycarbonate (PC), and polypropylene (PP). Retrieved from Rochman et al., 2022.*

Estuarine sediments likely have evidence of microplastic accumulation dating back to the 1950s (Lloret et al., 2021). Certain plastic debris like PET and PVC usually sink in the water column where they accumulate in sediments. Low-Density PE and PP are often found in surface water, although the accumulation of small organisms can increase plastic or microplastic densities (Li et al., 2016). Plastic materials of various types were identified in the Delta, with polyurethane (PU), polyvinyl butyral (PVB), polypropylene (PP), and polycarbonate (PC) being the predominant ones confirmed to have originated from agricultural sources **(Figure 3)** (Rochman et al., 2022). The physical content of microplastics in the Delta not only influences their distribution within the ecosystem but also interacts intimately with ecological processes and organisms. Microplastics deposited within the sediment or suspended in the water column can serve as substrates for microbial colonization, leading to further changes within the ecosystem influenced by microplastics (Marinaeu & Wright, 2014).

Increased rainfall in agricultural areas could potentially lead to the transport of microplastics from these lands into the Delta through runoff. Investigations into microplastic abundance in estuarine environments have shown that freshwater inflows, particularly following rainfall events, may contribute to increased microplastic levels within estuaries (Hitchcock & Mitrovic, 2019). This suggests that microplastic abundance in estuarine environments, such as the Delta, may be influenced by factors like freshwater inflows from surrounding agricultural lands. Studies have revealed dynamic microplastic abundance and distribution patterns, highlighting the complex interplay of environmental processes shaping microplastic dynamics in the Delta ecosystem. This study also found that there were no significant relationships between microplastic abundance and other environmental variables such as discharge from wastewater treatment plants, temperature, nutrient levels, or turbidity across the estuaries studied (Hitchcock & Mitrovic, 2019). This variability emphasizes the need for continuous monitoring efforts to track changes in microplastic pollution over time and space, facilitating targeted mitigation strategies.

Chemical Impacts

Microplastics in the Delta not only pose physical threats but also introduce chemical contaminants into the ecosystem. Plastics contain a variety of chemical additives that are incorporated during the manufacturing process to enhance their properties or performance. Because plastic additives such as flame retardants and dyes are used during their production process (Miller et al., 2021). While these additives serve specific purposes in the production of plastics, they can persist in the material even after it has broken down into smaller fragments or microplastics, microplastics have the potential to expose organisms to these potentially harmful chemicals (Li et al., 2024). These pollutants can adsorb onto microplastic surfaces, potentially accumulating harmful substances in the surrounding environment as well as into the crops being grown (Abbasi, 2024). Microplastics were found to have a notable capacity to absorb elements due to their increased surface area (Miller et al., 2019). This suggests that at least some microplastics can affect the availability of nutrients and the chemical composition of the soil, influencing soil quality and potentially impacting plant growth and ecosystem health (Abassi, 2024). This could potentially influence the availability of nutrients for plant uptake and ultimately impact local ecosystems further. Moreover, the degradation of microplastics releases additives and plasticizers, further compromising water quality and posing risks to aquatic organisms (Prata et al., 2019). The interaction between microplastics and chemical contaminants in the Delta underscores the multifaceted nature of microplastic pollution and its far-reaching implications for ecosystem health.

Biological Impacts

Once adsorbed onto the surface of microplastics, these pollutants can remain bound to the particles for extended periods, potentially leading to their bioaccumulation in organisms upon ingestion (Okeke et al., 2022). When ingested by organisms, microplastics can release these additives and adsorbed pollutants into their digestive tracts, where they may be absorbed into the bloodstream or accumulate in tissues over time (Bakir et al., 2014). Microplastics have been found in blood, placenta, and other tissues and organs across multiple species, leading to higher concentrations in predator species (Hitchcock & Mitrovic, 2019; Bailey et al., 2021). This poses significant risks to all terrestrial and aquatic organisms and ecosystems of varying sizes, as well as potential risks to humans through the consumption of contaminated seafood (Hope et al., 2021). The toxicological impacts of microplastic bioaccumulation are difficult to plainly state because it is heavily dependent on the morphology, material, and chemical additives that are accumulated, but they have been found to cause endocrine disruptions, tissue inflammation, and alter gene expression (Coffin et al., 2022).

While the Delta now predominantly serves agricultural purposes, it has long existed as a wetland ecosystem vital for various bird species, particularly those migrating along the Pacific Flyway (Shuford et al., 2019). During winter, flooded crop fields, irrigated pastures, and managed wetlands play a crucial role in providing habitats for these migrating birds. The flooding of fields, especially those cultivating crops like rice and corn, aids in decomposing leftover crop residues, essential for preparing the fields for the next planting season (Shuford et al., 2019). However, the increased transport of microplastics from agricultural fields into waterways during high-flow events poses a potential threat to migrating birds, the organisms they feed upon, and the organisms that live in this area year-round (Vermeiren et al., 2016). These microplastics could bioaccumulate systems, leading to adverse effects on their physiology, reproduction, and overall health (Yao et al., 2019). Several of these migratory birds hold positions as apex predators within this ecosystem, consuming fish and various invertebrates, thus exacerbating the accumulation of microplastics within their bodies (Shuford et al., 2019; Bailey et al., 2021). Ingestion of microplastics by fish, birds, and invertebrates can result in physical harm, gastrointestinal blockages, and other adverse effects on organism health even at a cellular level (Yao et al., 2019). In light of the rippling biological impacts of microplastics on the Delta ecosystem, it is crucial to implement effective mitigation and management strategies. By taking proactive measures to reduce microplastic pollution and protect the ecosystem, we can better safeguard the health of aquatic organisms and maintain the ecological balance of this vital habitat.

Mitigation and Management Strategies

Evolution of Plastic Regulation in California

The regulatory landscape concerning microplastic pollution in the Sacramento-San Joaquin Delta and San Francisco Bay Estuary is multifaceted, encompassing various policies and initiatives aimed at mitigating environmental contamination. Regulatory agencies at the federal, state, and local levels have implemented measures to address microplastic pollution, recognizing its detrimental effects on ecosystem health and water quality (COPC, 2022). California has proactively advanced its research efforts concerning microplastics, especially after the enactment of SB 1263 in 2018. This legislation required the State Water Resources Control Board to adopt and implement a plan for monitoring microplastics in drinking water, showcasing the state's dedication to tackling emerging environmental challenges (COPC, 2022). This reflects the state's commitment to addressing emerging environmental challenges. Following the enactment of this bill, the California Ocean Protection Council (OPC) worked closely with various agencies and research institutions to bolster the scientific understanding of microplastics. This collaborative effort produced the Statewide Microplastic Strategy, a detailed plan aimed at tackling microplastic pollution in California's aquatic ecosystems. It coordinates statewide actions to protect marine ecosystems by outlining key initial steps and research priorities (COPC, 2022). This strategy encompasses various objectives and actions aimed at understanding, monitoring, and mitigating the impacts of microplastics on marine and freshwater environments (COPC, 2022).

To strengthen efforts across the state against plastic and microplastic pollution, Senate Bill 54 (SB 54), known as the Plastic Pollution and Packaging Producer Responsibility Act, was signed into law in June 2022 by Governor Gavin Newsom to reduce single-use plastic waste while promoting a circular economy in California (Cal EPA 2024). Producers of single-use plastic packaging and products will be required to manage the end-of-life disposal of their products, promoting measures to reduce single-use plastics, increase responsible waste management practices, and explore sustainable alternatives (Cal EPA 2024). While SB 54 does not directly address plastic use in agriculture, its provisions have implications for the broader plastic supply chain, including agricultural practices involving plastic materials.

Collaborative Efforts

While SB 54 holds the potential for mitigating microplastic pollution in California, additional collaborative initiatives are required to tackle this pressing issue effectively. Microplastics are a growing concern in other agencies, like the Department of Toxic Substances Control (DTSC). DTSC's Safer Consumer Products (SCP) program has been actively involved in addressing microplastic pollution by proposing to add microplastics to the Candidate Chemicals List, a move that emphasizes the growing recognition of microplastics as a significant environmental concern (DTSC, 2024). The Candidate Chemicals List is a compilation of substances that DTSC identifies as potentially harmful to human health, or the environment, based on various criteria including toxicity, persistence, and potential for bioaccumulation (DTSC, 2024). By proposing this addition, DTSC aims to evaluate product-chemical combinations containing microplastics or those that may release microplastics into the environment for potential consideration as Priority Products in the future (DTSC, 2024). The inclusion of microplastics on the Candidates Chemicals List doesn't automatically set new regulations, but it may eventually prompt regulatory actions or incentives to minimize the use of plastic materials in agriculture, particularly those that contribute to microplastic pollution. Heightened awareness of microplastic pollution and regulatory scrutiny may drive agricultural practices toward more sustainable alternatives such as the use of biodegradable mulch over plastic options.

DTSC has also collaborated with the San Francisco Bay Regional Monitoring Program on the Estuary Blueprint. The Estuary Blueprint is a collaborative effort among diverse stakeholders, agencies, and organizations involved in the management and conservation of the San Francisco Bay Estuary (SFEP, 2022). It serves as a guiding document that outlines strategic priorities, goals, and actions aimed at protecting and restoring the ecological health of the San Francisco Bay Estuary Ecosystem. The blueprint includes strategies for addressing environmental challenges such as building climate resilience, stormwater management, managing sediment, increasing carbon sequestration on agricultural lands, and addressing emerging contaminants (SFEP, 2022). DTSC collaborates with the Regional Monitoring Program to update monitoring strategies regarding contaminants of emerging concern (CECs) and microplastics (SFEP, 2022). These ongoing monitoring and research efforts, including the classification of microplastics as CECs, demonstrate the importance of stakeholder collaboration.

Recycling programs aim to minimize plastic waste generation, promote recycling and reuse of plastic materials, and prevent plastic litter from entering waterways (Karbalaei et al., 2018). However, the implication of only 9% of all plastics produced since the 1950's being recycled is concerning and highlights the inefficiency of current recycling systems and the inadequacy of recycling infrastructure to manage the sheer volume of plastic waste generated globally (Geyer, et al., 2017). Low recycling rates underscores the need for a paradigm shift in waste management practices, emphasizing the importance of reducing plastic consumption, the promotion of alternative materials, and implementing more sustainable packaging solutions. It certainly doesn't help that plastics exhibit a wide variety of characteristics, compositions, and types making recycling costly and difficult (NASEM, 2022). However, this does not mean that incentivizing proper disposal and recycling of plastic products wouldn't contribute to reducing the influx of microplastics into the Delta and surrounding water bodies, thereby mitigating their environmental impact (Krone, 2020; Rochman et al., 2017).

Role of Sustainable Farming Practices and Local Actions

Best management practices tailored to agriculture also play a crucial role in reducing microplastic pollution in the Delta and estuarine systems. Sustainable farming techniques like cover cropping, no-till farming, and crop rotation can help improve soil health and potentially minimize the use of plastic materials (Hofmann, 2023). The California Department of Food and Agriculture offers programs like the State Water Efficiency and Enhancement Program (SWEEP), Alternative Manure Management

Program (AMMP), and the Healthy Soils Program (HSP) to farmers that could indirectly contribute to mitigating microplastic pollution in agriculture by encouraging sustainable agriculture, conserving natural resources, and reducing environmental pollution (CDFA, 2024). By optimizing irrigation and fertilization practices to promote soil conservation measures and reduce the need for plastic mulch, erosion, and runoff could potentially decrease, reducing plastic usage on agricultural lands (Bucci & Rochman, 2022). While regulatory measures and statewide programs play a role in implementing sustainable practices, local actions are equally crucial in effecting change at the grassroots level (Rochman et al., 2022). By adopting tailored practices unique to their circumstances, farmers can reduce the release of microplastics from agricultural activities, thereby safeguarding water quality and ecosystem health in the Delta region (COPC, 2022).

Gaps in Knowledge and Future Research Directions

Limitations of Existing Studies

Microplastic pollution in the Sacramento-San Joaquin Delta and San Francisco Bay Estuary presents a complex and multifaceted challenge, necessitating further research to address existing knowledge gaps and inform effective management strategies. Despite significant progress in understanding microplastic pollution, several limitations exist in current research efforts in the Delta and estuarine systems. Existing studies often focus on specific aspects of microplastic contamination, such as abundance and distribution, while overlooking other critical factors, such as the sources and fate of microplastics in the environment (Hofmann et al., 2023). Many studies are limited in spatial and temporal scope, failing to capture the full extent of microplastic pollution dynamics in the Delta and estuarine ecosystems (Miller et al., 2021)

There is a lack of standardized methodologies for sampling and analyzing microplastics which has led to inconsistencies in data interpretation and hinders cross-study comparisons (Bucci & Rochman, 2022). One recurring observation from various studies is that microplastics tend to be smaller than 200 micrometers. A study on estuaries of varying human impact in Australia found, on average, 68% to 76% of the particles measured fell within this size range, with the most prevalent sizes ranging from 45 to 100 micrometers (Hitchcock & Mitrovic, 2019). While microplastics are commonly defined as particles less than 5,000 micrometers in size, there is inconsistency regarding lower size limits (Vermeiren, 2016). Accurate and consistent data are essential for policymakers and regulators to develop effective policies and regulations aimed at mitigating microplastic pollution. Having this in place would enable a more efficient allocation of resources for research, monitoring, and mitigation efforts.

Areas Requiring Further Investigation

In evaluating the intricate challenges posed by microplastic pollution, it becomes evident that establishing a robust foundation of accurate and consistent data is crucial for informed policymaking and decision-making processes. While agricultural lands were identified as a notable source of microplastics in this region of California, the varying concentrations observed throughout the Delta and the downstream San Francisco Bay emphasize the importance of consistent monitoring to discern significant pathways (Rochman et al., 2022). This variability is heavily influenced by surrounding land use. Although agricultural runoff isn’t conventionally considered a major source of microplastics, ongoing research may reveal different findings (Sutton et al., 2019).

Historically, early research on plastic pollution focused on larger plastic items and their visible impacts on marine life and ecosystems (Ullah et al., 2021). However, with advancements in technology and growing concerns about plastic pollution, more attention has shifted towards studying microplastics. Several key areas warrant further investigation to enhance our understanding of microplastic pollution in the Sacramento-San Joaquin Delta and San Francisco Bay Estuary. Standardizing methodologies across research is an essential first step to ensure that data collected from different studies or research projects are comparable and can be confidently integrated and analyzed (Ullah et al., 2021). This standardization is crucial for establishing baseline measurements, conducting long-term studies, or evaluating the effectiveness of interventions or policies over time.

In addition to methodological standardization, research efforts should focus on identifying and quantifying sources of microplastics, including contributions from urban runoff, industrial discharges, and agricultural activities (Miller et al., 2021). Understanding the ecological impacts of microplastic pollution on native species, food webs, and ecosystem functioning in the Delta and estuarine environments is vital for developing effective mitigation strategies (Miller et al., 2021). Future research should continue to explore the long-term fate and transport of microplastics in aquatic systems, including their interactions with sediments, biota, and water column dynamics (COPC, 2022). While initial research has begun to shed light on some of these areas, further investigation is necessary to comprehensively identify all contributors so that policymakers and stakeholders can develop targeted mitigation strategies.

Importance of Interdisciplinary Research

Interdisciplinary collaboration is paramount in comprehensively addressing the complex issue of microplastic pollution in estuarine environments. By uniting scientists, policymakers, stakeholders, and community members, collaborative efforts can develop holistic approaches to microplastic management and mitigation (Krone, 2020). Given the diverse origins of microplastic pollution, effective solutions necessitate expertise from various fields. Interdisciplinary research frameworks integrate these diverse perspectives, methodologies, and expertise, enabling a comprehensive approach to tackling the multifaceted challenges of microplastic pollution (Bailey et al., 2021). Through such collaboration, researchers can leverage complementary strengths and resources to generate innovative solutions and inform evidence-based decision-making processes for managing microplastic pollution in the Delta and estuarine systems (Bucci & Rochman, 2022). Ultimately, gaining a comprehensive understanding of the impacts of microplastics from agriculture contributes to informed decision-making, promotes sustainable land management practices, and preserves environmental quality for future generations.

International collaborations and efforts are also underway to address microplastic pollution in estuarine environments, like the Sacramento-San Joaquin Delta and San Francisco Bay Estuary. Collaborative initiatives involve sharing knowledge, best practices, and resources among countries and organizations to develop comprehensive strategies for combating microplastic pollution (COPC, 2022). These efforts aim to harmonize regulatory frameworks, promote scientific research, and implement innovative technologies to monitor and mitigate microplastic contamination in estuarine ecosystems (Krone, 2020).

Conclusion

Implications for Policy and Management Strategies

While agriculture stands as one of humanity's oldest innovations, the integration of plastics into modern agricultural methodologies marks a significant advancement. This evolution has improved a range of agricultural practices, introducing innovative tools and materials that have enhanced efficiency and productivity. They have truly become an indispensable asset to agriculture today. As it stands, this innovation is also playing a role in environmental degradation. The presence of microplastic pollution in the Sacramento-San Joaquin Delta and the SF Bay Estuary has significant implications for policy and management strategies. Efforts to mitigate microplastic pollution in these estuarine environments should continue to prioritize reducing plastic inputs from upstream sources, implementing effective wastewater treatment measures, and enhancing sediment management practices. Policy interventions include regulations to limit the use of single-use plastics, promote recycling and waste management practices, and incentivize the development of alternative materials that are less prone to fragmentation and accumulation in the environment. Management strategies should also focus on increasing public awareness and education about the impacts of microplastic pollution and encouraging behavioral changes to reduce plastic consumption and littering.

Recommendations for future actions

Moving forward, it is imperative to take proactive measures to address microplastic pollution in the Sacramento-San Joaquin Delta and the SF Bay Estuary. This includes prioritizing interdisciplinary research efforts to further understand the sources, transport pathways, and ecological impacts of microplastics in these estuarine environments. Long-term monitoring programs should be established to track changes in microplastic abundance and distribution over time, facilitating the development of targeted mitigation strategies. Collaboration between scientists, policymakers, industry stakeholders, and the public is essential to develop and implement effective management and conservation measures to safeguard the ecological integrity of the Delta and the broader estuarine ecosystem. Mitigating microplastic pollution from agricultural activities offers multifaceted benefits, extending beyond estuarine ecosystems. By addressing this issue, we can enhance soil health, safeguard water quality, and ultimately, protect biodiversity and human health.

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