Estimating Wetland Gross Primary Production Loss Due to Land-use Change in the San Francisco Bay

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1 Introduction

The San Francisco Bay (herein referred to as the Bay) sits at the terminus of a great drainage system: the Sacramento-San Joaquin basin, which covers 40% of the land area of California and deposits sediments into the bay and provides approximately 20 billion cubic meters of freshwater flow into the bay annually. Over the last 10,000 years, the balance between the rate of tidal submergence due to rising sea levels and sedimentation from the rivers created and controlled the size of the Bay's estuary and the extent of its tidal marshes (Atwater et al. 1977). Estuaries are amongst the most productive ecosystems in the world. The mixture of freshwater from streams and saltwater from the tides creates fertile habitats for a diverse range of species.

Arguably the most important habitat in the Bay are the wetlands. Wetlands support aquatic life and wildlife by offering food and habitat for a range of species and populations. The wetlands in the Bay are especially important because of the wildlife habitat it provides to migratory birds as well as endangered salt marsh harvest mouse. Wetlands also play an important role in carbon dynamics, as they have a high potential for large amounts of carbon sequestration due to their large soil carbon pools and limited decomposition rates in anaerobic soils (Knox et al. 2017). Based on ^{210}Pb-dated sediment cores from six wetlands across the Bay estuary, annual carbon sequestration rates within tidal wetlands are on average around 80 g C m^{-2} (Callaway et al. 2015). Other benefits from wetlands include improved water quality, flood protection, reduce erosion and recreation. Thus the Bay's wetlands are an important contributor to local ecosystem resilience and play an important role in climate regulation and regional carbon dynamics.

Before 1850, the region sustained 1,400 square kilometers of freshwater wetlands and 800 square kilometers of salt marshes. However since then, the Bay and its wetlands have undergone large scale land-use transformations. In the late 1800's, about one fifth of the Bay's marshes were reclaimed and converted to pastures hayfields, salt ponds or croplands when the use of mechanical dredges became commercially available to landowners (San Francisco Bay Development and Conservation Commission 2002). The 20th century brought about rapid increases in the population, which lead to most of the marshes being converted to salt-evaporation ponds or converted for other human uses such as residential areas, facilities and garbage dumps. Approximately 75 km^2 of new tidal marsh have also been created in the Bay since the Gold Rush, largely due to hydraulic mining in the Sierra Nevada, which had the effect of washing large amounts of sediment into streams and then into the Bay estuary. Additionally, building levees and jetties promoted deposition which had the effect of creating marshland. Only 125 km^2 of undiked marshes remain of the original 2,200 km^2, representing a 95% loss of crucial tidal marsh habitat. The remaining 125 km^2 of wetlands are still threatened by development, erosion, pollution, and especially sea-level rise (Atwater et al. 1977).

2 Objectives

Our research represents an effort to quantify the effects that land-use change in the Bay has had on the regional carbon cycle and carbon sink. Our original goal was to quantify the amount of NPP lost as a result of land-use change in the Bay by spatially correlating NDVI to NPP through an ordinary-least squares regression equation. However, spatial NPP data provided by NASA's Terra satellite caused difficulties. Most notably, the MODIS derived NPP data exists at 500 m spatial resolution, while our Landsat derived NDVI data exists at 30 m resolution. Additionally, low spatial resolution in the NPP data led many wetland areas along the coast of the Bay to be assigned fill values corresponding to open-water or developed areas with minimal NPP. Despite the seemingly positive spatial relationship between modis NPP and Landsat NDVI (appendix figure 1), running ordinary least squares regression between these two data sources provided an equation with a negative slope, or a negative relationship between NDVI and NPP. We would expect a positive relationship between NDVI and NPP, thus correlating these two data sources proved to be inherently inaccurate and unusable for the purposes of our research.

Due to these data limitations, we had to revise our methods as well as our research objective. Knox et al. (2017) provides an evaluation the suitability of using Landsat data as a means of estimating gross primary production (GPP) in restored wetlands and showed that Landsat imagery can be used to model photosynthesis in restored wetlands. The researchers took eddy covariance measurements of CO2 at two restored wetland sites in order to quantify wetland GPP through time and subsequently performed linear least square regression of various Landsat imagery indices against the calculated GPP values. Using the regression equation for wetland GPP from NDVI provided by Knox et al. (2017), we changed our objectives to quantifying the amount of wetland GPP lost due to human-induced land use change in the Bay.

3 Methods

Our first step was to collect data pertaining to the Bay's modern land-use types and habitats, historic wetlands extent and satellite imagery. The San Francisco Estuary Institute (SFEI) provides spatial data pertaining to the current land uses in the bay, circa 1998 (appendix map 5), and the historic size of the bay and its wetlands, circa 1850. From this historical baylands shapefile, we extracted the regions of occupied by tidal flat and tidal marsh land types (appendix maps 3 and 4). The SFEI also provided the Bay Area Aquatic Resources Inventory (BAARI) dataset, which is a regional inventory of the Bay's aquatic features and habitats, circa 2009. From the BAARI dataset, we extracted all vegetated wetland areas around the Bay using the select by attributes function in ArcMap (appendix map 6).

To be able to predict how much wetland GPP has been lost using the equation provided by Knox et al (2017), we would need to acquire a satellite dataset that would enable us to calculate the NDVI (Normalized Differential Vegetation Index), a measurement of how healthy the vegetation is in a scene. In addition to that it would have to be taken at a similar time to when the researchers in the Knox paper conducted their research, to minimize variance . We chose to use two scenes of the Bay from the Landsat 8 satellite, taken on January 13th, 2014 and July 24th, 2014. The scene contains the entire baylands area across the 9 bands. We then calculate NDVI using Arcmap's internal NDVI function, which resulted in a raster dataset containing values ranging from 0-255, assigned to each of the squares in the scene, with 255 being vegetation with higher health (appendix map 1 and map 2).

We applied the GPP equation given in Knox et al. (2017) to each NDVI raster cell for the two NDVI scenes (equation given below). Then using the zonal statistics tool in arcmap, we summed the GPP raster values that fell within the vegetated wetland areas. Each GPP raster cell represents a 30m by 30m area of land, so in order to get total GPP in our area of interest, we multiplied the summed GPP raster values by $900m^2$. This gave us the daily GPP for the modern baylands based on two Landsat scenes from July and January.

$$\text{GPP\_daily (g C m}^{-2}\text{ day}^{-1}\text{)} = 1.52 + (\text{NDVI})*0.63$$

In order to get annual GPP, we extrapolated the GPP results from each of the Landsat scenes through the whole year. The GPP values for the January 13th Landsat scene represented the dormant non-growing season, in which wetland GPP is relatively low. The GPP values for the July 24th Landsat scene represented the growing season, in which wetland GPP is relatively higher. We multiplied each of the the daily GPP values by 182.5, which represents half of the year. We then added the two seasonal GPP values together to get annual GPP values.

GPP_season = (GPP_daily)*182.5
GPP_annual = GPP_growing + GPP_nongrowing

To find the historic wetland GPP, we took the average NDVI values from our two scenes (115 and 104 for July and January, respectively) and then calculated GPP from the Knox et al. (2017) equation, which gave us daily GPP per unit area. To find yearly total GPP, we multiplied those values by 182.5 to get growing and non-growing season GPP, and summed them together to find total GPP.

4 Results

	Area(m^2)	GPP Growing Season (g C)	GPP Non-Growing Season (g C)	Total GPP(g C/yr)
Historic	768,849,533.00	10,379,103,491,972	9,406,720,266,348	19,785,823,758,320
Modern	32,492,412.14	5,004,461,472,750	4,392,853,274,250	9,397,314,747,000
Difference	736,357,120.86	5,374,642,019,222	5,013,866,992,098	10,388,509,011,320
% lost	95.77	51.78	53.30	52.50

5 Discussions

Our results show that diking and infilling of the Bay's wetland habitats has resulted in a loss of around 52.5% of the wetland GPP, or 10.39 million metric tons of carbon per year of GPP. Per unit area, our results for the amount of annual GPP provided by the modern wetland area is approximately 289,216 grams of C m^{-2}. Compared with other studies which quantify GPP CO_2 fluxes in coastal wetlands, our results are a large overestimation of GPP fluxes. Zhong et al. (2016) studied the carbon dioxide fluxes in a reclaimed coastal wetland in the Yangtze estuary using eddy covariance techniques 14 years after this wetland had been reclaimed and found a total annual of GPP flux of 1297.9 g C m^{-2}. Lu et al. (2017) conducted a meta-analysis of CO_2 fluxes of 21 coastal wetlands across the globe and found that coastal wetlands have annual GPP fluxes in the range of 500 g C m^{-2} to 2800 g C m^{-2}.

The fact that our estimates for wetland GPP values are around 2 to 3 orders of magnitude higher than wetland GPP values that have been determined by previous studies indicates that method for GPP estimation from Landsat-derived NDVI provided by Knox et al. is not accurate on the much larger regional scale that is relevant to our research objectives. Knox et al. did their research on recently restored wetlands, which are young in age. Conversely, the wetlands that we extracted from BAARI are preserved naturally vegetated wetland areas, which do not represent recently restored habitats. Recently restored wetlands such as those studied by Knox et al. are likely to have higher growth rates than the much older, naturally occuring established wetlands. The assumption that the wetlands which Knox et al. worked on are representative of all wetlands in the Bay is not an accurate or valid assumption to make. The implications of this assumption is that our calculated GPP values for the wetlands of the Bay are an overestimation of the actual amount of GPP provided by the wetlands.

Despite the large GPP overestimations, our research results highlights the magnitude of lost photosynthetic ability that resulted from extensive land use changes along the Bay's tidal wetland habitats. A significant amount of wetland gross primary production has been lost due to land use change. This ongoing land use change and human development has likely turned this region from a net carbon sink (pre-1850) to a net carbon source. Carbon emission from natural gas, electricity generation and transportation in the Bay Area is estimated at 49.7 million metric tonnes for the year of 2015 (Vital Signs 2017). Our estimates for the amount of GPP provided by the total historic wetland area is approximately 19.8 million metric tonnes, which is less than half of the emissions generated by human activity. And much of this carbon sequestered through wetland GPP would be re-emitted through respiration and decomposition of organic matter. Additionally, if we apply the estimates provided by Callaway et al. (2015) of 80 g C m^2 per year of wetland sequestered carbon to the total area of historic wetlands in the bay, we get a value of approximately 61,508 metric tonnes of carbon sequestered per year by the Bay's wetlands, which is less than a percent of the total human emissions each year from the Bay

Area. Thus, while restoring large areas of the Bay's wetlands would significantly bolster the region's ability to sequester carbon, our analysis shows that it would do little to turn the region from a net carbon source to a net carbon sink.

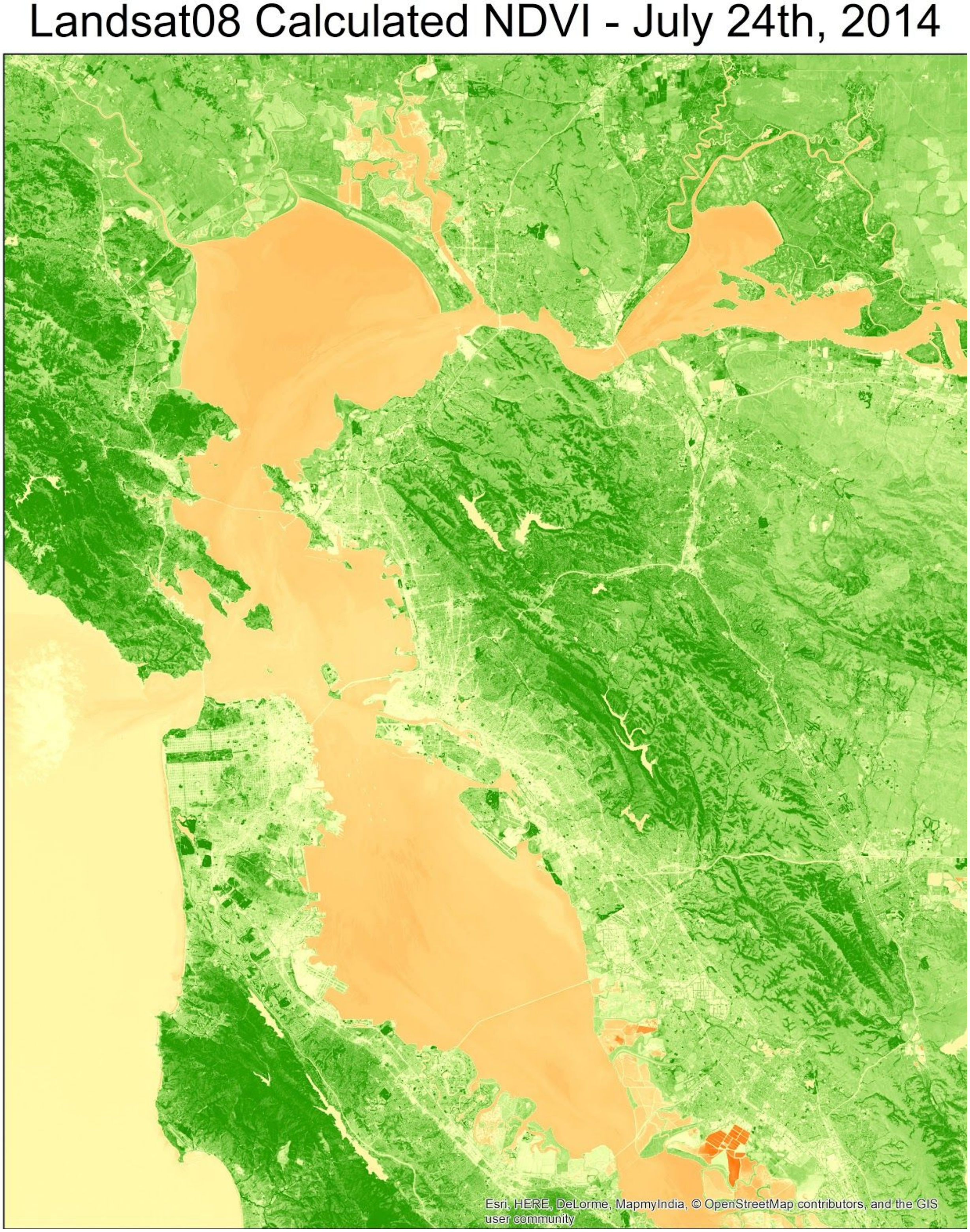
6 Conclusions

This research demonstrates an effort to predict wetland carbon fluxes on a regional scale from publicly available remote imagery data and a ground-truthed model. Our results show that using the relationship provided by Knox et al to predict regional GPP fluxes from wetlands results in an overestimation of the magnitude of regional wetland GPP. Remotely sensed imagery has the potential to allow researchers and policymakers to monitor GPP on a regional scale. However, the model relationship between wetland GPP and NDVI would have to be improved in order to allow for a more accurate prediction of regional wetland GPP from Landsat-derived NDVI. To predict the potential for carbon sequestration offered by the Bay's wetlands, not only would the model's accuracy need to be greatly improved, but it would have to be paired with extensive data relating to soil depth and GHG emission from wetlands across the Bay (Callaway et al. 2015).

Due to the high potential for carbon sequestration offered by tidal wetlands, restoring the Bay's wetlands could serve as tool for climate change mitigation and could recieve credits under carbon management policies. Efforts to monitor wetlands growth and carbon uptake through time using satellite imagery are important for any large-scale wetland restoration work in the Bay. Our methods can be built on to more accurately evaluate the change in regional wetland or Bay carbon storage through time or compare the costs and benefits of different land-uses for areas that were previously natural wetlands. Determining the total amount of carbon storage offered by wetlands would be crucial in order to determine whether or not the marshes are worth the cost of saving them.

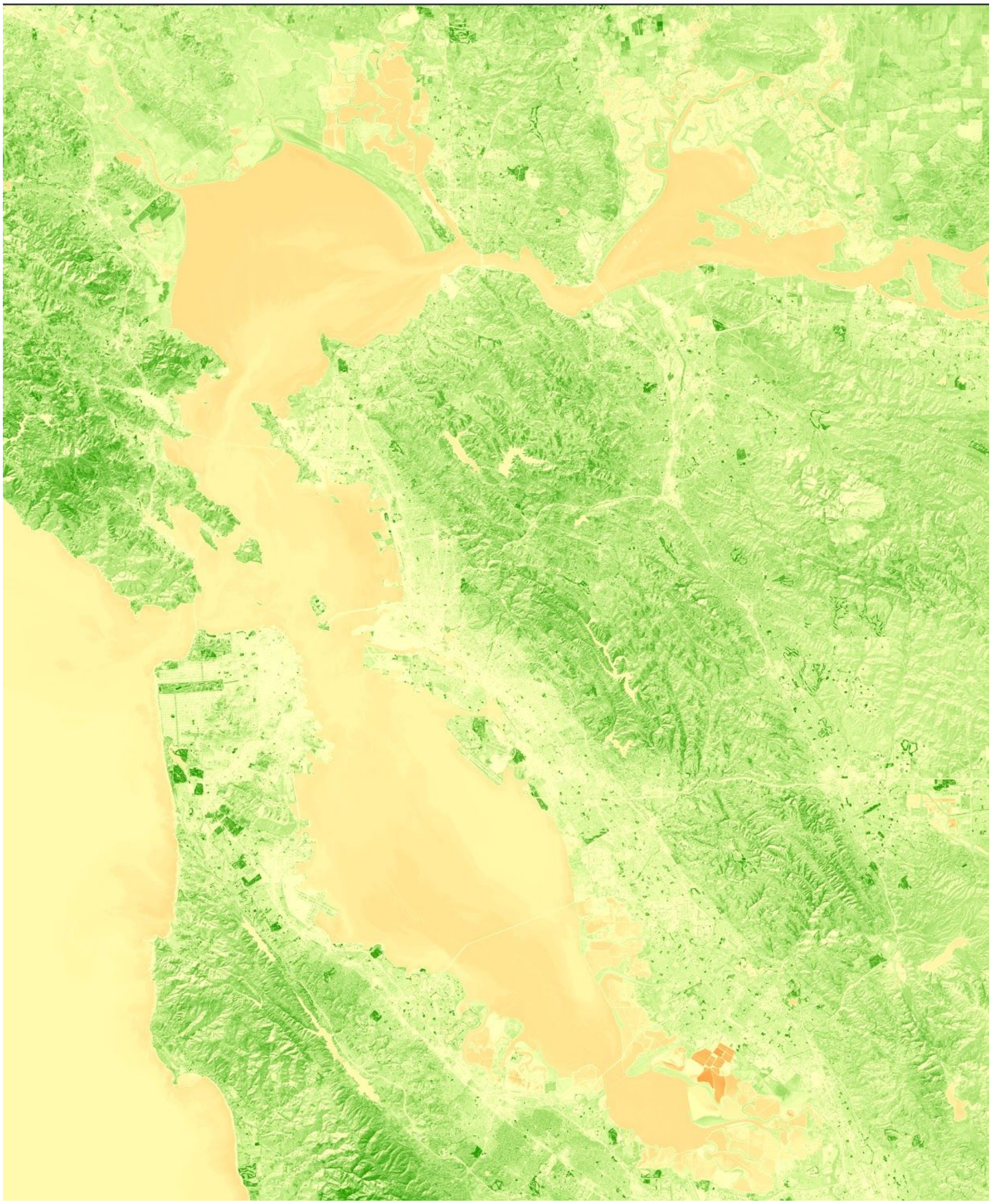
Appendix: Maps & Figures

Map 1 - July NDVI scene:



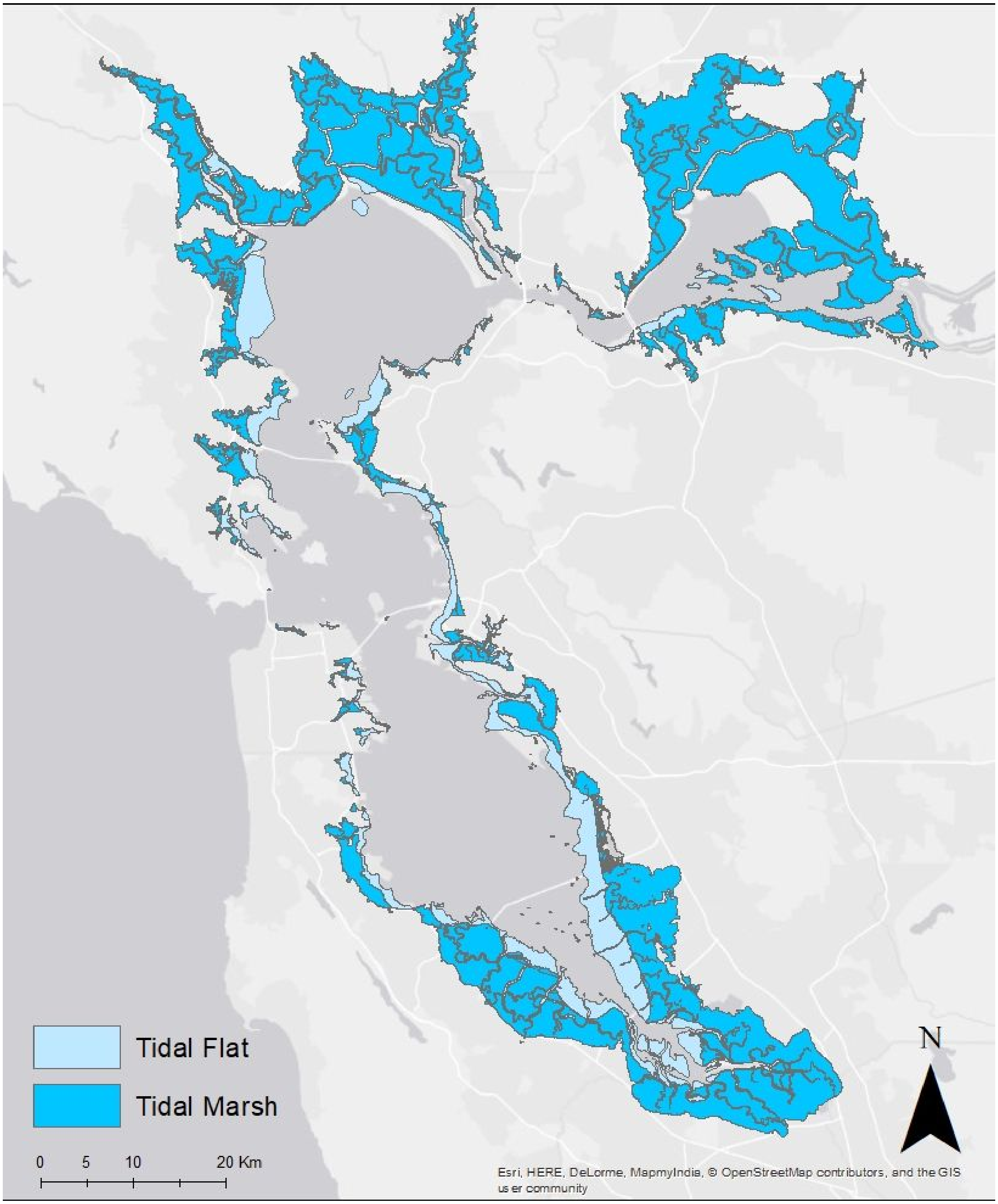
Map 2 - January NDVI Scene:

Landsat08 Calculated NDVI - January 13th, 2014



Map 3 - Historic wetlands:

Historic Tidal Flat and Tidal Marsh, c.1850



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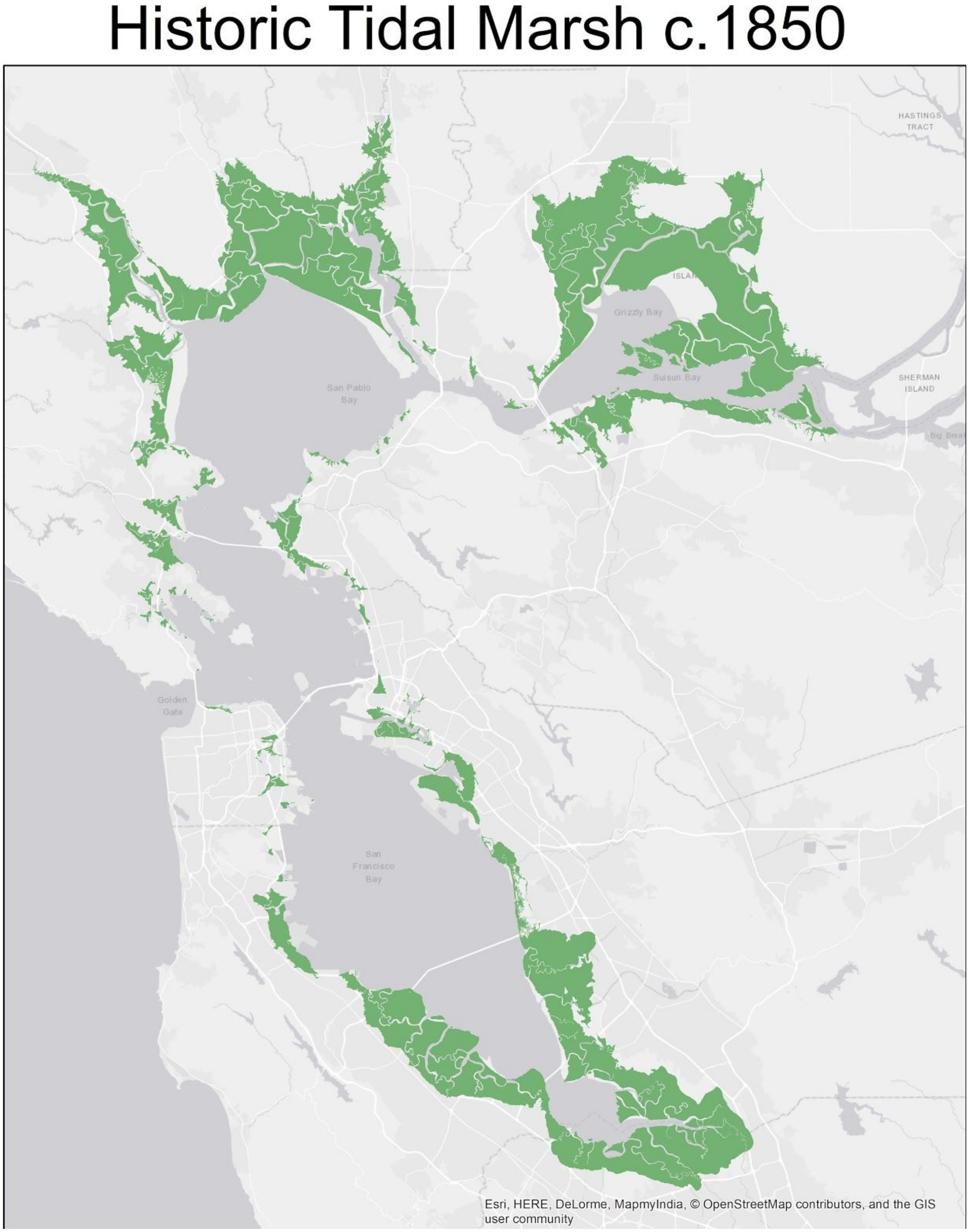
Map 4 - Historic Tidal Marsh



Historic Tidal Marsh c.1850

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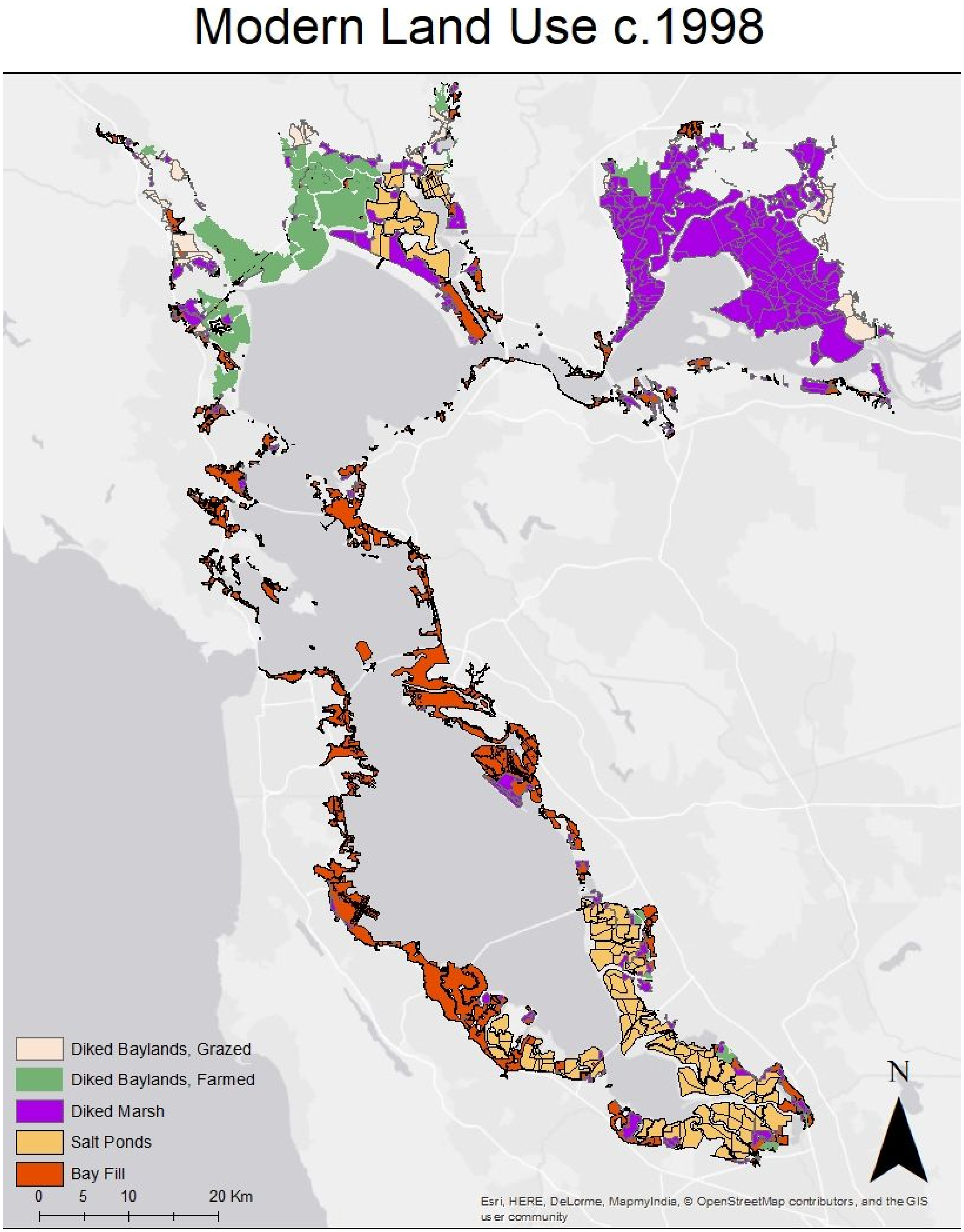
Map 5 - Modern Land Use:



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Map 6 - Modern Tidal Vegetation:

Modern Tidal Vegetation c.2009

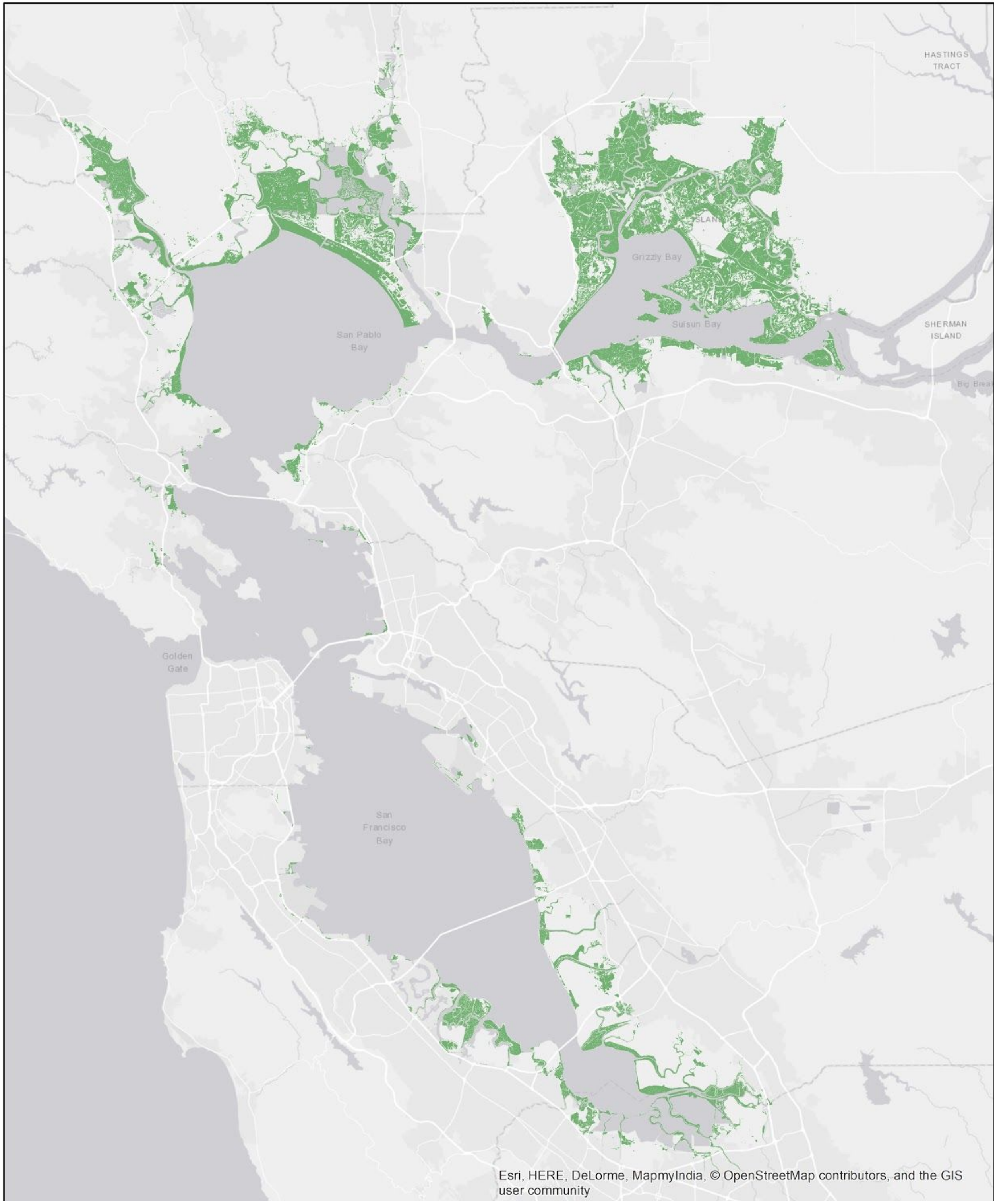

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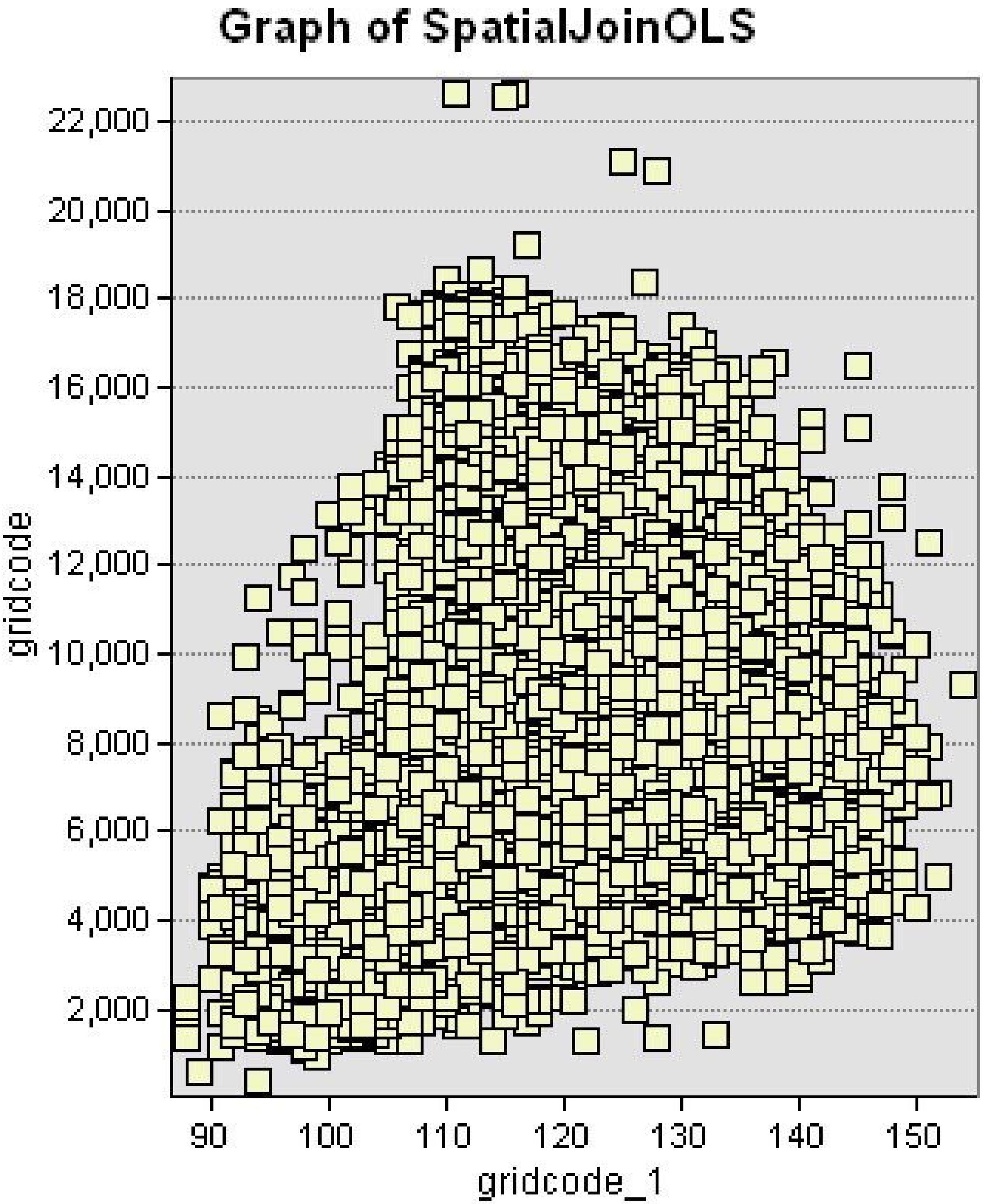
FIgure 1 - Regression screenshot:



Summary data screenshot

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