Research Article

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A Study of Avian Population Recovery after Habitat Restoration Using Remote Sensing and Community Science Bird Observation Data

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Abstract
During the last two centuries, the contiguous United States has lost over half of its wetland habitats. Preserving the remaining wetland habitats and reversing this trend is of critical importance. Fernhill Wetlands in Forest Grove, Oregon is a natural wastewater treatment site that was transformed from unused wastewater ponds to a complex natural wetland habitat in 2014-15. To assess restoration effect on biodiversity changes, previous studies involved manual observations of changes to bird populations. In this study, LANDSAT-8 and SENTINEL-2 satellite imagery and PRISM climate data were used to calculate vegetation, water and climate indices for Fernhill Wetlands for pre- and post-restoration periods, ranging from 2013 to 2018. Then, for the first time quantitative correlations were established between these indices and community science bird observation data from the Cornell University eBird database. The study showed previously unobserved effects of the habitat restoration, positive and negative, on several species. Shorebirds, marsh birds and others that lived at the water's edge showed much subtler and sometimes unexpected reactions to the habitat change. Further, supervised machine learning classification was used to obtain clarity on land, vegetation and water changes in the region of interest. This study could be of interest to wetland managers to help guide further habitat modifications.

Introduction
Bird habitats in general, and wetland habitats in particular, have come under increasing pressure due to human development, loss of vegetative cover, diversion of water for human consumption and irrigation, climate change, and other factors. During the last two centuries, the contiguous United States has lost over half of its wetland habitats; averaging a rate of 60 acres lost per hour [1]. It is therefore critically important to take steps to preserve and enhance birding habitats to ensure the health of the entire ecosystem.

Fernhill Wetlands is a historically important birding site in Washington County in the Portland, Oregon metropolitan area and has been designated as an Important Birding Area (IBA) by the National Audubon Society and Birdlife International. It is nominally a wastewater treatment facility managed by Clean Water Services (CWS), the water resources management utility for urban Washington County.

Fernhill Wetlands provides habitat for a variety of local wildlife as well as marsh, lake and riparian habitat for a variety of native and migratory birds. Winter waterfowl populations can number in the thousands and the site is an important stopover for waterfowl and other migratory birds due to its location in the middle of the Pacific Flyway migration route (Figure 1).
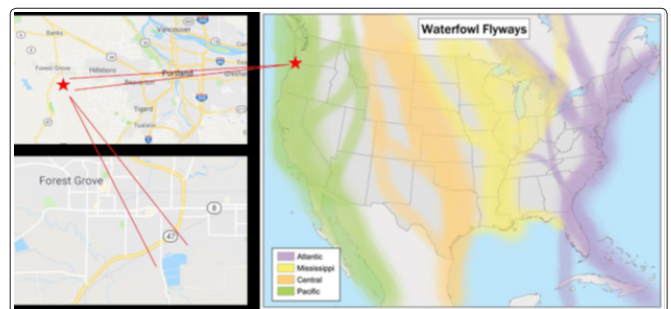
Figure 1: Fernhill Wetlands, Forest Grove, OR, is located on the Pacific Flyway. Credit: Google Maps, U.S. Fish and Wildlife Service

Background
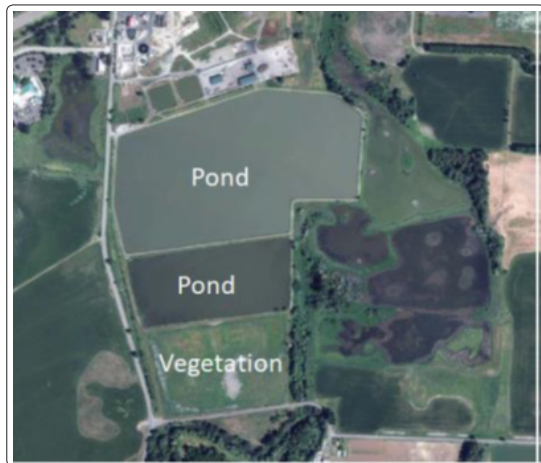### The Fernhill Wetlands Restoration Project
Starting in June 2014 and extending into February 2015, CWS undertook a massive habitat restoration project to transform Fernhill Wetlands from a collection of large unused wastewater ponds into a complex of native wetland habitats that would also naturally treat wastewater. This approach is known as a Natural Treatment System (NTS) and has been shown to have several advantages [2]. It creates a high-quality wildlife habitat, while improving wastewater treatment techniques at a lower cost. NTS approaches have been and are being

widely adopted in Oregon and elsewhere in the country, like Arcata Marsh in Arcata, California and Sweetwater Wetlands in Arizona [3].

The original Fernhill Wetlands site consisted primarily of 3 waste water holding ponds (Figure 2). The restoration project involved replacement of these ponds with smaller areas of water along with marshes and land areas that could support a wider variety of passerine, aquatic and marsh-based wildlife. The planned layout of the site (Figure 3) clearly indicates much greater diversity in habitats.

Prior Audubon Society of Portland Bird Monitoring
The Audubon Society of Portland (ASOP) worked with CWS to monitor the bird response to the habitat restoration effort at Fernhill Wetlands. Bird surveys were performed in the fall of 2015 after restoration was complete, as well as follow-up surveys in the spring and fall of 2016. Bird observation data was also used in this preliminary study from the community science eBird database. These data were compared to pre-restoration data from the eBird database to make an assessment of how the habitat restoration improved the richness and diversity of avian fauna at the Fernhill site [4].

Figure 2: Google Earth satellite Image of Fernhill Wetlands in 2013, prior to habitat restoration [4]

Figure 3: The Fernhill Wetlands restoration plan called for a significant increase in the area covered by land and marsh, with open water reduced significantly (show in the upper right in the Google Earth Satellite image)

The ASOP survey placed all bird species observed at Fernhill into 8 categories – secretive marsh birds, waders, wintering grebes, diving ducks, dabbling ducks, wetland-associated songbirds, migratory shorebirds and raptors. They used the survey data to look at how the habitat changes affected the populations of each of these categories.

The survey found an increase in species richness post-restoration, especially in summer. It also detected shifts in species, from largely aquatic species pre-restoration, to higher abundance of both terrestrial and marsh-dependent species, which is to be expected based on the change in habitat. The complete details of the report can be found online and further surveys are occurring [4].

Goal of This Study
The preliminary ASOP study conducted earlier used bird survey data to study avian population response. This study did not aim to establish quantitative correlations between bird population and changes in the physical characteristics of the Fernhill site.

The goal of this follow-up study was to expand on the ASOP preliminary study by using satellite remote sensing and climate data to see how quantitative changes in vegetation, water, and climate indices correlated with eBird observation data for the period between 2013 and 2018 at the Fernhill Wetlands. This would provide an alternate way of assessing and predicting the avian response to physical changes after a habitat restoration activity and would also include analysis for additional years and growing seasons after the restoration activity completed compared to the preliminary ASOP study.

Specifically, the study attempted to:
1. Generate satellite remote sensing multi-band raster data maps of Fernhill Wetlands
2. Extract quantitative metrics for vegetation cover, water surface area, temperature and precipitation from the satellite and climate data
3. Perform a statistical analysis to establish correlation between vegetation and water indices, temperature, and precipitation with the populations of various bird species obtained from eBird.

Through this activity, the study would help establish detailed correlations between changes in land, water, and climate for the Fernhill site and the avian fauna populations observed. These correlations may be useful for CWS personnel at the Fernhill Wetlands to inform management of the site and to maximize benefit to avifauna as much as possible within the constraints of other water management requirements at the site.

Hypothesis
The hypothesis at the start of the project was that increasing the vegetation index would benefit land species like raptors and songbirds as well as dabbling ducks that rely on aquatic vegetation for cover and food, while decreasing open water would adversely affect diving ducks and other deep-water species.

Additionally, shorebirds depend on both water and vegetation. Moreover, they tend to be associated with mudflat habitat for forage and roosting. As a result, it is expected that they would behave in more unpredictable ways depending on the relative impact of the vegetation and water indices and availability of mudflats during and after the restoration activity.

Finally, the hypothesis is that the statistical correlations will reveal more subtle trends than a simple comparison of pre-restoration and post-restoration data would show. If demonstrated, this may be a useful tool for the managers of Fernhill Wetlands to have a more nuanced understanding of how the habitat changes affect the wildlife.

Materials, Datasets, and Tools
Materials used in the Project
This project relied heavily on online and cloud resources and hence the only physical material needed was a laptop. A Dell 5579 laptop running Windows 10 with an I5-8250 CPU and 8 GB of RAM was used for data analysis. All the software packages and datasets selected for this study were freely available for public use or could be freely obtained with permission.

Datasets used in the Project
Satellite Data
Remote sensing satellite imagery data used in this project came from two satellites – LANDSAT-8 and SENTINEL-2.

LANDSAT-8 is a satellite launched and managed by NASA and the US Geological Survey (USGS). It captures images of each part of Earth's surface in 9 bands twice a month. The resolution of the visible and infrared sensors, which are the ones used in this study, is 30 meters. LANDSAT-8 data is available for the entire range of dates that were considered for this study. 254 LANDSAT images were used for the analysis in this study.

SENTINEL-2 is a European Space Agency Earth observation mission consisting of two satellites, SENTINEL-2A and SENTINEL-2B. They acquire images with 10-meter resolution in 13 spectral bands. There were between 2 and 12 images available per month for the time period needed for this study. However, SENTINEL-2 data only goes as far back as 2015. For this reason, only LANDSAT-8 data was used for the primary analysis, and the SENTINEL-2 data used for high-resolution validation of the results. 230 SENTINEL-2 images were used for the analysis in this study.

Geospatial Climate Data
In addition to satellite imagery, temperature and precipitation data were also used in the project to determine correlations to the wildlife observed. These data were obtained from the PRISM database, which is a historical record of climate data from 1895 to the present, maintained by the PRISM climate group at Oregon State University [5].

This gridded climate dataset that has a spatial resolution of ~3300 m was chosen since it is the most widely used spatial climate dataset in the United States and is the official climate data set of the USDA. There are 9 climate bands, but for this study only the 2 bands – tmean (Monthly average of daily mean temperature) and ppt (Monthly total precipitation, including rain and melted snow) were used. 60 PRISM images were used for the analysis in this study. This data was also imported into Google Earth Engine for analysis.

The eBird Database
The eBIRD database is a community science database of bird observations maintained by the Cornell Lab of Ornithology and is considered to be the world's largest biodiversity-related community science project, with more than 100 million bird sightings contributed each year by eBirders around the world [6]. Birders can enter their data of bird observations (number, species, location, date/time, weather conditions, etc.) into the eBIRD database.

eBIRD data can have errors and biases and must be cleaned up before scientific analysis. A comparison of sanitized eBIRD data to that taken by expert birders has shown a reasonably high level of correlation [2].

eBIRD data from 2013 to 2018 for the Fernhill Wetlands site was used in this study to track how changes in the habitat of Fernhill Wetlands affected the number and diversity of avian fauna at the wetland location [7]. ~146,000 rows of eBIRD data were used for this study.

Tools Used in the Project
Google Earth Engine (GEE)
The analysis of satellite imagery and spatial climate data was performed using Google Earth Engine. GEE was selected as the primary tool for the analysis since it is a powerful application freely available for public use. The advantage of GEE is that much of the heavy and resource-intensive processing and manipulation of satellite imagery and other large spatial datasets can be done in the cloud in a relatively easy manner using a standard scripting language like Javascript.

Excel and R
Using a combination of Microsoft Excel 2016 and R for Windows version 3.5.1, a free statistical software package, the summary data from GEE was cleaned up and the final correlation graphs were generated.

Vegetation and Water Metrics Used
One of the powerful analysis techniques that can be done using Google Earth Engine is computation of metrics for the vegetation and water that can be seen in the satellite imagery.

Two metrics were extracted from the satellite imagery for vegetation cover – the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI).

NDVI is a metric that determines the amount of vegetation that is present in the image. This metric is based on the fact that the chlorophyll in plants absorbs red light, while the structure of the plant's leaves reflects light in the near infrared part of the spectrum [8]. Since satellite images are available in RGB as well as IR, the NDVI can be calculated from them. NDVI values range from -1 to 1. Values below zero indicate no vegetation, while positive values indicate the presence of vegetation. The more the vegetation, the higher the NDVI value.

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

The EVI is an optimized vegetation index that is designed to enhance the sensitivity in high biomass regions and is less sensitive to atmospheric variations than NDVI. EVI and NDVI complement each other in most analyses. EVI values range from -1 and 1. Healthy vegetation has an EVI value above 0.2.

$$EVI = \frac{2.5 \times (NIR - RED)}{(NIR + 6 \times RED - 7.5 \times BLUE + 1.0)}$$

Normalized Difference Water Index (NDWI) is a metric that is similar to NDVI, except that it is a measure of water area in the

image. Just like NDVI, it takes values from -1 to 1, with values below zero indicating lack of water, and positive values indicating presence of water. The higher the NDWI, the more the percentage of area in the image that is covered with water.

$$NDWI = \frac{(GREEN - NIR)}{(GREEN + NIR)}$$

Procedure / Method

The experimental procedure consisted of three stages: 1) Data Collection 2) Data Processing and 3) Data Analysis. Flowchart 1 shows the steps in the procedure.
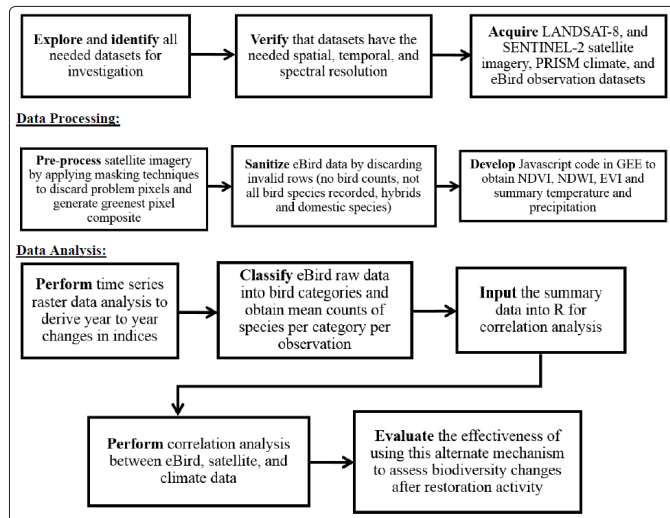

Flowchart 1: Data collection, data processing, and data analysis steps in the procedure

Data Collection

a. LANDSAT-8 was selected as the primary data source. The LANDSAT-8 imagery was also augmented with the higher resolution SENTINEL-2 Imagery for recent months for comparison.

b. Using the Google Earth Engine (GEE) Interface and Javascript, the Landsat 8 Collection 1 Tier 1 calibrated top-of-atmosphere (TOA) reflectance images and the SENTINEL-2 MultiSpectral Instrument images were directly downloaded. These were done for the full range of dates to cover the pre-restoration and post-restoration time periods.

c. Also, using GEE and Javascript, the PRISM Monthly Spatial Climate Dataset for historic temperature and precipitation data for the Fernhill region was imported.

d. Further, the eBird dataset for all avian species for the Fernhill Wetlands hotspots for the 2013-2018 timeframe was obtained from the Cornell Institute of Ornithology eBird website.

Data Processing

a. All LANDSAT-8 and SENTINEL-2 images were processed by developing scripts in GEE.

b. The images were pre-processed by applying masking techniques to filter out cloudy pixels (Figure 4).
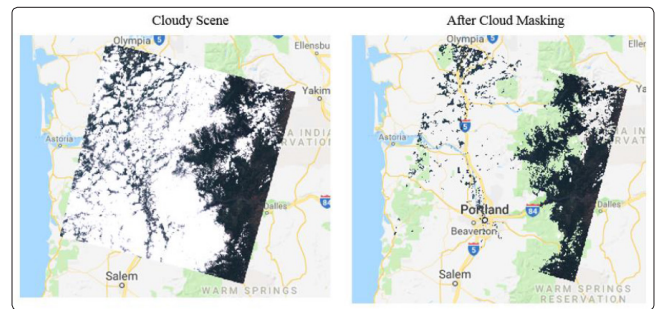

Figure 4: LANDSAT-8 Image of a Fernhill Wetlands Scene before and after applying cloud mask

c. The NDVI values were then programmatically calculated for each pixel in the image and were included as a separate band for easy recognition of vegetation.

d. Then, the greenest pixel false color composite (Figure 5) was generated for each season from the image collection for the season.

e. The greenest pixel composite was then clipped to the Fernhill geometry (Figure 6).

f. The script also similarly calculated the EVI, and the NDWI for the Landsat-8 images.

g. At this stage, a composite image for every season of interest within the project analysis timeframe was created and all of its key metrics (NDVI, EVI, and NDWI) calculated.

h. The tmean and ppt bands of PRISM data for the region of interest were then separated.

i. The eBird dataset was sanitized to exclude reports with 'X' values for observation counts, rows that did not include all bird species, rows in which the species were not identified, and observations of domestic or hybrid species. The resulting filtered dataset contained 146,457 observations (rows) and 10 variables (columns) for the Jan 2013 - Oct 2018 period.
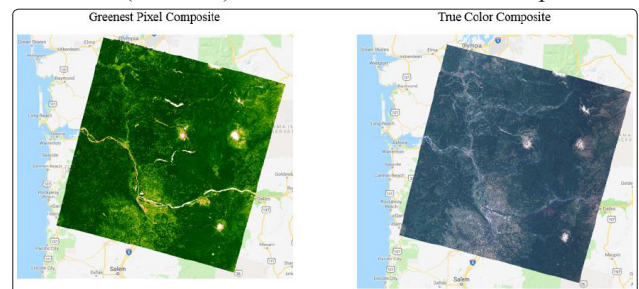
Figure 5: Greenest Pixel Composite of LANDSAT-8 Image of a Fernhill Wetlands Scene compared to a True Color Composite
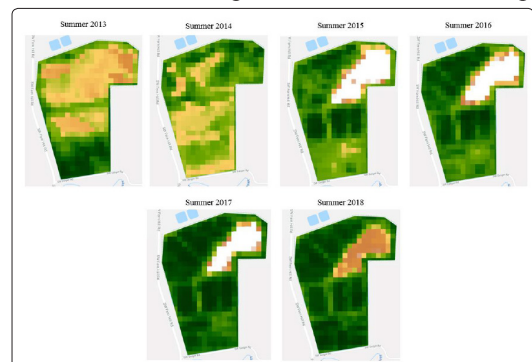
Figure 6: LANDSAT-8 Greenest Pixel False Color Composite

Image Clipped to the Fernhill Geometry Shows Transformation from Large Wastewater Ponds to Complex Native Wetland Habitat.

Data Analysis

a. A time series analysis was then programmatically scripted in GEE to extract year to year changes in vegetation index, water index, mean temperature, and precipitation.

b. All the eBird data was classified into a handful of bird classes based on behavior, preferred habitat, etc. The classes that were used in this study are shown below in Table 1. The complete list of all bird species used in this study and which classes each species was assigned to is shown in Appendix 1.

c. Monthly mean counts per observation per bird class was obtained to get an estimate of abundance of that type of bird.

d. The eBird data for the various bird species classes, as well as the vegetation and water index data and the temperature and precipitation data were pre-processed in Excel and then imported into R.

e. A correlation analysis using the Pearson Parametric Correlation Test was performed between the bird counts for the various bird classes and the satellite vegetation and water indices as well as the temperature and precipitation indices. The resultant data was analyzed to determine positive and negative correlations for the various species groups to determine if the results matched the hypothesis or not, and if there were any subtle effects for species like the marsh birds and waders that inhabit the boundaries between the land and water areas.

f. Finally, the results of this approach were compared to the old report methodology to see what additional knowledge on bird-habitat interactions could be obtained from the data.

Table 1: Fourteen bird classes used in the analysis. Categories were developed based on behavior, habitat, etc. The complete list of birds and class allocation is shown in the Appendix

| Aerial	Cormorant	Dabbling Duck
Diving Duck	Goose	Grebe
Kingfisher	Marshy Songbird	Raptor
Secretive Marsh Bird	Shorebird	Songbird
Swan	Waders	

Results

LANDSAT-8 Visual Data

Snapshots of the LANDSAT-8 greenest pixel composite images clipped to the Fernhill geometry from 2013 to 2018 are shown in Figure 6. The white pixels represent water, while the green pixels represent vegetation. The yellow and brown pixels represent low values for the vegetation index and represent watery areas with aquatic vegetation. The summer images are shown because they capture the full diversity of the different habitat zones on the site. The images show the transformation of the Fernhill Wetlands area from large wastewater ponds to a much richer and more diverse habitat containing plants and marshes in addition to a reduced water area.

Supervised Machine Learning Classification

In addition to creating false color composites for NDVI, NDWI, and EVI, supervised machine learning classification was used to monitor the progress of vegetation, ground and water areas after the restoration activity (Figure 7). It is intended that this will provide additional visual clarity on some of the subtle effects that the habitat restoration had on some bird species (see Section 9). This machine learning technique was used as an alternate method for land cover classification using the GEE's in-built CART (Classification and Regression Tree) classifier to obtain additional clarity on the pixels by performing the following steps:

1. Collect training data for ground, water, and vegetation
2. Instantiate a classifier in GEE.
3. Train the classifier using the collected training data.
4. Classify an image.
5. Display the results.

Summer 2013   Summer 2016   Summer 2017
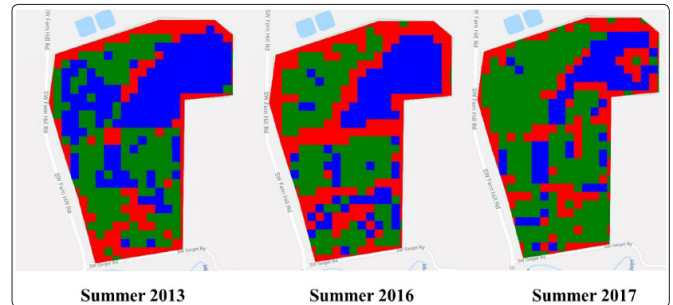
Figure 7: Supervised classification algorithm output with trained data points for ground (red), vegetation (green) and water (blue)

LANDSAT-8 Metrics Data and PRISM Weather Trends

All the images in the dataset were then processed and the vegetation and water metrics were extracted from them. The NDVI, EVI and NDWI data trends for the entire timeframe of the study is shown in Figure 8. The variation of temperature and rainfall through the timeframe of the study is shown in Figure 9.


Figure 8: NDVI, EVI and NDWI trends for Fernhill Wetlands through the entire timeframe of the study
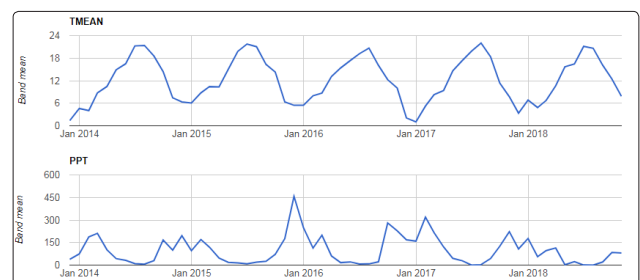
Figure 9: Temperature and Precipitation variation through the timeframe of the study in the Fernhill Wetlands area

eBird Data Correlation with Physical Changes at Fernhill

Results of correlation of the eBird data with vegetation, water, and climate indices are shown (Figure 10). Red dots represent negative correlation and blue dots represent positive correlation with the degree of correlation shown in the size and color intensity of the dot.
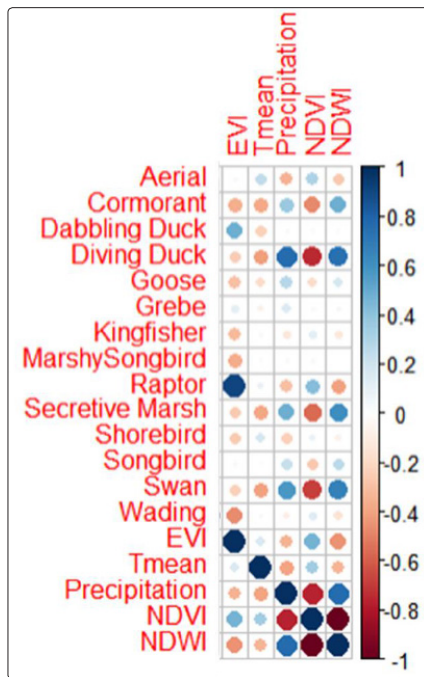
Figure 10: Correlation using R of population of various avian classes with vegetation, water area, temperature and precipitation

Discussion

Discussion of Habitat Change Data at Fernhill Wetlands

Satellite imagery for the Fernhill wetlands area clearly shows the significant change in habitat that was planned and executed as part of the restoration project (Figure 6). It is clear that as per the design of the new habitat, the water area is substantially reduced compared to the vegetation area.

The oscillatory behavior in the seasonal changes in NDVI, EVI and NDWI as a function of time (Figure 8) was expected and reflects the dry and warm summers and cool, rainy winters of western Oregon. In summer months, the vegetation area increases and has a peak, while the water area reduces and is the smallest. Conversely, in winter, with the rains and cooler temperatures, the water area has a maximum, while the plants are dormant or die off and hence the vegetation indices are the lowest.

One interesting observation is that both the peaks and the valleys of the NDVI increase over time. This means that the greater areas allocated to land and marsh result in greater vegetation not just in summer but in winter as well. Conversely, both the peaks and valleys of the NDWI graph decrease over time. This means that the water area is lower in winter and in summer as well. In summer, the shrinking water area exposes mudflats that are then populated by shorebirds like killdeer and sandpipers. The reduced water area during summer could potentially have an impact on the shorebird populations over time. However, CWS can control water levels and so can limit impacts to some of the bird species that require particular features - e.g. mudflats for migratory shorebirds.

Discussion of Climate Data

Temperature and precipitation varied through the timeframe of the study in the Fernhill Wetlands area (Figure 9). Other than the seasonal changes in temperature and rainfall, there isn't a significant trend for the timeframe of the study. The only deviation that is noteworthy is that the winter of 2016 was unusually wet, and this may have had some impact on avian populations during that season.

Discussion of Wildlife Data and Correlation with Vegetation/Water Indices and Climate

Several important conclusions validating the hypothesis can be obtained from the correlation plot (Figure 10).

- As indicated in the hypothesis, the increase in NDVI and EVI over the course of the study period (Figure 6) had a potential positive impact on the raptor population. This makes sense because raptors depend on greater vegetation for nesting and cover. Moreover, it is possible that a greater vegetation index also means that the prey species for raptors – rodents, reptiles, etc. also increase. However, the ranges for the raptors likely extend well outside the Fernhill boundaries, and hence the increase in this population may not be due to changes in Fernhill alone.
- Also, dabbling ducks have a strong positive correlation to EVI. Although dabbling ducks inhabit both the land and the water, their primary habitat is the marshy perimeter of the water and they feed on aquatic plants. So, this result is consistent with the hypothesis.
- Similarly, as hypothesized earlier, the diving duck population is strongly correlated to NDWI and precipitation. This is because diving ducks require deep water to dive for their primary prey– fish and crustaceans. The diving duck population decreased over the course of the study because NDWI decreased (Figure 11). The same is true for other species classes that prefer deep water, like swans. The same correlation is also present, although somewhat less strong, for cormorants, another diving species that eats fish.
- Aerial birds like swallows also have a positive correlation with NDVI. This is again likely due to two reasons: 1) greater nesting opportunities with increased vegetation, and 2) increased abundance of insects, their primary prey, from increased vegetation at the edge of the water.

The songbird population, on the other hand, did not match the hypothesis for land birds. The expectation that they would have a positive correlation with the vegetation index is not borne out by the data (Figure 10). Songbirds, instead, have a positive correlation with NDWI and precipitation, and a negative correlation with NDVI. This could be because reduced water area may possibly decrease the feeding opportunities due to reduced insect availability. It is possible that songbird populations will increase in a few years after shrubs and newly planted trees have had a chance to grow and provide cover and nesting sites [4].

Also, as expected in the hypothesis, the birds that inhabit the fringes of the water did not have very consistent behavior.

- Marshy songbirds are negatively correlated to EVI but don't have a strong correlation to NDWI. Similarly, waders are negatively correlated to EVI. It is possible that the EVI and NDVI indices are dominated by land cover and less by marshy

areas which are the areas relevant to these species. A greater EVI and NDVI may actually mean less water and therefore fewer aquatic plants or prey species for them. Once again, more data is needed before definitive conclusions can be drawn.

• The shorebird populations show mixed responses to NDVI, EVI and NDWI as well. The speculation, as suggested in is that there were rapid changes and inconsistency in water levels as a result of the drastic habitat changes and this may have affected the mudflats at the perimeter of the water, thereby making the habitat for shorebirds much more variable and inconsistent [4]. This could possibly have led to the unusual correlation results. This analysis will be repeated over the next 2 or 3 seasons.
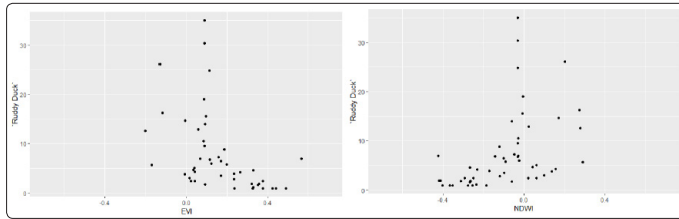

Figure 11: Scatter plot of diving duck species population showing negative correlation to EVI and positive correlation to NDWI

### The Case of the Dabbling Ducks – Extending the Analysis
Dabbling ducks have strong positive correlation to EVI and depend on vegetation near shore. However, they also show low to no correlation to NDVI or NDWI. A careful analysis of the dabbling duck data (Figure 12) shows conflicting population trends in species. Species-level analysis (Figure 13) reveals that there is a significant increase in Gadwalls (Mareca strepera) and American wigeons ($P < .01$), while there is a significant decrease in Northern shovelers (Anas clypeata) ($P < .01$).

Gadwalls and wigeons are shore vegetation feeders (NDVI, EVI). However, northern shovelers are very different, relying more on open water (NDWI). The data suggests that the decrease in northern shoveler counts offsets the increase in other species, and this may be muting the NDWI response of dabbling ducks.

A key learning from this example is that avian category selection should be done with careful attention to feeding behavior in addition to habitat and taxonomic relationships. The dabbling duck analysis also highlights the power of the indices-based method developed in this study. If heuristics can be added to the analysis to detect and flag unusual and inconsistent behavior or the indices as potentially worthy of a closer look, it can increase the power of the technique.
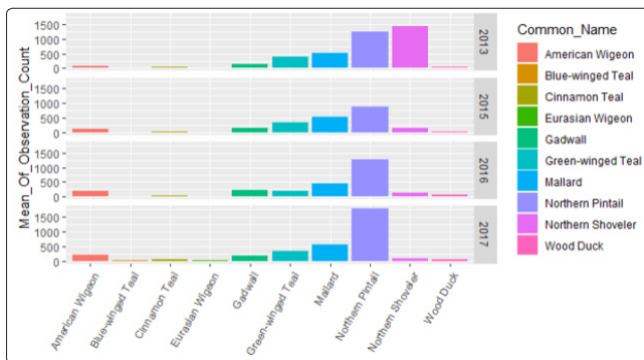
Figure 12: Yearly Change in Dabbling Duck Species' Mean Observation Count
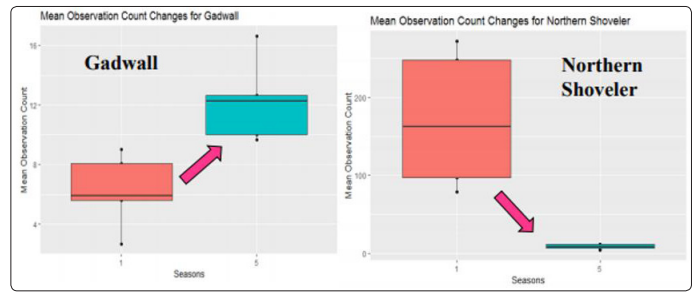
Figure 13: Figure 12. Mean Observation Counts per eBird survey of Gadwalls and Northern Shovelers during the pre-restoration (2013-2014) and post-restoration (2017-2018) periods in the greater Fernhill 5 Wetlands area. Analysis is restricted to counts conducted from Oct - Feb. Surveys during all times of day were included

Error Analysis and Biases
The sources of error that needed to be accounted for as part of the analysis in this study:

• Being in a very rainy and cloudy area of the country, Fernhill Wetlands had many cloudy days and LANDSAT images were not available for a few weeks. Other images close by temporally had to be substituted for the analysis.
• The LANDSAT image resolution was 30m, which is coarser than what was ideal. The Sentinel image resolution is 10m which is much better, but the data only was available from 2015 onwards. The lack of resolution prevented me from being able to distinguish between different plant species, something that would have been very useful.
• eBird data is based on human observation and hence subject to error or biases. Bad data - rows with 'X' values for observation counts, rows that did not include all bird species, rows in which all species were not identified, and observations of domestic or hybrid species - were removed, and sampling was increased to reduce errors and biases in eBird data.
• There is also a potential bias in the different skill levels of birders that contributed to the eBird database. Effort is underway to filter the eBird data based on known expert user contributions only to see if it yields different results.
• Applying remote sensing data to a small site (Fernhill NTS) which spans 90 acres may increase chance of spurious results because LANDSAT-8 data has a pixel resolution of 30m. The goal is to try to use SENTINEL-2 data for future high-resolution correlation analyses.

Conclusions
The goal of this study was to use satellite imagery to do a detailed analysis of the impact of habitat change at Fernhill Wetlands on the avian population in that location.

Google Earth Engine was used to develop a powerful technique to quantify habitat change in terms of NDVI, EVI and NDWI, and to establish correlation of these parameters to the abundance of different kinds of avian species.

Quantitative metrics like NDVI, EVI and NDWI offer an opportunity to extract more subtle correlations to avian populations and this is what was observed from the R analysis.

Raptors, dabbling ducks, diving ducks, swallows, and swifts' correlation with satellite-derived data fit hypothesis predictions. Songbirds, on the other hand, show a correlation to the vegetation and water indices that was unexpected. More data is needed to determine the root cause of this, but it might be related possibly to greater food sources near the water, and underdeveloped shrub and tree cover which should improve with time. Also, a more nuanced analysis of insectivores versus seed-eaters or frugivores may shed light on the root cause for this unexpected result.

The birds that occupy the fringes between water and land – herons, egrets, and the subset of songbirds that inhabit the marshes at the water's edge, show more complicated behavior that is not consistent with the indices. This, once again, was speculated about in the hypothesis. More data may need to be collected, especially with the greater maturity of the habitat over the next 2 or 3 years to help understand their behavior better.

Follow-Ups
Collecting more data over next few seasons and filtering data by expert users:
The main follow-up is to continue this study over the next few seasons to get more statistics on the various species and to get better long-term behavioral data. This will also allow more time for the habitat to mature. Also, filtering eBird data by known expert user observations may yield some differences.

Splitting songbird group:
As mentioned in Section 10, dividing the songbird population into insectivores, seed-eaters, and frugivore classes may help uncover the reason for the mixed correlation with the indices. It may be that when these groups are lumped together, the resultant correlation metric is inconsistent.

Using Machine Learning:
The supervised classification discussed in Section 8.1 shows the ability to provide a significantly more detailed description of the Fernhill Wetlands habitat. Further refinement of this algorithm is ongoing with the goal to be able to distinguish between different types of vegetation through differences in NDVI and EVI data for the relevant pixels. With such an improved algorithm, it will be possible to associate different vegetation types with different bird species and be able to get much deeper insight into how those specific types of vegetation influence those populations. Such data can help guide the CWS managers to better plan for further habitat modifications or improvements depending on which species needs them.

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