Fall 2023

Was the Grass Always Greener? Mapping the Historical Extent of Grassland Ecosystems in the San Juan Islands

Kailey Marie Schillinger-Brokaw
Western Washington University, schillk3@wwu.edu

“Was the Grass Always Greener?” Mapping the Historical Extent of Grassland Ecosystems in the San Juan Islands

By

Kailey Schillinger-Brokaw

Accepted in Partial Completion

of the Requirements for the Degree

Master of Arts in Environmental Studies

ADVISORY COMMITTEE

Dr. Aquila Flower, Chair

Dr. Andy Bach

Dr. Jenise Bauman

GRADUATE SCHOOL

Dr. David L. Patrick, Dean

Master's Thesis

Kailey Marie Schillinger-Brokaw

July 24, 2023

Was the Grass Always Greener? Mapping the Historical Extent of Grassland Ecosystems in the San Juan Islands

A Thesis

Presented to

The Faculty of

Western Washington University

In Partial Fulfillment

Of the Requirements for the Degree

Master of Arts in Environmental Studies

by

Kailey Marie Schillinger-Brokaw

July 2023

Abstract

The San Juan Islands, an archipelago in the Salish Sea between Vancouver Island and the Washington coast, are one of the few places native temperate grasslands are found in western Washington State. These ecosystems are important sources of biodiversity and support many rare and endemic species. In addition to their ecological importance, native temperate grasslands have profound cultural significance to the Coast Salish peoples who historically stewarded these landscapes using traditional land management practices-particularly fire-for the production of bulb crops such as common camas (*Camassia quamash*). Unfortunately, these ecologically and culturally valuable ecosystems have become rare, greatly impacted by the combined pressures of changes in land use, invasive species, and the exclusion of fire from the landscape. While land managers and conservation experts are aware of the current threats facing native temperate grasslands, the lack of historical context and baseline knowledge has made it impossible to fully understand the long-term trends in extent and distribution of this ecosystem. To address this knowledge gap, I used historical landcover data and multispectral imagery to create a high-resolution, spatially explicit dataset in ArcGIS Pro, representing grassland landcover on the San Juan Islands at multiple time periods since the early years of European and American colonization. Spatial analysis of the dataset was conducted in ArcGIS Pro to quantify grassland loss between time periods, and identify landcover types replacing grasslands. The results reveal significant decreases in grassland extent between time periods, resulting in a 78% decrease in the extent of non-agricultural grasslands since 1890. These changes are primarily a result of conversion to agriculture, and encroachment or succession to forest. The spatial data and analyses created in this study help to develop the historical baseline of native temperate

grasslands on the San Juan Islands, adding to our understanding of the lingering legacy that changes in land use have had on this ecosystem, with the potential to aid in the development of effective conservation and restoration practices.

Acknowledgements

When I reflect on my academic experience, I am awed and humbled by how many individuals have impacted my journey. From my colleagues and peers within the College of the Environment master's program, to the instructors and professors who have shared their knowledge and guidance, to the administrative faculty and staff that continuously strive to make the program better for graduate students- you have my deepest gratitude.

A very special thanks to my phenomenal advisor, Dr. Aquila Flower, without whose support, guidance, and mentorship this thesis and the completion of my master's degree would have been impossible. Aquila's wealth of biogeographical knowledge, creative problem-solving skills, and commitment to my growth and success as a spatial analyst are gifts that I cannot thank them enough for.

I would also like to thank my incredibly patient committee members: Dr. Jenise Bauman and Dr. Andy Bach, whose expertise in ecology and geography allowed me to push the scope of my research beyond what I thought possible.

Finally, I must thank my friends, family, and especially my incredible partner Tyler, for all your unconditional love and support over the past two years. Your encouragement, enthusiastic belief in me, and reminders to occasionally take a break are what kept me going-thank you.

Table of Contents

List of Tables and Figures

Figures

Tables

Introduction

Native temperate grasslands are among the most imperiled ecosystems across the globe. This biome provides a wealth of ecosystem services, from carbon sequestration and soil stability to flood mitigation and critical habitat, but only 4.6% of the planet's temperate grasslands are within established protected areas (Carbutt et al., 2017; Hoekstra et al., 2005; Zald, 2009). Faced with the combined pressures of conversion to agriculture, urbanization, the exclusion of fire from the landscape, over-grazing, increases in the presence of invasive species and encroachment, not to mention new emerging threats posed by climate change, we are losing these ecosystems at a rate of eight times greater than the rate at which we are protecting them (Carbutt et al., 2017; Hoekstra et al., 2005). Evidence of this biome crisis is clear in the Pacific Northwest, where studies show that non-agricultural temperate grasslands throughout the region have been greatly diminished-in some cases, such as in the southern Puget Sound, to a mere 10% of their historical extent (Crawford & Hall, 1997; Zald, 2009). This trend casts an ominous shadow on the fate of lesser-known grasslands, such as the old-growth temperate grasslands of the San Juan Islands, located in the Salish Sea between Washington state and Vancouver Island.

Despite the known historical presence of temperate grasslands on the San Juan Islands, there remains a lack of *accessible spatial data* that shows how these ecosystems have changed since the arrival of European and American settlers in the mid-1800s- specifically, the disruption of the Coast Salish systems of land management that had maintained temperate grasslands for thousands of years (Coffey et al., 2019; MacDougall et al., 2004). Little is known regarding precisely how much temperate grassland area has been lost on the San Juan Islands, when that loss occurred, and what the leading causes of grassland landcover loss are. This lack of historical reference data limits our ability to understand the lingering legacies of historical land use across the islands, as well as the leading causes of temperate grassland ecosystem loss (Higgs et al., 2014; MacDougall et al., 2004). In turn, this knowledge gap poses a challenge to conservation and restoration initiatives targeting temperate grasslands in the San Juan Islands.

This study aims to address the dearth of knowledge regarding historical baseline conditions of temperate grassland ecosystems on the San Juan Islands. Using GIS and remote sensing techniques, I used historical land cover data and aerial imagery to create a spatially explicit dataset depicting the changes that occurred in temperate grassland landcover between 1890 and 2021. I used these datasets to quantify the extent of temperate grassland loss and fragmentation during this time period, and to identify the landcover types replacing grasslands and the primary factors responsible for ecosystem conversion.

Study Area: The San Juan Islands

Figure 1: The Salish Sea Bioregion, and the location of the San Juan Islands.

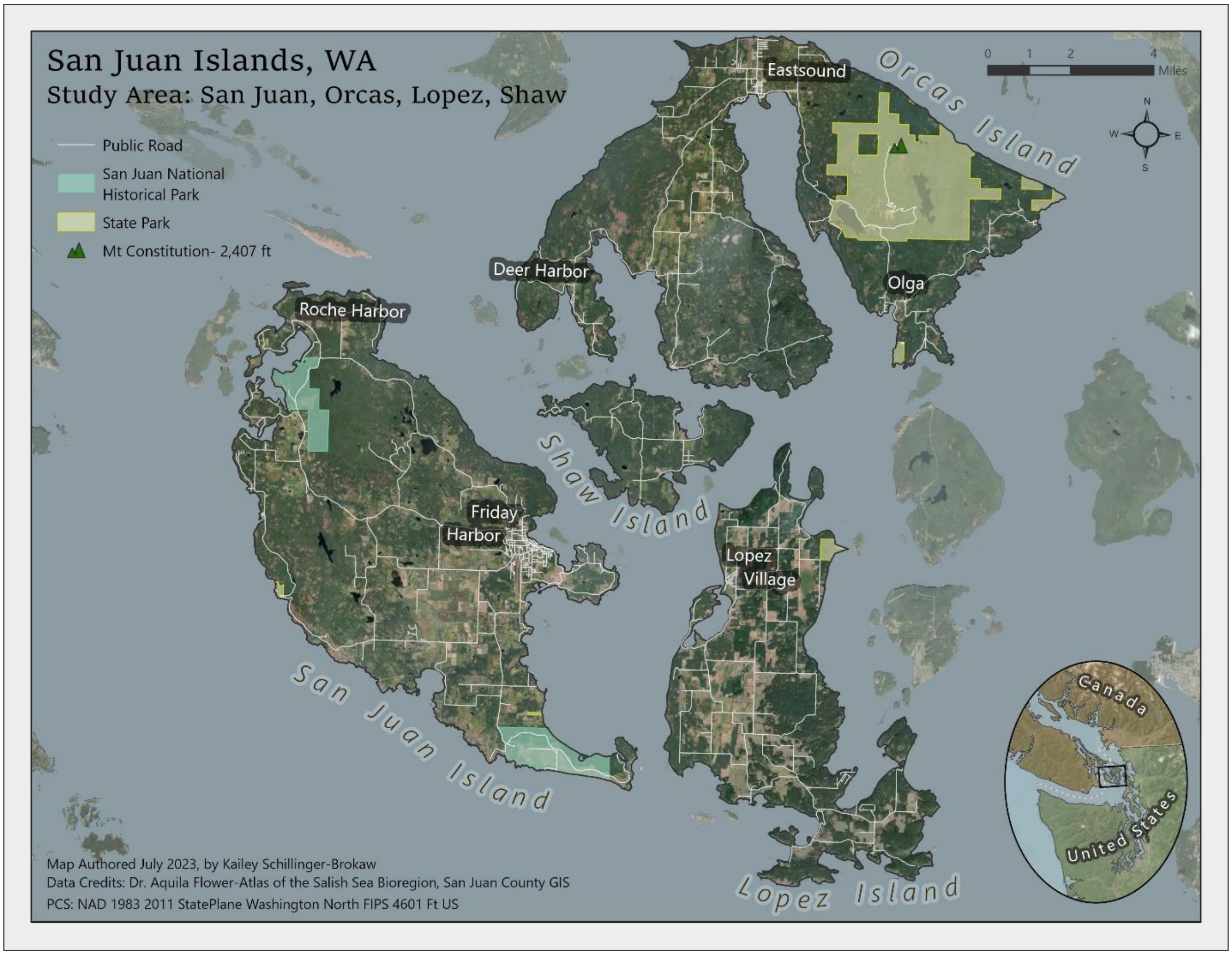


Figure 2: Map depicting the San Juan Islands, indicating the four islands included in the study area (Orcas, San Juan, Lopez, and Shaw Island).

Located off the coast of western Washington in the Salish Sea, the San Juan Islands form an archipelago of over 400 “permanent” islands and rocky protrusions (permanent refers to protrusions that are always exposed, even during high tide *(World Atlas (San Juan Islands)*, 2022). Part of a submerged mountain range connecting Vancouver Island to the mainland, the rugged and rocky terrain of the islands is covered with signs of glacial movement. Deep striations on the mountain tops and moraines are reminders of the glaciers that carved out the valleys and fjords of the San Juans during the last glaciation (*The Geology of the San Juan Islands (Topography)*, 2006).

Figure 3: San Juan Islands, photograph credits: San Juan Islands Visitor's Bureau

The Olympic Mountains to the South and Vancouver Island to the West form a rain shadow that dramatically impacts the climate of the San Juans, creating a sunnier, drier environment than what is found on the mainland. The average temperature ranges from 42.1 degrees F in January to 61.6 degrees in August, and the average precipitation ranges from a max of 2.98 inches in November to a minimum of 0.48 inches in July, with a mean annual precipitation of about 18 inches (see Figure 3; NOAA, 2023). As a result, the streams on the islands tend to be small and intermittent during the drier, summer months (*The Geology of the San Juan Islands (Topography)*, 2006). Prior to 1850, a healthy population of beavers on the larger islands helped to hold freshwater in dammed ponds. However, their extirpation due to excessive trapping resulted in most of these larger bodies of freshwater drying out (*San Juan Islands - Ecology*, 2022.) While there are lakes on the larger islands of Orcas, Lopez and San Juan, access to freshwater can be limited during the driest part of the year from June-September.

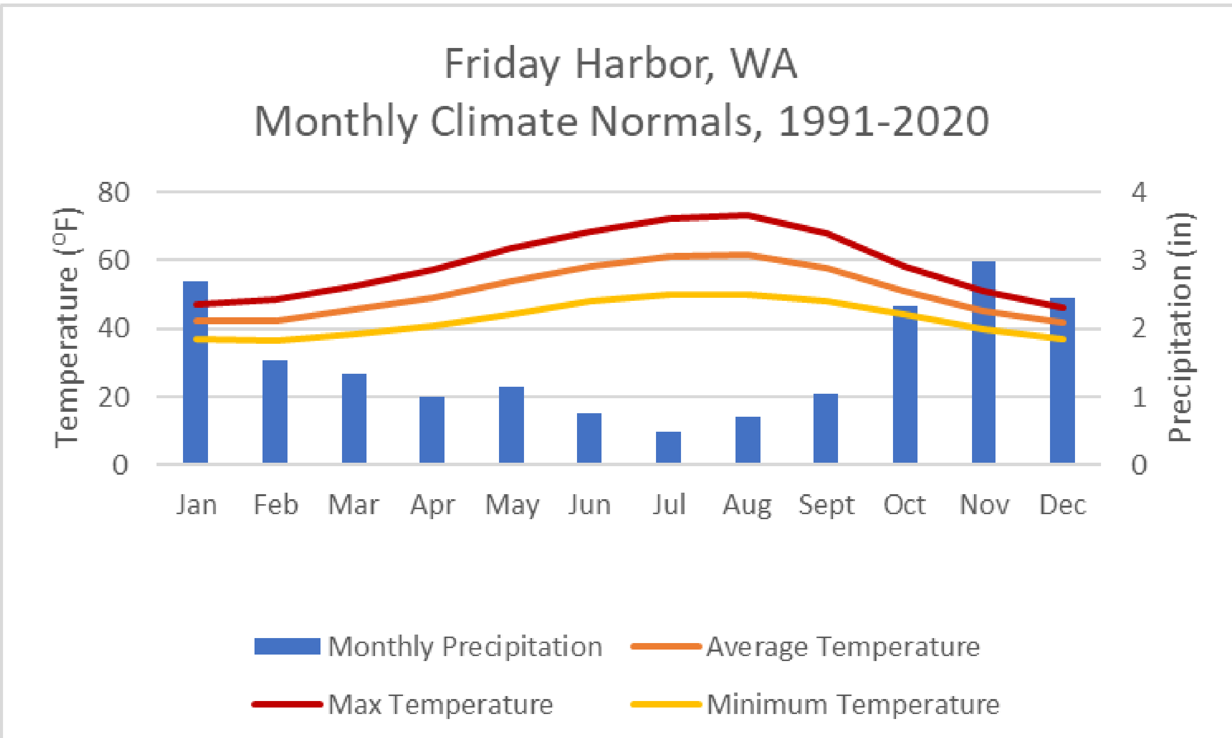


Figure 4: Friday Harbor, WA climate station, monthly climate normals (1991-2020). Data Accessed from: NOAA National Centers for Environmental Information, June 2023.

Grassland Ecosystems: Defined

Temperate Grasslands are a terrestrial biome characterized by a mean annual precipitation range of 11-39 inches, with evapotranspiration exceeding precipitation during the growing season

(Glen M. MacDonald, 2003). There must be a minimum of 10% vegetation cover, of which the structure is dominated by grasses and forbs, with occasional scattered with trees and shrubs forming less <10% canopy cover (Carbutt et al., 2017). Found between 25-55° latitude in both the northern and southern hemispheres, this biome type may be referred to by a variety of names depending on the geographical region, often called "prairies" in North America, "pampas" in South America, "savannahs" in Africa, and "steppes" in much of northern Asia (Carbutt et al., 2017).

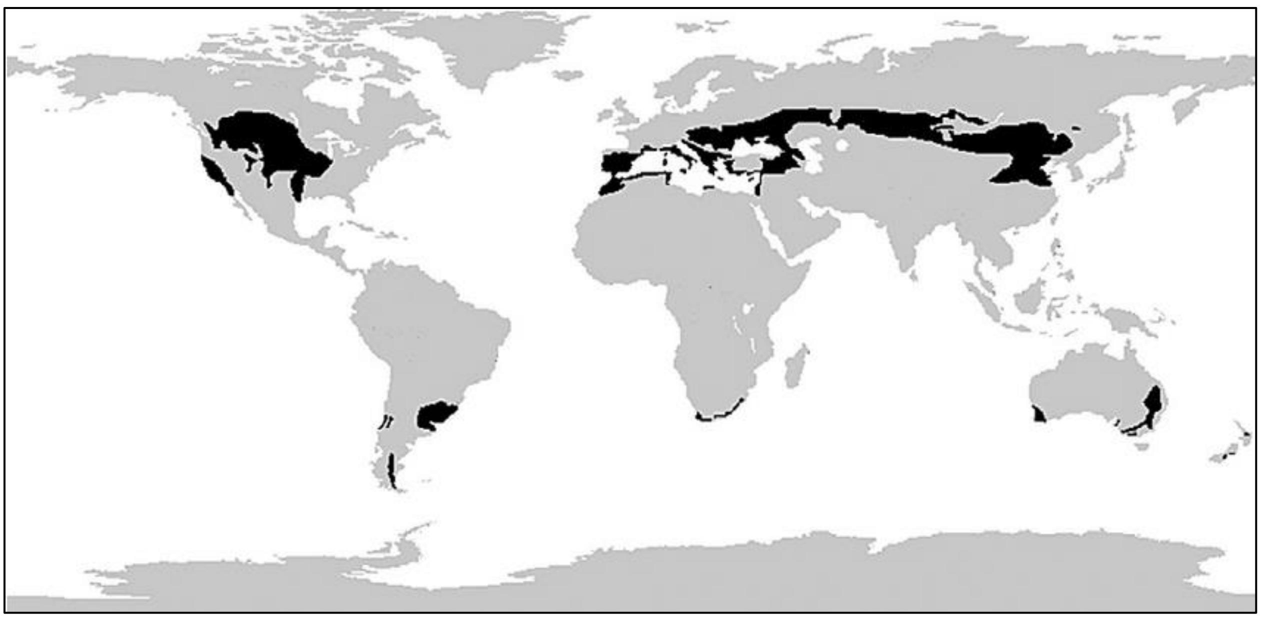


Figure 5:Map of the global distribution of temperate grassland ecosystems. Sala, Osvaldo & Vivanco, Lucía & Flombaum, Pedro. (2013). Grassland Ecosystems. 10.1016/B978-0-12-384719-5.00259-8.

It is important to note that while in some parts of the world abiotic factors such as climate and soil type are sufficient forces to maintain open grasslands, in areas such as the San Juan Islands, trees and shrubs may ultimately encroach unless regular disturbances such as fire or heavy browsing disrupt the cycle of succession (Bengtsson et al., 2019; Dunwiddie, 2002).

Grasslands of the San Juan Islands:

The term “grassland” is broad, and even when limited to temperate grasslands it still includes many different ecosystems. For the purposes of this study the term “grasslands” will be used to refer to ancient, or “old-growth” temperate grasslands- these are grasslands that have assembled over hundreds of years, have a high diversity of native species (often many perennial species), and intricate subsurface structures, all of which enable the ecosystem to rebound after disturbances (Buisson et al., 2022). This more limited definition includes prairies, grassy/rocky balds, Garry-oak savannahs and Garry-oak woodlands, and some meadows (see Figure 6). It is worth noting that while all these terms describe temperate grasslands, each definition comes with its own subtle connotations. For example, the term “prairie” typically refers to large grasslands (in the Puget lowland these can range from hundreds to thousands of acres) with deep, fertile soils on fairly level terrain (Chappell, 2006); “balds” on the other hand, are small patches of grassland (between 5-100 hectares) that occur on slopes with shallow, rocky soils (Chappell, 2006). “Garry-oak woodlands and savannahs” are grasslands with up to 26% Garry-Oak dominated forest cover, and can be found on rocky slopes, patchy mixed-woodlands, or open savannah (Barlow et al., 2021). Finally, the term “meadow” is associated with flower rich grasslands, including those dominated by native species, and managed fields such as hay pastures (*Moor Meadows,* 2015). Although pastures, abandoned agricultural fields, and deforested clearings dominated by grasses may all be considered “meadows,” note that derived grasslands such as abandoned agricultural fields, cultivated pastures, and deforested clearings do not meet the definition of “grasslands” that is used in this study[1].

[1] Although significant efforts were made to distinguish between different types of meadows throughout this study, without detailed vegetation surveys it is impossible to guarantee that every grassland polygon depicts an old-growth grassland. See “*Limitations”* and “*Future Research*” sections in the Discussion for further detail.

Figure 6: Different types of temperate grasslands found on the San Juan Islands. From left to right: A Garry-oak bald restoration site on Jones Island (photo credit: Kailey Schillinger-Brokaw), native prairie at American Camp, San Juan Island (photo credit: National Park Service).

Ecological History of the San Juan Islands:

The grasslands of the San Juan Islands first formed around 9,500 years ago during the warm, dry climatic period that followed the retreat of the Cordilleran ice sheet at the end of the Fraser Glaciation (Coffey et al., 2019). 6,200 years later, (3,800 years before present (ybp)) a shift to a cooler and wetter climate resulted in a successional transition to Western red cedar *(Thuja plicata)* and Douglas-fir *(Pseudotsuga menziesii)* forests in many parts of the San Juan Islands (Pellatt & Gedalof, 2014). However, some drier, south facing slopes of the islands were slower to transition. While the persistence of these patches of grassland can be partially attributed to environmental conditions such as shallow soil and intense exposure to wind or sun (Agee & Dunwiddie, 1984; Coffey et al., 2019), there is likely more to the story. Records indicate that while fire activity on the islands was relatively low from 3800 ybp to present day, many grassland sites continued to experience frequent burns during that time, inconsistent with the forested areas surrounding them and indicative of cultural burning (Brown and Hebda, 2002; Pellatt & Gedalof, 2014).

Cultural Significance and the Role of Fire

The oral traditions of Coast Salish peoples, in conjunction with studies of the fire history of the San Juans, indicate that many of the grassland ecosystems of the San Juan Islands bear the marks of thousands of years of management by Coast Salish peoples, including the Lummi, Samish, Swinomish, Saanich, and Lekwungen (Gomes, 2013; Coffey et al., 2019). From the histories of these tribes, we know that many grasslands were agricultural sites of significance and were carefully managed and maintained for the sustainable production of bulb and root crops, such as common camas (*Camassia quamash*), chocolate lily (*Fritillaria afinis*), Columbia lily (*Lilium columbianum*), crown brodiaea (*Broadiaea coronaria*), and wild carrot (*Conioselinum spp.*) (Brown & Hebda, 2002; Gomes, 2013; Pratt, 2019). These accounts also tell us that open grasslands were maintained using annual, low-intensity burns following the late spring harvest of bulbs. This fire regime would prevent the encroachment of trees and large shrubs, while also increasing the productivity of crops such as *C. quamash* in the following year (Shebtiz and Storm, 2006).

Fire studies conducted on the San Juan Islands and the nearby Gulf Islands of British Columbia indicate similar patterns. Dendrochronological studies using burn scar analysis to document the fire history of the San Juan Islands have been able to date incidences of fire on the islands as far back as 1530 (Sprenger and Dunwiddie, 2011), with a significant decrease in both anthropogenic and naturally occurring fires post European-American settlement of the islands, or around 1870 (Bakker et al., 2016; Sprenger and Dunwiddie, 2011; Spurbeck and Keenum, 2005). These findings have been supported by forest structure analysis on several islands including Orcas and Yellow Island, in which stand composition indicates that portions of the forested landscape have changed from open woodlands to closed canopy forest since the 19th century (Dunwiddie, 2002; Peterson and Hammer, 2001).

Due to the generations of maintenance and management by the Coast Salish Peoples of the San Juan Islands, the grasslands of the San Juan Islands could be considered a "cultural landscape." Defined as the "*combined works of nature and of man, they [cultural landscapes] are illustrative of the evolution of human society and settlement over time, under the influence of the physical constraints and/or opportunities presented by their natural environment…*" (Operational Guidelines for the Implementation of the World Heritage Convention, 2021.) Simply put, human intervention and action maintained a naturally occurring landscape, and played an active role in the gradual development of old-growth temperate grasslands. The resulting ecosystem is an essential part of the greater biological community, that when unaltered or degraded provides a suite of ecoservices that greatly impact the ecological balance of the Salish Sea bioregion.

One of the most notable features of old-growth grasslands is their high levels of biodiversity. The grasslands of the San Juan Islands are no exception, and support many plant and animal species that are not found in other ecosystems; in fact, a study conducted in 2004 found that 60% of the plant species identified in grassland prairies of the Salish Sea bioregion had high habitat fidelity, and were unlikely to be found anywhere else (Chappell, 2006; Pellat & Gedalof, 2006). Furthermore, these grasslands provide critical habitat for over 100 at-risk, threatened and endangered species, including the Island Marble butterfly (*Euchloe ausonides insulanus*), Taylor's checkerspot butterfly (*Euphydryas editha taylori*), streaked horned lark (*Eremophila alpestris*), and golden paintbrush (*Castilleja levisceta*) (Chappell, 2006; NPS).

In addition to being a source of biodiversity, old-growth grasslands have the potential to be a source for foraged foods. While grasslands dominated by invasive grasses and shrubs provide limited opportunity for foraged foods, ecologically diverse grasslands boast a diverse array of nutrient dense edible plants (Sarkar et al., 2020; Thompson, 2022). Furthermore, natural (i.e. unmanaged) grasslands are believed to provide superior fodder for livestock (Bengtsson et al., 2019). The use of grasslands for rangeland and pasture is common across the globe and is one of the main uses of grasslands on the San Juan Islands today. However, it should be noted that in this case, the use of old-growth grasslands for grazing has resulted in extensive alteration and degradation of the ecosystem (see “Current Threats” section). Due to their diverse assemblage of perennial species and complex below-ground structures, old-growth grasslands provide a remarkable number of regulating services. Native grass species, which are well adapted to local seasonal shifts in precipitation and temperature, have root systems that improve water infiltration and storage-in some cases reducing runoff by as much as 20% when compared to cropland (Bengtsson et al., 2019). These root systems are also responsible for reducing erosion by stabilizing the soil (Bengtsson et al., 2019). On the San Juan Islands where there are many rocky bluffs with steep slopes and shallow soils, this is an exceptionally valuable service.

While forests are well recognized for their carbon sequestering properties, grasslands are widely uncelebrated for providing the same service. Permanent grasslands can store large amounts of carbon in the soil-in some cases, just as much if not more than forest soils (Bengtsson, 2019; Buisson et al., 2022). In fact, although temperate grasslands make up only 8% of terrestrial ecosystems, they are responsible for storing 10-30% of soil carbon reserves (Bork and Badiou, 2017). In addition to providing carbon sequestration, grasslands have temperature-lowering benefits due to their high reflectance properties (Carbutt et al., 2017).

Pollination services are critical for the production of both wild and cultivated foods (FAO, nd). In order to perform this essential service, pollinators require suitable habitat and foraging opportunities-which for some species, such as the Island Marble butterfly (*Euchloe ausonides*), can be highly specialized (Schultz et al., 2011). Native pollinator species are also often uniquely adapted to pollinate local plants and thrive in the climatic conditions of a given area, pollinating more efficiently than non-native species (Morales et al., 2017). For example, a study conducted in the San Juan Islands found that approximately 90% of spring-summer pollination in the region is conducted by native bumblebees (Kwiaht, 2023). The grasslands of the San Juan Islands host a variety of flowering plants that provide essential habitat and food sources that support pollinator species that are native to the grasslands of the Pacific Northwest, such as the Sitka bumblebee (*Bombus sitkensis*), and the fuzzy-horned bumble (*Bombus mixtus*) (Kwiaht, 2023). Maintaining a diverse population of pollinators not only improves local food production, but also provides resistance to pollinator diseases and biological pests (Pirk et al., 2017).

Lastly, it is important to acknowledge the cultural services the San Juan Island grasslands provide. These services may take the form of spiritual fulfillment, connection to cultural heritage, recreational opportunity, providing aesthetic value, or even opportunity for scientific study (Bengtsson et al., 2019; Milcu et al., 2013). Given their profound significance to Coast Salish peoples, the grasslands of the San Juan Islands certainly provide cultural ecosystem services in the form of connection to cultural heritage and traditional ways of life. The wildflower meadows, bluffs, and balds of the islands provide recreational opportunities and aesthetic value, drawing tourists to the islands every year-particularly in the spring and summer (San Juan Islands Visitors Bureau, 2023). Finally, the endemic species and rare ecosystems associated with the native grasslands of the San Juan Islands offer opportunities for scientific research. For example, the Island marble butterfly thought to be extinct and rediscovered in 1998 on San Juan Island, has been the subject of several studies exploring the roles of non-invasive introduced plants in conservation and restoration (Anderson and Lambert, 2019).

Colonization, and Introduction of Western Agriculture

When European and American explorers first encountered the San Juan Islands, they made special note of the prairies and oak-savannah woodlands. Early European explorers described these ecosystems using adjectives such as “luxurious” and “park-like” even going so far as to compare the grasslands to Eden (MacDougall et al., 2004). This appreciation was also held by early white settlers, who began establishing permanent settlements in the late 1840s. Historical accounts, such as the reports of the Northwest Boundary Survey (1857-1862) and the journals of the Belle Vue Sheep Farm, reveal that grasslands were coveted by early settlers due to their agricultural potential, and were readily converted to cropland and pasture (Dunwiddie & Bakker, 2011; Pratt, 2019).

Despite being aware of the use of fire by the Coast Salish People, settlers eschewed the use of it themselves, and seem to have been unaware of its role in maintaining the prairies and meadows they so admired. An account from surveyor James Douglas on nearby Vancouver Island captures the general sentiment of early settlers with acute irony: “the soils]... produce [an] abundance of grass and several varieties of red clover on the rich moist bottoms... We saw several acres of clover growing with a luxuriance ... more resembling the close sward of a well-managed lea than the produce of an uncultivated waste” (MacDougall et al., 2004).

The spread of colonization and western agriculture accelerated throughout the late 1800s and into the 1900s, with the recorded population of the San Juan Islands increasing from 147 adults in 1860 to 272 adults and 185 children in 1870 (Eighth Census of the United States, 1860; Pratt, 2019). The influx in population was mirrored by an increase in homesteads, and transition of natural landscapes-particularly grasslands-to western agriculture and pastureland (Dunwiddie & Bakker, 2011; Hall & Crawford, 1996). In addition to the increase in agriculture, another significant impact of the increase in settlement was the exclusion of fire from the landscape. In the absence of a regular fire regime, grasslands that were not being maintained in some other way (such as grazing) began to show signs of encroachment by conifers and shrubs (Boyd, 1999; Coffey et al, 2019; Pellat & Gedalof, 2014; Pyne, 1982). When agriculture was replaced by tourism as the main economic industry on the islands in the 1970s (Vance-Sherman, 2022) the pace of encroachment accelerated. With abandoned fields no longer being maintained for production or grazing, open spaces have quickly filled in with fast growing blackberry (*Rubus armeniacus*), snowberry (*Symphoricarpos albus*), nootka/rugosa rose (*Rosa rugosa*), and Douglas fir.

Current Threats

Although native temperate grasslands have been identified as a highly at-risk ecosystem, they are one of the least protected ecosystems worldwide, and one of the most heavily transformed (Carbutt et al., 2017; Henwood, 2010; Hoekstra et al., 2005). As is the case with native temperate grassland ecosystems worldwide, the grasslands of the San Juan Islands are faced with a variety of threats including landcover conversion, utilization for agriculture, pressure from invasive species, and suppression of regular disturbances such as fire (Bengtsson et al., 2019; Carbutt et al., 2017; Dixon et al., 2014; Fuchs, 2001; NPS, 2015). Without active management, these combined pressures pose a serious threat to the remaining grasslands of the San Juan Islands.

Landcover Conversion and Use for Agriculture

Conversion to cropland is one of the most significant causes of native temperate grassland loss globally; a trend that is also apparent in the native grasslands of the Pacific Northwest, as conversion to agriculture has impacted native grasslands in the Willamette Valley-Puget Trough-Georgia Basin (Dunwiddie & Bakker, 2011). Historical records such as the journal entries of early settlers reveal that native grasslands were prized agricultural land due to the minimal amount of clearing needed in these areas for cultivation, and the richness of the soil (MacDougall et al., 2004). In addition to an initial loss of habitat, the conversion of grasslands to agriculture has also resulted in the introduction of invasive species, leading to further degradation of remaining grasslands (Rocchio, 2012).

Invasive Species

At many sites across the San Juan Islands, invasive plant species such as velvet grass (*Holcus lanatus*), bentgrass (*Agrostis ssp*.), quackgrass (*Elymus repens*), Kentucky bluegrass (*Poa pratensis*), Canada thistle (*Cirsium arvense*), and Himalayan blackberry (*R. armeniacus*) have displaced the native grasses and plants that provide habitat for native wildlife, such as Roemer‘s fescue (*Festuca idahoensis ssp. roemeri*), red fescue (*F. rubra ssp.*), California oatgrass (*Danthonia californica*), foothill sedge (*Carex tumulicola*), common camas (*C. quamash*), great camas (*C. leichtlinii*), field chickweed (*Cerastium arvense*), western buttercup *(Ranunculus occidentalis*), chocolate lily (*Fritillaria lanceolata*), and many-flowered wood rush (*Luzula multiflora)* (Rocchio, 2012). In fact, out of the 700 acres of grassland managed by the NPS on San Juan Island, only 30 acres can currently be considered native grassland (NPS, 2023).

Another example of how invasive species have impacted the grasslands of the San Juan Islands is the European rabbit (*Oryctolagus cuniculus*). Introduced in the late 1800s to a landscape with very few natural predators, the species spread quickly (Rocchio, 2012). European rabbits are unselective herbivores, and will clear areas of vegetation, leaving behind bare, open soil. This behavior has been exceptionally destructive on the San Juan Islands, where the native plants are not well-adapted to such heavy grazing. This, in conjunction with their tendency to create extensive systems of burrows, can dramatically impact the soil as well as water retention; the result being a decrease in native plants, leaving voids that are filled by non-native species (Rocchio, 2012).

Suppression of Fire

Fire has played a substantial role in shaping and maintaining the old-growth grasslands of the San Juan Islands, primarily by preventing the encroachment of tree and shrub species (Agee & Dunwiddie, 1984; Coffey et al., 2019; Dunwiddie & Bakker, 2011; Peterson & Hammer, 2001; Sprenger and Dunwiddie, 2011). The suppression of fire that began with the arrival of early settlers has resulted in extensive encroachment of trees and shrubs into grasslands, particularly Douglas-fir, snowberry, and one-seed hawthorn (*Cratageus monogyna*) (Agee & Dunwiddie, 1984; Peterson & Hammer, 2001; Rocchio, 2012; Schwemm (ed), 2020). Although the importance of regular disturbance such as fire is now recognized in the maintenance of native grassland ecosystems, its implementation on the San Juan Islands has been limited. This is largely due to uncertainty regarding an appropriate regime, and how plant community composition will be affected by new disturbances-particularly the balance of native and invasive species (Coffey et al., 2019; MacDougall et al., 2004).

Research Questions and Goals

Grassland ecosystems have been a key aspect of the San Juan Islands' ecological identity for centuries (Agee, 1984). Providing a wide range of ecosystem services from flood mitigation and erosion control to providing pollinator habitat and climate stabilization, native grasslands do much to improve the ecological health of the San Juan Islands (Degagne et.al, 2021). Given this, as well as their cultural significance to Coast Salish peoples, it is not surprising that there has been a rise in native grassland restoration and preservation projects including: targeted species reintroduction efforts, invasive species removal, and the reintroduction of fire to the landscape. However, despite the surge in initiatives to protect native grasslands, management efforts are hindered by a lack of knowledge regarding historical ecological patterns and conditions on the islands (Smith, 2007; White and Walker, 1997).

Defining a historical baseline of the extent and distribution native grasslands in the San Juan Islands is critical to fully understanding the scope of land cover change in the Pacific Northwest. However, there is a distinct lack of detailed, spatially explicit, accessible historical landcover data for the San Juan Islands throughout the 19th and 20th centuries. This knowledge gap regarding the historical extent of native grasslands poses a significant challenge to land managers and conservationists looking to protect and restore grasslands on the San Juan Islands.

I aimed to address this knowledge gap by using GIS techniques and historical landcover data sources to create spatial datasets describing the locations of grassland ecosystems on the San Juan Islands over the past 133 years. Specifically, I asked the following questions:

- What was the historical extent and distribution of grassland ecosystems on the San Juan Islands at the start of widespread European and American colonization (1890)?

- How has the extent and distribution of grasslands changed quantitatively and spatially over the past 133 years, with regards to:
    - Area- What are the changes in overall grassland patch size?
    - Fragmentation- How has the average distance between grassland patches, and the ratio of edge-to-core area, changed over time?
    - Changes in land use/land cover (LULC)- What landcover types have replaced grassland ecosystems during this time period?

This information will make it possible to calculate how much grassland habitat has been lost on the San Juan Islands, determine what landcover types have replaced grasslands, and track the rate of change over time. These data and the metrics that can be derived from them could assist land managers such as the San Juan Islands National Historic Park or the San Juan Islands Conservation District in developing informed restoration and conservation initiatives and policies.

Methods

In this study, I aimed to create spatial datasets that depict the locations and extent of non-agricultural grassland ecosystems on the San Juan Islands during the early historical period (mid-17th century-late 19th century) and up to the present day (Sprenger et al, 2011). To achieve this, I used the spatial analysis software ArcGIS Pro to digitize historical landcover data sources including hand drawn maps and black and white aerial photographs. This process involved acquiring historical data sources, ensuring that they were accurately georeferenced (aligned to accurate locations on the earth's surface), and manually tracing landcover features to create landcover polygons that could subsequently be analyzed. To address the question of how the extent and distribution of these ecosystems has changed, I undertook the task of creating a contemporary landcover dataset, which could be compared to the historical datasets and used to calculate general ecological trends. This process was also conducted using ArcGIS Pro and involved acquiring multiband spectral imagery for the study area. The imagery was used to generate a "stack" that included multiple images and indices used to measure various qualities of the landscape, such as vegetation health and density. This stack was then analyzed by a classification model that utilized carefully chosen training samples to evaluate the image and generate a new raster showing the classified landcover of the study area.

My analysis of the landcover datasets created by the above processes aimed to address the questions of *how* the extent and distribution of grassland ecosystems on the San Juan Islands has changed over the past 133 years. Using a combination of analysis in ArcGIS Pro and Excel, I measured and compared various attributes of the landcover datasets, including area, distance between patches, edge-core ratio, and what landcover types replaced grasslands. These results are shared as tables, charts, and in a series of maps of the study area. The maps, as well as the datasets used to create them, are available for use through my user account on ArcOnline. By ensuring that this information is accessible to land managers and stewardship organizations, I hope to aid in the efficient and effective implementation of grassland restoration projects on the San Juan Islands.

Data Sources:

Table 1: Data sources used, dates covered, and point of access.

Historical Data Source	Collected By	Time Frame	Accessed From	Details
T Sheets	United States Coastal Survey (USGS)	1888-1897	Puget Sound River History Project, University of Washington's Digital Collection	Data Type- Hand drawn maps Resolution- 1:10,000
Aerial Photographs	Canadian Military	1932	San Juan County GIS, ArcOnline	Data Type- Black and white aerial photograph Pixel Resolution- 1x1 (ft)
Remotely Sensed Imagery	NAIP	2021	USDA Aerial Imagery Program/NOAA WA	Data Type- 4-band multispectral aerial imagery Resolution- 60X60 (cm)

T-Sheets

The "T-sheets" refers to a series of hand drawn topographic maps that were created by the United States Coastal Survey (later renamed to the United States Coast and Geodetic Survey) in the late 1800s (1852-1926). The survey covered coastal areas in the Puget Sound and up into the Strait of Georgia, including the San Juan Islands and Point Roberts. The maps that cover the extent of the San Juan Islands were completed during 1888-1897, and provide valuable insight to the landcover and extent of development on the islands during that time.

Figure 7: T-Sheet 2194, San Juan Island (Northwest)

Each island in the study area was mapped at a scale of 1:10,000, and includes 20 ft contour lines, the total miles of shoreline and roads for each island, the area of the island in sq miles, as well as buildings, fence lines, and at least eight different categories of landcover represented by unique patterns: forest, sparse or slashed forest, grassland, cultivated field, orchard, marsh, wooded marsh, and bluff/beach. In some areas multiple landcover types appear to be intermixed, likely representing ecotones or more nuanced ecosystems such as oak-savannah grasslands. Although the original T-Sheets do not include a legend, the most commonly used and widely accepted legend for these documents was developed in 2000 by Tom Schroeder, and is based off of a US Coast and Geodetic Survey Report that includes an appendix on topographic symbols used by the organization at that time (WSU Libraries Digital Collections - WSU Libraries Digital Collections).

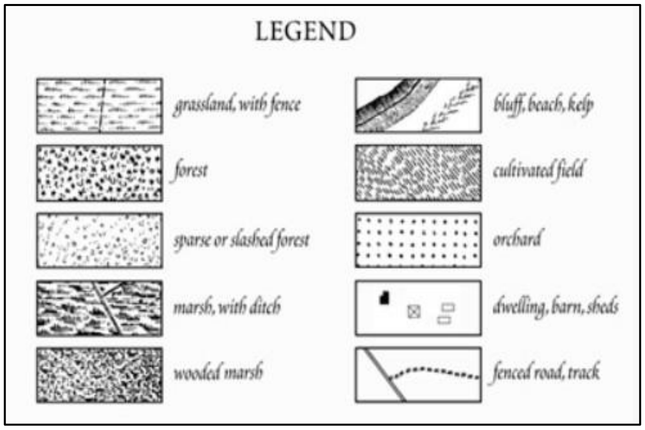


Figure 8: T-Sheet legend, WSU Libraries Digital Collections

The T-sheets have been converted to contemporary datums (NAD 27 and NAD 83), scanned, and georeferenced by the Puget Sound River History Project (PSRHP), a research group within the Department of Earth and Space Sciences at the University of Washington. I downloaded a total of 15 T-Sheet image tiles from the PSRHP website to cover the extent of the four islands included in the study area for this project. The T-sheets for this study area were downloaded in the NAD 27 datum UTM Zone 10 PCS, but were projected to NAD 83 State Plane Washington North (US Feet) to ensure consistency with other datasets (see "*Creating Historical Landcover Datasets-1890*").

It must be acknowledged that the T-sheets are not the earliest maps with landcover data of the San Juan Islands. They are predated by a series of cadastral plat maps from a Public Land Survey of the Puget Sound created by the General Land Office (GLO) between 1850-1890. Plat maps from this survey show cadastral plots within a township or region, and include field notes describing the landcover and other notable features of the plot. These historical survey records are available through the Bureau of Land Management website. Unfortunately, not all of the plat maps and field notes from the 1850-1890 survey for the San Juan Islands are available. Due to the lack of complete data for the study area and particularly the lack of field notes containing landcover descriptions, I decided to forgo the use of the GLO plat maps, and use the T-Sheets as the earliest data point for this study.

Aerial Survey of the San Juan Islands

In 1932 the Canadian military conducted an aerial survey of the San Juan Islands, capturing a set of about 500 black and white photographs of the islands. These photographs are surprisingly clear when compared to other aerial photographs taken at that time period and provide a detailed record of the landcover, land use, and development on the islands at the start of the 1930s. The photographs were likely taken over several months, given that planes at the time could only remain aloft for several hours at a time (A snapshot of history | The Journal of the San Juan Islands (sanjuanjournal.com). Although there is no acquisition date associated with these photographs, the density of foliage on both forests and orchards, as well as the clear patterns in croplands from plowing, hay mowing, and harvesting suggest that these photographs were taken during the late spring or summer months.

Through a partnership between San Juan County's Public Works department and the Washington Department of Natural Resources, the photos have been scanned, georeferenced and mosaiced into a single imagery layer that is hosted as a basemap on the county's GIS imaging software, Polaris, as well as on ArcOnline.

Figure 9: Northern San Juan Island, scale   Screen capture from aerial imagery basemap, (data credits: San Juan County GIS)

Multispectral Imagery

The multispectral imagery utilized for present day classification of landcover was acquired through the United States Department of Agriculture (USAD) National Aerial Imagery Program (NAIP). The program conducts surveys to capture high resolution multispectral imagery of the entire United States during the peak growing season. Capturing imagery when foliage is most full can make it easier to distinguish landcover types and specific agricultural crops, as well as vegetation health (*2010 NAIP Color and Color Infrared Orthophotography*, n.d.). The imagery for this study includes four spectral bands: red, blue, green, and near infrared. These bands can be used to generate natural color and false color images, and to create indices to measure the health and density of vegetation such as NDVI (Normalized Difference Vegetation Index) and SAVI (Soil-Adjusted Vegetation Index).

There are other types of multispectral imagery that include more bands, enabling the user to generate a wider range of indices; Landsat 9, for example, includes eleven spectral bands. However, the spatial resolution of these images is far coarser than the NAIP imagery; Landsat 9 imagery has a resolution of 30 x 30 meters, while the most recent NAIP imagery for the San Juan Islands has a resolution of 60 x 60 cm. Given the relatively small extent of my study area and the generally small size of the grassland ecosystems found there, fine spatial resolution of multispectral imagery was prioritized over higher spectral resolution (the quantity of bands of electromagnetic energy recorded).

Table 2: NAIP Imagery Metadata, USDA FPAC-BC-GEO

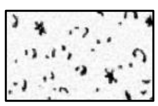
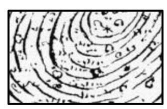
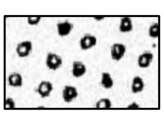
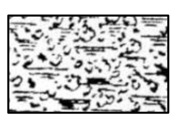
Image Acquisition Date	07/19/2021
Camera Type & Model	Digital, SH120
Aircraft Type	C441 (Cessna 441)
Spatial Resolution	60 cm
Bands Included	Red, Green, Blue, Near-Infrared
Pixel Depth	

Creating Historical Landcover Datasets-1890

Scanned versions of the T-Sheets covering the extent of my study area were downloaded from the Puget Sound River History Project’s data portal. These image layers were georeferenced by PSRHP researchers using the NAD 27 UTM Zone 10 North Projected Coordinate System (PCS). Although this projection is suitable for areas in northern Washington state, the T-Sheets were projected to use the NAD 83 Washington State Plane North (US Feet) PCS to ensure consistency with the 1932 datasets. A feature dataset was created to contain all historical data layers derived from the T-Sheets, ensuring that all feature classes created within the dataset would share a common coordinate system and projection (NAD 83 State Plane Washington North (US Feet), while also allowing for the creation and application of coded domains to individual fields within feature classes.

Applying a coded domain to a field within a feature class allows a user to establish possible attributes for a given field prior to any data creation. This ensures that only the attributes included in the coded domain will be available to apply to new features, and that the attributes will be applied with consistent casing, spelling, and aliases. For this project, a coded domain was created for the “Type” field of the “Landcover-1890s” feature class. The values for this domain, and their codes and descriptions are shown in the table below. The landcover types to be included in the domain were determined based off the map legend.

Table 3: Landcover symbology and descriptions from the T-Sheets.

Land Cover-1890s				
Forest	Sparse Forest	Grassy Forest	Grassland	Cultivated Field
				
Forested landcover	Landscapes with sparse tree/canopy cover, or recently cleared/logged areas	Landscapes with sparse tree cover and grassland intermixed. Includes Garry-Oak savannahs and woodlands	Includes prairies, meadows, and fenced pastures	Farmland-includes cropland and homesteads
Orchard	Marsh	Wooded Marsh	Beach/Bluff	
			 	
Farmland in production of tree fruits	Includes marshes and other wetlands	Marshes and wetlands with some tree cover	Beaches, rocky bluffs, prominent sandbars, rocky protrusions	

To improve the efficiency of the digitization process, a shorezone polyline feature class was used as a boundary for the islands. Created by the Washington State Department of Natural Resources ShoreZone Inventory Program between 1994-2000 (Berry et al., n.d.), this shoreline feature class provided a reasonably accurate boundary that digitized landcover polygons could be aligned to. Although the shoreline of the present day is not identical to the shoreline that is delineated in the T-Sheets, the changes in shoreline detail are not significant enough to impact the general location of inland landcover polygons. In areas where the T-sheet nearshore areas extended beyond the contemporary shoreline feature, landcover was mapped only to the extent of the shoreline and areas extending beyond were not included.

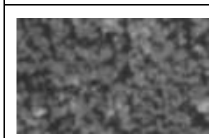
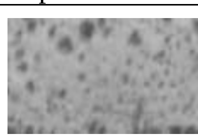
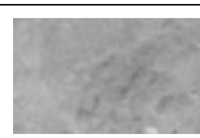
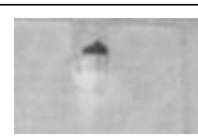
Map topology rules were established for the digitization process, ensuring that newly created features would be aligned without gaps or overlapping. Each T-sheet was manually digitized at a scale of 1:1,500, using precise visual assessment of the landcover patterns. A preliminary review of the T-sheets revealed that there were multiple instances of grassland symbology overlapping with sparse forest or forest symbology. While this intermixing of landcover types could represent an ecotone, it may have been intended to represent Garry-oak savannahs and grassy bald ecosystems (two types of grassland ecosystems that include sparse tree cover). Given the prevalence of these ecosystems on the San Juan Islands, it was deemed appropriate to include an additional landcover category “Mixed Forest/Grassland,” as this classification more accurately represents these nuanced areas than classifying them as “Grassland” or “Forest.” When the landcover of each of the islands in the study area was fully digitized, the dataset was reviewed for errors and consistency in interpretation of landcover symbology.

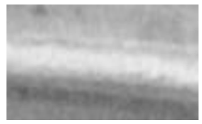
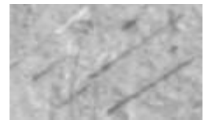
Creating Historical Landcover Datasets-1932

Using the georeferenced and mosaiced aerial imagery basemap hosted by San Juan County, a similar digitization process was preformed to create a landcover dataset for 1932. Given that the 1932 aerial imagery basemap was only available in the PCS NAD 1983 StatePlane Washington North FIPS 4601 (US Feet), the shoreline layer was projected into the same PCS. The feature dataset and landcover feature class for the 1932 dataset were set to use the NAD 1983 StatePlane Washington North PCS as well. A coded domain was applied to the "Landcover Type" field of the "Landcover-1932" feature class, with the same codes as the 1890 "Landcover Type" domain, with the addition of a "Cleared Land" category due to the presence of bare patches that were noticeably different from areas with sparse tree cover, which have scattered, widely spaced trees (see Table 4 below).

The landcover of the islands was carefully evaluated and digitized at a scale of 1:1,500 into the ten different categories described in Table 4 below, using extensive visual assessment of the aerial imagery and consideration of seven visual cues commonly used in aerial imagery analysis: shape, size, pattern, tone, texture, shadow, and context (Kinn, 2020).

Table 4: 1932 Aerial imagery landcover classification examples and descriptions.

Landcover-1932				
Forest	Sparse Forest	Grassy Forest	Grassland	Cultivated Field
				
Forested landscapes	Landscapes with sparse tree/canopy cover	Landscapes with intermixed grassland and sparse tree cover. Includes Garry-Oak savannahs/ woodlands	Includes prairies, meadows, balds, and fenced pastures	Farmland-includes cropland, mowed/sown pastures, and homesteads.

Orchard	Marsh/Wooded Marsh	Beach/Bluff	Cleared Land	Developed
				
Orchards or berry fields	Marshes, wooded marshes, and other wetlands	Beaches, rocky bluffs, prominent sandbars, rocky protrusions	Areas that were forested in 1890, but are cleared of trees in 1932	Areas with a high concentration of buildings and other infrastructure

Given the visual similarity between some landcover types, such as grassland or recently cleared forests, it was essential to consider the history of land use when digitizing the 1932 land cover. Areas that were difficult to classify were evaluated in comparison to the 1890 landcover layer using a paired map view. The landcover of the targeted area circa 1890 could then be used to infer the conditions in 1932. For example, the patch in Figure 10 represents a region on San Juan Island. When viewed in isolation, the area could potentially be grassland, or a recently cleared forest. However, when viewing the same area in 1890, we see that 30 years before the aerial imagery was captured the area was forested. This indicates that the patch in the 1932 landcover cannot be considered native grassland, but rather cleared land or new farmland.

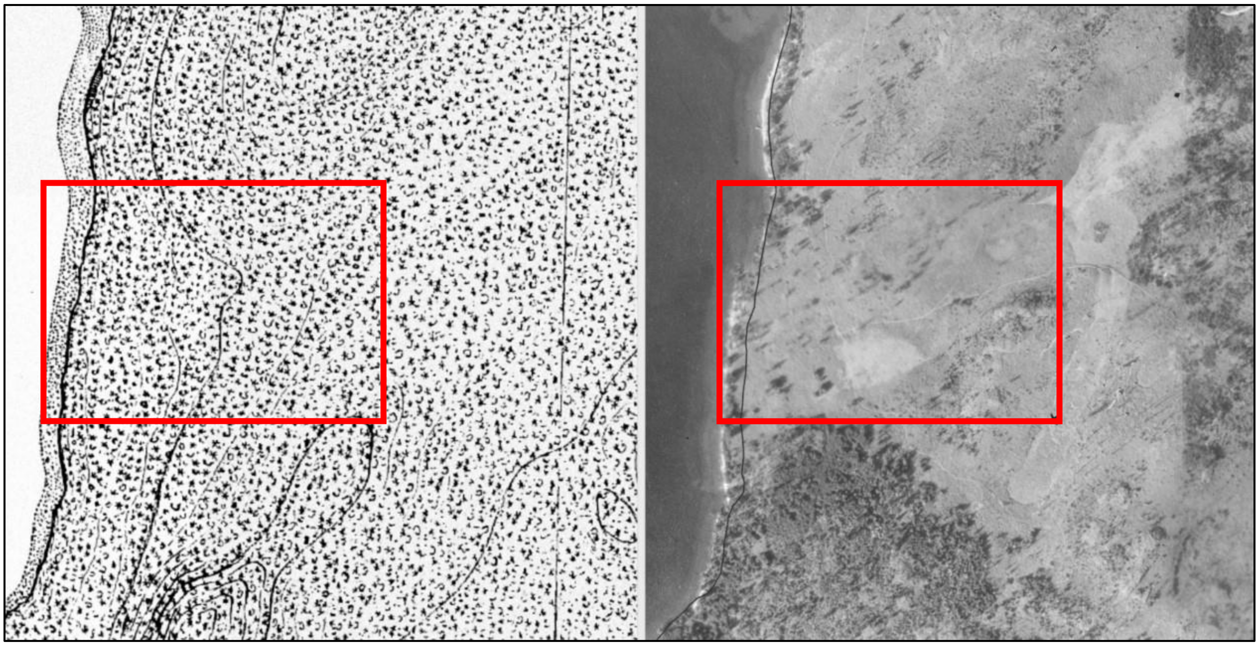


Figure 10: The images above show the same area on Orcas Island. The image to the left shows the area in 1890, and the image to the right shows the same area in 1932. Given that the area was forested in 1890, we can conclude that the landcover in 1932 is cleared land and not native grassland.

There were some instances in which distinguishing between grassland and farmland was exceptionally challenging. While comparing the landcover conditions in 1932 to those in 1890 would provide clarification in those instances in which previously forested areas were cleared, there were many cases in which former grasslands were converted to agriculture or pasture. In these situations, it was necessary to thoroughly consider the characteristics of the patch, as well as the surrounding region.

Table 5: Grassland vs farmland visual assessment considerations

Factors considered for visual assessment of 1932 imagery		
Visual Cue	**Indicator of grassland**	**Indicator of farmland/agriculture**
Shape	Area boundary is irregular, with a gradual transition to other landcover types	Area has sharp, clear borders
Context	Area unfenced	Area fenced

Context	No nearby structures	Nearby structures such as dwellings or barns
Pattern	No regular patterns	Repeating patterns of ripples or grooves (such as furrows from a tractor, plow, or from harvesting)?
Texture/Tone	Texture/tone is irregular, suggesting presence of several plant species growing at different paces	Texture/tone of area is fairly homogeneous (suggesting dominance of a singular plant species)

Creating a Contemporary Land Cover Dataset Using Multi-Spectral Imagery

The multispectral imagery required for the creation of a high-resolution contemporary land cover dataset was imported into ArcPro, clipped to the extent of the study area, and projected into NAD 1983 State Plane Washington North FIPS 4601 (US Feet) PCS. A classification schema was created for the project that closely matched the landcover classification categories used for the 1932 aerial imagery, with the addition of a “Deciduous Forest” category (this was added after an initial classification attempt failed to accurately distinguish between deciduous forests and wetlands, indicating a need for more targeted training samples- see, “Discussion”). Prior to creating training samples, additional landcover layers were added to the project to establish clear boundaries for known locations of certain landcover types. These layers included a wetlands polygon layer (accessed from Washington State DNR, 2023) and a 30-meter resolution landcover raster (USGS National Land Cover Database, 2019).

To minimize bias in sample size, an equal number of similarly sized training samples were created for each landcover group. Samples were evenly dispersed across each of the four islands in the study groups (with the exception of Shaw Island, which received fewer samples than San Juan, Orcas, and Lopez Island due its smaller size). Samples were placed with consideration of known landcover locations-meaning that only areas where landcover was definitively known were used as training sample sites.

I conducted two preliminary rounds of pixel based, supervised classification using the Support Vector Model and Random Trees Classification, to allow for comparison of results. These attempts at classification evaluated only the single 4-band NAIP imagery raster, and utilized 64 training samples per land cover type. Both rounds of classification yielded unsatisfactory results, with presence of wetlands being highly overpredicted in areas of deciduous forest, and high levels of visual "noise." By generating spectral signature charts for each of the landcover types, I observed that the spectral signatures between farmland and grassland landcover classes to be exceedingly similar, indicating a need for more spectral information in the classification process (Figure 11).

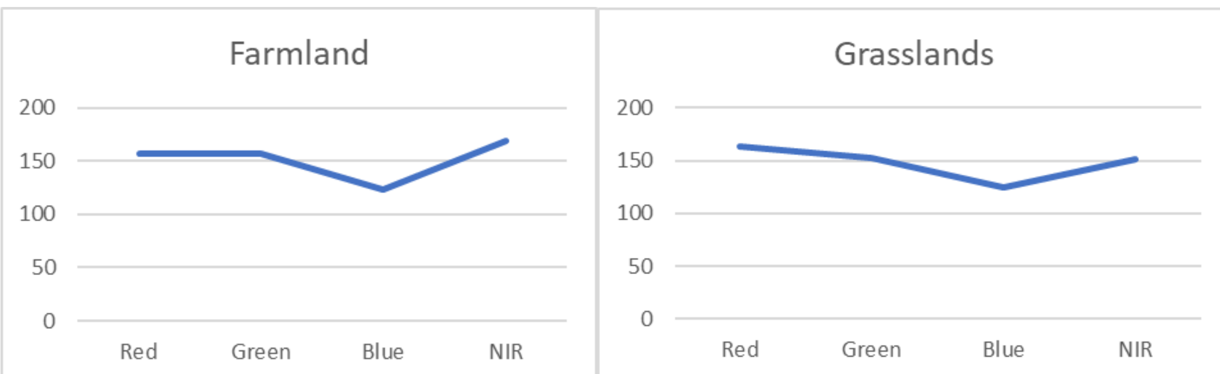


Figure 11: Spectral signature charts generated from 2021 NAIP aerial imagery.

To refine the classification process, several steps were implemented. First, an additional landcover category was created for deciduous forest, and a total of thirty training samples were generated for that additional class. Secondly, following precedent established by USDFW (United States Department of Fish and Wildlife) in the creation of a High-Resolution Land Cover Data layer using 4-band NAIP imagery, classification was conducted on an imagery stack instead of the single 4-band NAIP raster (Pierce, 2015). The stack consisted of the original 4-band imagery, and three indices generated from the original raster: NDVI, SAVI, and a variance raster to emphasize texture, generated from the NIR band.

The variance raster was created by calculating the mean value of pixels within a 9x9 neighborhood using block statistics, then using the raster calculator function to subtract the neighborhood mean from the individual pixel values within the neighborhood to determine the deviation from the mean. The deviation value for each pixel in the neighborhood was squared, then summed. The total was divided by N-1 where N=9 (the neighborhood size).

Sample Variance:

$$s^2 = \frac{\sum(x_i - \bar{x})^2}{(N-1)}$$

This imagery stack was then segmented- a process that groups pixels into objects or *segments*, based on similar spectral characteristics within a neighborhood. These segments are then evaluated for classification as an object, instead of as individual pixels. The result is a landcover raster that represents individual landscape features in a way that mimics the visual interpretation of aerial imagery performed by humans better than pixel-based classification methods.

The image segmentation process in ArcPro allows the user to set certain parameters specifying spectral and spatial detail, and minimum segment size. These parameters determine the smoothness of the image, where higher values of spectral and spatial detail result in greater discrimination between segments, and larger minimum segment values result in fewer individual segments. Given the similarities between landcover classes in the preliminary rounds of classification, I used a high level of spectral detail (20), a moderate value for spatial detail (15) and a minimum segment size of 200 pixels.

I classified the final 6-image stack using the Support Vector Model OBIA method, to minimize noise and manage for any unintended variations in training sample sizes between classes. I reviewed the resulting landcover raster and assessed the accuracy overall, and specifically the accuracy of grassland classification. I first assessed the general accuracy of my landcover raster by conducting a visual comparison of concurrence between my classification results and a series of other landcover datasets (see Table 6 below), including layers representing: wetlands, areas zoned for agricultural use in the Salish Sea bioregion, oak woodlands and grasslands of the Puget Trough ecoregion, and forested lands derived from a 2016 landcover raster. While the classification of developed areas and forested areas seemed accurate based on a qualitative, visual assessment, there were areas where grassland and farmland were clearly misclassified, indicating a need for data review and reclassification. I selected areas classified as grassland or farmland and converted these to a polygon layer, then individually assessed each. I compared each potential grassland polygon with the multispectral NAIP aerial imagery from 2021, Google Earth, and data layers representing parks/protected areas and agriculture areas (Atlas of the Salish Sea Bioregion; USDA National Agricultural Statistics Service), the locations of oaks and grasslands (Washington Natural Heritage Program, Washington DNR), and zoning/tax parcel data within San Juan County (San Juan County GIS) to determine if the polygon represented grassland, farmland, or lawns and other vegetation.

Table 6: Data used for qualitative accuracy assessment of land cover classification raster.

Data Layer	Description	Date/Source Accessed	Details
NAIP Aerial Imagery	Natural color multispectral imagery of the study area, captured in 2021	USDA NAIP aerial imagery program Date accessed: May 2023	Data Type: Raster Resolution: 60 cm

Washington State Croplands Data	Crop-specific landcover data for Washington state, derived from satellite imagery captured during the 2022 growing season. Last updated: January 2023	USDA National Agricultural Statistics Service Date Accessed: September 2023	Data Type: Raster Resolution: 30m
Salish Sea Bioregion Agricultural Areas	Land zoned to prioritize agricultural uses in the Salish Sea Bioregion. Last updated: November 2011	Dr. Aquila Flower's Atlas of the Salish Sea Bioregion Date Accessed: May 2023	Data Type: Vector
Salish Sea Bioregion Parks and Protected Areas	Federal, state, and local parks and other protected areas for the Salish Sea Bioregion. Last updated: November, 2021	Dr. Aquila Flower's Atlas of the Salish Sea Bioregion Date Accessed: May, 2023	Data Type: Vector
Oaks and Grasslands of the Puget Trough Ecoregion	Oak and mixed oak communities, native and non-native grasslands and shrublands. Last updated: October 2022	Washington DNR GIS Open Data Date accessed: March 2023	Data Type: Vector
Parcels	Parcels and attributes for San Juan County WA. Last updated: March 2023	San Juan County Open GIS Data Site Date accessed: July 2023	Data Type: Vector
Wetlands- Forest Practices and Regulations	Wetlands of Washington State, based off of the National Wetlands Inventory (NWI), with reclassified wetland codes.	Washington State DNR GIS Open Data Date accessed: July 2023	Data Type: Vector

Calculation of Change in Grassland Ecosystems

To address my specific research questions regarding what change has occurred in grassland ecosystems on the San Juan Islands since 1890, I conducted statistical analysis of my datasets in ArcGIS Pro and Excel. Changes in grassland area over time were determined by calculating the mean, minimum, and maximum area of grassland patches on each island, as well as the mean patch size across all islands, during each time period. Fragmentation was assessed as a function of the ratio between grassland edge (patch perimeter) to core habitat (patch area). The edge-core ratio was calculated for each grassland patch during each time period, and mean edge-core values for each island during 1890, 1932, and 2021 were derived from these calculations. Distance between grassland patches was calculated by isolating grassland polygons from other landcover types and generating a distance accumulation raster for this layer. Trends in LULC were determined by running an intersect between landcover layers for each time period. Landcover types that overlapped with grassland polygons from the previous time period were identified, and the overlapping area was measured and recorded for all four islands both individually and overall. To determine the percentage of existing grassland sites that are on protected land and identify sites where conservation efforts may be most impactful, I compared the contemporary grasslands data with a protected lands dataset (see Table 6). Areas with a high concentration of grasslands that have been present since 1890 were identified; of these, sites that occur on unprotected land or not currently undergoing known conservation efforts were labeled as "Recommended for Conservation or Restoration."

Results

Extent and Distribution of Grassland Ecosystems on the San Juan Islands, 1890-2021

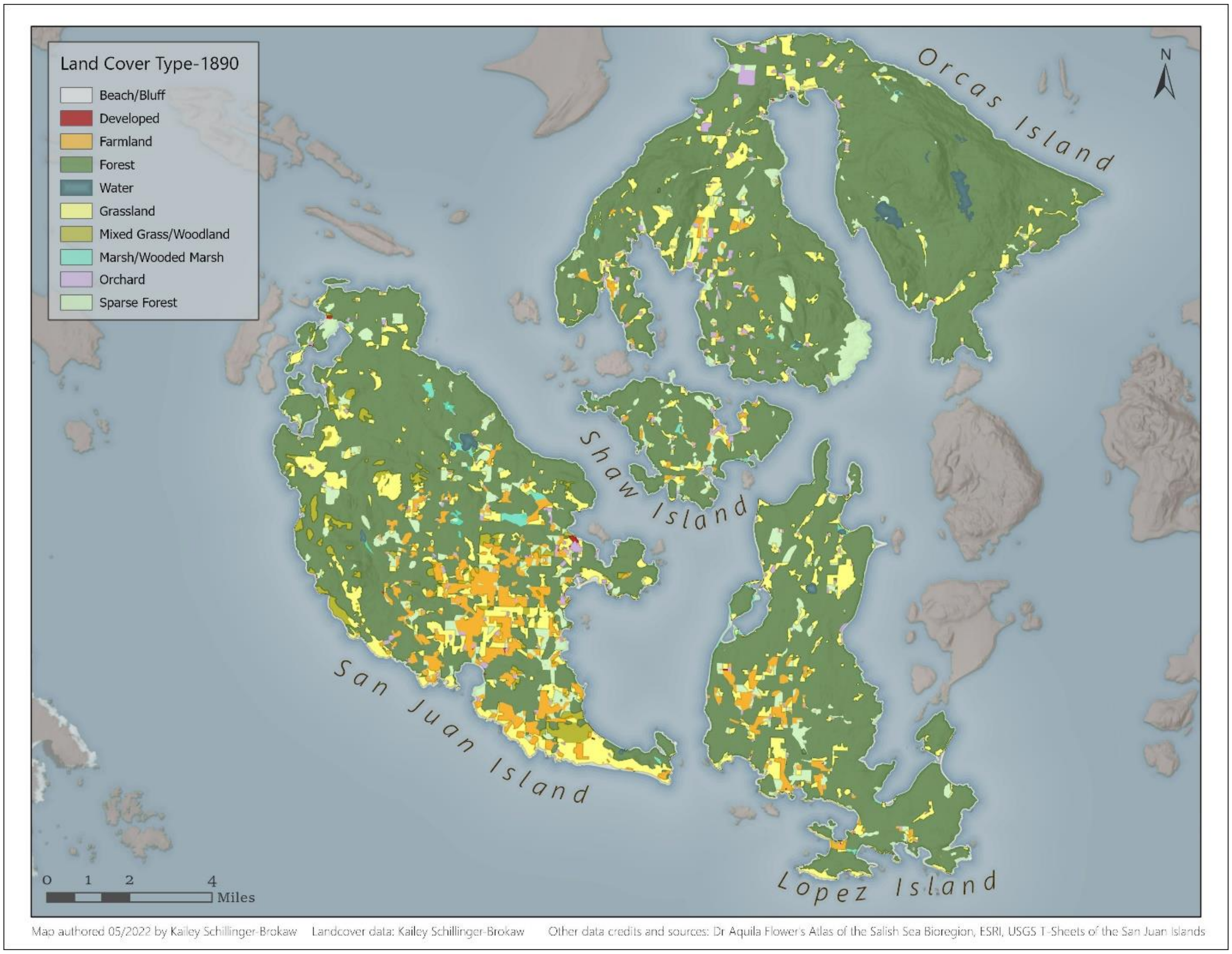
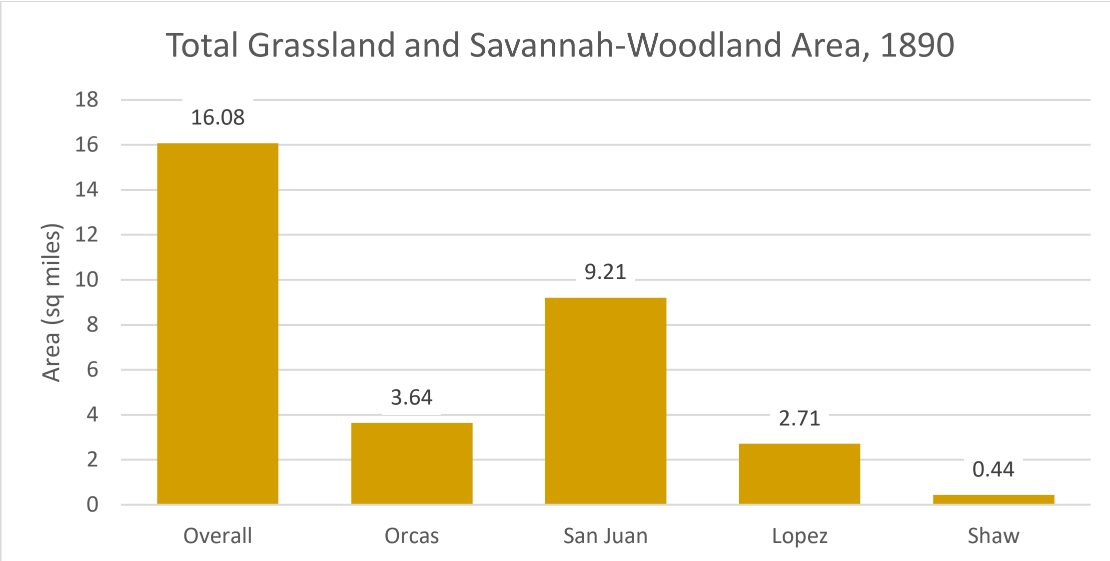


Figure 12: Map showing the landcover of the four largest San Juan Islands in 1890, based off hand drawn survey maps (the T-Sheets).

Digitization of the T-sheets revealed that in 1890 there was a total of 16.08 sq miles of grassland and mixed savannah-woodland on the San Juan Islands, which comprised about 10.7% of the total landcover of the study area at that time. The majority of these grasslands were found on San Juan Island, which had a total of 9.21 sq miles of grassland. This was followed by Orcas Island, with a total of 3.64 sq miles, and Lopez Island with 2.71 sq miles. Shaw had the least area by far, with a total of 0.44 sq miles. Percentage of grassland landcover was highest for San Juan, which had 16.5% of its landcover as grassland or mixed savannah in 1890. Lopez Island had 9.2% grassland landcover, and Orcas and Shaw Island had the least with 6.3% and 5.7%, respectively.



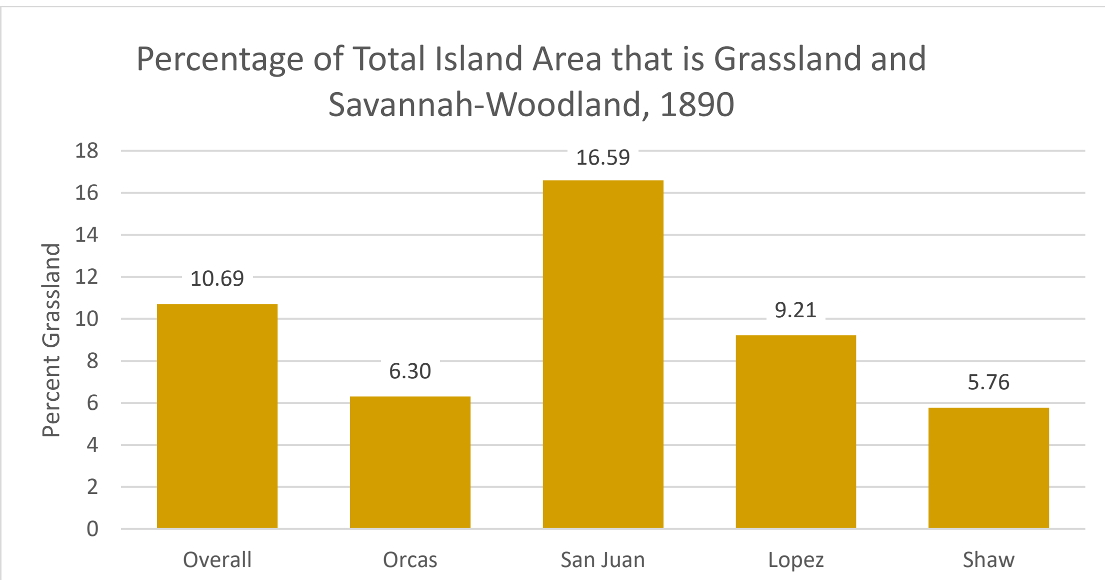


Figure 13: Summary of total grassland and mixed grassland/woodland area and percentage of total landcover on the San Juan Islands in 1890, reported for individual islands and overall.

The mean fragmentation value across all four islands, represented by the ratio of edge to core habitat, was 0.03 in 1890. The mean ratio value of the individual islands ranged from 0.01 (on

Orcas Island) to 0.06 (on San Juan Island), with Shaw Island and Lopez Island having values of 0.02 and 0.03, respectively.

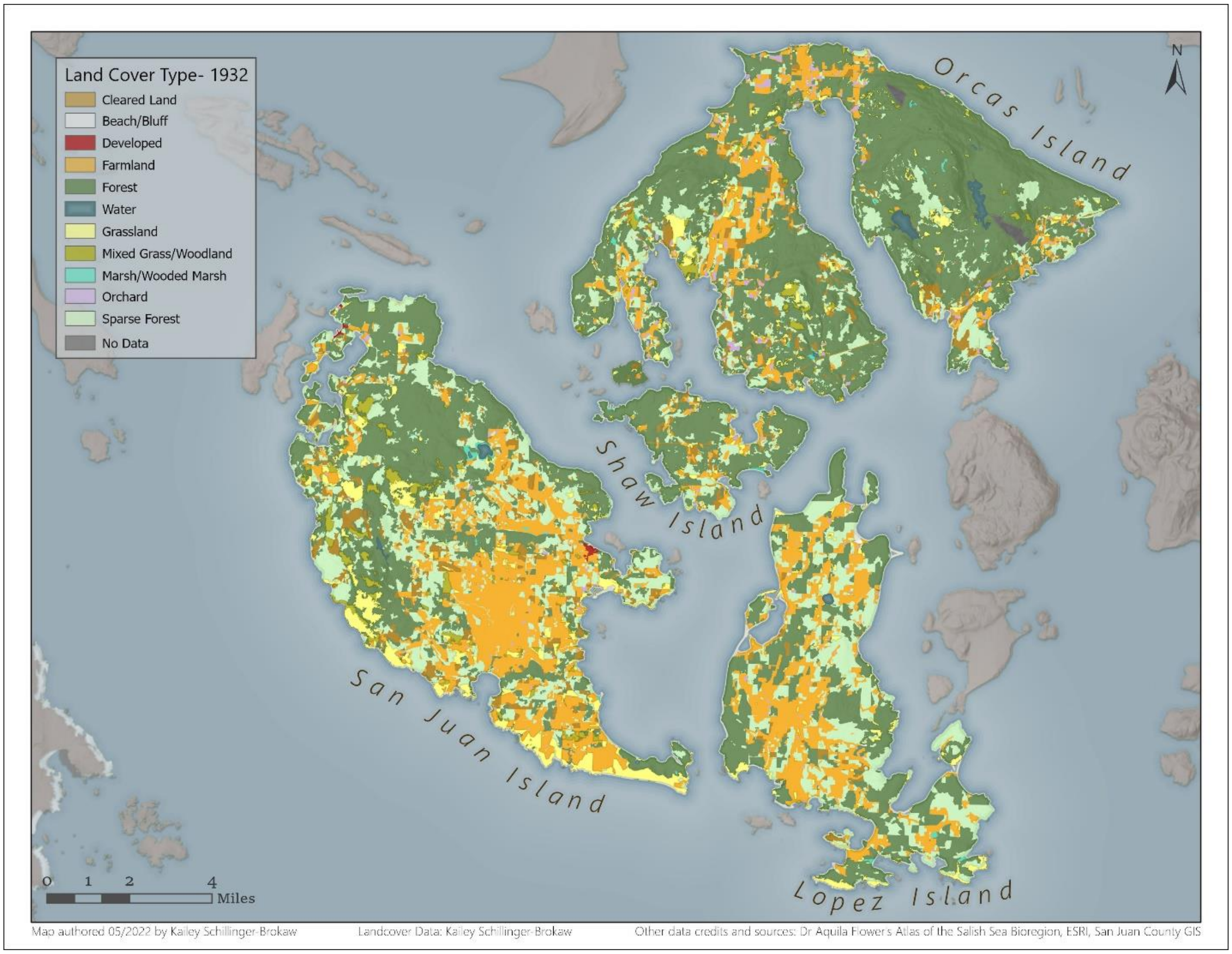
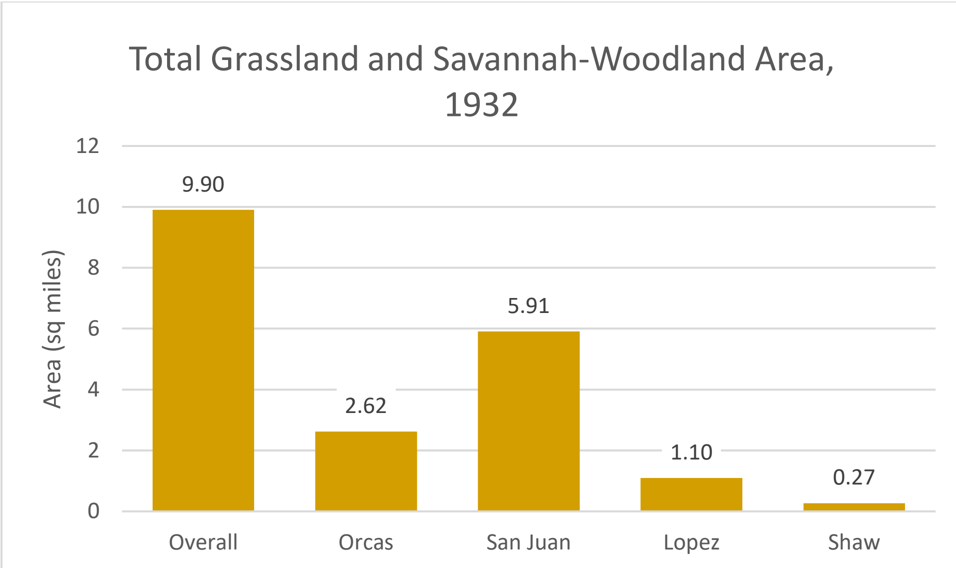


Figure 14: Landcover of the San Juan Islands (1932)

By 1932, the landcover of the study area was approximately 6.59% grassland, totaling about 9.90 sq miles. San Juan Island had the largest total area of grasslands at 5.91 sq miles, which composed about 10.65% of the island's overall landcover. Orcas Island had the second highest amount of total grasslands at 2.62 sq miles, which composed 4.52% of the island's landcover- slightly more than Lopez Island, which was 3.74% grassland and had a total area of 1.10 sq miles. Shaw Island had 0.27 sq miles of grassland, comprising 3.51% of the island's landcover.



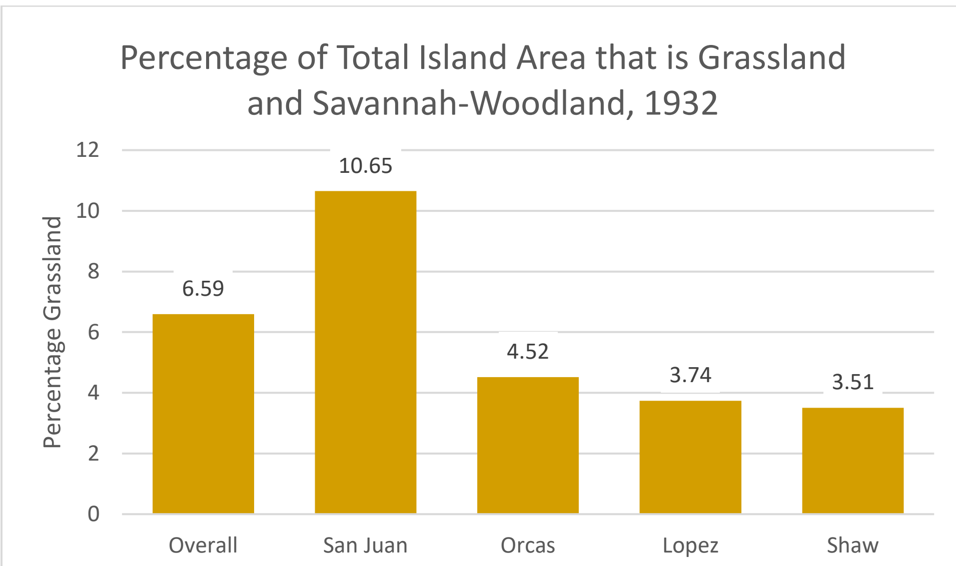


Figure 15: Summary of total grassland and mixed grassland/woodland area on the San Juan Islands in 1932, reported for individual islands and overall.

In 1932, the mean edge-core ratio value across all four islands had increased from 0.03, to 0.22. The mean ratio value of individual islands ranged from 0.04 (San Juan Island) to 0.46 (Lopez Island). Orcas Island had a mean edge-core value of 0.26, and Shaw Island had a mean edge-core value of 0.08.

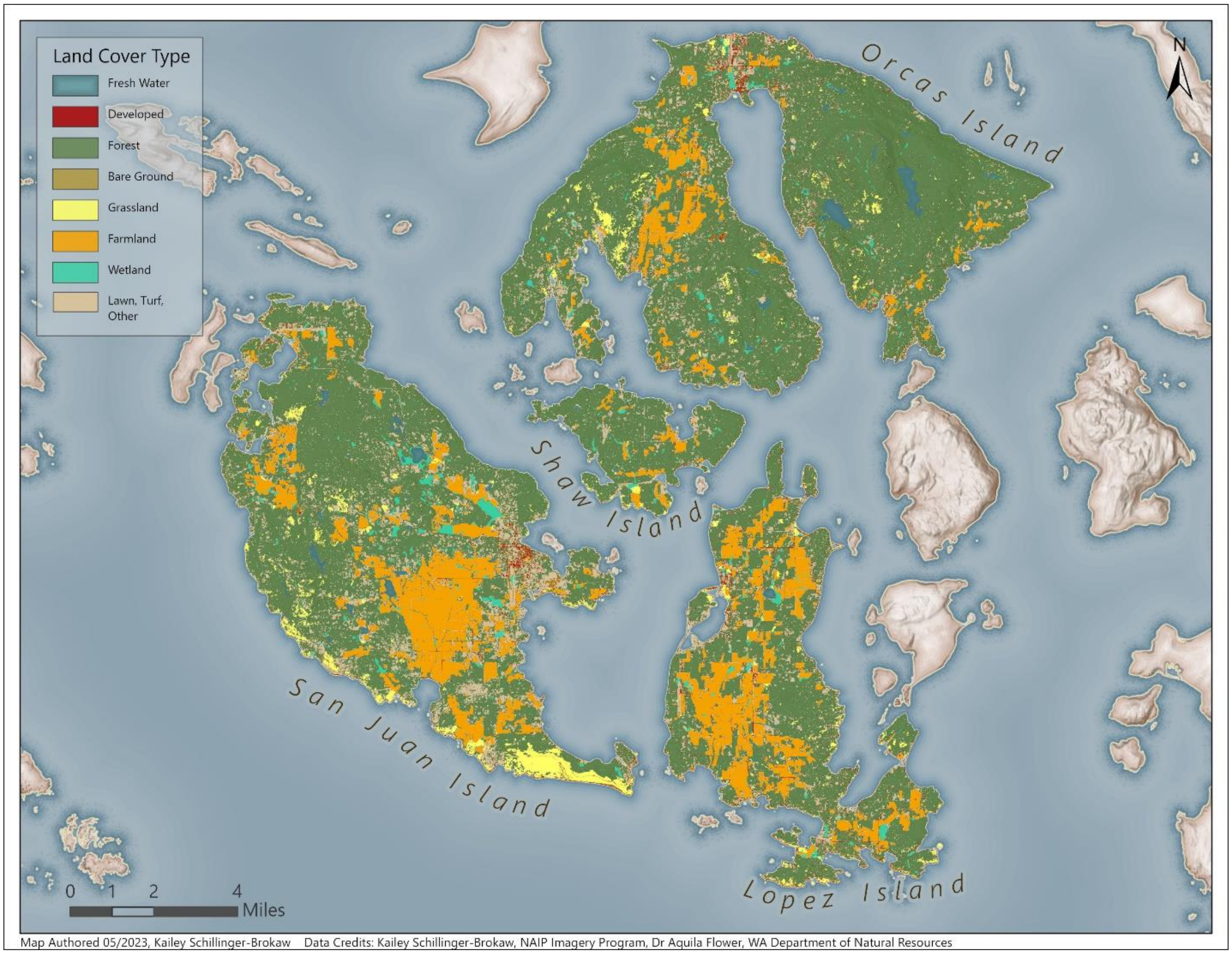
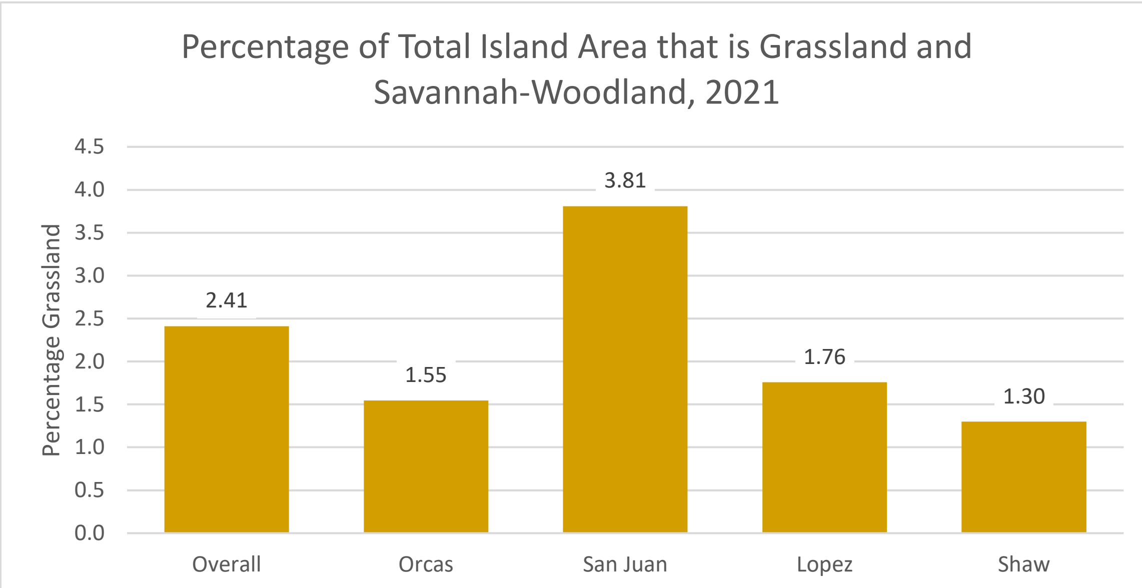


Figure 16: Landcover of the San Juan Islands, 2021

The landcover data generated from the 2021 NAIP imagery (see Figure 16) indicates that as of 2021 there was a total of 3.63 sq miles of grassland on the four islands in my study area, constituting 2.41% of the total landcover on the islands. The majority of these grasslands are found on San Juan Island, which contains 2.07 sq miles-amounting to 3.81% of the island's landcover. Orcas Island hosts the second largest total amount of grasslands at 0.84 sq miles, followed by Lopez Island with 0.47 sq miles, and finally Shaw Island with 0.06 sq miles. As seen in other years studied, although Orcas Island has a larger total amount of grassland than

Lopez Island this does not equate to a higher percentage of grassland landcover. Lopez Island has the second highest percentage of grassland landcover after San Juan Island, with grasslands composing 1.76% of the island's landcover. Grasslands constitute 1.55% of the landcover on Orcas Island, and 1.30% of the landcover on Shaw Island in 2021.



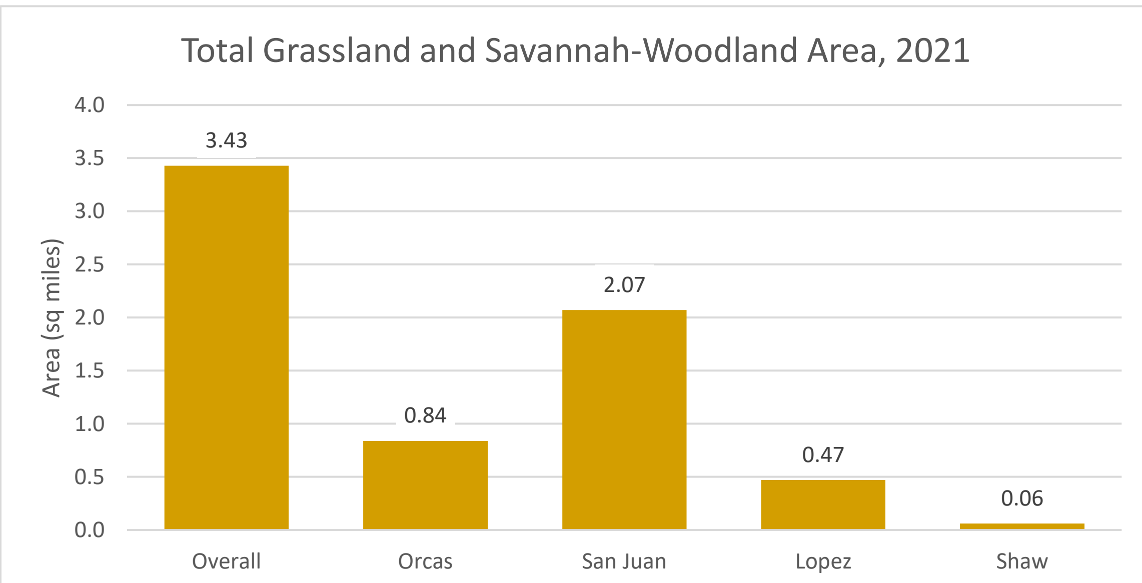


Figure 17: Summary of total grassland and mixed grassland/woodland area and percentage of total landcover that is grassland on the San Juan Islands in 2021, reported for individual islands and overall.

By 2021, the mean edge-core ratio across the islands in the study area had increased from 0.22 to 0.67. The mean values on each island ranged from 0.44 on San Juan Island, to 0.80 on Lopez Island. Orcas Island had an average value of 0.76, and Shaw had a value of 0.54.

Change in Area and Percent Cover of Grasslands and Mixed-Woodlands

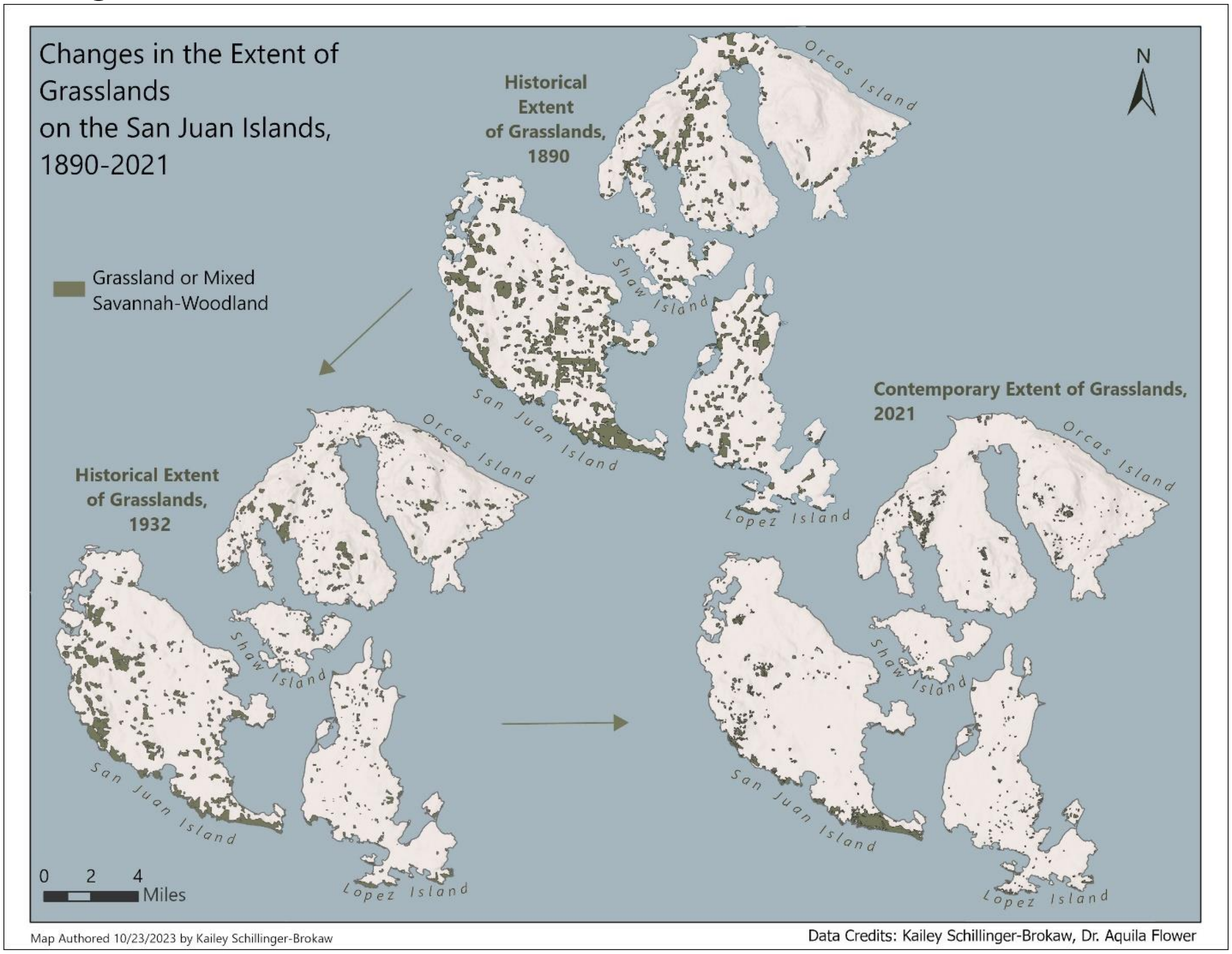


Figure 18: The extent of grassland ecosystems on the San Juan Islands, from 1890-2021.

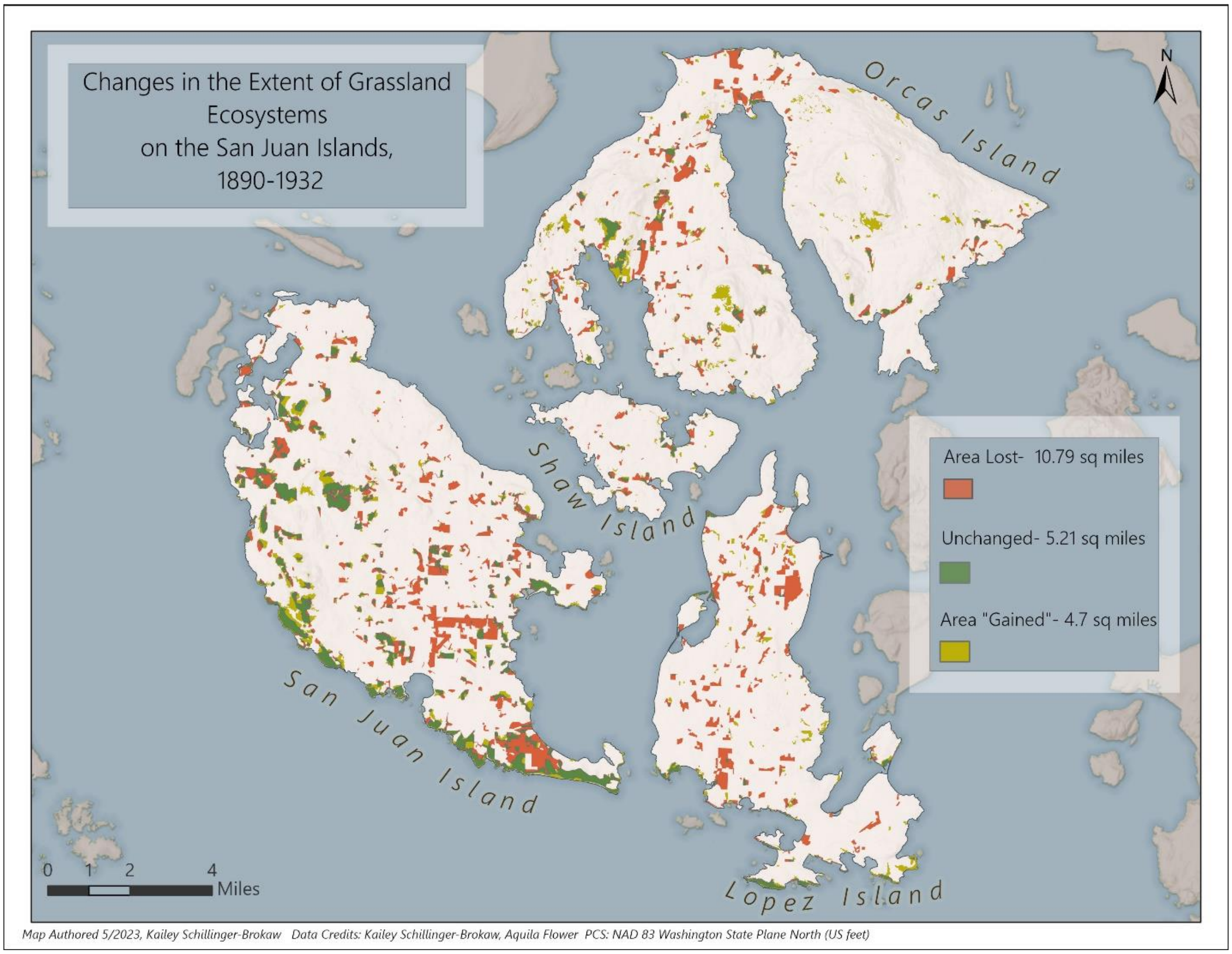


Figure 19: Map showing the changes in grassland area between 1890 and 1932 on the four largest San Juan Islands.

Changes in total grassland area on the four largest San Juan Islands are shown in Figures 18-21. Between 1890 and 1932 there was approximately a 28% decrease in grassland landcover within the study area, due to a loss of 10.79 sq miles of grasslands ecosystems and a gain of 4.7 sq miles-these changes equate to an overall decrease in grassland area from 16.08 sq miles to 9.90 sq miles (see "*Discussion-Limitations*" for an explanation of area gained). The largest change occurred on Lopez Island, which lost 66.45% (a total area of 1.6 sq miles) of grasslands that had been present in 1890. San Juan Island experienced a 37% decrease in grassland landcover, losing a total of 3.30 sq miles of grassland. The loss experienced on other islands was less severe; Orcas Island had a 10% decrease in grassland landcover losing 1.02 sq miles, and Shaw Island had a 23% decrease in grassland landcover, losing 0.17 sq miles of grassland.

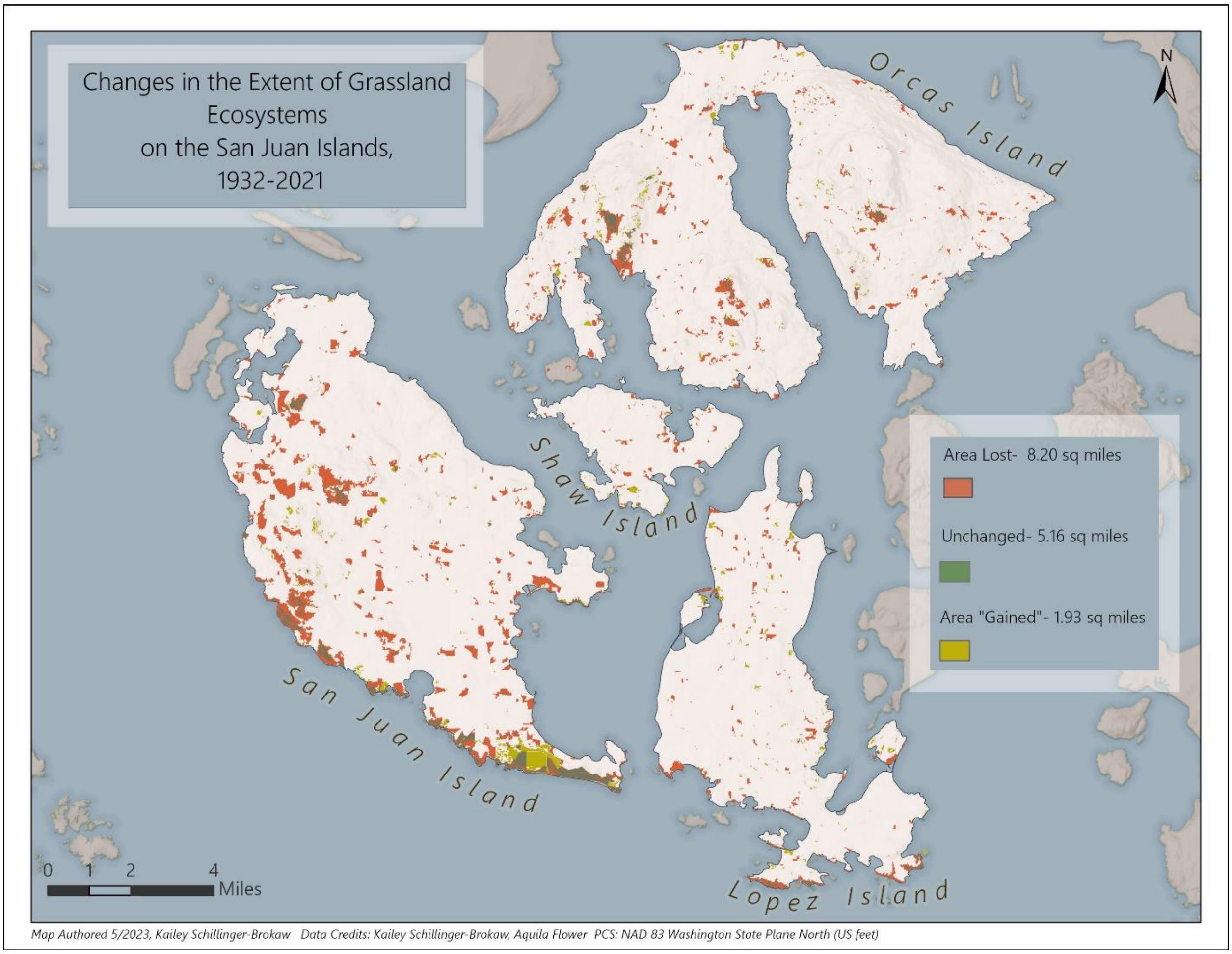


Figure 20: Map showing the changes in grassland area between 1932-2021 on the four largest San Juan Islands.

Between 1932 and 2021, there was a further loss of 8.20 sq miles of grassland across all four islands in the study area, slightly offset by a gain of 1.93 sq miles of grasslands-resulting in an overall decrease from 9.90 sq miles to 3.43 sq miles. These changes equate to a 69% decrease in grassland landcover since 1932. The most significant change occurred on Lopez Island, where there was a 74% decrease in grassland landcover, totaling 1.47 sq miles of lost grassland ecosystems. Orcas Island lost 73% of its remaining grasslands, equating to a loss of 2.40 sq miles. Shaw Island experienced a 71% decrease in grassland area, due to a loss of 0.24 sq miles of ecosystem. San Juan Island experienced the smallest amount of change between 1932 and the present day, with a 65% decrease in grassland landcover equating to a loss of 3.87 sq miles.

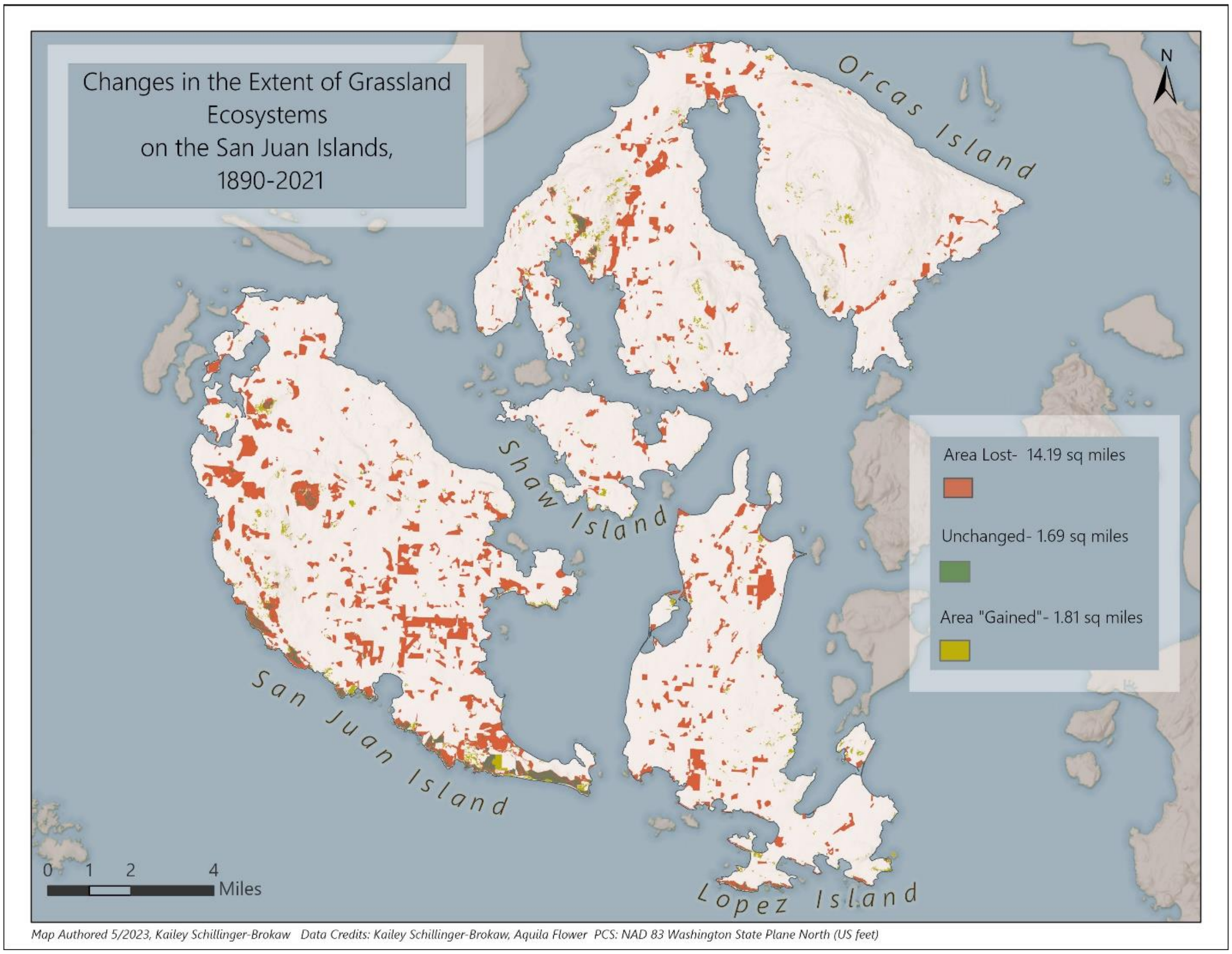


Figure 21: Map showing the changes in grassland area between 1890-2021 on the four largest San Juan Islands.

The changes in grassland landcover that occurred from 1890-2021 (Figures 21-25) were substantial; a total of 14.19 sq miles of grassland ecosystems was lost and 1.81 sq miles gained during this time period, resulting in an overall loss of 12.65 sq miles of grassland- a 78% decrease from the historical extent in 1890. All four islands experienced significant decreases, with grassland area decreasing by 82% (2.56 sq miles) on Lopez Island, 77% (7.85 and 2.80 sq miles, respectively) on San Juan and Orcas, and 85% (0.42 sq miles) on Shaw Island.

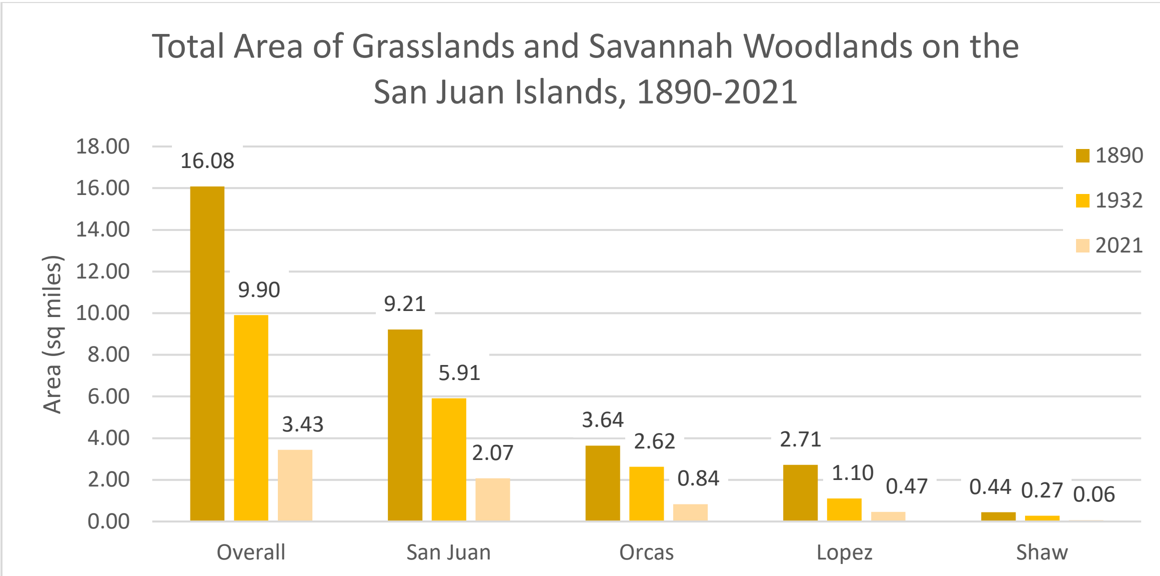


Figure 22: Change in total grassland/savannah-woodland area, 1890-2021

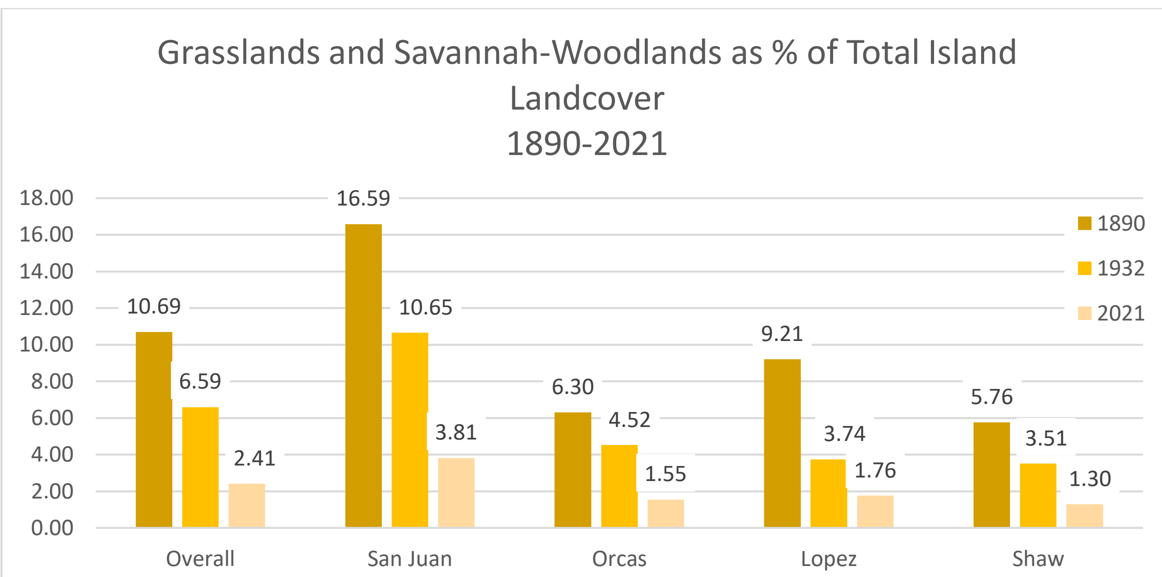


Figure 23: Change in the percentage of landcover on the San Juan Islands in grasslands and savannah-woodlands, 1890-2021

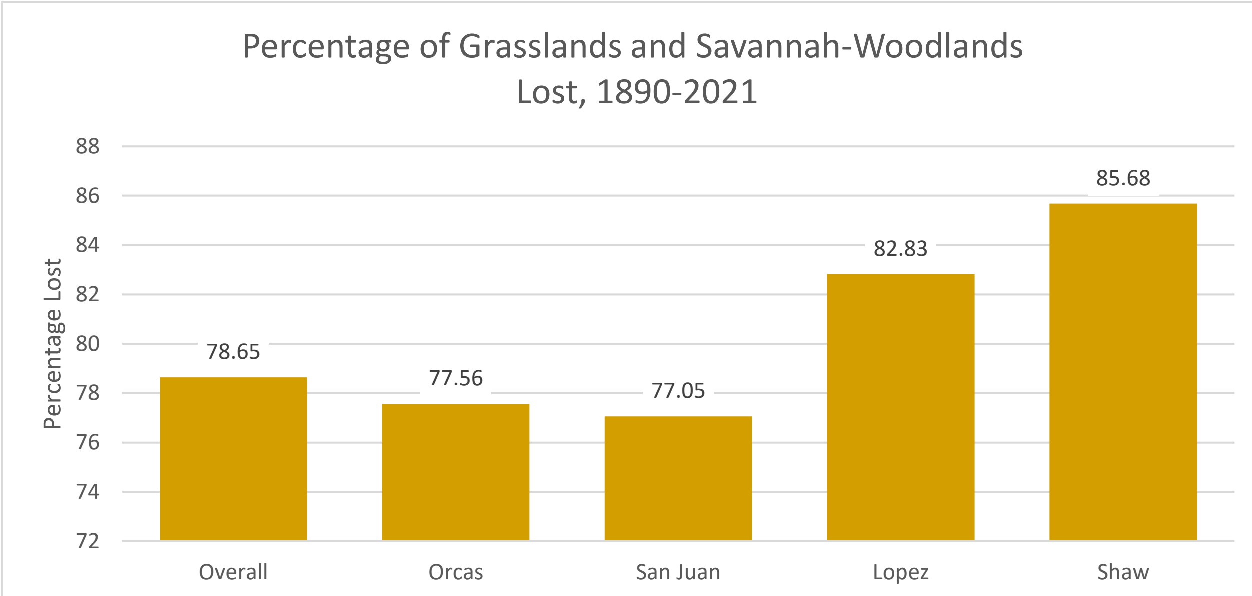


Figure 24: Percent loss of grasslands that were present in 1890, by 2021.

Overall, the changes in grassland area that occurred between 1890 and 2021 amount to a 78.66% decrease in grassland landcover since 1890, and a loss of 12.65 sq miles of grassland across all four islands. Lopez Island has experienced an 82.83% decrease in total grassland landcover since 1890, and a loss of 2.24 sq miles of grassland landcover. San Juan Island had a 77.05% decrease in total grassland landcover, and a total loss of 7.14 sq miles. Orcas Island experienced a 77.56% decrease and a loss of 2.80 sq miles of grasslands, and Shaw Island experienced an 85.68% decrease and a loss of 0.38 sq miles of grassland since 1890.

Change in Fragmentation of Grasslands and Mixed-Woodlands

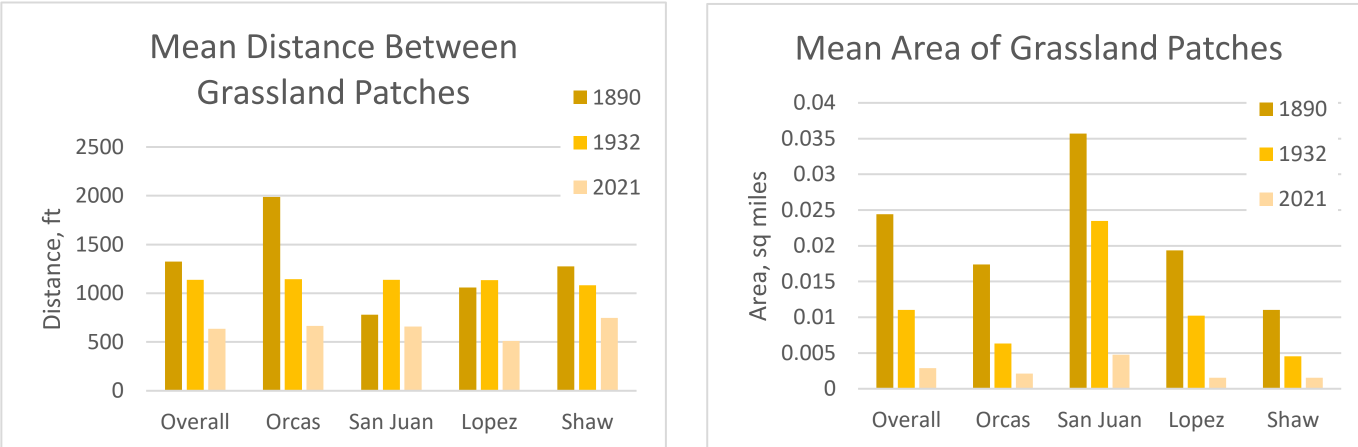


Figure 25: Charts showing changes in distance between grassland patches and average patch size on the San Juan Islands from 1890-2021. The minimum distance between patches for all time periods is <0 ft, and minimum area is <0 sq miles.

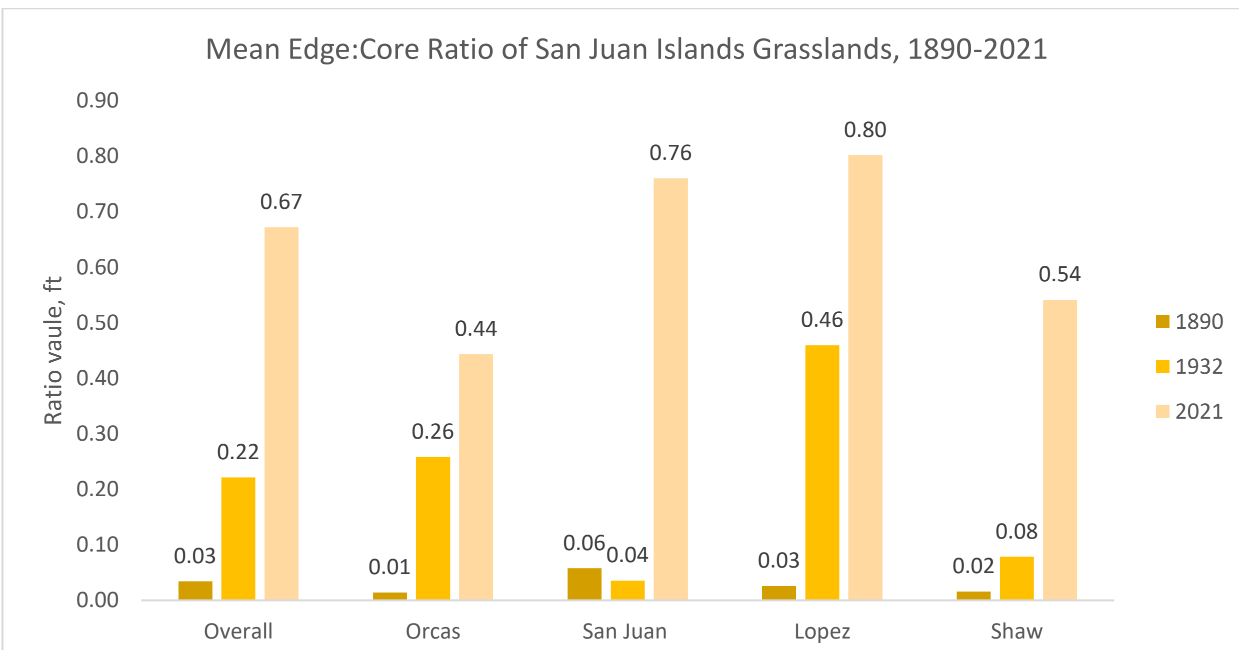


Figure 26: Chart shows changes in ratio of grassland perimeter per unit of area. A higher value indicates more "edge" in relation to core habitat area.

Changes in fragmentation are shown as a function of changes in the average distances between patches of grassland and average grassland patch size, as well as changes in the ratio between mean perimeter of grassland patches and mean core area (see Figures 25 and 26). Over the time period studied, the average distance between grassland patches decreased from 1,349.72 ft in 1890 to 660.79 ft in 2021. The average size of individual grassland patches on the four study islands decreased between time periods, with the average patch size decreasing from 0.03 sq miles in 1890 to 0.003 sq miles in 2021. This is reflected in the steady increase of the mean edge-core ratio across all four islands. In 1890, the average ratio value of perimeter to core habitat in grassland patches was 0.03. This increased to 0.22 in 1932, and had increased again to 0.67 by 2021.

Trends in Changing Land Use and Land Cover

General trends in landcover are shown in Tables 8-9, where the total area of each landcover type replacing grassland ecosystems is shown for the study area overall as well as for each individual island. The charts in Figures 23-24 show the percentage of grassland area that was lost since 1890, and what landcover types lost grassland was replaced by. These calculations are shown for each set of time periods, indicating transitions that occurred between 1890-1932, 1932-2021, and 1890-2021.

46.47% of the grasslands that were present in 1890 were replaced with farmland (including cultivated fields and orchards) by 1932, which accounted for 7.44 sq miles of the 10.78 sq miles of converted area. Although this transition occurred on all four islands in the study area, the most significant change was on Lopez Island, where 69.63% of grasslands (1.89 sq miles) were converted to farmland. Forest and sparse forest were the second largest sources of change in grassland area, replacing approximately 17.96% of the grasslands present in 1890 by 1932. These changes in landcover amounted to a conversion of 2.87 sq miles of grassland into forest across all four islands. The largest instances of this conversion were seen on San Juan Island and

Orcas Island, where forest and sparse forest replaced 1.52 sq miles and 0.85 sq miles of grassland. Other landcover types appear to have relatively low conversion factors during the 1890-1932 time period, with marshes, beaches, cleared land, developed land, and freshwater landcover replacing a total of 0.48 sq miles of lost grassland.

Table 7: Table shows trends in total area of landcover types replacing grasslands on the San Juan Islands between 1890-1932.

Land Cover Replacing Grasslands, 1890-1932, Area sq miles					
	Overall	**Orcas**	**San Juan**	**Lopez**	**Shaw**
Farmland, Orchard	7.44	1.84	3.52	1.89	0.18
Forest, Sparse Forest	2.87	0.85	1.52	0.39	0.11
Marsh	0.02	<0.00	0.01	0.00	<0.00
Beach	0.06	0.01	0.01	0.03	<0.00
Cleared Land, Developed	0.40	0.13	0.24	0.01	0.01
Total Grassland Area Replaced	**10.79**	**~2.84**	**5.3**	**2.32**	**~0.31**

Table 8: Table shows trends in total area of landcover types replacing grasslands on the San Juan Islands between 1932-2021.

Landcover Replacing Grasslands, 1932-2021, Area Sq Miles					
	Overall	**Orcas**	**San Juan**	**Lopez**	**Shaw**
Farmland, Orchard	1.08	0.16	0.71	0.15	0.06
Forest/Sparse Forest	5.44	1.68	3.03	0.57	0.15
Marsh	0.38	0.09	0.23	0.05	0.01
Cleared Land, Developed, Lawn, Turf	1.31	0.31	0.78	0.19	0.03
Total Grassland Area Replaced	**8.20**	**2.24**	**4.75**	**0.96**	**0.25**

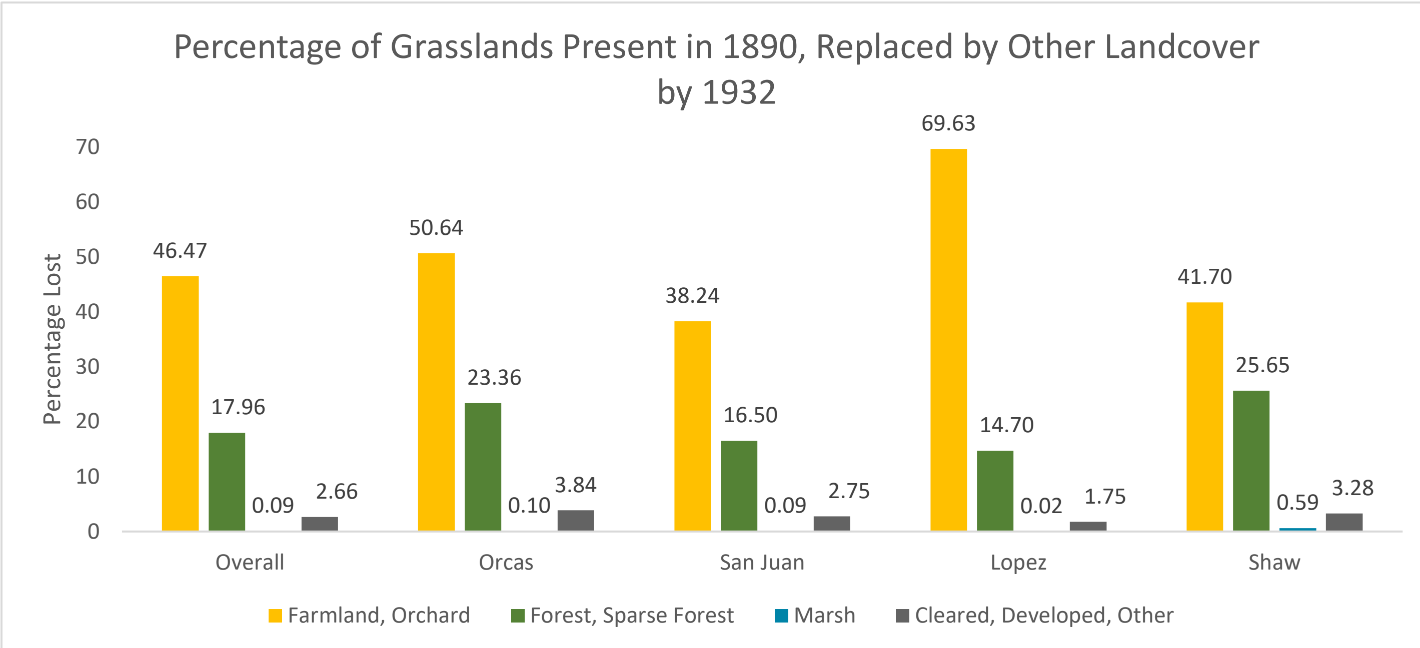


Figure 23: Percentage of grasslands lost since 1890, visualized by landcover type replacing grasslands.

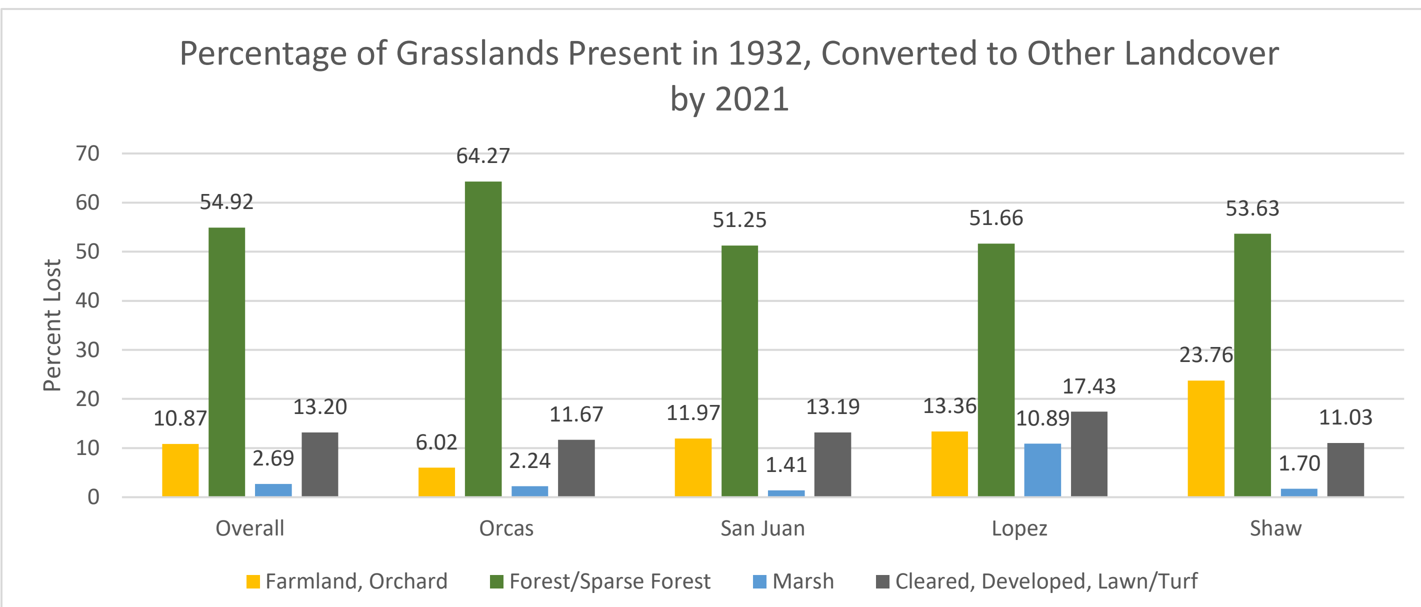


Figure 24: Percentage of grasslands lost from 1932-2021, visualized by landcover type replacing grasslands.

From 1932 to 2021, 85% of the remaining grasslands on the San Juan Islands were converted to other landcover types. Forest and sparse forests had the biggest impact, replacing 54.92% of grasslands that were present in 1932 and amounting to 5.44 sq miles of converted land. This change was the most significant on Orcas Island, where 64.27% of the grasslands present in 1932 were lost to forests by 2021. San Juan, Lopez, and Shaw Island experienced slightly lower rates of conversion to forest, losing 51.25%, 51.66%, and 53.63% of grasslands present in 1932 to forest, by 2021.

Farmland replaced 10.87% of grasslands from 1932-2021, with a total of 1.08 sq miles of land being converted to agriculture during this time. Lopez Island and Shaw Island experienced the highest loss of grasslands to agriculture, as 13.36% of grasslands on Lopez Island and 23.76% of grasslands on Shaw Island were converted to farmland by 2021. While wetlands and cleared or developed land also replaced grasslands on all four islands between 1932 and 2021, these categories had a smaller impact than forests. Wetlands replaced 2.69% of grassland during this time period, most notably on Lopez Island where 10.89% (0.05 sq miles) of grasslands were converted. Cleared and developed land (including lawns and turf) replaced 13.20% of grasslands between 1932 and 2021, amounting to 1.31 sq miles of area. Conversion to cleared or developed land was somewhat more prevalent on Lopez Island and San Juan Island, where it accounted for 17.43% and 13.19% of grassland loss. Overall, a mere 10.51% (1.69 sq miles) of grassland have persisted as grassland since 1890, and only 46% of these grasslands are on protected lands.

Discussion

Area Changed

The results of my landcover analysis indicate that grassland ecosystems have been dramatically impacted by human activity since 1890, decreasing by 78.65% from their extent at that time. A total of at least 12.45 sq miles have been lost during this time period[2], and have been primarily replaced by farmland and forest, with farmland being the primary cause of loss between 1890-1932, and afforestation being biggest cause of loss from 1932-2021. Furthermore, the grasslands that have remained between each of the study years show signs of increasing fragmentation. The edge-core ratio comparing mean patch perimeter and mean patch size increased from 1,354.26:231,649.29 (0.006) in 1890 to 2,397.45:57,989.1 (0.04) in 2021. The increasing value indicates an increase in the amount of edge habitat per unit of area over time (Fonseca, 2008). Another way to reveal the increasing fragmentation of grasslands is to examine changes in mean distance between grassland patches, and mean patch size. Although the mean distance between individual grasslands has decreased since 1890, so has total grassland area. This is due to a "splintering" effect; as grasslands are broken into increasingly smaller, and less resilient, patches, the distance between grasslands decreases along with the average patch size.

The general trends of decreasing grassland area and increasing fragmentation are similar across all four islands studied. However, the results indicating leading causes of landcover loss between time periods show some interesting variations between islands. For example, Lopez Island experienced a greater loss of grassland to agriculture between 1890 and 1932 than any other island, and the highest rate of loss to development from 1932-2021. It is interesting to note that of the four islands studied, San Juan Island had the lowest percentage of grassland loss to agriculture from 1890-1932, and the second lowest from 1932-2021. This is despite having the highest percentage of agricultural landcover in 1890 (10%), and the second highest in 1932

[2] Although there are small amounts of area that were classified as grassland in 1932 or 2021 despite not being identified as grassland in 1890, the presence of these "gained" grasslands can largely be attributed to inconsistencies in resolution between datasets, as well as some limitations in methodology (see "*Limitations*" section).

(23%) and 2021 (13%). As the first of the four islands to be settled in the mid-1800s, it is likely that many grasslands on San Juan Island had already been converted to agriculture by 1890. This would explain the contradiction of lower rates of grassland loss to agriculture and high percentage of agricultural landcover, relative to the other islands.

Conversion of natural landscapes to Euro-American agricultural landscapes has clearly been a significant factor in the decline of grasslands on the San Juan Islands, especially from 1890-1932. The population of European and American settlers rose quickly during this time, driving an expansion of farmland and homesteads into native grasslands- the rich soil and minimal tree cover making these ecosystems coveted agricultural land (Pratt, 2019; Dunwiddie & Bakkar, 2011). In addition to converting grasslands to cropland, agricultural activity has impacted grasslands via the introduction of non-native and invasive species, which can outcompete or even fully exclude native grasses and forbs. Evidence of these impacts can be seen at American Camp within the San Juan National Historical Park, where large sections of grassland were converted to pasture before reverting to altered or "secondary" grassland, after agricultural activities in the area had ceased. Non-native grass species that were introduced for pasture such as quackgrass (*Elymus repens*), Kentucky bluegrass (*Poa pratensis*), and bentgrass (*Agrostis* ssp.) still dominate much of formerly farmed landscape throughout the park (Rocchio, 2012).

While agriculture was the most significant driver in grassland loss prior to 1932, it was replaced by forestation as the leading cause of grassland loss between 1932-2021. This can be explained by the decline in agriculture that occurred throughout the 1900s. Reaching its peak in 1920, the number of farms and total acreage of farmland on the San Juan Islands declined steadily through the 1970s (see Figure 28). Although the number of farms began to slowly rise again in 1978, this has not equated to an increase in farmland, with the total acreage remaining around 18,000 acres

(USDA Census of Agriculture). With this decrease in agricultural activity, formerly cultivated fields fell out of production and disturbances have become less frequent-resulting in increased rates of encroachment from trees (particularly Douglas-fir), shrub species such as Nootka rose (*Rosa nutkana*) and common snowberry (*Symphoricarpos albus*), and non-native invasive forbs such as Scotch broom (*Cytisus scoparius*) and Himalayan blackberry (Chappell et al., 2008; Schultz et al., 2011; Shaff & Foster, 2003;).

The combined pressures of agriculture, forest encroachment, and human development have severely diminished and altered the grassland ecosystems of the San Juan Islands. While the full consequences of this may not yet be completely understood, some effects are undeniable. For example, the dry-prairie community *Festuca roemeri – Camassia quamash – Cerastium arvense* is so fragmented that it is considered functionally extirpated in Washington State (Schwemm, 2020). Such reductions in viable grassland habitat disproportionately affect native species with high habitat fidelity; as a result, these species are experiencing regional declines and, in some cases, extirpation (Altmann, 2011). On a final note, a natural resource condition assessment of San Juan National Historical Park conducted in 2020 found that, "in the absence of significant and aggressive restoration actions, the current trend in the areal extent of actual native prairie is likely to be a gradual loss" (Schwemm, 2020). Given the ominous trajectory of loss and fragmentation, it seems clear that substantial conservation and restoration efforts must be implemented to preserve remaining grasslands and restore those that are degraded or altered.

The trends identified in this study are consistent with those seen in other temperate grassland ecosystems in the Pacific Northwest. Studies have found that in the 150 years following Euro-American settlement, the ancient grasslands of the Southern Puget Sound have been reduced to less than 10% of their historical range (Crawford & Hall, 1997). Similarly, researchers working in British Columbia report that the agricultural and urban development that followed European settlement has had profound effects on Garry Oak ecosystems, and estimate that only 1-5% of the historical habitat have not been degraded (Fuchs, 2001; MacDougall et al., 2004). In both these instances, researchers found that large-scale conversion to agriculture and the suppression of fire regimes, followed by encroachment and forestation, were major causes of reported ecosystem loss. The same story is playing out on a global scale, as temperate grasslands from the Americas all the way to Australia are heavily altered by human activity, and continue to face threats from conversion to agriculture, altered disturbance regimes, encroachment, and even afforestation (Buisson et al., 2022; Carbutt et al., 2017; Henwood, 2010). Increasing recognition for how imperiled these ecosystems are has led to the formation of new target goals and plans for temperate grassland conservation, such as the Temperate Grasslands Conservation Initiative (TGCI), which aims to increase communication and global cooperation in conservation efforts (Carbutt et al., 2017; Henwood, 2010). While communication and cooperation are an essential aspect of transboundary conservation work, they must be accompanied by aggressive conservation and restoration measures if we hope to preserve old-growth grasslands (Carbutt et al., 2017; Hoekstra et al., 2005).

In the case of disturbance-dependent grasslands, such as those found in the San Juan Islands, the Gulf Islands, and southern Puget Sound, introducing a disturbance regime that supports native species is key. However, restoring appropriate disturbance-vegetation feedbacks in these heavily altered grasslands can pose complex challenges. Although fire was historically used, attempts to reintroduce a burn regime have been faced with the added challenge of ensuring that native plant species are able to reestablish after a fire before being crowded out by non-native and invasive species (Buisson et al., 2022; Dunn, 1998; Sprenger & Dunwiddie, 2011; Storm & Shebitz, 2006). The most promising efforts in these areas have been multifaceted; prescribed burns are applied, followed by active replanting of native grassland species and continued removal of invasive species. The process is iterative, as it can take centuries for degraded grasslands to regain former ecological function and traits (Buisson et al., 2022).

Recommendations

Although agriculture has played an undeniably significant role in the loss of grasslands on the San Juan Islands, there are several indications that its current impacts on grasslands are less direct than in past decades. Firstly, this study found that more grasslands were replaced by forests than farmland from 1932-2021. Second, according to the USDA Census of Agriculture (see Figure 24), despite an increase in the number of farms on the San Juan Islands, there has been little growth in the total acreage of farmland since 1978. Both the San Juan County Agricultural Strategic Action Plan (2011) and the San Juan County Food Assessment (2022) reference this trend, as well as a gradual loss of active farmland. The primary cause of this is subdivision of historically farmed parcels, many of which were once actively managed pasture, and once sold or leased, are often developed or left fallow (Bill et al., 2011). Although there is a clear desire to protect the agricultural history and culture of San Juan County (as evidenced by the work of the San Juan Agricultural Resource Committee), these efforts are primarily focused on keeping currently farmed lands in production and preserving historically farmed land (Bill et al., 2011; Coffey et al., 2022). These actions seem unlikely to result in the further conversion of previously untouched grasslands to farmland and may even reduce certain threats to grasslands through agricultural conservation initiatives that prevent development and promote sustainable agricultural practices and noxious weed removal (Bill et al., 2011). Although further conversion of grassland to agriculture seems uncertain if not unlikely, the encroachment of conifers and shrubs poses an imminent threat to both previously untouched grasslands and those formed after degradation of old-growth grasslands (Rocchio, 2012; Schwemm, 2020; Sprenger & Dunwiddie, 2011).

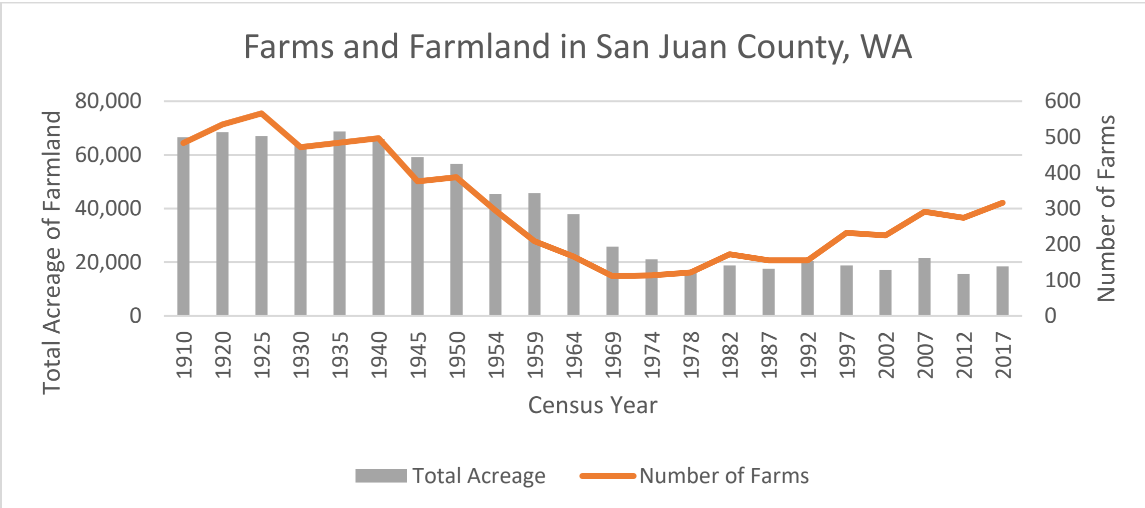


Figure 27: Total number of farms and acreage if farmland in San Juan County, WA, 1910-2017. Chart created with data accessed from the USDA Census of Agriculture (USDA - National Agricultural Statistics Service - Census of Agriculture).

While grasslands occurring within National or State Park boundaries and other protected areas benefit from regular monitoring and restoration programs that include invasive species removal, mowing, and planting of native species, this only accounts for 46% of current grasslands. The remaining 54% do not receive the same degree of protection, placing them at a higher risk of further degradation and succession to forest, after which restoration becomes extremely difficult and expensive (Chappell, 2006; Rocchio, 2012). Active monitoring of these grassland sites is needed to assess their condition and vulnerability and is a precursor to the development of appropriate and effective conservation strategies. Collaborating with landowners to develop conservation strategies and to protect grassland remnants that occur on private property is essential to ensuring the resilience and longevity of old-growth grassland ecosystems on the San

Juan Islands. Current resources for private landowners include conservation easement programs available through the San Juan County Conservation Land Bank and the San Juan Preservation Trust, and land management consultation services and technical assistance through the San Juan Islands Conservation District. Financial incentives from the federal government are available for private landowners to implement wildlife habitat development plans; or protect, enhance, or restore habitat that benefits species at risk on private land. However, to utilize these incentives landowners must be aware of the habitat and species present on their property. Expanding services to increase outreach and education to private landowners with grassland remnants on their property could enhance the effectiveness of grassland conservation and restoration efforts. Therefore, it is my recommendation that grassland conservation efforts on the San Juan Islands should include a thorough evaluation of the following grassland sites (see Figure 28 below), followed by the implementation of a conservation or restoration plan suited to the needs of the individual site. The following sites were selected as potential conservation priorities due to the following factors: 1) The following sites all contain grasslands that have been present since at least 1890; 2) the sites contain contiguous patches of grassland, as opposed to minute fragments, and 3) the sites primarily occur on unprotected land.

- San Juan Island:
    1. The western side of San Juan Island, to the north and south of False Bay,
    2. The areas north and south of Edwards Point Community
    3. The region 0.5 miles south of San Juan County Park
    4. The southern slopes of Cady Mountain
- Lopez Island:
    1. The areas at Point Colville and the end of Watmough Head Rd (partially protected by Watmough Bay Preserve)
    2. The areas south of Henderson Lake
    3. The areas near John’s Point Beach and Agate Beach County Park

- Orcas Island:
    1. The region .25 miles east of East Sound Beach
    2. The summit of Orcas Knob

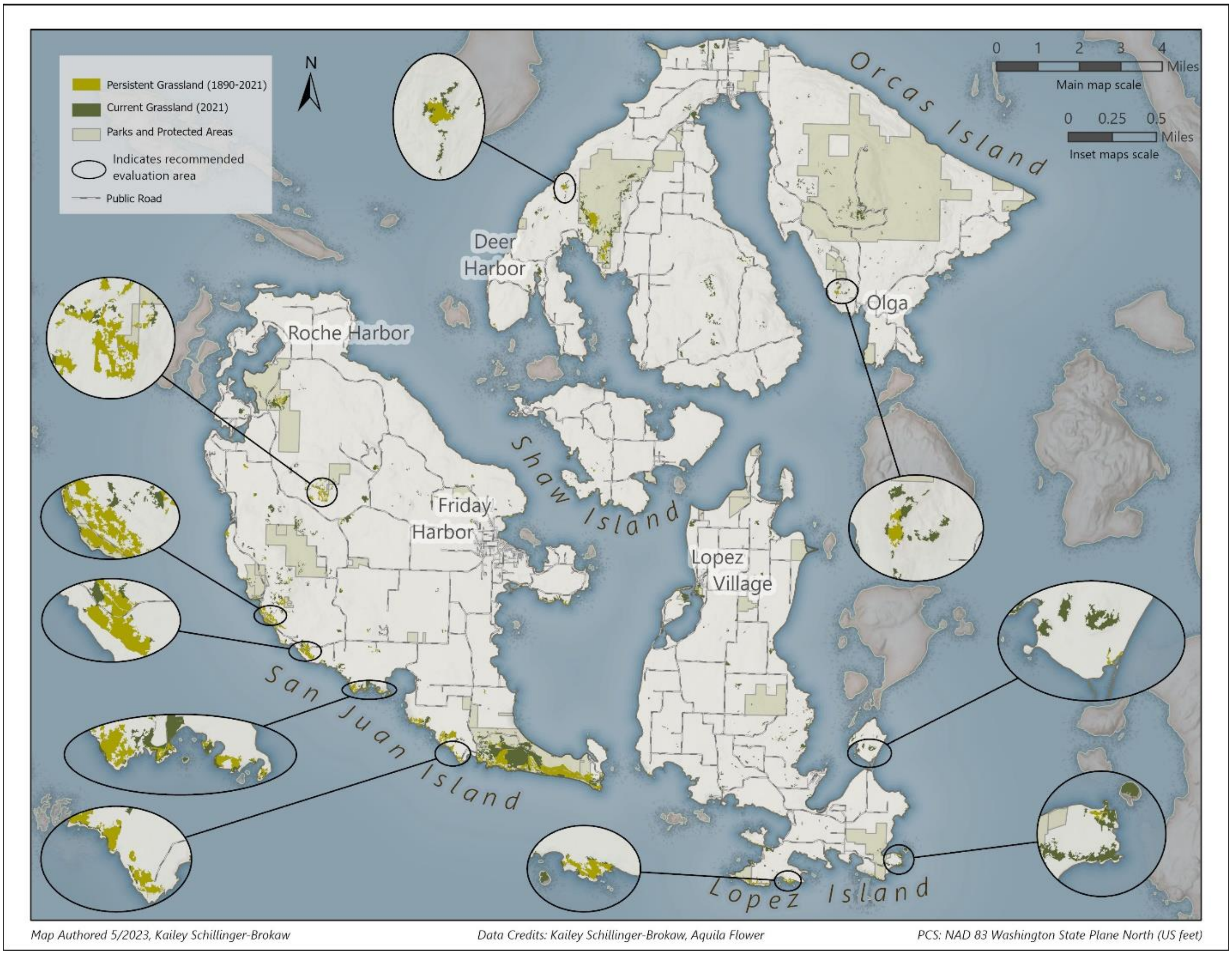


Figure 28 : Areas recommended for evaluation of grasslands. Indicated sites should be evaluated for species composition, and presence of threats such as presence of invasive species and encroachment of conifers and shrubs.

Significance

My findings provide site-specific insights into how grassland ecosystems have been affected by the changes in land use that we know have occurred since 1890. These results and datasets serve a key role in summarizing and disseminating valuable historical reference information (the T-Sheets, and 1932 aerial imagery) regarding landcover and land use on the San Juan Islands. Such information can be used to understand the legacy of an area and improve our understanding of the ecological traits, tendencies, or even constraints that may be present, thereby informing restoration practices (Higgs et al., 2014). In addition to providing historical reference, these datasets can be used to enhance our understanding of the human history of the San Juan Islands and how post-settlement practices impacted both grassland ecosystems and Coast Salish traditional ways of life. As local governments, non-profits, national parks, and other land management groups begin (and hopefully continue) to recognize the grasslands of the San Juan Islands as a cultural landscape and the role that traditional land stewardship practices had in shaping these ecosystems, spatial data that highlights where these ecosystems were and when they were lost will be critical in ecosystem recovery, as well as the revival of traditional practices such as regular burning.

Limitations: Data Sources and Methodology

The data sources and methodology utilized for this study were effective in providing a detailed sense of the changes that occurred in grassland ecosystems on the San Juan Islands. However, some limitations were encountered that bear discussion. First, it is likely that the USGS cartographers creating the T-Sheets did not survey the entirety of the San Juan Islands, resulting in at least two areas of missing data or landcover being misclassified. This is evident on Orcas Island, where there are two unmapped areas: one near Mt. Constitution and one on western Orcas near Mt. Woodlard. This absence of landcover data suggests that the surveyors were unable to accurately map that area. In addition, it must be noted that there are no notes or metadata that accompany the T-Sheets to explain the landcover classification system that was used for these maps. Given this lack of clarification, it is impossible to know exactly what was considered a "grassland" by these past surveyors. For example, it is possible that areas of mixed grassland and trees, such as Garry oak savannahs, were occasionally classified by past surveyors as "Sparse Forest," or that pastures dominated by hay and other introduced vegetation were classified as "Grassland." Although comparing landcover between time periods was useful in distinguishing between some landcover types (see "Methods" section), it cannot be considered a full substitute for detailed metadata regarding the landcover classification systems used in 1890.

The differences in resolution between the T-Sheets and the 1932 and NAIP aerial imagery used for dataset creation also posed an issue. The resolution of the aerial imagery was higher than that of the T-Sheets, which in addition to being a coarser resolution, have very generalized boundaries between landcover types. Given these differences, I was able to digitize much more nuanced ecotones for the 1932 and 2021 landcover than was possible for the 1890 dataset. This difference in resolution could potentially have resulted in slight differences in grassland area between time periods, even in regions where grasslands were unaltered.

Finally, it must be acknowledged that there was some difficulty in distinguishing between true grasslands and farmland such as pastures, hay fields, or other cultivated land in the 1932 and present-day imagery. While I used many additional data layers and visual analysis techniques to improve my grassland classification (see "Methods" section), it is likely that some areas classified as "grassland" are abandoned pasture or hay fields, heavily altered by introduced pasture grasses. To verify the species composition of each patch would require extensive ground truthing and vegetation surveys, which was beyond the scope of this study. Given the potential of novel and hybrid ecosystems to fulfill similar ecological roles as native grasslands, such as providing pollination services or habitat for endemic species (Hobbs et al., 2009; Schultz et al., 2011), I recommend that such sites be evaluated on a case-by-case basis.

Further Research: Extending the Baseline, Refining Results, and Additional Evaluation

While this study adds to our understanding of the historical baseline of grassland ecosystems on the San Juan Islands, further research such as refining classification results, evaluating current grassland conditions, or extending the known historical baseline, could enhance that understanding and improve the efficacy of restoration initiatives.

Although availability of historical reference data limits our ability to understand past landcover conditions, there are a wide range of methods available for mapping current landcover. Future studies could refine current landcover datasets by employing more advanced imagery analysis software and additional spectral bands to more accurately distinguish untilled and non-agricultural grassland ecosystems from other non-forested ecosystems, such as farmland. There is strong potential in using lidar to identify tractor or plow furrows underneath vegetation, making it possible to distinguish between cultivated areas and unaltered grasslands in aerial imagery (Fisher et al., 2018). A mixed method approach that combines imagery analysis with remote sensing techniques, followed by rigorous ground truthing would likely be the most effective way to create a highly accurate and comprehensive grassland landcover dataset.

This study focused on identification of grassland ecosystems, leaving any evaluation of individual site health or species composition to the land managers who may ultimately be using this data to develop restoration policies. However, it is highly unlikely that all areas classified as

“Grassland” in this dataset are truly old-growth grasslands, or are able to fulfill the ecological functions associated with native grasslands- in fact, it is likely that many are not. Given that there is an ecological distinction between exotic grasslands, degraded grasslands, and old-growth grasslands, future research in this area should consider the conditions and ecological health of grasslands identified by this study. Plant surveys conducted at each site would help determine the composition of the grasslands, evaluate the presence of invasive species, and make note of potential stressors or threats to grassland health and stability (such as over-browsing or encroachment).

Expanding our knowledge of the historical baseline prior to 1890 (prior to the impacts of settler-colonialism) would inform our understanding of the historical extent and conditions of these ecosystems. While this study tracks the changes in extent and distribution that occurred prior to the height of the settlement period, many changes had undoubtedly already been wrought by 1890. Therefore, the results of this study are an underestimation how much grasslands have decreased from their historical extent on the San Juan Islands. By collaborating with the Coast Salish tribes that have lived in the San Juan Islands since time immemorial, and incorporating Traditional Ecological Knowledge, oral histories, and participatory mapping, it could be possible to reveal exactly what changes had already occurred by 1890.

Conclusion

Extensive changes in land cover and land use have occurred on the San Juan Islands since the peak of settler-colonialism-changes that include a dramatic reduction in the extent and distribution of native temperate grasslands. These highly biodiverse ecosystems perform a wealth of ecoservices that benefit the San Juan Islands and have a strong cultural significance to Coast Salish peoples. Due primarily to changes in land use, non-agricultural temperate grasslands on the San Juan Islands have decreased to less than 22% of their historical extent in 1890. As alarming as this statistic is, it likely underestimates the full extent of grassland ecosystem loss that has occurred since settlement of the San Juan Islands. This is due to the fact that some conversion of grasslands to agriculture had already occurred by 1890. Therefore, the full extent of grasslands prior to the effects of colonization is not represented, and full loss of this habitat was not captured by this study.

There are a variety of factors responsible for the reduction in old-growth grasslands, including conversion to agriculture, the development and expansion of urban areas, and succession to forest. By quantifying the sum and percentage of grassland area that was replaced by different landcover types between time periods, I found that the primary causes of grassland loss between 1890-2021 were conversion to agriculture and encroachment or succession to forest. Though the impact of these factors was significant across all time periods, conversion of grasslands to agriculture was highest between 1890-1932, and encroachment or succession to forest or shrubland was highest between 1932-2021. The combined impacts of conversion to agriculture and encroachment of tree and shrub species into old-growth grasslands are substantial, accounting for over 60% of the reduction in grassland landcover that has occurred since 1890, and 70% of the loss that has occurred since 1932. These figures are particularly concerning given that agriculture and forestation can be highly disruptive to old-growth grasslands due to their impacts on below-ground structures and processes, and that it can take decades for degraded grasslands to regain their old-growth characteristics (i.e., species richness, erosion control, water flow regulation) (Buisson et al., 2022). Therefore, the magnitude of grassland ecosystem loss on the San Juan Islands indicates a clear and urgent need for conservation and restoration before the degree of degradation becomes irreversible.

By considering these historical landcover datasets in conjunction with contemporary evaluations of grassland ecosystems conditions, land managers can develop informed management practices and restoration policies that are guided by a profound understanding of how post-settler human activity has impacted the grassland ecosystems of the San Juan Islands.

References

Agee, J., & Dunwiddie, P. (1984). Recent forest development on Yellow Island, San Juan County, WA. *Canadian Journal of Botany*, *62*. https://doi.org/10.1139/b84-282

Agee, J., & Intermountain Research Station (Ogden, UT). Symposium on Fire in Wilderness and Park Management *Proceedings: Symposium on Fire in Wilderness and Park Management : Missoula, MT, March 30-April 1, 1993*. U.S. Dept. of Agriculture, Forest Service, Intermountain Research Station. https://archive.org/details/CAT10714714

Altman, B. 2011. Historical and current distribution and populations of bird species in prairie-oak habitats in the Pacific Northwest. Northwest Science 85:194–222.

Anderson, R. M. (2017). *From non-native "weed" to butterfly "host": knowledge, place, and belonging in ecological restoration* (Doctoral dissertation).

Bakker, J. D., Jones, E., & Sprenger, C. B. (2019). Evidence of a historical frequent, low-severity fire regime in western Washington, USA. *Canadian Journal of Forest Research*, *49*(6), 575–585. https://doi.org/10.1139/cjfr-2018-0354

Bengtsson, J., Bullock, J. M., Egoh, B., Everson, C., Everson, T., O'Connor, T., O'Farrell, P. J., Smith, H. G., & Lindborg, R. (2019). Grasslands—More important for ecosystem services than you might think. *Ecosphere*, *10*(2), e02582. https://doi.org/10.1002/ecs2.2582

Berry, H. D., Harper, J. R., Mumford, T. F., Bookheim, B. E., Sewell, A. T., & Tamayo, L. J. (n.d.). *The Washington State ShoreZone Inventory User's Manual*.

Bill, P., Clark, T., Hover, K., Jagel, C., & Pratt, B.C. (2011). *Growing Our Future: Agricultural Strategic Action Plan for San Juan County*. San Juan County, Washington. https://drive.google.com/file/u/0/d/1k6zo222QpHGh2KqPRKOOHfOu6_4z9Bet/view?usp=sharing&pli=1&usp=embed_facebook

Bjorkman, A. D., & Vellend, M. (2010). Defining Historical Baselines for Conservation: Ecological Changes Since European Settlement on Vancouver Island, Canada. *Conservation Biology*, *24*(6), 1559–1568.

Bork, E., & Badiou, P. (2017). The Importance of Temperate grasslands in the Global Carbon Cycle. *Ducks Unlimited, Canada*.

Brown, K. J., & Hebda, R. J. (2002). Ancient Fires on Southern Vancouver Island, British Columbia, Canada: A Change in Causal Mechanisms at about 2,000 ybp. *Environmental Archaeology*, *7*(1), 1–12. https://doi.org/10.1179/env.2002.7.1.1

Carbutt, C., Henwood, W. D., & Gilfedder, L. A. (2017). Global plight of native temperate grasslands: Going, going, gone? *Biodiversity and Conservation*, *26*(12), 2911–2932. https://doi.org/10.1007/s10531-017-1398-5

Chappell, C. B. (2004). *Plant Associations of Balds and Bluffs of Western Washington*. 72.

Coffey, S. E., Anderson, W. B., & Tanner, B. R. (2019). Understanding the Fire History of the San Juan Islands, Washington, Through Charcoal Accumulation Rates and Traditional Ecological Knowledge. *Journal of Northwest Anthropology*, *53*(2), 243–261.

Coffey, S., Leck, C., Limbach, L., Mikulak, K., & Rezabek, K. (2022). *Community Food Assessment*. San Juan County Agricultural Resource Committee. https://sjiagguild.com/wp-content/uploads/2023/03/SJC-Community-Food-Assessment.pdf

Cousins, Sara A.O. 2001. "Analysis of Land-Cover Transitions Based on 17th and 18th Century Cadastral Maps and Aerial Photographs." *Landscape Ecology* 16 (1): 41–54. https://doi.org/10.1023/A:1008108704358.

Crawford, R. C., & Hall, H. (1997). Changes in the south Puget prairie landscape. *Ecology and conservation of the south Puget sound prairie landscape. The Nature Conservancy, Seattle, WA*, 11-15.

Dixon, A. P., Faber-Langendoen, D., Josse, C., Morrison, J., & Loucks, C. J. (2014). Distribution mapping of world grassland types. *Journal of Biogeography*, *41*(11), 2003–2019. https://doi.org/10.1111/jbi.12381

Damschen, E. I., Harrison, S., & Grace, J. B. (2010). Climate change effects on an endemic-rich edaphic flora: Resurveying Robert H. Whittaker's Siskiyou sites (Oregon, USA). *Ecology*, *91*(12), 3609–3619. https://doi.org/10.1890/09-1057.1

Degagne, R., Pizzino, D., Friedrich, H, Gough, M., Joseph, G., Iovanna, R., Smith, C. and Strittholt, J. 2021. Mapping Conservation Reserve Program Grasslands in Washington, Kansas, and Colorado with Remote Sensing and Machine Learning. CBI Technical Report 2022-1. 70 pp. (DOI:10.6084/m9.figshare.19141853)

Donaldson, J. T., Schubert, N., & Huff, L. C. (n.d.). *Management Of Grassy Bald Communities In The Roan Highlands*. 1.

Dunn, P., Ewing, Kern, & Nature Conservancy of Washington, publisher. (1997). *Ecology and conservation of the South Puget Sound prairie landscape*. Seattle, Wash.: Nature Conservancy of Washington

Dunwiddie, P. W., & Bakker, J. D. (2011). The Future of Restoration and Management of Prairie-Oak Ecosystems in the Pacific Northwest. *Northwest Science*, *85*(2), 83–92. https://doi.org/10.3955/046.085.0201

Foster, D. R. (2000). From bobolinks to bears: Interjecting geographical history into ecological studies, environmental interpretation, and conservation planning. *Journal of Biogeography*, *27*(1), 27–30. https://doi.org/10.1046/j.1365-2699.2000.00376.x

Faber-Langendoen, D., T. Keeler-Wolf, D. Meidinger, C. Josse, A. Weakley, D. Tart, G. Navarro, B. Hoagland, S. Ponomarenko, J.-P. Saucier, G. Fults, and E. Helmer. 2015c. Classification and description of world formation types. General Technical Report RMRS-GTR-000. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO

Fisher, R. J., Sawa, B., & Prieto, B. (2018). A novel technique using LiDAR to identify native-dominated and tame-dominated grasslands in Canada. *Remote Sensing of Environment*, *218*, 201–206. https://doi.org/10.1016/j.rse.2018.10.003

Fonseca, M. S. (2008). Edge Effect. In S. E. Jørgensen & B. D. Fath (Eds.), *Encyclopedia of Ecology* (pp. 1207–1211). Academic Press. https://doi.org/10.1016/B978-008045405-4.00486-9

Fuchs, M. A., (2001). *Towards a Recovery Strategy for Garry Oak and Associated Ecosystems in Canada: Ecological Assessment and Literature Review*. Technical Report GBEI/EC-00-030. Environment Canada, Canadian Wildlife Service, Pacific and Yukon Region.

Gomes, T. C. (2013). Novel ecosystems in the restoration of cultural landscapes of Tl'chés, West Chatham Island, British Columbia, Canada. *Ecological Processes*, *2*(1), 15. https://doi.org/10.1186/2192-1709-2-15

Hoekstra, J. M., Boucher, T. M., Ricketts, T. H., & Roberts, C. (2005). Confronting a biome crisis: global disparities of habitat loss and protection. *Ecology Letters*, *8*(1), 23–29.

Kapfer, Jutta, Radim Hédl, Gerald Jurasinski, Martin Kopecký, Fride H. Schei, and John-Arvid Grytnes. 2017. "Resurveying Historical Vegetation Data – Opportunities and Challenges." *Applied Vegetation Science* 20 (2): 164–71. https://doi.org/10.1111/avsc.12269.

Luft, J., & Schiewe, J. (2021). Automatic content-based georeferencing of historical topographic maps. *Transactions in GIS*, *25*(6), 2888–2906. https://doi.org/10.1111/tgis.12794

Mallupattu, P. K., & Sreenivasula Reddy, J. R. (2013). Analysis of Land Use/Land Cover Changes Using Remote Sensing Data and GIS at an Urban Area, Tirupati, India. *The Scientific World Journal*, *2013*, e268623. https://doi.org/10.1155/2013/268623

Milcu, A. I., Hanspach, J., Abson, D., & Fischer, J. (2013). Cultural Ecosystem Services: A Literature Review and Prospects for Future Research. *Ecology and Society*, *18*(3). https://www.jstor.org/stable/26269377

Monteiro, A. T., Fava, F., Hiltbrunner, E., Marianna, G. D., & Bocchi, S. (2010). Assessment of land cover changes and spatial drivers behind loss of permanent meadows in the lowlands of Italian Alps. *Landscape and Urban Planning*, *100*(3), 287–294.

Morales, C., Saez, A., Garibaldi, L., & Aizen, M. (2017). *Disruption of Pollination Services by Invasive Pollinator Species* (pp. 203–220). https://doi.org/10.1007/978-3-319-45121-3_13

Pellatt, M. G., & Gedalof, Z. (2014). Environmental change in Garry oak (Quercus garryana) ecosystems: The evolution of an eco-cultural landscape. *Biodiversity & Conservation*, *23*(8), 2053–2067. http://dx.doi.org/10.1007/s10531-014-0703-9

Peterson, D. L., Hammer, R.D.. (2001). From open to closed canopy: a century of change in a Douglas-fir forest, Orcas Island, Washington. *Northwest science, 75(3),* 262-269.

Pirk, C. W. W., Crewe, R. M., & Moritz, R. F. A. (2017). Risks and benefits of the biological interface between managed and wild bee pollinators. *Functional Ecology*, *31*(1), 47–55. https://doi.org/10.1111/1365-2435.12768

Puget Sound River History Project, Department of Earth and Space Sciences, University of Washington (2005). Puget Sound River History Project (washington.edu)

Pyne, S.J. (1982) Fire in America. A cultural history of wildland and rural fire. Princeton University Press, Princeton

Rocchio, F. J., R. C. Crawford, and C. Copass. 2012. San Juan Island National Historical Park vegetation classification and mapping project report. Natural Resource Report NPS/NCCN/NRR—2012/603. National Park Service, Fort Collins, Colorado.

Rogers, D. A., Rooney, T. P., Hawbaker, T. J., Radeloff, V. C., & Waller, D. M. (2009). Paying the Extinction Debt in Southern Wisconsin Forest Understories. *Conservation Biology*, *23*(6), 1497–1506. https://doi.org/10.1111/j.1523-1739.2009.01256.x

Sala, Osvaldo & Vivanco, Lucía & Flombaum, Pedro. (2013). Grassland Ecosystems. 10.1016/B978-0-12-384719-5.00259-8.

Schultz, C.B., Henry, E., Carleton, A., Tyler Hicks, Thomas, R., Potter, A., Collins, M., Linders, M., Fimbel, C., Black, S., Anderson, H.E., Diehl, Grace., Hamman, S., Gilbert, Rod., Foster, Jeff., Hays, D., Wilderman, D., Davenport, R., Steel, E., Page, N., Lilley, P.L., Heron, J., Kroeker, N., Webb, C., Reader, B., "Conservation of Prairie-Oak Butterflies in Oregon, Washington, and British Columbia," *Northwest Science*, 85(2), 361-388, (1 July 2011).

Shaff, S. E., & Foster, J. R. (2003). Forest colonization of Puget Lowland Grasslands at Fort Lewis, Washington. https://research.libraries.wsu.edu:8443/xmlui/handle/2376/1031

Sprenger, C. B., & Dunwiddie, P. W. (2011). Fire History of a Douglas-Fir-Oregon White Oak Woodland, Waldron Island, Washington. *Northwest Science*, *85*(2), 108–119. https://doi.org/10.3955/046.085.0203

Stephenson, K. E. (2011). Distribution of Grasslands in 19th Century Florida. *The American Midland Naturalist*, *165*(1), 50–59.

Storm, L., & Shebitz, D. (2006). Evaluating the Purpose, Extent, and Ecological Restoration Applications of Indigenous Burning Practices in Southwestern Washington. *Ecological Restoration*, *24*(4), 256–268.

Thompson, C. E. (2022, September 13). *Fields of Blue*. Fix. https://grist.org/fix/food-farming/indigenous-stewardship-restoring-camas-prairies/

Turner, N. J. (2014). *"An uncultivated waste": Balancing Cultural Ecosystem Services and Differing Values in the Salish Sea Region*. 48.

Turner, N. J., & Berkes, F. (2006). Coming to Understanding: Developing Conservation through Incremental Learning in the Pacific Northwest. *Human Ecology*, *34*(4), 495–513. http://dx.doi.org/10.1007/s10745-006-9042-0

Vellend, M., Brown, C. D., Kharouba, H. M., McCune, J. L., & Myers-Smith, I. H. (2013). Historical ecology: Using unconventional data sources to test for effects of global environmental change. *American Journal of Botany*, *100*(7), 1294–1305. https://doi.org/10.3732/ajb.1200503

White, P. S., & Walker, J. L. (1997). Approximating Nature's Variation: Selecting and Using Reference Information in Restoration Ecology. *Restoration Ecology*, *5*(4), 338–349. https://doi.org/10.1046/j.1526-100X.1997.00547.x

Zald, H. S. J. (2009). Extent and spatial patterns of grass bald land cover change (1948–2000), Oregon Coast Range, USA. *Plant Ecology*, *201*(2), 517–529. https://doi.org/10.1007/s11258-008-9511-1

Digital Data Sources

Aquila Flower, Atlas of the Salish Sea Bioregion. (2021, November). *Salish Sea Bioregion Agricultural Areas.* Retrieved from https://wwu.maps.arcgis.com/home/search.html?restrict=false&sortField=relevance&sortOrder=desc&searchTerm=owner%3A%22aquilaflower%22#content

Aquila Flower, Atlas of the Salish Sea Bioregion. (2021, November). *Salish Sea Bioregion Parks and Protected Areas.* Retrieved from https://wwu.maps.arcgis.com/home/search.html?restrict=false&sortField=relevance&sortOrder=desc&searchTerm=owner%3A%22aquilaflower%22#content

Puget Sound River History Project, Department of Earth and Space Sciences, University of Washington. (2005, April). *Puget Sound and Strait of Juan de Fuca United States Coast & Geodetic Survey Topographic Sheets*. Retrieved from http://riverhistory.ess.washington.edu/tsheets/framedex.htm

San Juan County GIS. (2019, August). *1932 Aerial Ortho Imagery.* Retrieved from https://sjcgis.maps.arcgis.com/home/item.html?id=daf3b6d7716b41d68b5228a6aab87c24

San Juan County GIS. (2019, August). *Assessor Land Use Codes.* Retrieved from https://data2017-01-09t190539232z-sjcgis.opendata.arcgis.com/datasets/SJCGIS::assessor-land-use-codes-1/explore

USDA National Agriculture Imagery Program, NOAA Office for Coastal Management. (2022, October). *2021 Washington NAIP 4-Band 8 Bit Imagery*. Retrieved from https://coast.noaa.gov/dataviewer/#/imagery/search/where:ID=9586

USDA National Agricultural Statistics Service. (2023, January). *2022 Washington Cropland Data Layer*. Retrieved from https://croplandcros.scinet.usda.gov

Washington Department of Natural Resources, Forest Practices Division reselect of USFWS National Wetlands Inventory data. (2017, January). *Wetlands- Forest Practices Regulation.* Retrieved from https://www.dnr.wa.gov/opendata

Washington Department of Natural Resources, Washington Natural Heritage Program. (2017, February). *Oaks and Grasslands of the Puget Trough Ecoregion.* Retrieved from https://www.dnr.wa.gov/opendata