Assessing Woody Plant Encroachment in Marin County, California, 1952-2018

by

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To my wonderful parents, Jane and Jonathan

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Abbreviations

CAS	Cartwright Aerial Surveys
DOQQ	Digital Orthophoto Quarter Quadrangles
GCP	Ground Control Point
GGNPC	Golden Gate National Parks Conservancy
GGNRA	Golden Gate National Recreation Area
GIS	Geographic Information Systems
GIST	Geographical Information Science and Technology
LULC	Land Use and Land Cover
MMWD	Marin Municipal Water District
MrSID	Multiresolution Seamless Image Database
MTSP	Mount Tamalpais State Park
NAPP	National Aerial Photography Program
OBCD	Object-Based Change Detection
PAI	Pacific Air Industries
RMS	Root Mean Square Error

Abstract

Land managers and ecologists aim to maintain the healthy balance of an ecosystem. Ecosystems are not static but are vulnerable to change and have been especially impacted by humans. Ecological restoration often involves reestablishing habitat to a previous condition or mitigating changes in ecosystem functioning. Stewards of the land must understand an area's historical ecological context to inform restoration decisions. In Marin County, the study area for this thesis, woody plant encroachment caused by fire suppression is an ecological concern. Where indigenous people once managed the land with frequent burning, fire suppression throughout the past two centuries has caused ecological changes. Transitions from grassland to shrubland and from shrubland to woodland are a result of woody plant encroachment and can lead to decreased biodiversity. This thesis classified and compared historical and modern aerial imagery to assess changing vegetation communities in Marin County. Land cover change was calculated and visualized from 1952 to today. Ultimately, it was found that herbaceous plant communities and shrubland have shrunk by 62% and 51%, respectively, while woodland has increased by 307%. The mosaiced landscape of 1952 is now more homogenous. 44% of total woody plant encroachment consisted of woodland replacing shrubland, while 39% consisted of woodland replacing grassland, and 17% consisted of shrubland replacing grassland. More shrubland was lost than gained, and the most common shrub species replacing grassland was coyote brush. The most common woodland species replacing grassland and shrubland was Douglas fir. These results point to specific targeting of coyote brush and Douglas fir establishment in areas of known encroachment. While this study provides valuable data on type conversion over the past 70 years, future research should focus particularly on vegetation changes in the last decade to support proactive approaches to managing encroachment.

Chapter 1 Introduction

Over the past 200 years, fire suppression has led to the encroachment of woody vegetation in certain areas of Marin County, CA. This type of encroachment leads to a change in plant communities as herbaceous communities are converted into shrubland or woodland. These woody plants support a different composition of wildlife that could threaten native species and decrease biodiversity.

Native grasslands in Marin, California include species such as Blue wildrye (*Elmus glaucus*) and Purple needlegrass (*Nassella pulchra*). Native shrubland species include Mount Tamalpais manzanita, California sagebrush, and California coffeeberry. Many insect, bird, and mammal species depend on these native species. Woody plant species such as coyote brush (*Baccharis pilularis*) and Douglas fir (*Pseudotsuga menziesii*) have encroached upon these critical habitats. Once the woody plants are established, it can be difficult to revert the process and restore grassland. Efforts to mitigate encroachment today can be targeted based on past land cover trends. This thesis aimed to help the agencies that manage land in this region. This project classified and compared grassland, shrubland, and woodland cover on Bolinas Ridge, Mount Tamalpais using high-resolution aerial photography from 1952 and 2018. Land cover change detection quantified changes in life forms, thus resulting in maps that visualize woody plant encroachment between these time periods. These results can aid in pinpointing the changing ecology and inform potential restoration efforts on Bolinas Ridge.

1.1. Research Questions

This thesis was designed to assist land managers in addressing the shifting ecology occurring due to woody plant encroachment. While this research is of broad interest to land managers in many regions, this study focused on Marin County, California. This thesis addressed three types of woody plant encroachment between 1952 and 2018: shrubland and woodland that replaced grassland, and woodland that replaced shrubland. The terms “woodland” and “forest” will be used interchangeably throughout this thesis. Also, it should be noted that “woody” plants refer to not only woodland species but also shrub species, and “woody plant encroachment” includes encroachment of both forest replacing grassland and shrubland, and shrubland replacing grassland.

Using historical and contemporary aerial photography, this thesis tracked vegetation change over time and mapped areas of encroachment over the past 70 years. The area studied is one of the highest priority areas for restoration efforts to mitigate conversion from one habitat to another. This thesis can inform land managers and ecologists, both in Marin County and beyond, to manage vegetation at scale and ensure that ecosystems can function.

1.2. Study Area

This thesis focused on Marin County, California, which is located just north of San Francisco. Marin encompasses roughly 520 square miles and is home to almost 260,000 people, making it the smallest county in the Bay Area (U.S. Department of Commerce n.d.). The typical wet season in Marin extends from October to April, with dry summer months. The fire season generally coincides with the hot summer and fall months. West Marin, the focus of this thesis, is particularly prone to wildfires. The occurrence of fires is different for East and West Marin because West Marin is covered mostly by forests, grasslands, and agriculture, whereas East Marin contains more densely populated urban areas.

Roughly 85% of Marin County is protected, undeveloped land which is crucial to humans as well as wildlife. The study area for this project is Bolinas Ridge on Mount Tamalpais, the highest mountain peak in Marin (Figure 1). This study area is mostly uninhabited apart from the town of Stinson Beach located on the coast. Mount Tamalpais includes four reservoirs that provide drinking water to the residents of Marin: Alpine Lake, Bon Tempe, Lake Lagunitas, and Phoenix Lake. The Southern tip of Alpine Lake is included at the top of the study area.

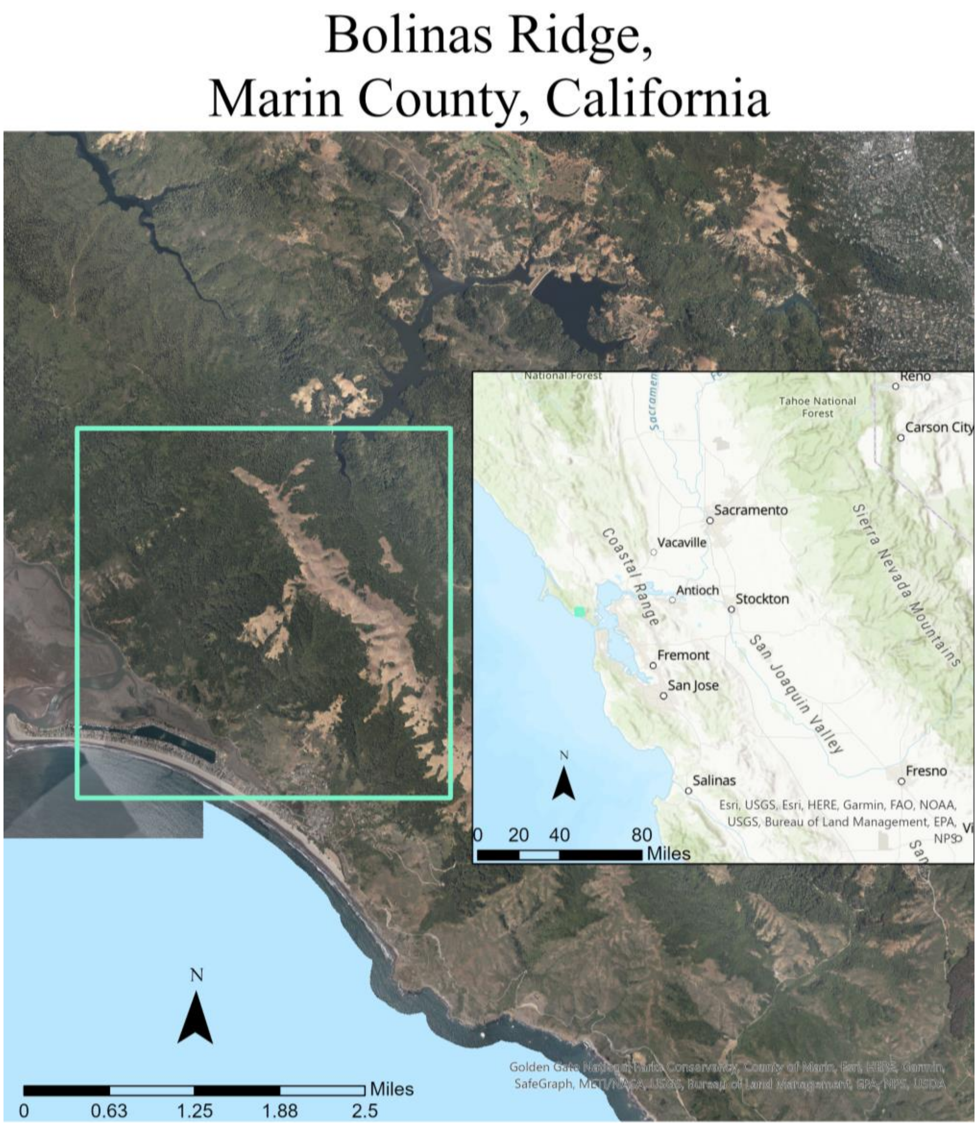

Figure 1. The study area (blue) comprises a portion of Bolinas Ridge on Mount Tamalpais. This area includes the town of Stinson Beach in the lower left of the study area.

Bolinas Ridge provides important habitat for native fauna and flora, including protected species such as the Coast redwood (S*equoia sempervirens*) and the yellow-legged frog (*Rana boylii),* and rare plant species such as indigo bush (*Amorpha californica var. napensis*), Bolinas ceanothus (*Ceanothus masonii*), and Tamalpais oak (*Quercus parvula var. tamalpaisensis*).

This thesis addressed the effects of woody plant encroachment on Bolinas Ridge over the past several decades. Herbaceous communities, which support many native species, are being displaced by woody plants. Additionally, conifer encroachment is displacing coastal shrublands. Native grassland species in this study area include blue wildrye (*Elmus glaucus*), purple needle grass (*Stipa pulchra*), and California fescue (*Festuca californica*). Native perennial herbs include yarrow (*Achillea millefolium)*, pearly everlasting (*Anaphalis margaritacea*), and California mugwort (*Artemisia douglasiana*), and annual herbs include common fiddleneck (*Amsinckia intermedia*) and mountain dandelion (*Agoseris heterophylla).* Native shrub species include Mount Tamalpais manzanita (*Arctostaphylos montana*), coyote brush (*Baccharis pilularis*), beaked hazelnut (*Corylus cornuta*), and sticky monkeyflower (*Diplacus aurantiacus*). Native woodland species include Coast redwood (*Sequoia sempervirens*), Douglas fir (*Pseudotsuga menziesii*), Pacific madrone (*Arbutus menziesii*), Buckeye (*Aesculus californica),* bigleaf maple (*Acer macrophyllum*), and oak woodlands. Oak woodlands typically contain Oregon white oak (*Quercus garryana*), California black oak (*Quercus kelloggii*), tanoak (*Notholithocarpus densiflorus*), and Coast live oak (*Quercus agrifolia*) (CalFlora. n.d.).

This thesis aimed to inform land management agencies about the historical trends of woody plant encroachment. The land in this study area includes the Golden Gate National Recreation Area (GGNRA), managed by Golden Gate National Parks Conservancy (GGNPC), Mount Tamalpais State Park (MTSP), managed by California Department of Parks and

Recreation, and land managed by the Marin Municipal Water District (MMWD) (Figure 2). There is some overlap of land management between GGNRA and MTSP (California State Parks 2022, Marin GeoHub 2017).

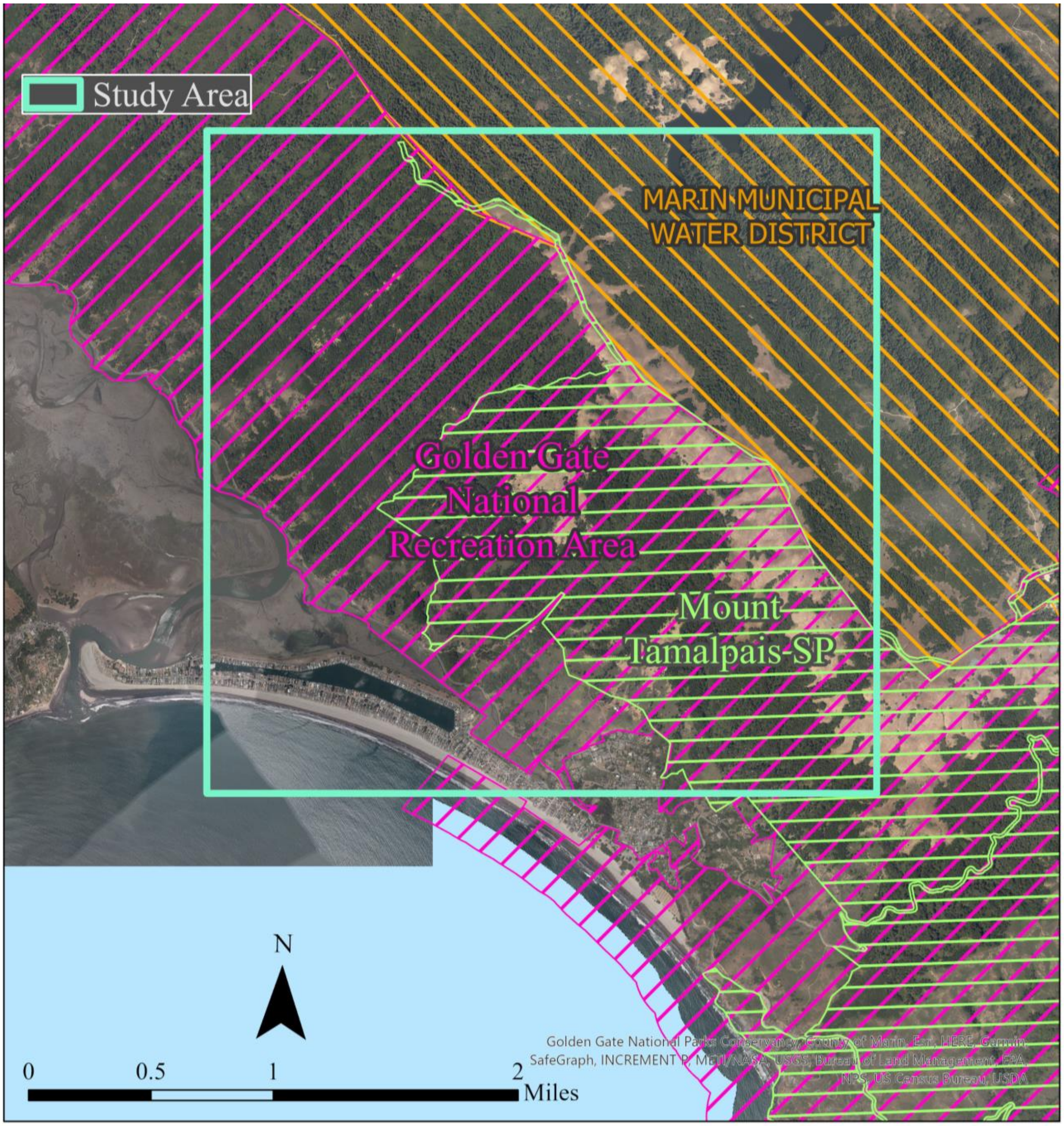

Figure 2. Land ownership in the study area includes Mount Tamalpais State Park, GGNRA, and MMWD.

1.3. Motivation

Over the past 200 years, urbanization has caused massive land cover changes. Although the study area for this project has remained mostly undeveloped, woody plant encroachment is causing shifts in the ecology on Mount Tamalpais. Ecologists understand that woody plant encroachment has been exacerbated over the last two centuries by fire suppression. This project aimed to visualize and quantify the changes in vegetation from 1952 to 2018 due to woody plant encroachment using aerial imagery. The goal was to help guide land management decisions concerning woody plant encroachment by providing a visualization of areas of encroachment over the past 70 years on Bolinas Ridge.

There are many types of ecological concerns that this thesis did not address. For example, recent restoration efforts have been aimed at fire protection, reducing fuel load, and improving forest health. Other restoration efforts include removing many different invasive species. The scope of this thesis included classifying life forms, broad categories of vegetation, and subsequently identified individual species.

1.3.1. Historical ecology

Referencing historical records helps provide context when researching and developing this project. As restoration ecology attempts to return sites to their historic conditions, historical records can paint an important picture of a place's ecological history from which restoration ecologists can model their objectives. Historical maps, journal records, core samples, fossil records, and other cultural records can provide context for understanding the ecology of the study site. This thesis referenced journal records from Spanish explorers describing the landscape to shed light on previous ecological conditions (Mensing 2006). Tending the Wild, which was written using many historic sources, provided context for the link between indigenous culture and ecology (Anderson, K. 2013).

1.3.2. Land Cover Change

Earth's land cover has been changing since the beginning of time due to various biophysical conditions. However, human disturbance has been the major cause of land cover change since the 1700s (Briassoulis 2009). Land cover change can be either conversion from one type of land cover to another, or a modification of land. Drivers of land cover change not addressed in this thesis include large-scale agriculture requires clearing of forests for monocrop agriculture. Additionally, the interface between urban and rural land is rapidly expanding as habitats shrink due to development of infrastructure. Land cover change has social and cultural implications, and in the case of this study, ecological implications. This study addressed physical consequences of woody plant encroachment over time: large scale changes from one form of vegetation to another.

1.3.3. Remote Sensing to Address Ecological Concerns

Remote sensing has wide applications in land management due to the ability to collect data at high temporal and spatial resolution at local, regional, and global scales. The biophysical environment is constantly changing, and remotely sensed imagery can broaden and deepen our understanding of ecosystems. Remote sensing is essential for managing protected land and informing restoration efforts over vast landscapes.

Remote sensing of vegetation has a history beginning in the 1970s. Ecological analysis using remote sensing was initially limited to a coarse spatial resolution of over 10m, for example, Landsat's Thematic Mapper first launched in 1972 (Aplin 2005). As remote sensing technology improved to have finer spatial and spectral resolutions, more accurate and detailed investigations of ecological structure and function were possible. For example, the IKONOS satellite launched in 1999 provided 1m panchromatic and 4m multiband images, and the QuickBird satellite, launched in 2001, collected panchromatic data at 0.61m and multispectral data at 2.44m spatial resolution (Wulder et al. 2004). Colombo et al. (2003) used IKONOS data to measure the Leaf Area Index of different agricultural crops. Clark et al. (2004) used IKONOS and QuickBird data to evaluate tree mortality rates in an old-growth tropical rainforest in Costa Rica.

Today, remote sensing technology is available at high temporal resolution to allow for land cover change detection in nearly real-time. Multispectral, high-resolution images capture sub-meter accuracy in the visible and infra-red spectrum. Contemporary land management benefits from this technology because most environmental devastation is now human-caused and rapid.

That said, remote sensing has limitations with respect to capturing ecosystem conditions. Aerial photos typically do not capture the understory, including both vegetation and wildlife. Aerial imagery is better used to classify plant communities rather than distinguish between species, especially when using historical imagery which is often substandard to modern imagery. Despite these limitations, remote sensing plays a vital role in managing and protecting important ecosystems globally. The following sections will outline two ecological applications of remote sensing in land cover change detection, the second of which pertains to this thesis.

1.3.3.1. Deforestation

Deforestation is a global issue leading to loss of habitat and biodiversity and contributing to greenhouse gas emissions and climate change. Multitemporal remote sensing can be used to monitor deforestation, target illegal activities, enforce policies to mitigate the issue, and predict future trends in forest loss. Pozzobon de Bem et al. (2020) monitored deforestation in the Brazilian Amazon using remote sensing and land use change detection. Deforestation in the Amazon is spatially correlated with roads which provide access to resource extraction, creating a 'fishbone' pattern of deforestation. The authors compared imagery taken during June and July in 2017, 2018, and 2019. Using imagery from the same time of year was important for their change detection analysis to reduce noise caused by varying seasons, cloud cover, phenology of vegetation, and sun angle, which affects lighting and shadows. This thesis, which also used change detection, had to consider the possible effects of comparing imagery taken during different seasons. The authors concluded that using radar data which penetrates the cloud cover would improve their research by providing monitoring multiple times a year rather than annually (Pozzobon de Bem et al. 2020).

Ayele et al. (2019) assessed the socio-economic causes and impacts of deforestation and predicted future deforestation in the Delo Mena District in Ethiopia. Like Pozzobon de Bem et al. (2020), Ayele et al. (2019) used Landsat imagery from the same season in 2000, 2010, and 2015 to minimize the seasonal variation in the reflectance of the land cover. The authors found that from 2000 to 2015, forest was lost mainly to farmland and shrubland. By modeling deforestation from 2000 to 2015 using variables such as distance to roads, elevation, and soil type, they predicted the amount of forest that would be lost by 2030. Finally, they identified agricultural expansion as the leading cause of deforestation worldwide (Ayele et al. 2019).

1.3.3.2. Encroachment

Encroachment refers to one type of vegetation dominating and replacing another type of vegetation. When one plant community transitions to another, changes in ecosystem functions can sometimes lead to decreased biodiversity. Researchers that are interested in monitoring the changes in vegetation caused by encroachment can use remotely sensed images. Images of the same area taken at different times can reveal the changes over large or small time periods.

Oddi et al. (2021) used high resolution drone imagery to capture the initial stages of woody plant encroachment in a subalpine grassland. Imagery with high spatial resolution is important to accurately classify vegetation and avoid pixel mixing. They used semi-automatic methods to classify the vegetation. Torri et al. (2013) looked at human-caused erosion and vegetation changes in the *biancana* badlands in Italy using aerial imagery from 1954 and 2005. They used an object-oriented approach to classify vegetation types and analyzed the changes. There are many options online to access high resolution images for free, like the high-resolution aerial imagery used in this thesis to monitor encroachment.

1.3. Thesis Organization

The following chapters are organized as follows: Chapter 2, Related Work; Chapter 3, Methodology; Chapter 4, Results; and Chapter 5, Discussion and Conclusions. The next chapter connects this work to related literature on historical ecology, type conversion and ecological restoration, historical imagery, and land cover change detection. Chapter 3 describes the methods used to analyze the study area using aerial imagery. Chapter 4 examines the results, and Chapter 5 discusses these findings in the context of land management.

Chapter 2 Related Work

Historical ecology and cultural shifts over the past two centuries provide context for the recent woody plant encroachment in Marin County. Specifically, fire suppression has led to type conversion from grasslands to shrublands and woodlands, and from shrublands to woodlands. This literature review provides background as to the ecological, technical, and theoretical underpinnings of this thesis.

2.1. Historical Ecology

The field of historical ecology explores the past ecological conditions, natural processes, and culture of an area. Understanding these historical patterns provides context of changes that have occurred in the landscape and insight into current management strategies and restoration efforts. For example, Ethington et al. (2020) explored the historical ecology of the Los Angeles River watershed, a region that has undergone rapid urbanization, to reveal the fauna and flora that would have thrived historically in the area. These findings aim to inform restoration efforts and management of open spaces.

In her thesis, Anderson (2015) investigated the historical ecology over the past 170 years in the Florida Split Oak Forest to inform land managers and ecologists. This important protected area has been significantly modified by humans. Her analysis incorporated many documents from 1844 to 2015, including historical soil maps, hand-drawn General Land Office survey maps, aerial photographs, Digital Orthophoto Quarter Quadrangles (DOQQs), and high resolution Orthoimagery. Anderson (2015) successfully classified natural plant communities from the 19^{th} century survey maps but acknowledged that they were generalized and included some inconsistencies because they were hand-drawn. She used 20^{th} century soil maps and aerial photographs to verify her findings from the hand-drawn maps. Aerial photographs are useful in change analysis if they are georeferenced and changes in seasons or sun angle are accounted for.

This thesis relied on the history of land management in Marin County, particularly how changes in fire regimes over the past two centuries have had profound impacts on the vegetation and allowed for woody plant encroachment. Pre-colonization, California was densely populated by native tribes. Anderson (2013) describes indigenous culture with a deep connection to the land using fire as an integral part of their lives. Instead of pruning, shrubs used in basketry and musical instruments were burned to encourage vigorous resprouting. Fire was the primary way that tribes such as the Pomo and North Fork Mono managed their plots of hemp by clearing dead material and preventing other plants from shading out the crop. Frequent fire disturbance rids plants of unwanted dead material, spurs new growth and nutrient recycling, reduces risk of infection and disease, and promotes longevity (Anderson 2013). At the community level, frequent wildfires increase species composition and heterogeneity and maintain fire-dependent ecosystems such as Oak woodlands and native grasslands.

At least 35 tribes in California used prescribed burning regimes to manage the land. These frequent wildfires preserved the ecological balance and benefited many fire-adapted plant communities, such as Oak woodlands and grasslands, which resprout after even a high-intensity fire (Cocking et al. 2015). Reports from early Spanish explorers describe open grasslands and woodlands dominated by large Oak trees. Oak woodlands hold cultural importance to indigenous tribes; for example, acorns were and still are an important food source (Mensing 2006).

However, over the last two centuries, fire regimes have changed massively from indigenous practices. Controlled burning has been suppressed in Marin County since the late 1800s due to the threat it poses to the ever-expanding population. To this day prescribed burning is used very little to manage land in Marin and is not used at all on Mount Tamalpais. Marin contains vast areas of wilderness, and neighborhoods that border these natural areas are especially at risk of being burned. While fire has been suppressed for the safety of human communities, it has led to unintended consequences in fire-adapted plant communities. Forest densification occurs because fire-sensitive vegetation that would normally be burned are allowed to germinate (Mensing 2006; Cocking 2011). Not only do fuel loads increase, but also fire-sensitive trees encroach upon adjacent fire-resistant communities which leads to a transition in plant communities.

2.2. Type Conversion and Ecological Restoration

Ecological type conversion is the shift from one life form to another. Life forms refer to vegetation with similar characteristics that are associated with certain environments. They also tend to respond similarly to environmental factors, making life form a useful classification in ecology. Ecologists may be concerned with type conversion when it threatens sensitive habitats or native species, decreases biodiversity, or limits ecosystem functioning. Type conversion is often a result of urbanization, deforestation, habitat fragmentation, or invasive species. Invasive species can cause type conversion because they grow vigorously in harsh or changing conditions and easily dominate other species.

This thesis looks at type conversion occurring on Mount Tamalpais due to woody plant encroachment. This encroachment takes the form of forest replacing coastal shrub communities and herbaceous ecosystems, and woodland replacing shrubland. One of the contributing factors to woody plant encroachment in Marin County is reduced fire frequency over the past two centuries. Fire suppression on Mount Tamalpais has allowed fire-sensitive plants to invade fire-resistant communities. These fire-sensitive species are at an advantage due to highly competitive methods of resource acquisition and seed dispersal, acculturation to disturbed areas, and few natural predators. Land managers must address this ecological shift and understand where to use targeted measures including prescribed burning and mechanical removal of encroaching species.

The Marin Municipal Water District is an agency engaged with various restoration projects on Mount Tamalpais and woody plant encroachment is a major ecological concern. For example, current projects include mitigation of conifer encroachment in Oak woodlands and grasslands. The Mount Tamalpais Natural Resources Report outlined Douglas fir as a high priority species for mapping and monitoring. An important metric is the area of land with and without canopy-piercing Douglas fir (Edson, et al. 2016). This ecological concern influenced the data analysis conducted in this thesis, and hopefully can be of use to land managers such as MMWD in the future. Conifer encroachment and mitigation efforts are discussed further in Section 2.2.1.1.

2.2.1. Woody Plant Encroachment on Grasslands

Encroachment of woody plants onto perennial grasslands, including native and/or invasive shrubs and trees, is an ecological concern. Woody plant encroachment on grasslands has been one of the major land cover changes in the last century (Eldridge et al. 2011). Changes from herbaceous to woody vegetation fundamentally alters the ecosystem structure and supports different species of wildlife. Ecologists recognize the value of maintaining both herbaceous and woody plant communities. The effects of woody plant encroachment deserve a nuanced assessment. A meta-analysis by Eldridge et al. (2011) revealed that shrub encroachment does not necessarily lead to habitat degradation. Other studies have found that woody plant encroachment leads to a decrease in biodiversity. On the other hand, a meta-analysis by Ratajczak et al. (2012) determined that woody plant encroachment was associated with a significant decrease in species diversity in North American herbaceous ecosystems. Additionally, a negative relationship has been found between woody vegetation and nesting success of grassland birds (Bakker 2003). Woody plant encroachment can also increase erosion, dust, and pollen, which may be caused by a combination of global and local factors, including overgrazing of cattle, fire suppression, and climate change (Archer 2010).

Woody plant encroachment can cause an irreversible loss of grasslands that may require human intervention to support recovery. Since woodlands will not naturally shift back to grasslands, they are referred to as “steady state” ecosystems (Ansley and Wiedemann 2008). However, efforts to reverse encroachment have had limited success. Lett and Knapp (2005) studied woody plant encroachment onto tallgrass prairies in the central U.S. These grasslands that were once maintained by fire are being taken over by shrubland due to fire suppression and changes in land use. This encroachment supports expansion of forests while displacing graminoid species. Lett and Knapp (2005) found that a combination of fire and mechanical removal of shrubs did not successfully restore open grassland community structure in the short term. Fire alone will not eliminate shrub communities once they are established because they easily resprout from the root. Mechanical shrub removal followed by herbicide treatment had some success in restoring forb species, but not graminoid species, which may take several years to recover. Ansley and Wiedemann (2008) also discuss restoration methods to target woody plant encroachment in their study on Juniper encroachment into U.S. grasslands. These interventions include a combination of mechanical removal by chaining followed by prescribed fire.

The studies discussed above suggest that proactive measures are preferable to reactive measures because the longer woody plants become established, the harder it is to remove them and restore herbaceous ecosystems. This area of research has been recognized and incorporated within the Marin Municipal Water District (MMWD), one of the land management agencies this thesis will ideally inform. They have successfully removed encroaching shrubs from grassland using grazing, regular prescribed fire, and a combination of mechanical removal and herbicide (Sherry Adams, email message to author, December 11, 2021).

2.2.1.1. Conifer Encroachment

Conifer encroachment is a specific type of woody plant encroachment of concern in Marin County, where Douglas firs threaten oak woodland, shrubland, and grassland ecosystems. Conifer encroachment threatens biodiversity, degrades woodlands and grasslands, and alters the fuel bed structure (Engber et al. 2011). This thesis identified species of conifer, for example Douglas fir, encroaching onto other communities. Although Douglas fir trees are native to California, historically the population would have been managed by frequent fires. Douglas fir saplings with trunks less than 15cm are killed by wildfires and only gain fire resistance as mature trees (Mensing 2006). However, due to decreased fire frequency over the past two centuries, shade-tolerant Douglas firs grew rapidly in the understory of Oak woodlands and encroached on herbaceous ecosystems. These conifers can grow up to 70m tall, eventually piercing the Oak canopy and shading out other species. This process, known as conifer over-topping, can hinder the growth of slow-growing, shade-intolerant Oaks and can ultimately be detrimental (Cocking 2011). The acorns produced by Oak woodlands provide an important food source for native wildlife including birds, black bears, and White-tailed deer (Cocking 2011).

Ecologists manage conifer encroachment using various restoration methods such as mechanical removal and prescribed burning, but these techniques have had mixed results depending on how advanced the encroachment is. Livingston et al. (2016) compared restoration treatments to mitigate conifer encroachment in The Bald Hills Oak woodlands in the Pacific-

Northwest U.S. The authors found increased understory species diversity resulting from mechanical removal and fire treatment. However, this increase was in non-native as well as native species which may be counterproductive to overall ecological health. Additionally, only high-severity fire was successful in reducing conifer dominance and allowing fire-tolerant Oaks to resprout and remain intact. Low-intensity fire, although it has fewer safety concerns, could be counterproductive in reducing conifer encroachment. The low-intensity fire kills saplings but not mature trees, which go on to produce seeds and thus spread. High-intensity fire, the most effective method, may not be a practical option in areas where it poses a risk to nearby populations.

Although prescribed burning is beginning to be considered again in Marin County, it is controversial due to the proximity of neighborhoods to open spaces like Mount Tamalpais. Additionally, fire may not be an effective method in Marin's long-unburned ecosystems where conifer encroachment has been established for more than ten years. In these areas, mechanical removal may be the only way to mitigate encroachment (Cocking et al. 2015). MMWD has treated Douglas fir invasion using various methods of mechanical removal. MMWD tried removal of mature Douglas fir trees in an area that was historically open grassland. The unintended result was conifers were replaced by coyote brush or invasive grasses. This result suggests that restoration of native grassland in an area with long-established woody plant encroachment is unlikely without long-term active management. One reason is the lack of native seed bank of herbaceous plants in long-established forests or shrubland. Instead, MMWD now targets areas of recent conifer encroachment by removing small saplings around ten years or younger by hand (Sherry Adams, email message to author, December 11, 2021). Targeting recent encroachment may be more time and cost effective and more practical given that once established, woody plants form a steady state community. Another effort of MMWD is to reduce over-topping of Oaks by conifers by thinning out the understory.

2.3. Historical Imagery

This thesis required the integration of historic and modern aerial imagery to analyze changing vegetation over an extended period. Historical imagery is often widely available, can cover landscapes at a large scale, and can be processed automatically or manually (Lydersen and Collins 2018). Historical aerial photographs broaden the ability to conduct land cover change analysis. Once projected into a coordinate system, historical aerials can be directly compared to modern images, as well as spatial analysis and change detection performed.

Historical imagery, while useful, presents challenges. Historical images that are not spatially referenced require georeferencing to ensure the alignment of imagery in a common planar projection so that change calculations can be made. There is the potential for small errors to be introduced during this process (Stancioff et al. 2014). Occasionally historical imagery presents challenges because the film has been damaged over time (Hudak and Wessman, 1998).

Comparing images through time or creating a mosaic of multiple images requires accounting for differences in spatial and spectral resolution. Historical imagery often has a lower spatial resolution than modern imagery which affects the minimum detectable patch size (Stancioff et al. 2014). Additionally, black-and-white historical imagery may be compared to color imagery, as was done in this thesis, but fewer types of land covers can be distinguished in black-and-white photos (Lydersen and Collins 2018). Spectral differences occur in photos acquired under different weather conditions or seasons. Also, the changing angle between the sun and the remote sensor causes brightness gradients (Hudak and Wessman, 1998). Eitzel et al. (2014), who compared historical and modern aerial images to map Conifer encroachment into

Oak woodlands, were unable to consistently distinguish between Conifer and Oak using supervised classification. They found it especially hard in mixed forests in historical aerials where contrast and sun angle varied greatly (Eitzel et al. 2014).

2.3.1. Methods For Handling Historical Imagery

Unreferenced aerial imagery contains errors that need correction before use, including geometric and radiometric correction (Bolstad 2019). Radiometric correction will not be necessary for the purpose of my study because classification is not based on the reflectance of each individual image (Chen et al. 2015). Two main sources of geometric error are tilt displacement and relief displacement. Tilt displacement in aerial images occurs because airplanes can rotate on three axes: front-to-back, side-to-side, and vertically. These rotations are known as roll, pitch, and yaw. Roll occurs when one wing lifts while the other wing drops. Pitch refers to the nose of the plane lifting while the tail drops, or vice versa. Yaw is the left-to-right movement of the nose of the aircraft (Verhoeven et al. 2013). Relief displacement occurs due to topographic variation, causing objects to appear displaced towards or away from the center of the image. In addition, the pixels on the edges of historical images are sometimes distorted due to camera panning. This distortion may require the edges of the image to be clipped.

Image rectification can correct for some of these errors and project historical imagery into the same coordinate system as referenced imagery using Ground Control Points (GCPs). When a raster is projected from one coordinate system to another, it undergoes a geometric transformation, which corrects for geometric errors. This transformation involves resampling cells from the input raster to create the output. Bilinear interpolation, the resampling method used in this thesis, calculates the value of the output cell from the distance weighted average of the four nearest neighbors. This resampling method is appropriate for quantitative data, continuous data, and aerial imagery. Nearest neighbor, on the other hand, retains the spectral integrity of the original pixels and should be used with categorical or qualitative data where the value of the pixel cannot change.

Several studies informed the georeferencing methods used in this project and discussed the difficulty of selecting appropriate GCPs in heavily forested areas. Stancioff et al. (2014), who effectively incorporated historical maps dating back to 1840 into a modern forest change analysis, describe the need for a standard methodology for georeferencing historical maps. Using QGIS, the authors selected appropriate GCPs on a reference image with a known projection and matched these locations on historical maps. Anderson (2015) also used QGIS to georeference historical imagery, while Eitzel et al. (2014) georeferenced their imagery using Leica Photogrammetry Suite to select GCPs. Finally, Lydersen and Collins (2018) used Historical Airphoto Processing version 2.1 to create an orthorectified mosaic.

2.4. Land Cover Change Detection

For decades, land cover research has benefitted from aerial photography that captures landscapes at high spatial and temporal resolution. In the 1970s, the USGS began capturing the Land Use and Land Cover (LULC) data that today remains a standard for land cover. Comparison of multiple images of the same area at different points in time can reveal land cover trends and predict future patterns (Singh 1989). These trends may reveal associated social, economic, or environmental pressures (Campbell and Wynne 2011). Environmental hazards, superfund sites, deforestation, disaster recovery, and urban planning are all examples of issues that can be addressed using land cover change detection. In addition, land cover change can provide ecological context and direct the focus of land managers and ecologists. Land cover change was used in this thesis. This type of information can help agencies like MMWD and One

Tam calculate the area of land that has undergone type conversion, as well as pinpoint how to prioritize restoration efforts.

2.4.1. Land Cover Classification and Change Detection Methods

Integration of remotely sensed data and GIS is advancing our ability to monitor land and accurately detect land cover change. Land cover classification at large scales is done with remotely sensed or aerial images. Remotely sensed imagery is available globally in various spatial resolutions and scales. GIS can be used to classify land cover and detect change using automated methods including object-based change detection (OBCD). OBCD works by grouping neighboring pixels into objects defined by homogeneity in texture, spectral value, scale, shape, or compactness (Kindu et al. 2013). It has been shown that OBCD techniques work best for imagery with high spatial resolution where the pixel size is much smaller than the objects of interest (Blaschke 2010; Hussain et al. 2013). The advantage to this technique is it considers a group of neighboring pixels and their relationship to each other. Hudak and Wessman (1998) studied shrub encroachment in South African savannas and captured variation in bush density over several decades. Using aerial photos taken at different times, the authors applied a textural analysis to classify five bush density classes. Automated classification was preferred because the vegetation of interest was small and sparse over a large study area. Textural analysis measures variation between neighboring pixels, which they argue is superior to automated classification methods that consider only the individual pixel. One constraint to this method is that textural analysis works only for high resolution imagery. The authors found their analysis was successful for comparing bush density across space but not across time due to the differences in spatial resolution of their historical imagery (Hudak and Wessman 1998).

Manual digitization is another option that may be preferable to automated classification. Heads-up digitizing is a method of manual classification which involves identifying and tracing features of interest on an image to create polygons. Although automated classification can be faster, Stancioff et al. (2014) explain that heads-up digitization can produce more detailed and accurate results, especially if relying on images with different types of data and colors. Additionally, heads-up digitizing can be time-consuming and inefficient for large areas but is appropriate for detecting small-scale changes in the landscape (Anderson 2015). Stancioff et al. (2014) used heads-up digitizing to map patches of forest in the Arroux River valley region in France. They digitized forest during six different time periods spanning 160 years and analyzed the area of forest gained and lost. This thesis classified three life forms: grassland, shrubland, and woodland. Heads-up digitization was appropriate for this study because of the relatively small study area and different types of images used.

Stancioff et al. (2014), Anderson (2015), Liu et al. (2009), and Zewdie and Csaplovics (2015) presented land cover change results using the cross-tabulation matrix. In their study of historic forest change in Burgundy, France, Stancioff et al. (2014) calculated land cover change using a pixel-based change detection method called Intensity Analysis. The authors outlined the results in a cross-tabulation matrix that identifies pixels as either forest loss, forest gain, forest persistence, or non-forest persistence (Stancioff et al. 2014). Anderson (2015) classified natural communities over ten time periods and used GRASS, a GIS plug-in, to produce the cross-tabulation matrix reporting change in natural communities for each time interval. Additionally, Liu et al. (2009) used Esri ArcGIS 9.0 to conduct cross-tabulation analysis showing the conversion of seven land use types in their study area near the Minjiang River in China, including settlement, farmland, grassland, shrubland, and forest. They then analyzed changes in the landscape pattern, for example using patch number and density to indicate the rate of fragmentation. Finally, Zewdie and Csaplovics (2015) outlined land cover gains and losses in a cross-tabulation matrix to determine that woodland had the highest loss and cropland had the highest gain from 1972-2010 in northwestern Ethiopia. This thesis outlined patterns of vegetation losses and gains in a series of tables similar to the cross-tabulation matrix to break down the changes in life forms that have occurred since 1952 due to woody plant encroachment.

Chapter 3 Methods

The goal of this project was to visualize and quantify changes in grassland, shrubland, and woodland communities to assess woody plant encroachment between 1952 and 2018 in Marin County. MMWD originally planned to complete this project to compare historical 1952 imagery to modern images through a private contract that ultimately lost funding. The historical images captured valuable history of woody plant encroachment but needed to be georeferenced and classified to be useful in facilitating ecological restoration. This project aimed to complete the necessary pre-processing and classification of aerial imagery and analyze the change in vegetation cover. This chapter describes the data used for this project, including the source and purpose, as well as the methodology developed to conduct the change analysis.

3.1. Data

This project used historical and current aerial imagery based on the study area, spatial resolution, and availability to assess land cover change. The 1952 aerial imagery is available from the University of California at Santa Barbara (UCSB) online library, courtesy of Pacific Air Industries, and the 2018 orthophotos are available on Marin Map. Marin Map is a Geographical Information System of Marin County available through a collaboration of governmental and other public agencies where many different types of spatial data, including aerial photographs, are available (Table 1).

Table 1. Data description, sources, and quality information

Dataset	Marin Municipal Water District boundary	CA State Parks boundary	2021 Marin County fine scale vegetation map	2018 orthophotos	1952 historical image DRH-1K-13
Spatial reference	CA State Plane Zone 3, NAD83 (2011) Units: Feet	CA State Plane Zone 3, NAD83 (2011) Units: Feet	CA State Plane Zone 3, NAD83 (2011) Units: Feet	CA State Plane Zone 3, NAD83 (2011) Units: Feet	None
Spatial extent	Marin County	CA	Designed to be used at scales ≤ 1:5,000	Min X: 5946000.0 Max X: 5952000.0 Min Y: 2159999.5 Max Y: 2164000.5 Area: 687,680 acres	Min X: 0 Max X: 5377 Min Y: 0 Max Y: 5388
Description	Feature layer depicting MMWD boundaries Format: Shapefile	Feature layer depicting CA State Parks boundaries Format: Shapefile	Semi-automated map including field work, machine learning, & manual aerial photo interpretation 106-class vegetation map for 2018 covering Marin County Format: Vector layer	Spatial res: 15.24cm Spectral res: bands 1, 2, 3, NIR Dates taken: Jun 13-14, 21, 23, 2018 Format: 4-band MrSID (8-bit county mosaic)	Spatial res: 25cm Spectral res: B&W panchromatic Marin County, vertical view Date taken: Aug 16, 1952, Pacific Air Industries (PAI) Format: TIF (1 out of 390 mosaicked images)
Purpose	Demonstrated land ownership within study area	Demonstrated land ownership within study area	Cross-referenced to provide species composition of woody plant encroachment	1952 & 2018 vegetation compared to assess trends in woody plant encroachment. Used as reference image for historical image rectification	1952 & 2018 vegetation compared to assess trends in woody plant encroachment. Required image rectification

Sources: Data from UC Santa Barbara Library n.d., Marin Map 2018, GGNPC et al. 2021, California State Parks 2022, Marin GeoHub 2017, National Park Service 2019

3.1.1. Aerial Photography

This thesis compared aerial imagery from 1952 and 2018 to assess changes in grassland, shrubland, and woodland. The image quality of the contemporary imagery is slightly better than the historical imagery. The 2018 orthophotos include the visible and near-infrared spectrum with a spatial resolution of 15cm, and the 1952 imagery is in black-and-white and has a spatial resolution of 25cm. The orthophotos are projected in California State Plane Zone 3, NAD83 (2011) and serve as a reference for georeferencing the historic imagery to enable direct comparison between the images.

The scope of this study was to compare two time periods. However, future research could improve on this study by exploring a greater number of time intervals. Other historical aerial images that could add to the depth of this study include the 1965 historical imagery from Cartwright Aerial Surveys (CAS) and imagery from the 1987 National Aerial Photography Program (NAPP). The advantage of this data is that it captures an intermediate period between 1952 and 2018. The 1965 imagery includes over 100 scanned aerial panchromatic images of Marin County and is available through the UCSB library. The 1987 images include color infrared photos of Marin County centered over quarters of USGS 7.5-minute quadrangles and are available through Earth Explorer.

3.2. Workflow Description

This thesis compared aerial imagery from 1952 and 2018 in ArcGIS Pro to assess woody plant encroachment in Marin County. First, the 1952 image was rectified to have the same projection and bounds as the 2018 image. The historical image was transformed using GCPs placed at landmarks throughout the image and ultimately projected to California State Plane Zone 3, NAD83 (2011). Both images were then clipped to the same study area. Next, grassland, shrubland, and woodland were classified on both images using heads-up digitization. Finally, the two images were compared to assess the change in these vegetation forms over time. Of particular interest for land managers is woody plant encroachment, shown in this study where grassland transitioned to shrubland and/or woodland, or where forest replaced shrubland. The extent of this thesis is to distinguish between grass, shrub, and woodland, but not to distinguish between different types within those categories. For example, distinguishing between hardwood and conifer forests to study Douglas fir encroachment is beyond the scope of this thesis.

3.2.1. Data Handling

The UCSB online library archive and the USGS Earth Explorer website provided the historical aerial imagery in TIF format, and Marin Map provided the 2018 orthoimagery in SID format. These formats are compatible in ArcGIS Pro.

3.2.2. Image to Image Rectification

Historical maps and scanned images are often unreferenced images that must be rectified in order to compare and analyze land cover in images of the same area at different times. Image rectification involves the use of GCPs and mathematical models to register an unreferenced aerial image to a reference image. The output image is projected in the same coordinate system as the reference image. Image rectification aligns the grid system of one image to a reference image, while georeferencing refers to assigning a coordinate system to the image. This thesis included image rectification of the 1952 aerial images using the Georeferencer tool in ArcGIS Pro following the Esri workflow (Esri n.d.). The unreferenced 1952 raster was aligned to the reference images using control points and transformed. The reference used were the 2018 Orthophotos in Multiresolution Seamless Image Database (MrSID) format and projected to California State Plane Zone 3, NAD83 (2011).

It is important for GCPs to be distributed evenly throughout the image, preferably towards the edges of the image. The user should be sure that the control points are the same in both images which is why major landmarks are used that have not changed over time. Careful placement of GCPs for this thesis included intersections of roads and trails, corners of buildings, dams, reservoirs, and bends in roads (Figure 3). The GCP pairs were selected starting by clicking on the point in the historical image, followed by clicking the same point in the orthophoto. After adding numerous GCPs, the pairs with the highest residual errors were deleted to achieve the best fit.

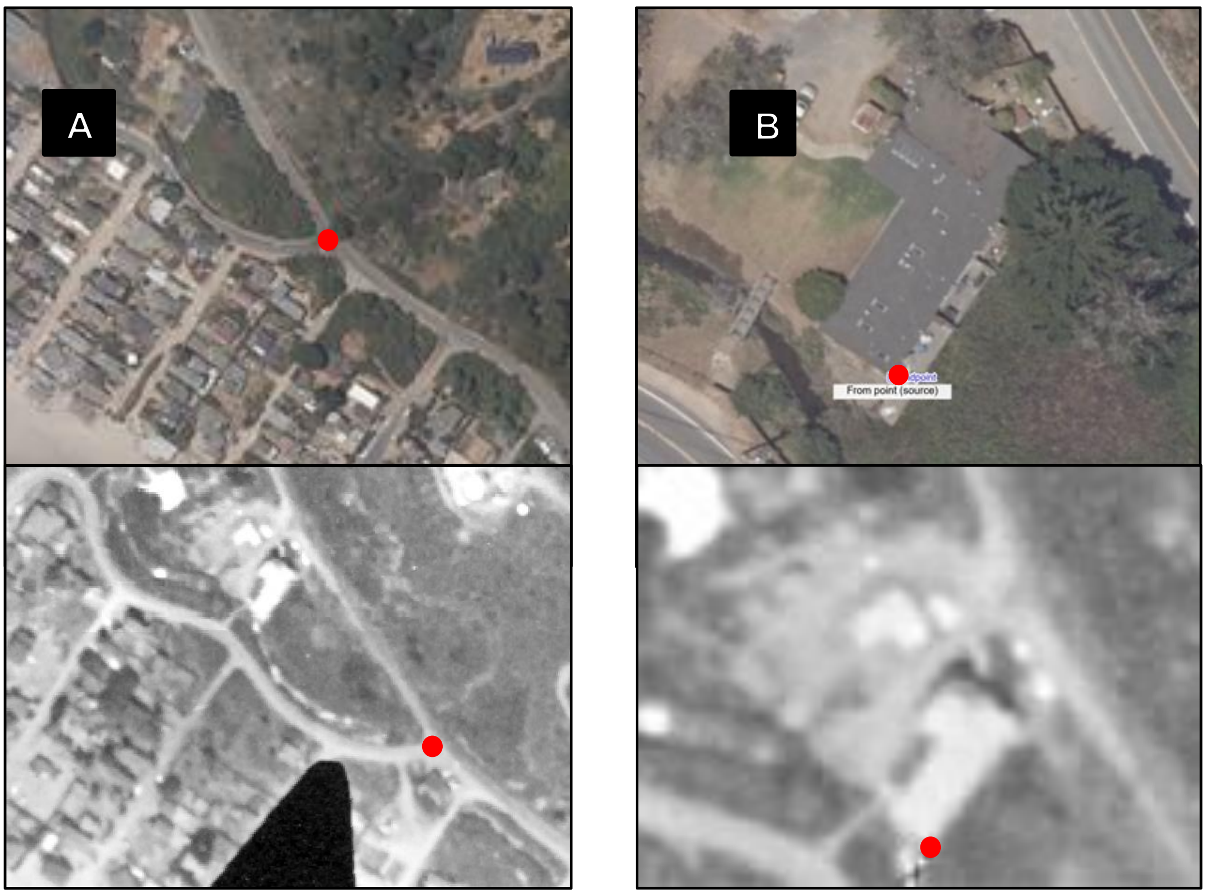

Figure 3. GCP pairs (red) placed on the 2018 reference image (above) and on the corresponding point on the 1952 unreferenced image (below). A) A road intersection, and B) The lower right corner of a building.

After selecting the desired GCPs, the Georeferencer tool calculated a polynomial equation representing the geometric relationship between the two images. The mapping function used is either first-order, second-order, or third-order transformation, depending on the level of distortion in the unreferenced image. The first-order function will stretch, scale, or rotate, while the second- or third-order function will bend or curve the image. The mapping function also determines the minimum number of GCPs needed. For example, the first-order transformation requires a minimum of three GCPs, while the second-order transformation requires a minimum of six. The general rule is to use the lowest-order function that produces an acceptable result, which for this study was the second-order transformation. Finally, the Root Mean Square Error (RMS) calculates the residual error between the GCPs and thus provides an accuracy assessment of the transformation equation. This study aimed for a RMS of <10, advised by the thesis committee members based on the scale and purpose of the study.

The historical image was rectified to the 2018 image using 13 control points. The resulting equation used second-order polynomial transformation with a residual (RMS) forward error of 7.047, inverse of 0.004, and forward-inverse of 0.001.7 (Figure 4). The georeferenced image was exported as a raster with 10,000 columns and 3000 rows.

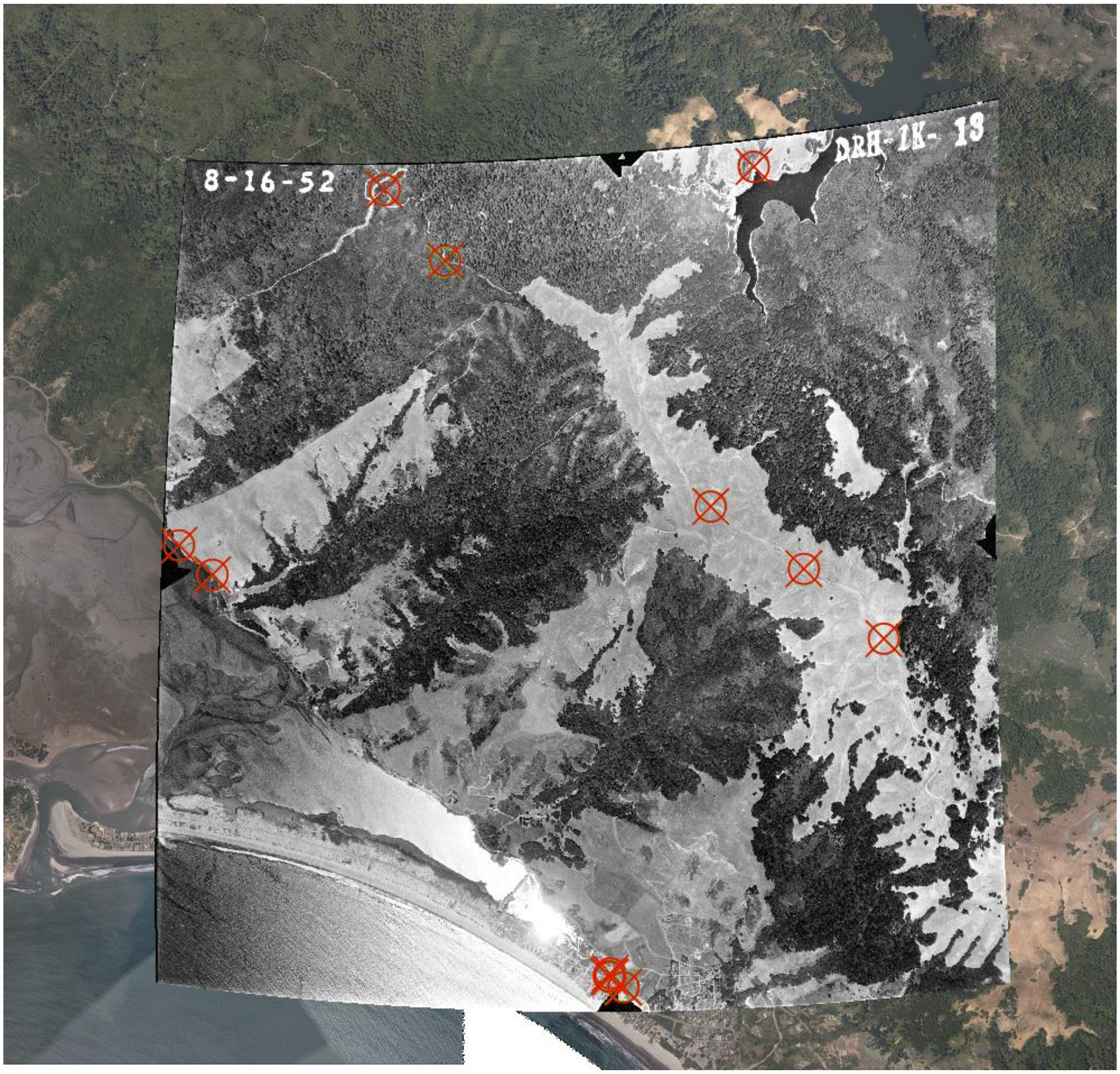

Figure 4. Historical image (black-and-white) rectified to the 2018 orthoimagery (background image) using 2nd order polynomial transformation with 13 GCPs (red).

3.2.3. Defining the Study Area

The edges of the historical image were curved after image rectification (Figure 4). To exclude the edges, the study area was bound by a rectangle and was transformed into a raster in California State Plane 3.

The raster needed to be clipped to a rectangular shape after it was transformed due to having curved edges. A new feature class was created to generate a bounding box that defined a rectangular study area for both images. The Extract by Mask tool clipped the 2018 and 1952 images to this bounding box. This area excluded the “No Data” areas and the text at the top of the historic image.

3.2.4. Digitizing

This project assessed type conversion of grassland, woodland, and shrubland by mapping changes in these land covers between 1952 and 2018. This work refers to these plant communities as either life forms or vegetation types. Grassland, shrubland, and woodland were distinguishable from one another on the aerial images and classified as separate land covers using heads-up digitization. A fourth land cover type defined all other surfaces: water, bare rock, dirt, buildings, roads, and trails, which are not of explicit interest in this study.

Heads-up digitization was done by manually tracing polygons around the corresponding vegetation types in ArcGIS Pro. Each vegetation type was clearly distinguishable in both images (Figure 5). The Create Feature Class tool created vector shapefiles containing the digitized polygons for each land cover class. Polygons were drawn using the Create tool, the Split tool was used to cut holes into existing polygons, and the Merge tool was used to combine adjacent polygons of the same land cover type.

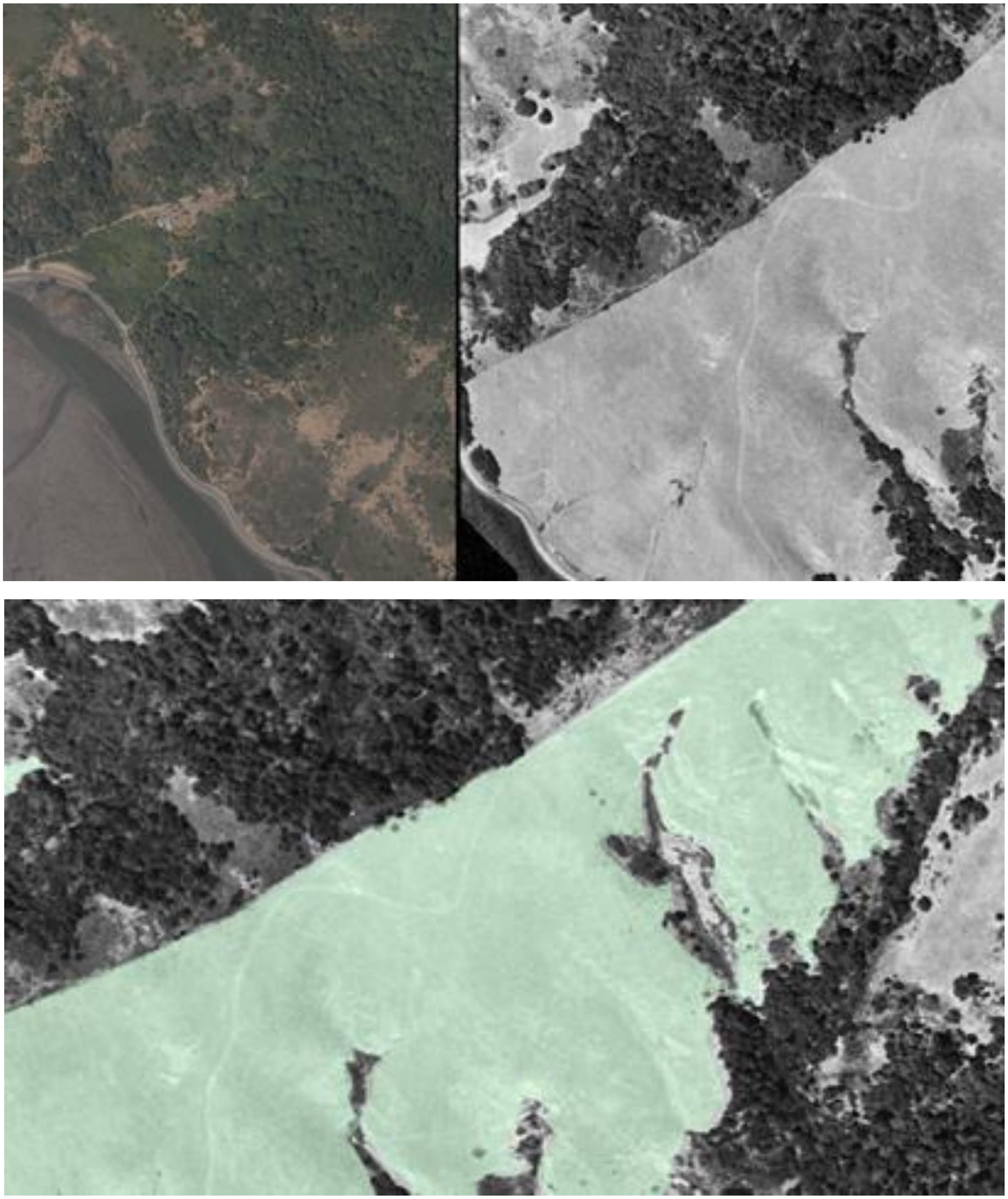

Figure 5. Grassland, shrubland, and woodland were distinguished in the 2018 (top left) and 1952 (top right) images. Woodland had the darkest color and roughest texture, grassland appeared lightest and smoothest, and shrubland was in between. For example, grassland (green) was classified in the lower image.

3.2.4.1. Minimum Mapping Unit

The minimum mapping unit, or the minimum area of a polygon included in the classification and analysis, helps with clarity and ease of interpretation (Montello and Sutton 2013, Bolstad 2019). The minimum mapping unit establishes a lower limit on the size of a polygon, so any object smaller than the minimum mapping unit is not included. For example, the U.S. Census Bureau uses counties as the minimum mapping unit (Montello and Sutton 2013). In general, the smallest identifiable feature must measure at least four pixels squared, but it depends on the application of the data. For example, the smallest possible minimum mapping unit for an image with a spatial resolution of 1m would be $2m^2$ (Herold 2011).

The digitizing process for this thesis included enough detail to be helpful for managers of restoration projects. For example, mapping every individual tree would be too much detail, but mapping small areas of continuous habitat would be of interest. The Marin fine scale vegetation map was a helpful reference for setting the minimum mapping unit as 0.25 acres (GGNPC et al. 2021). The attribute table for each layer included a field to calculate the geodesic area in acres of each polygon. Features with an area below the minimum mapping unit (<0.25 acres) were not counted, while all features equal to or larger than the minimum mapping unit (≥0.25 acres) were digitized. For example, the trees in the center and center-right of Figure 6 have an area below the minimum mapping unit (0.25 acres) and were therefore left out of the woodland layer (green). They instead became part of the surrounding grassland layer (yellow). All trees included in the woodland layer exceeded the minimum mapping unit.

Figure 6. Example of the minimum mapping unit. Trees with areas ≥0.25 acres were included in the woodland layer (green), and trees <0.25 acres were included in the grassland layer (yellow).

3.2.5. Change Analysis

This project compared changes in vegetation between 1952 and 2018 to assess woody plant encroachment. Comparison of the woodland, grassland, and shrubland cover between 1952 and 2018 resulted in a series of maps and tables.

First, net losses and gains for each life form were mapped using the layers classified in the previous section. The erase tool was used, functioning like a cookie cutter to erase any overlap between two layers, leaving only areas of the input layer that did not overlap with the other layer. For example, to visualize where grassland was lost, the erase tool was used with 1952 grassland as the input layer and 2018 grassland as the erase feature. To view the loss in shrubland or woodland, the same method applied. The minimum mapping unit was kept consistent at 0.25 acres. Shrubland was analyzed separately for total losses and gains because this shrubland was both encroaching and being encroached upon. Shrubland losses and gains are different processes likely with different ecosystems and shrub species. The gain in shrubland was found by switching the order of the inputs used in the erase tool so that the erase feature was the 1952 shrubland layer.

This thesis created a simplified version of Table 2 to summarize attributes for grassland, shrubland, woodland, and other surfaces in 1952 and 2018 (Table 2). Pontius et al. (2004) used a cross-tabulation matrix to compare land cover change between two times, where the rows display land cover for Time 1, and the columns display land cover for Time 2. This thesis focused on trends, such as reduced grass cover and increased shrub and wood cover between 1952 and 2018.

Table 2 also distinguishes between systematic and random changes, which this thesis will not include. The values on the diagonal indicate persistence because the land cover has not changed, and values off the diagonal indicate a change from one category to another, and finally displays the gross gains and gross losses.

Table 1. Cross-tabulation matrix comparing land cover change from two time periods.

	Time 2				Total time 1	Loss
	Category 1	Category 2	Category 3	Category 4		
Time 1						
Category 1	P_{11}	P_{12}	P_{13}	P_{14}	P_{1+}	$P_{1+} - P_{11}$
Category 2	P_{21}	P_{22}	P_{23}	P_{24}	P_{2+}	$P_{2+} - P_{22}$
Category 3	P_{31}	P_{32}	P_{33}	P_{34}	P_{3+}	$P_{3+} - P_{33}$
Category 4	P_{41}	P_{42}	P_{43}	P_{44}	P_{+}	$P_{4+} - P_{44}$
Total time 2	P_{+1}	P_{+2}	P_{+3}	P_{+4}	1	
Gain	$P_{+1} - P_{11}$	$P_{+2} - P_{22}$	$P_{+3} - P_{33}$	$P_{+4} - P_{44}$		

Source: Pontius et al. (2004).

Next, maps were made to visualize areas of encroachment: where woody plants have displaced herbaceous ecosystems, or where forest has replaced shrubland. These outputs were created using the Intersect tool to create polygons that represent areas of overlap between layers. As well as using the intersect tool to create new feature classes, the maps were also visualized by overlapping two partially transparent layers of different colors. For example, to calculate areas that were converted from grassland to shrubland, the intersection of the 1952 grass layer and the 2018 shrub layer was taken. To calculate areas that were converted from grassland to woodland, the intersection of the 1952 grassland layer and the 2018 woodland layer was taken. Finally, to calculate the areas converted from shrubland to woodland, the intersection of the 1952 shrub layer and the 2018 wood layer was taken.

3.2.5.1. Species Composition

This study referenced the Marin fine scale vegetation map to provide further detail of the species involved in woody plant encroachment (GGNPC et al. 2021). This map classifies 106 classes of vegetation on Mount Tamalpais (see Figure * in the Appendix). The layers described in the previous section were clipped to the Marin fine scale vegetation map. Polygons for each species in a layer were merged and then the area for each species calculated. To observe a minimum mapping unit of 0.25 acres, any polygon smaller than that size was removed. Percent cover was calculated by dividing the area of a certain species by the total area of that layer with a corresponding map.

The Marin fine scale vegetation map also revealed the classification accuracy. The percentage of each layer that was misclassified was calculated, and then the error was corrected by removing misclassified data. For example, shrub and herbaceous land cover was removed from any layer representing forest land cover. Because this thesis aims to help land management agencies interested in vegetation change, the results were presented after correcting for misclassification. The results before correcting for errors can be found in the Appendix.

Chapter 4 Results

This thesis assessed changes in vegetation using aerial imagery from 1952 and 2018. First, the 1952 image was rectified and projected to California State Plane 3. Then, the study area was defined as the same area on both images. Next, three life forms were digitized, grassland, shrubland, and woodland, which are explained further in section 2.2. Net changes in life forms were investigated, and woody plant encroachment was visualized in a series of maps including tables showing percent cover by species. For example, grassland replaced by shrubland between 1952 and 2018 was mapped. Then, the Marin fine scale vegetation map was referenced to identify the specific shrub species. The cover of each species was given as a percentage of the total area.

4.1. Study Area

After rectifying the historical image, the study area was defined by clipping both images to a bounding box (Figure 7). The resulting study area encompasses 4,745 acres, including Bolinas Ridge and the town of Stinson Beach on the Southwest side of Mount Tamalpais in Marin County, California.

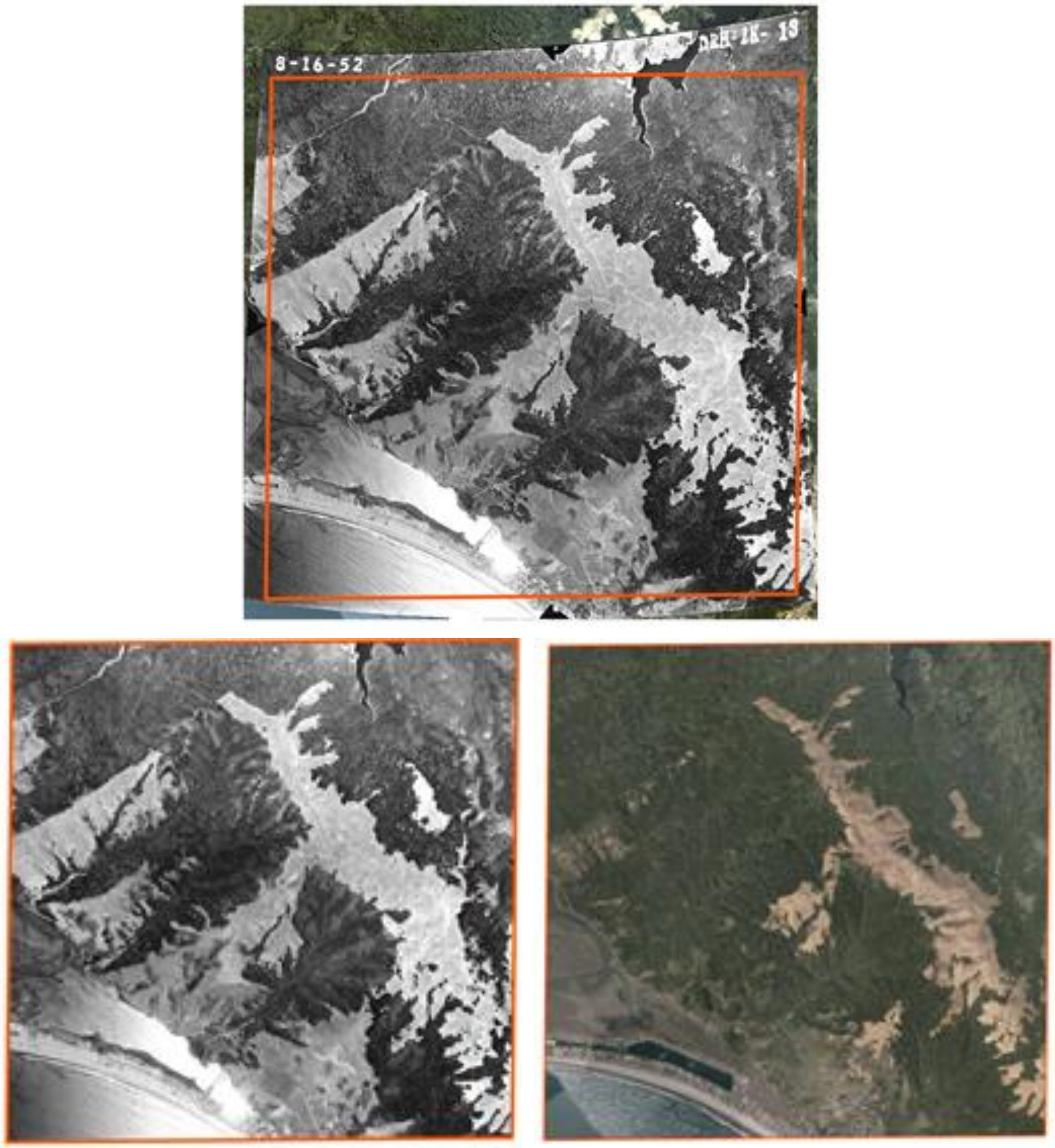

Figure 7. Bounding box (red) defining the study area for both aerial images (top) and cropped to the 1954 image (bottom left) and 2018 image (bottom right).

4.2. Land Cover Classification

This thesis digitized three life forms, grassland, shrubland, and woodland, for the 1952 and 2018 aerial images (Figures 8 and 9). A fourth category included all other surfaces: roads, bare rock, dirt, buildings, bodies of water, and trails. Initial comparison of the Figures 8 and 9 revealed that more grassland cover was lost than shrub or forest cover. The legends display the vegetation classes in order of cover. In 1952, grassland and woodland were prevalent throughout the study area growing in large, continuous patches. Shrubland covered less area and was more fragmented with a few larger patches. By 2018, grassland on the West-facing slopes had been replaced with mostly woodland and some shrubland, with grassland left intact in continuous patches mostly along the ridgeline. Shrubland cover was also reduced, for the most part replaced by woodland and becoming much more fragmented.

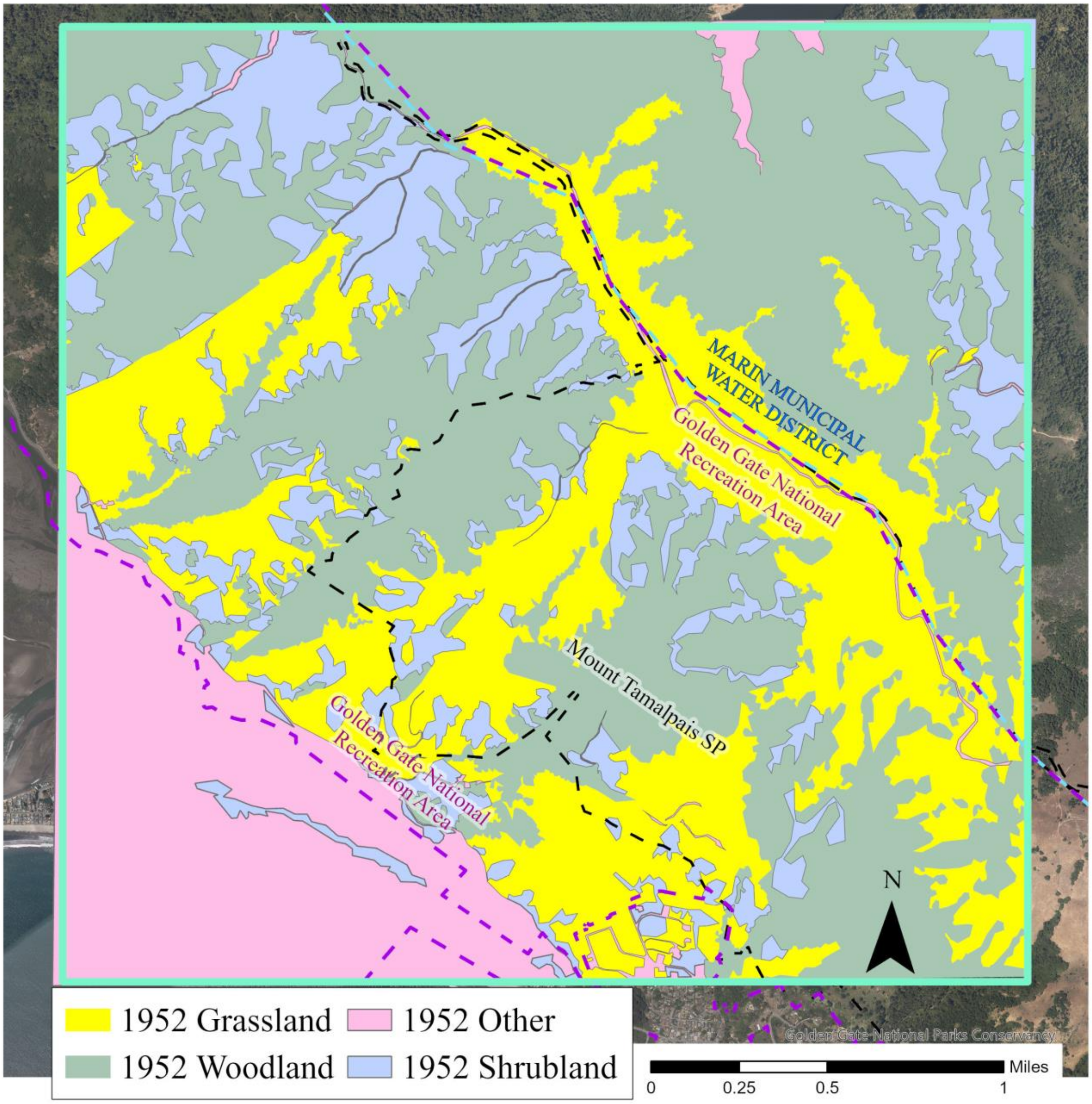

Figure 8. Life form classification of the 1952 aerial.

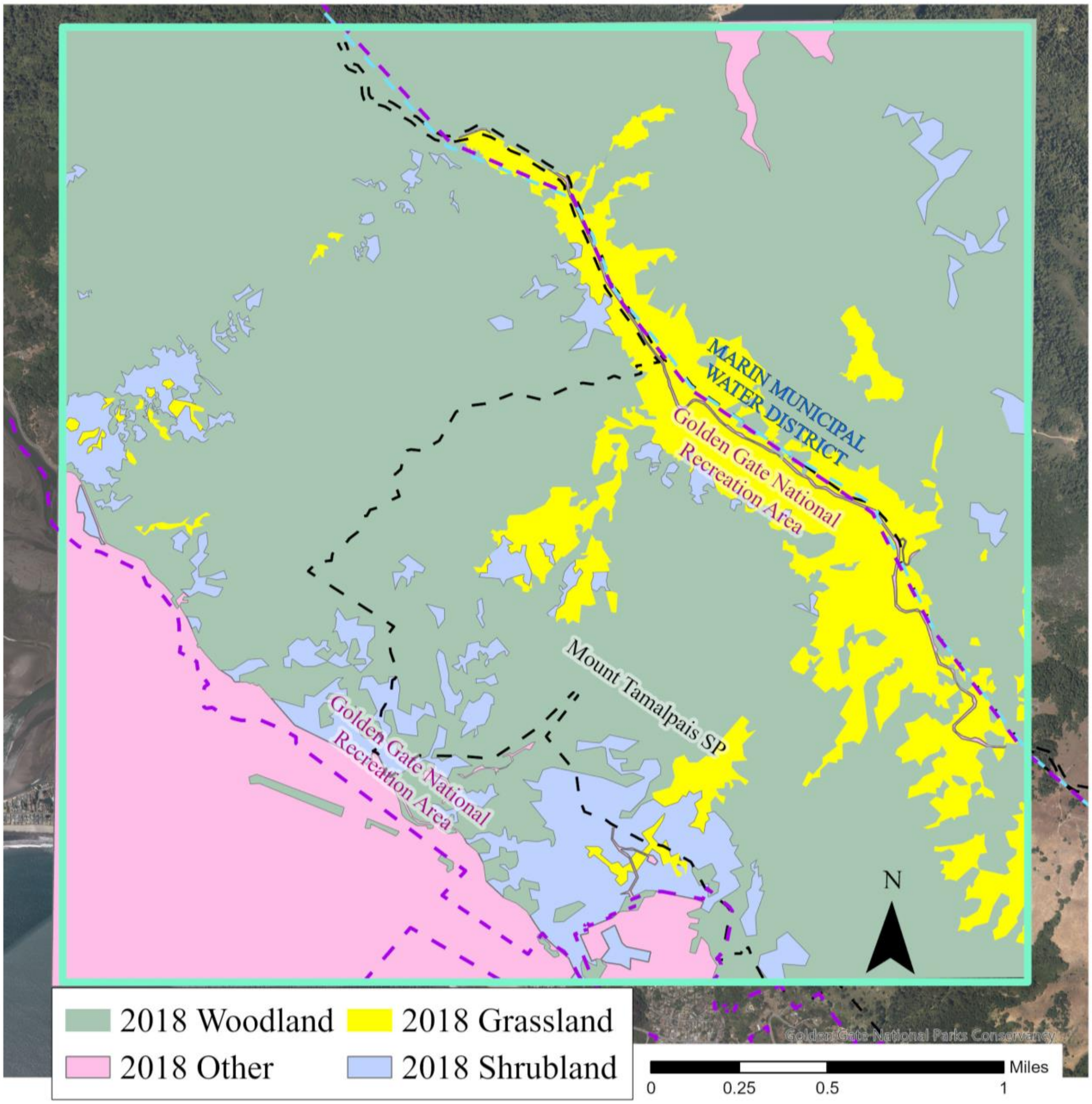

Figure 9. Life form classification of the 2018 orthophoto.

4.3. Changes in Life Forms

Between 1952 and 2018, woodland expanded while grassland and shrubland decreased in area (Table 3). The net changes in each life form were calculated as the total area in acres and the percent change from the original area. Grasslands decreased by 62%, shrublands decreased by 51%, and woodlands grew 307%. This initial finding supports the notion of woody plant encroachment between 1952 and 2018, and suggests forest comprised most of the woody plant encroachment. Shrubland gained and lost was separated out to explore these processes individually. Overall, more shrubland was lost than gained. Finally, "other" surfaces increased by 3%, which can be attributed in part to the expansion of the town of Bolinas.

Table 3. Net change and % change of grassland, shrubland, and woodland cover between 1952 and 2018. The area of shrubland gained and lost is further broken down.

	Area (acres)			
Year	Grass	Shrub	Forest	Other
1952	1,205	726	795	737
2018	455	359	3,237	758
Net difference	-750	-367	+2,441	+20.68
Net change (%)	-62	-51	+307	+3

	Area (acres)	
	Shrub gained	Shrub lost
	279	646
Change (%)	+38	-89

Between 1952 and 2018, there was a net loss of 750 acres of grassland, a reduction of 62% (Table 3). Grassland was lost mostly along the West-facing slopes and remains mostly intact along the ridgeline (Figure 10).

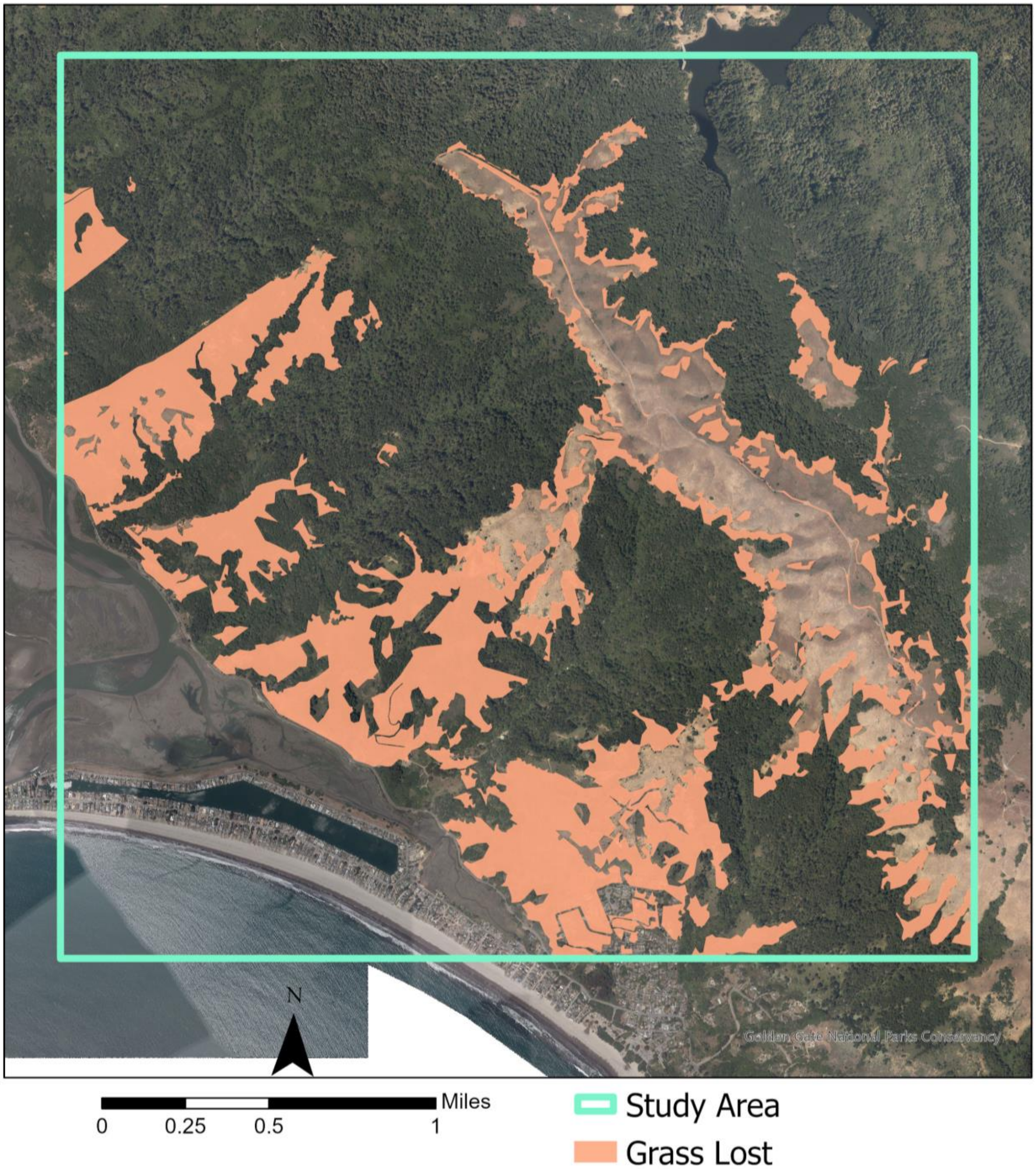

Figure 10. Grassland loss since 1952 (orange).

Between 1952 and 2018, there was a net gain of 2,441 acres of forest throughout the study area, or a 307% increase (Figure 11).

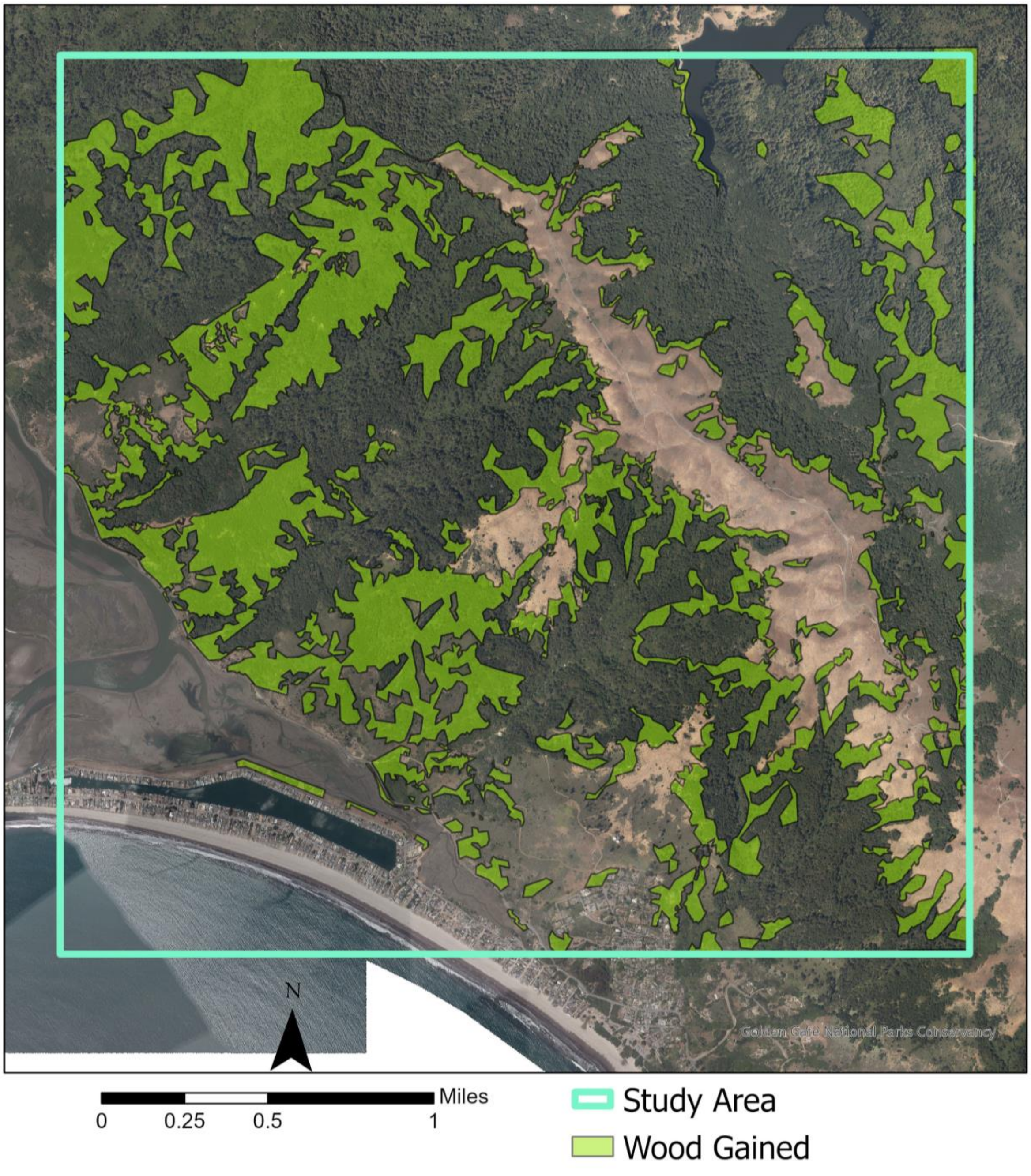

Figure 11. Areas in green transitioned to become forest from 1952 to 2018.

There was a net loss of shrubland. Shrubland gain and loss were visualized separately to investigate how these processes may differ in species composition (Figure 12). 279 acres of shrubland were lost and 646 acres were gained. Shrubland was mostly lost throughout the West-facing slopes, but generally gained only on the lower slopes.

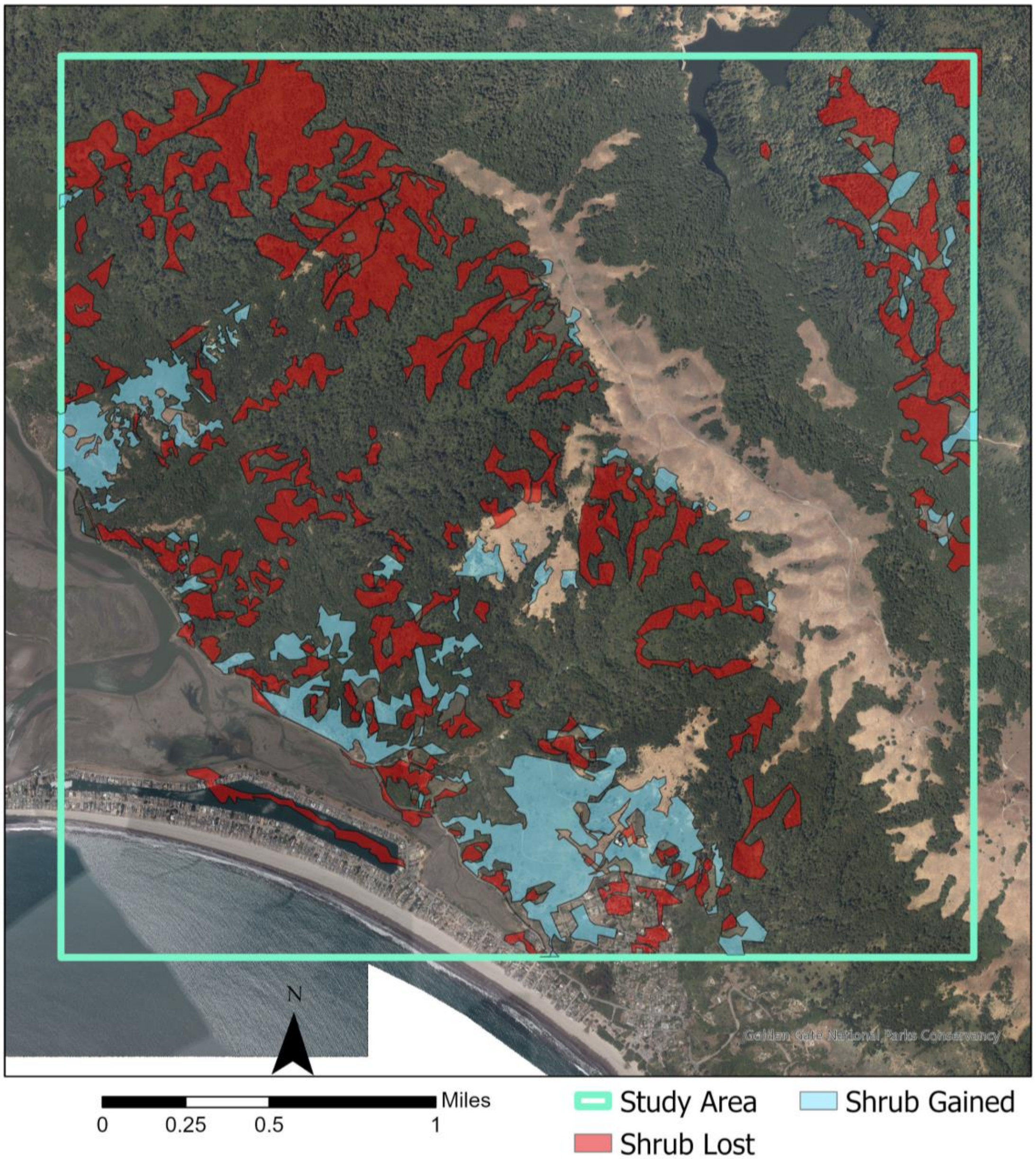

Figure 12. Areas in blue have transitioned to become shrubland since 1952. Areas in red show where shrubland has been lost since 1952.

A total of 1,390 acres of woody plant encroachment occurred between 1952 and 2018, which represents 29% of the total study area (Table 4 and Figure 13). Overall, more grassland was displaced than shrubland. Woodland encroachment onto shrubland was the most common type of woody plant encroachment, followed by woodland encroachment on grassland, and finally shrubland encroachment on grassland. There was roughly twice as much grassland replaced by woodland (39%) than by shrubland (17%). A total of 240 acres of grassland were replaced by shrubland, mostly on the lower West-facing slopes of the study area. 536 acres of grassland were replaced by forest, occurring mostly along the ridgeline at the edges of the grass and on the West-facing slopes below. 614 acres of shrubland were replaced by woodland.

Table 4. Total areas of woody plant encroachment in the study area between 1952 and 2018 after correcting for errors.

Woody plant encroachment (1925-2018)	Area (acres)	% of total area
Grassland replaced by shrubland	240	17
Grassland replaced by woodland	536	39
Shrubland replaced by woodland	614	44
Total	1,390	100

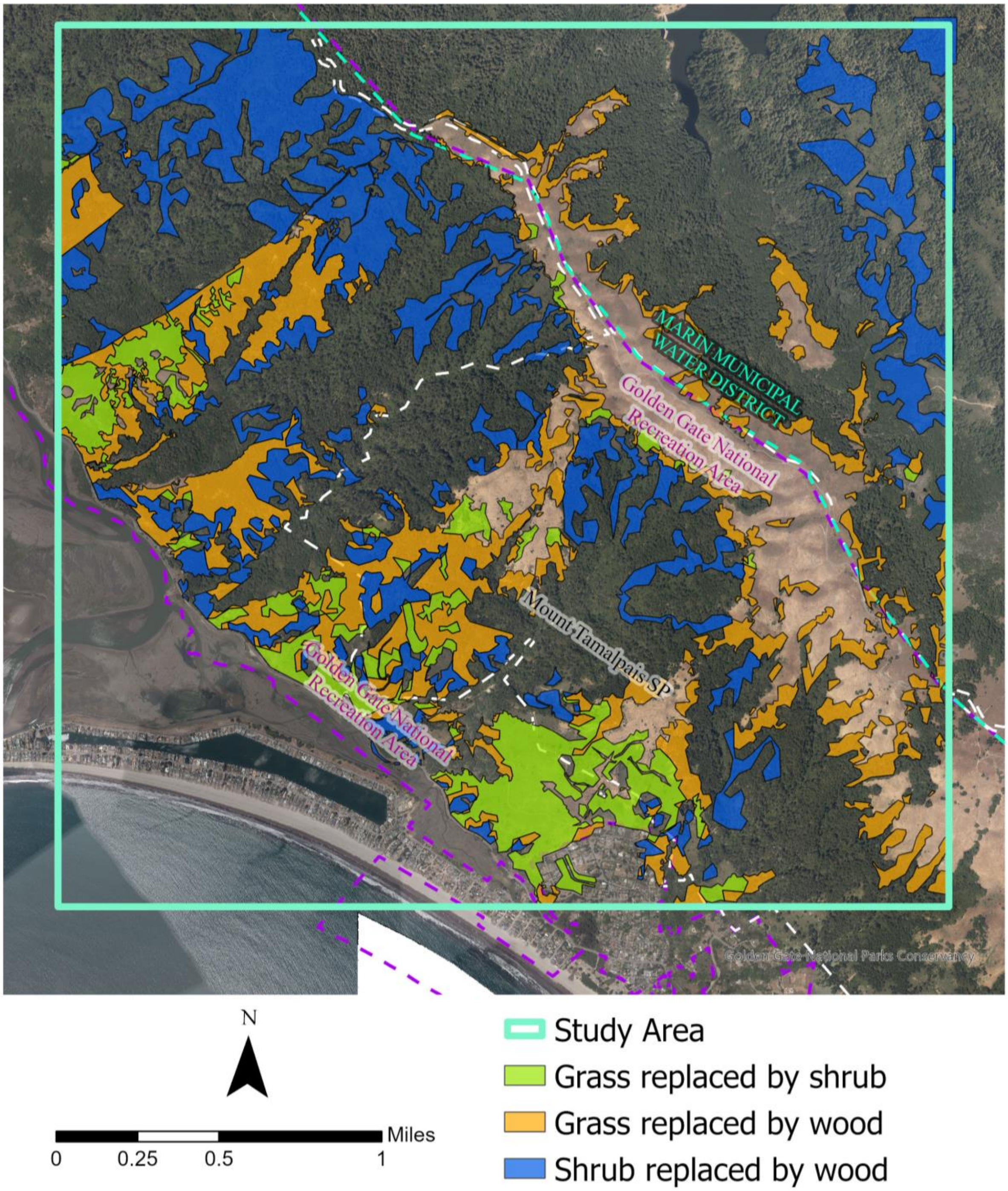

Figure 13. Encroachment of woody plants onto grassland and shrubland between 1952 and 2018.

4.3.1. Species Composition

Overlaying the Marin fine scale vegetation map onto the layers shown in Figure 13 revealed the species composition of each type of woody plant encroachment. The species composition was organized into the tables below showing the percent cover from greatest to smallest. The tables and figures show the results after correcting for errors.

189 acres of grassland was replaced by shrubland after correcting for errors (Table 5). The most common shrub species was coyote brush (80%), followed by California sagebrush (16%) (Table 5, Figure 14). The accuracy of shrubland replacing grassland was 79% before errors were removed.

Table 5. Shrub encroachment on grassland broken down by species cover from greatest to smallest.

Species	Scientific name	Life form	Cover (%)
Coyote brush	*Baccharis pilularis*	Native shrub	80
California sagebrush	*Artemisia californica*	Native shrub	16
Shrub fragment	…	Shrub fragment	2
Chamise	*Adenostoma fasciculatum*	Native shrub	1
Baker’s manzanita	*Arctostaphylos bakeri*	Native shrub	<1
California coffeeberry	*Frangula californica*	Native shrub	<1

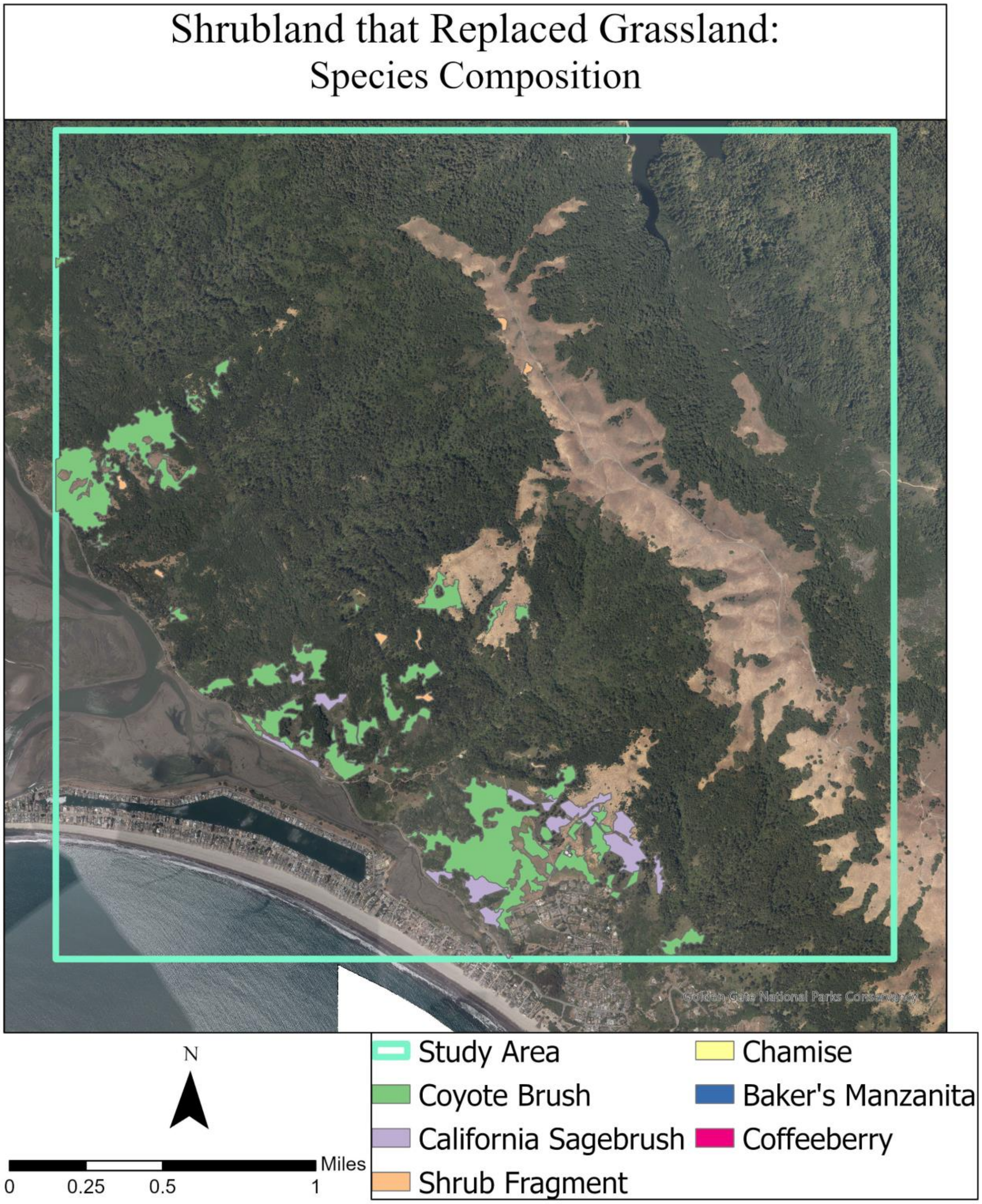

Figure 14. Shrubland species that replaced grassland between 1952 and 2018.

485 acres of grassland was replaced by woodland after correcting for errors (Table 4). The most common tree species was Douglas fir (81%), followed by California bay (7%) (Table 6, Figure 15). The accuracy of shrubland replacing grassland was 95% before errors were removed.

Table 6. Woodland species that replaced grassland between 1952 and 2018 after correcting for errors in order of cover from largest to smallest.

Species	Scientific name	Life form	Cover (%)
Douglas fir	*Pseudotsuga menziesii*	Native forest	81
California bay	*Umbellularia californica*	Native forest	7
Canyon live oak	*Quercus chrysolepis*	Native forest	5
Coast live oak	*Quercus agrifolia*	Native forest	5
Forest fragment	...	Mixed forest	<1
Monterey pine	*Pinus radiata*	Non-native forest	<1
Non-native forest	...	Non-native forest	<1
Douglas fir and tanoak	*Pseudotsuga menziesii & Notholithocarpus densiflorus*	Native forest	<1
Monterey cypress	*Hesperocyparis macrocarpa*	Non-native forest	<1
Coast redwood	*Sequoia sempervirens*	Native forest	<1

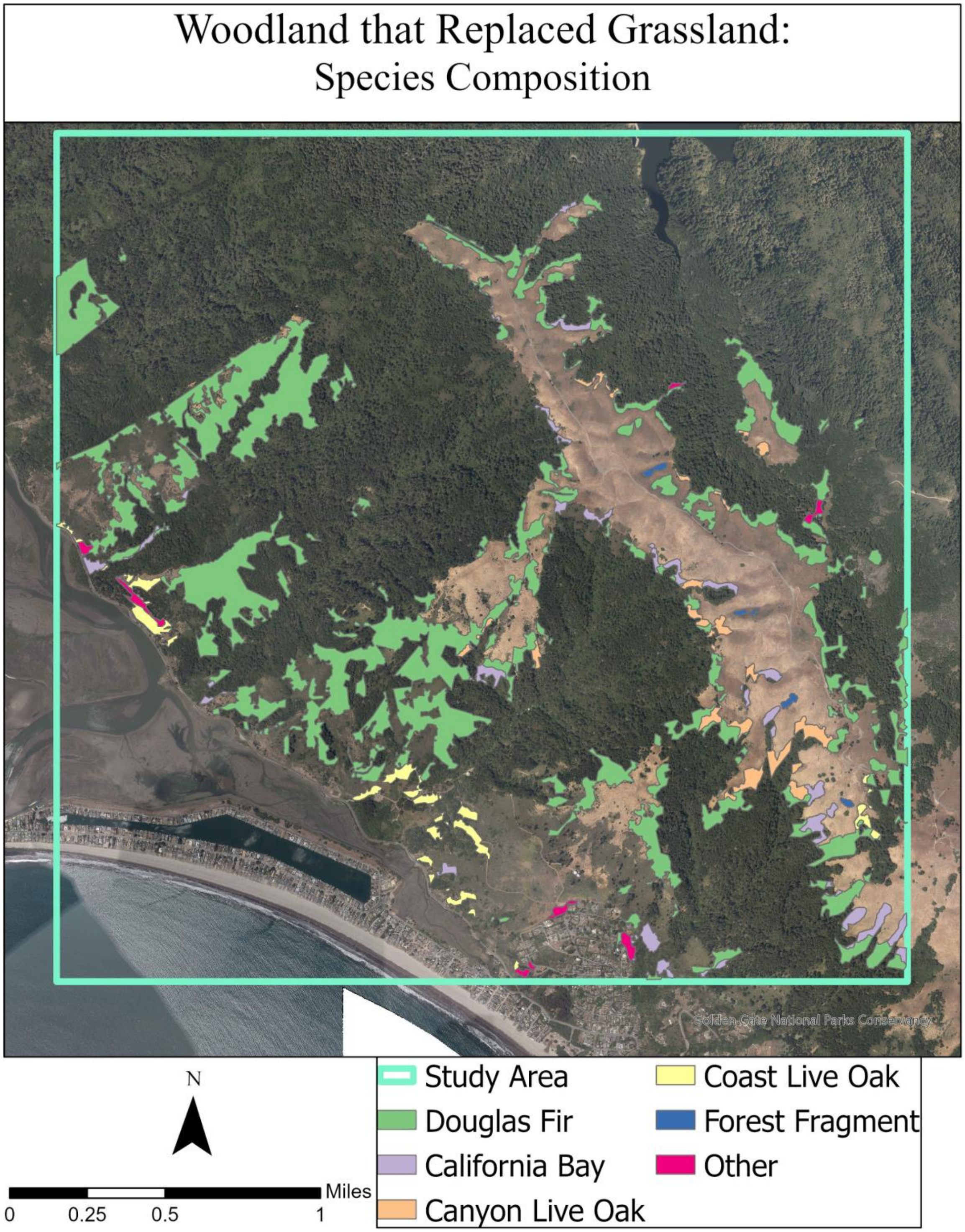

Figure 15. Woodland species that replaced grassland between 1952 and 2018.

583 acres of shrubland was replaced by woodland after correcting for errors (Table 4). The most common tree species was Douglas fir (71%), followed by California bay (14%) (Table 7, Figure 16). The accuracy of shrubland replacing grassland was 95% before errors were removed.

Table 7. Woodland species that replaced shrubland between 1952 and 2018 in order of cover from largest to smallest.

Species	Scientific name	Life form	Cover (%)
Douglas fir	*Pseudotsuga menziesii*	Native forest	71
California bay	*Umbellularia californica*	Native forest	14
Coast redwood	*Sequoia sempervirens*	Native forest	11
Coast live oak	*Quercus agrifolia*	Native forest	1
Canyon live oak	*Quercus chrysolepis*	Native forest	<1
Monterey pine	*Pinus radiata*	Non-native forest	<1
Blue gum and red gum	*Eucalyptus (globulus, camaldulensis)*	Non-native forest	<1
Forest fragment	...	Mixed forest	<1
Bigleaf maple	*Acer macrophyllum*	Native forest	<1
Pacific madrone	*Arbutus menziesii*	Native forest	<1

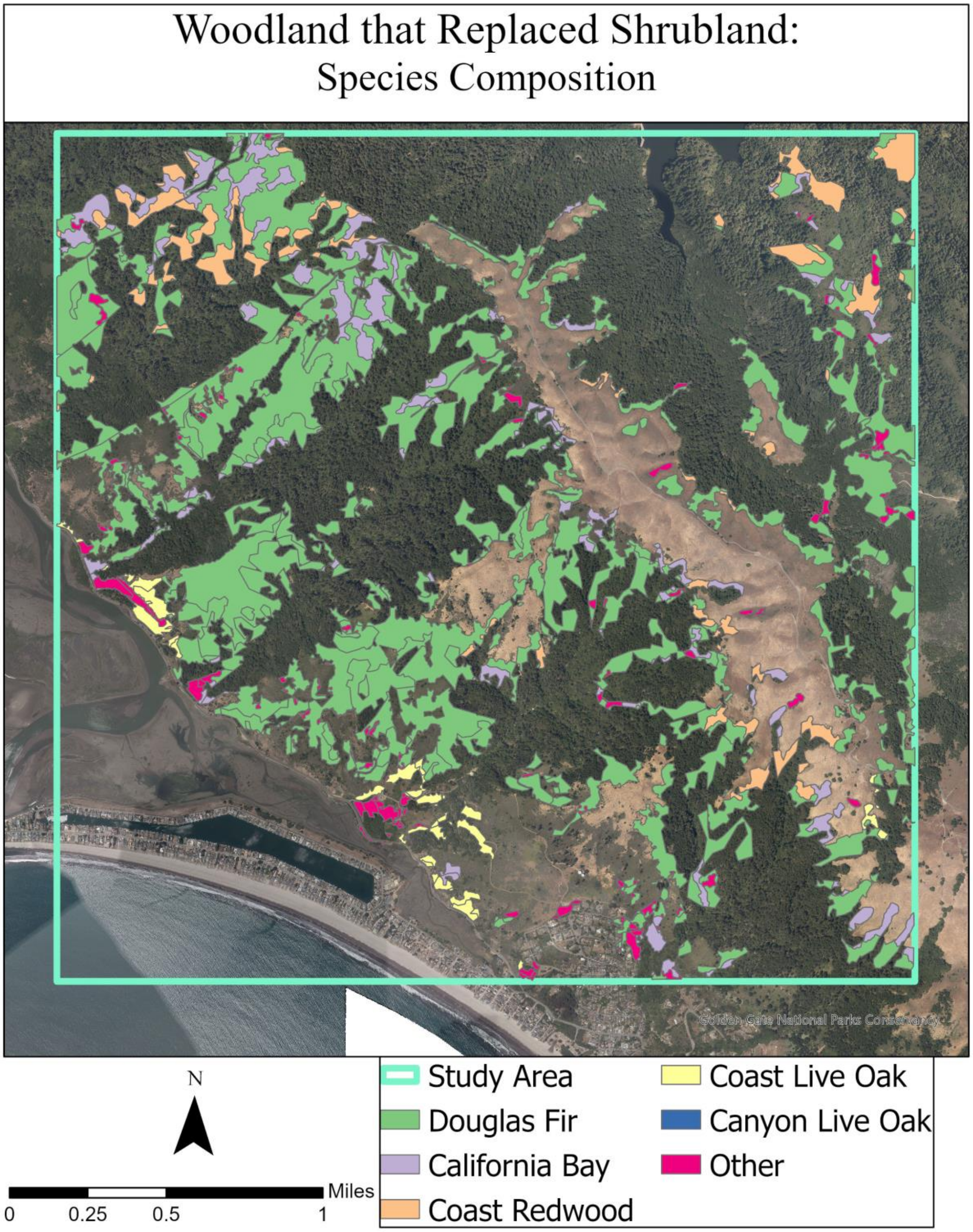

Figure 16. Woodland species that replaced shrubland between 1952 and 2018.

This thesis examined shrubland gain and loss separately. 279 (38%) acres of shrubland have been gained since 1952 while 646 acres (89%) have been lost (Table 3 and Figure 12). These areas result in a net loss of 51% of all shrubland.

The shrub species that have emerged since 1952 have been mostly native species. Coyote brush was the most common species covering 77% of the total area. California sagebrush was the second most common shrub species with 16% cover, followed by chamise (2%) and Eastwood manzanita (2%) (Table 8 and Figure 17). Classification of shrubland gained had 77% accuracy, and results before correcting for errors are detailed in the Appendix.

Table 8. Shrubland species that emerged between 1952 and 2018 in order of cover from largest to smallest.

Species	Scientific name	Life form	Cover (%)
Coyote brush	*Baccharis pilularis*	Native shrub	76.96
California sagebrush	*Artemisia californica*	Native shrub	15.74
Shrub fragment	…	Mixed Shrub	2.21
Chamise	*Adenostoma fasciculatum*	Native Shrub	2.04
Eastwood manzanita	*Arctostaphylos glandulosa*	Native Shrub	1.87
Baker’s manzanita	*Arctostaphylos bakeri*	Native Shrub	0.61
Arroyo willow	*Salix lasiolepis*	Native shrub	0.22
California coffeeberry	*Frangula californica*	Native Shrub	0.20
Glossy leaved manzanita	*Arctostaphylos (nummularia, sensitiva)*	Native Shrub	0.15

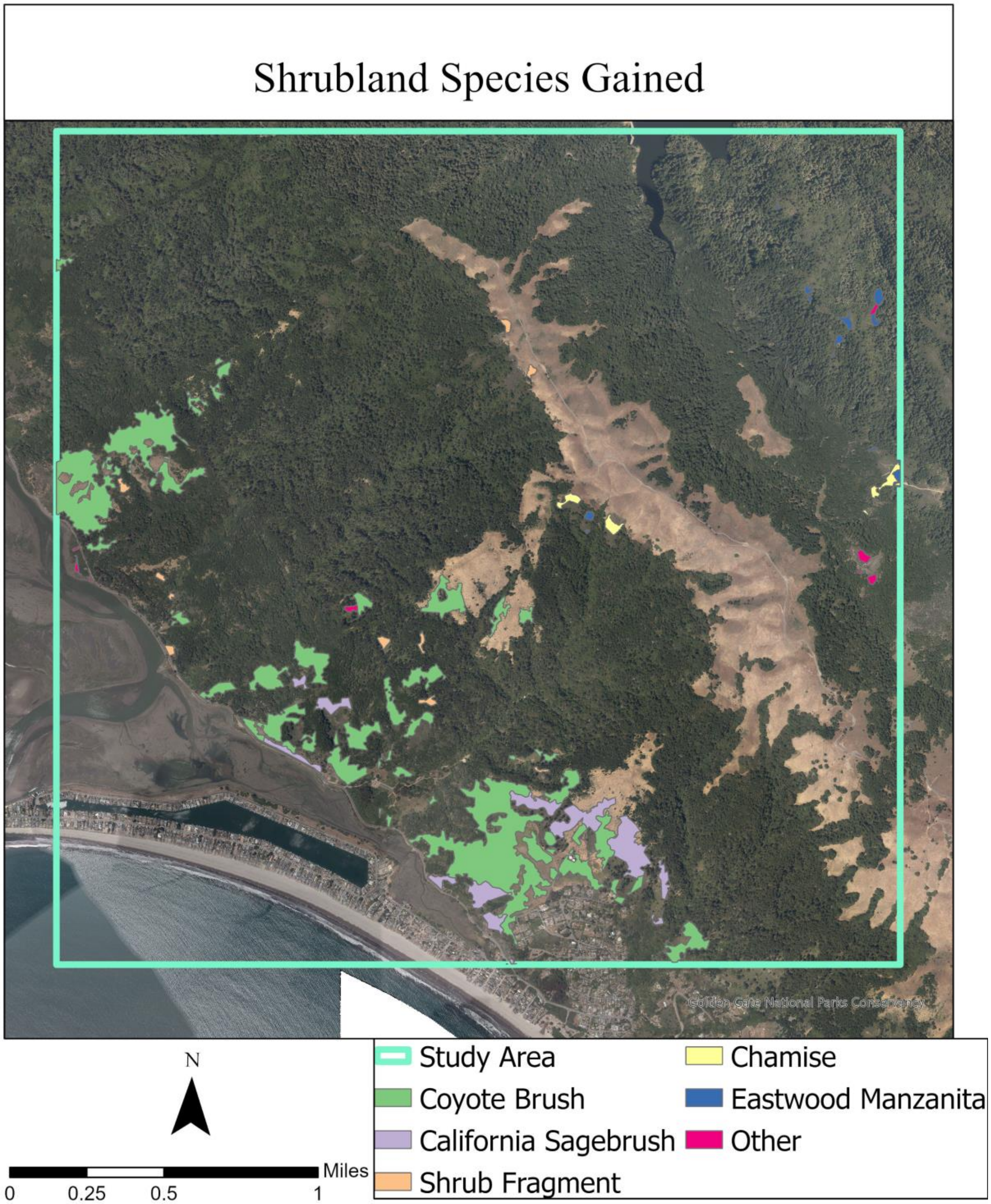

Figure 17. Shrub species gained between 1952 and 2018.

Shrubland loss was explored as a separate process to assess which plant species have displaced former shrubland since 1952. Douglas fir was the most common species covering 67% of the total area. California bay was the second most common species (12% cover), followed by Coast redwood (11%) and Coast live oak (1%) (Table 9 and Figure 18). 2% of shrubs were replaced by water which could be accounted for by the construction of the Seadrift Lagoon, shown in yellow in Figure 18. 1% of shrubland was developed by 2018, reflecting the residential expansion of the town of Stinson Beach, shown in blue in Figure 18. Classification of shrubland lost resulted in 97% accuracy. (Table 9 and Figure 18). Various native shrubs were misclassified and removed from these results, including glossy leaved manzanita (1%) and coyote brush (0.7%). Details can be found in the Appendix.

Table 9. Vegetation and land cover that displaced shrubland between 1952 and 2018 in order of cover from largest to smallest.

Vegetation or land cover type	Scientific name	Life form	Cover (%)
Douglas fir	*Pseudotsuga menziesii*	Native forest	67
California bay	*Umbellularia californica*	Native forest	13
Coast redwood	*Sequoia sempervirens*	Native forest	11
Water	…	Water	2
Developed	…	Developed	2
Coast live oak	*Quercus agrifolia*	Native forest	1
California annual & perennial grasslands	...	Grassland	<1
Canyon live oak	*Quercus chrysolepis*	Native forest	<1
Monterey pine	*Pinus radiata*	Non-native forest	<1
Major road	…	Major road	<1
Forest fragment	…	Mixed forest	<1
Blue gum and red gum	*Eucalyptus (globulus, camaldulensis)*	Non-native forest	<1
Bigleaf maple	*Acer macrophyllum*	Native forest	<1
Pacific madrone	*Arbutus menziesii*	Native forest	<1
Mudflat/dry pond bottom	…	Mudflat/dry pond bottom	<1
Pacific willow	*Salix lucida ssp. lasiandra*	Native forest	<1
Freshwater wet meadow & marsh	…	Freshwater wet meadow & marsh	<1
Desert saltgrass	*Distichlis spicata*	Tidal wetland	<1
Coastal gumplant	*Grindelia stricta*	Tidal wetland	<1

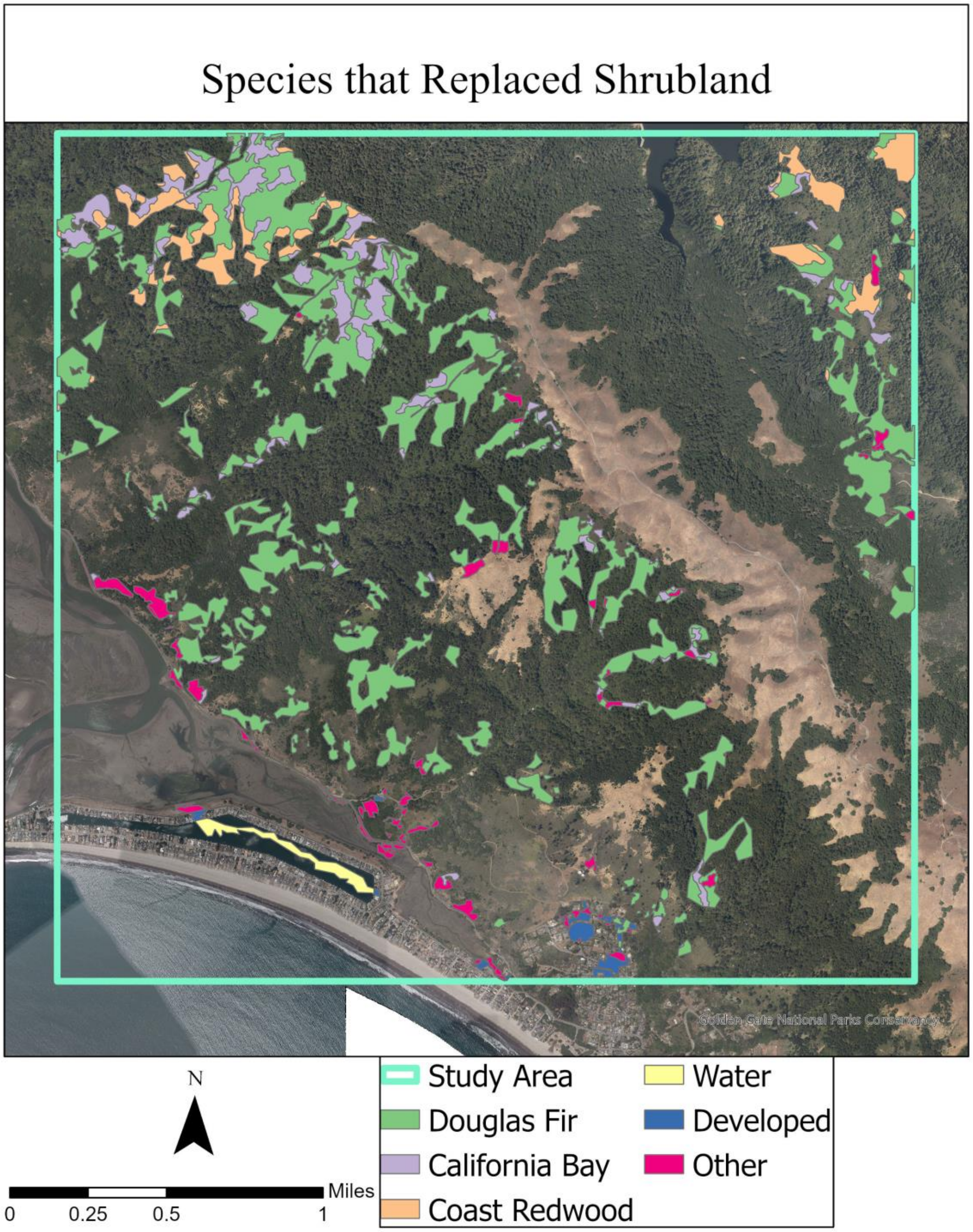

Figure 18. Species that displaced shrubland between 1952 and 2018 after correcting for errors. Douglas fir, California bay, and Coast redwood comprised 91% of the total cover.

Chapter 5 Discussion

The methodology used in this thesis demonstrates successful manual interpretation and classification of aerial imagery. These methods can inform future analysis using aerial images, especially comparing historic and modern aerials to measure changes in vegetation. Between 1925 and 2018, forests expanded while shrubland and grassland were lost. In fact, roughly half of all shrubland and grassland disappeared, while forest cover roughly tripled in area. While some shrubland was gained, there was overall a net loss. Grassland lost the most cover and was replaced by roughly twice as much woodland than shrubland. Douglas fir, California bay, Coast live oak, and canyon live oak comprised 98% of the woodland species that encroached on grassland. Coyote brush and California sagebrush comprised 96% of the shrub species that encroached on grassland. Douglas fir, California bay, and Coast redwood comprised 96% of the woodland species that encroached on shrubland.

5.1. Implications and Shortcomings of Methodology

Woody plant encroachment onto herbaceous ecosystems transformed the environment in a way that was distinguishable in the aerial images. The methods used in this thesis can be applied more broadly to other areas, for example measuring woody plant encroachment along the California Coast. A larger study area may require different classification methods, which is discussed in the following section. This thesis' methods could also be applied to classifying and measuring changes in other vegetation types. As long as the plants are visibly distinguishable on aerial images they can be analyzed. However, vegetation may or may not be distinguishable on aerials. It can depend on the image's spectral resolution, the vegetation's color, shade, and texture, as well as weather interference or if the plants are covered by anything. The size of the vegetation will determine the spatial resolution required of the images. Classification down to the species level may not be possible using aerials alone which is why this thesis used life form classifications of grassland, shrubland, and woodland, and subsequently referenced the Marin fine scale vegetation map to get the species composition. It is recommended to classify broad vegetation categories from the aerials and subsequently use other references to classify down to the species level.

5.1.1. Automated vs. Manual Classification

This thesis used images with high spatial resolutions because they were best to distinguish between the vegetation, but the spatial resolution of the historic image was slightly lower. Comparing images with different resolutions is possible; the image with the lowest spatial and spectral resolution will determine the limits of classification. The images also had differences in color, angle, and seasonality - the historical imagery during August and the modern imagery during June - which means there were possible differences in shadows, vegetation life stage, and weather. The images were digitized manually because the differences listed above could impact the ability of machines to detect the vegetation changes this thesis aimed to assess. Still, the digitizing process may include errors due to the historical photos being black-and-white and having a lower spatial resolution.

Creating standardized methods was important for heads-up digitizing to be consistent. The minimum mapping unit, which defines the minimum polygon size included, was 0.25 acres. The scale selected was the same as the Marin fine scale vegetation map and was intended to be useful for land managers. The minimum mapping unit cannot be smaller than the size of the image's pixel, which in this case it is not. This study therefore included only vegetation with an area of 0.25 acre or larger. In heterogeneous environments, for example, where small trees were surrounded by grass, the minimum mapping unit determined which trees to include in the woodland layer.

Although heads-up digitization achieves high accuracy for small study areas, it is time-consuming and therefore may not be appropriate for larger study areas. Such studies may benefit from automatic classification using semi or fully automated methods. Automated classification requires resampling the images to ensure their spatial and spectral resolutions match. Otherwise, they cannot be compared. For example, if automated classification is being applied to both a red-green-blue and a black-and-white image, the color image would have to be converted to black-and-white. Information may be lost in this step, reducing the quality of the resulting image and impacting the classification. This thesis used the best classification method given the types of data used.

5.1.2. Classification Accuracy

The classification accuracy was generally high, with woodland encroachment onto grassland and shrubland resulting in 95% and 97% accuracy, respectively. Classification of shrubland encroachment onto grassland was lower, with 79% accuracy. Classification of grassland and woodland was consistently more accurate than classification of shrubland. This result was expected because grassland and woodland were clearly different in color and texture on both images, with woodland appearing much darker than grass. Shrubland generally appeared less distinct than grass or forest and was sometimes confused with marshes or herbaceous cover. Douglas fir, annual and perennial grasslands, pampasgrass, and chamise were commonly misidentified as shrubland.

One potential confounding variable to the results was the major tanoak (*Notholithocarpus densiflorus*) die off during the 2000s due to sudden oak death (Rachel Kesel, phone conversation, June 30, 2021). This thesis found that there was a net gain in forest cover between 1952 and 2018, composed mainly of Douglas fir, California bay, Coast live oak, and canyon live oak. Tanoaks were not found to be part of the forest species gained, which may be attributed to the substantial loss of tanoaks in the 2000s. Without this die off, tanoaks may have been responsible for greater expansion of woodland species.

This thesis did the accuracy assessment of the modern image using the Marin fine scale vegetation map. Unfortunately, there was no way to do a classification accuracy for the historical imagery because no species level vegetation map exists for that time. The lack of related data is typical when working with historical images and future studies should consider this limitation. The accuracy of my classification for the modern image was 79-97%, which shows success. The classification accuracy of the modern image is probably higher than that of the historic image because the historic image has a lower spatial and spectral resolution. However, since the methods for digitizing both time periods were the same, it suggests that classification of the historic image was likely successful as well.

5.1.3. Intermediate Time Periods

Another shortcoming of the methodology is it compares only two time periods and there are no intermediate periods. It is impossible to determine the of rate of encroachment or whether it is speeding up or slowing down from only two points in time. Capturing additional time periods in the analysis may also reveal if there was sequential replacement over time; in other words, an initial grassland to shrubland conversion followed by another transition to woodland. Given the long timespan between the two images used in this thesis, the results may only reveal the second replacement of shrubland by forest. Appropriate images to represent intermediate time periods are available. Images from 1965 and 1987 are suggested to be investigated further because they have comparable spatial resolution to the images used in this study. The 1965 Cartwright Aerial Survey images are available on the UCSB Frame Finder archive and are in black-and-white. The 1987 images are color infrared USGS 7.5-minute quadrangles available on the Earth Explorer website.

Recent time periods could also be added to future analysis to pinpoint woody plant encroachment occurring in the last decade. Aerial imagery from 2008 and 2018 could be compared by following the same methods used in this thesis. These short-term trends could then be compared to long-term trends to assess which are the most common species that should be targeted. These results also support the efforts of land management agencies such as MMWD who have a proactive approach to managing encroachment.

5.2. Land Management Applications

Woodland encroachment onto shrubland was the most common type of woody plant encroachment. This result may support allocating more resources to manage forest encroachment than shrub encroachment. The results also suggest specifically targeting Douglas fir and coyote brush, as these were the dominant species causing woody plant encroachment.

An analysis of conifer encroachment into hardwood forest, an ecological concern known as overtopping, would be an excellent expansion of this study for other USC SSI students or spatial analysts. Given the scope of this thesis, it did not measure forests undergoing overtopping. These types of forests appear as a mix of hardwood and conifer trees which complicates classification. Eitzel et al. (2014) were able to differentiate between woody and herbaceous vegetation but were not able to consistently distinguish between different types of forest in aerial photos, even using supervised classification. Generally, conifer trees are not easily distinguishable from closed canopy woodlands because there is not enough height difference. A greater height difference would create shade, thus creating a visible difference in the image. It also tends to take longer for conifers to overtop a hardwood forest than to displace grassland or shrubland (Rachel Kesel, phone conversation, June 30, 2021).

Interestingly, the results showed that encroaching woody plants were often native species, not what you would typically think of as “invasive” species. For example, every one of the shrub species that invaded grassland were native, as were two thirds of the tree species that replaced grassland (Tables 5 and 6). Coyote brush contributed to 80% of shrub encroachment onto grassland, while Douglas fir made up 81% of the tree species that replaced grassland and 71% of the tree species that replaced shrubland. These findings suggest that simply the presence of native species does not necessarily lead to a balanced and healthy ecosystem. Douglas fir can convert other native habitats into forests in 70 years or less, and establishment of coyote brush in grassland areas takes even less time. Land managers should critically assess the role of a species in the ecosystem regardless of whether it is native or non-native.

When developing restoration strategies, agencies must consider the stage of the woody plant encroachment and be proactive rather than reactive. Proactive practices are best for managing encroachment because the longer plants are established, the harder they are to remove (Sherry Adams, email message to author, Dec 11, 2021). For example, it would be impractical to try to restore grassland habitat in an area where woody plant encroachment started 50 years ago. Restoration would involve removing mature trees, and even then, the establishment of native grassland may be difficult if the seedbank is depleted. A better approach is to target areas of recent encroachment where the woody plants are still small, sparse, and easy to remove. The vegetation being displaced then has a greater chance of reestablishing. Conifers that are established for fewer than 10 years can be treated with prescribed burning, but after 10 years of growth they become resistant to this method (Cocking, 2015). In areas where encroachment has long been established, the effort is better put towards stopping the further spread of encroachment.

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Appendix

Shrubland replaced 238 acres of grassland before correcting for misclassification (Table 10 and Figure 19). The majority of the shrub encroachment on grassland was confirmed to be coyote brush (63%), followed by California sagebrush (12%). Classification of shrubland encroachment on grassland resulted in 79% accuracy. 21% of the area was misclassified as a shrub, including Douglas fir, Coast live oak, and herbaceous vegetation.

Table 10. Shrub encroachment on grassland broken down by species cover from greatest to smallest, before correcting for misclassification.

Species	Scientific name	Life form	Cover (%)
Coyote brush	*Baccharis pilularis*	Native shrub	63
California sagebrush	*Artemisia californica*	Native shrub	13
Douglas fir	*Pseudotsuga menziesii*	Native forest	9
Annual and perennial grassland	...	Herbaceous	5
Shrub fragment	...	Mixed shrub	2
Pampasgrass	*Cortaderia selloana*	Non-native herbaceous	2
Coast live oak	*Quercus agrifolia*	Native forest	1
Poison hemlock	*Conium maculatum*	Non-native herbaceous	1
Chamise	*Adenostoma fasciculatum*	Native shrub	1
Forest fragment	...	Mixed forest	<1
Freshwater wetland	...	Freshwater wetland	<1
California bay	*Umbellularia californica*	Native forest	<1
Monterey pine	*Pinus radiata*	Non-native forest	<1
Developed	...	Developed	<1
Canyon live oak	*Quercus chrysolepis*	Native forest	<1
California coffeeberry	*Frangula californica*	Native shrub	<1

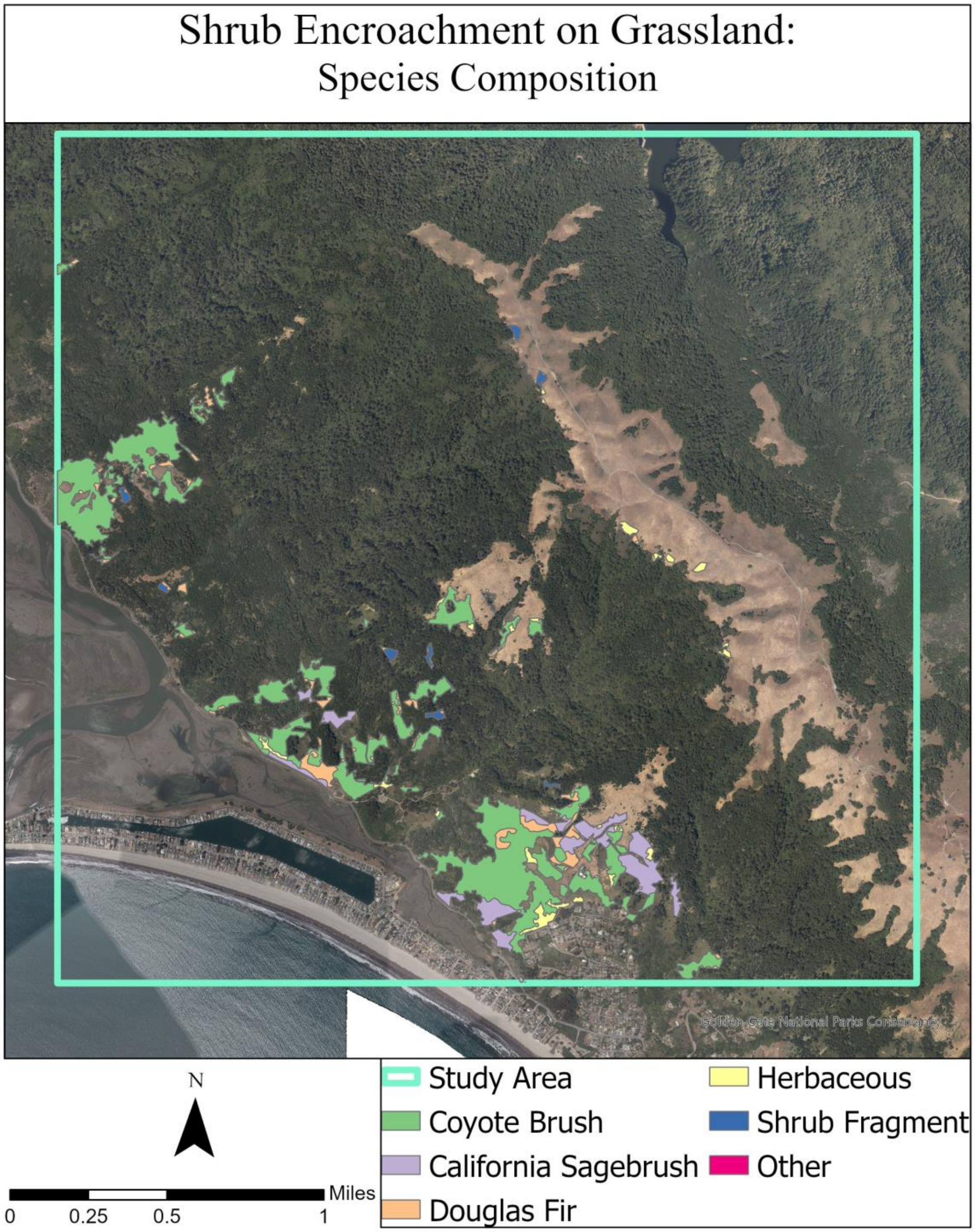

Figure 19. The species composition of shrubland that replaced grassland between 1952 and 2018 before correcting for errors.

Woodland replaced 511 acres of grassland before correcting for errors (Table 4). Douglas fir made up the majority (77%) of the cover, followed by California bay, canyon live oak, and Coast live oak (Table 11 and Figure 20). Classification of woodland encroachment on grassland resulted in 95% accuracy, according to the Marin fine scale vegetation map. 5% was misclassified, which included annual and perennial grassland, coyote brush, California coffeeberry, California sagebrush, and shrub fragments.

Table 11. Woodland that replaced grassland between 1952 and 2018 before correcting for errors in order of cover from largest to smallest.

Land cover	Scientific name	Life form	Cover (%)
Douglas fir	*Pseudotsuga menziesii*	Native forest	77
California bay	*Umbellularia californica*	Native forest	7
Canyon live oak	*Quercus chrysolepis*	Native forest	5
Coast live oak	*Quercus agrifolia*	Native forest	4
Annual and perennial grassland	...	Herbaceous	3
Coyote brush	*Baccharis pilularis*	Native shrub	1
Forest fragment	...	Mixed forest	<1
Monterey pine	*Pinus radiata*	Non-native forest	<1
Non-native forest	...	Non-native forest	<1
California coffeeberry	*Frangula californica*	Native shrub	<1
Arroyo willow	*Salix lasiolepis*	Native shrub	<1
Douglas fir and tanoak	*Pseudotsuga menziesii & Notholithocarpus densiflorus*	Native forest	<1
California sagebrush	*Artemisia californica*	Native shrub	<1

Land cover	Scientific name	Life form	Cover (%)
Monterey cypress	*Hesperocyparis macrocarpa*	Non-native forest	<1
Shrub fragment	...	Mixed shrub	<1
Coast redwood	*Sequoia sempervirens*	Native forest	<1

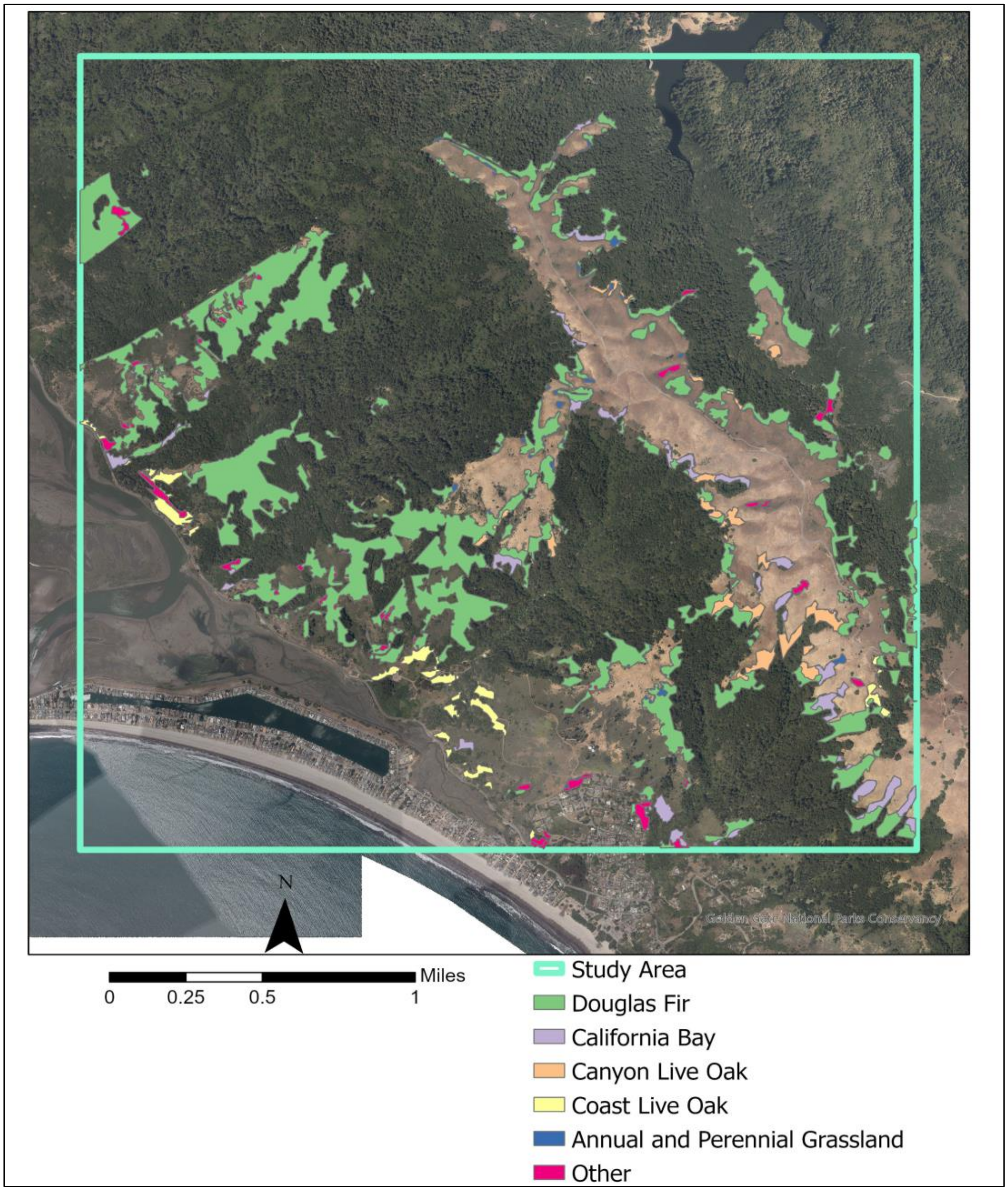

Figure 20. The species composition of forest that replaced grassland between 1952 and 2018 before correcting for errors.

A total of 603 acres of shrubland was replaced by woodland before correcting for errors with 97% accuracy. Douglas Fir was the most common species (69%), followed by California Bay (13%), Coast Redwood (11%), and Coast Live Oak (1%) (Table 12 and Figure 21). Shrubs commonly misclassified as woodland included Manzanita and California sagebrush. Interestingly, Douglas Fir encroachment on shrubland occurred throughout the West-facing slope, while encroachment of California Bay and Coast Redwood happened mostly on the upper slopes or on the East side of the ridge. Additionally, Coast Live Oak encroachment was restricted to the lower slopes close to sea level and only accounted for 1% of the total area.

Table 12. Woodland species that replaced shrubland between 1952 and 2018 in order of cover from largest to smallest before correcting for errors.

Land cover	Scientific name	Life form	Cover (%)
Douglas fir	*Pseudotsuga menziesii*	Native forest	69
California bay	*Umbellularia californica*	Native forest	13
Coast redwood	*Sequoia sempervirens*	Native forest	11
Coast live oak	*Quercus agrifolia*	Native forest	1
Glossy leaved manzanita	*Arctostaphylos (nummularia, sensitiva)*	Native shrub	1
Canyon live oak	*Quercus chrysolepis*	Native forest	<1
Coyote brush	*Baccharis pilularis*	Native shrub	<1
Arroyo willow	*Salix lasiolepis*	Native shrub	<1
Monterey pine	*Pinus radiata*	Non-native forest	<1
Eastwood manzanita	*Arctostaphylos glandulosa*	Native shrub	<1
Blue gum and red gum	*Eucalyptus (globulus, camaldulensis)*	Non-native forest	<1
Forest fragment	...	Mixed forest	<1

Land cover	Scientific name	Life form	Cover (%)
Bigleaf maple	*Acer macrophyllum*	Native forest	<1
Pacific madrone	*Arbutus menziesii*	Native forest	<1
Chamise	*Adenostoma fasciculatum*	Native shrub	<1
California sagebrush	*Artemisia californica*	Native shrub	<1
Shrub fragment	...	Mixed shrub	<1
Californian annual & perennial grassland	...	Herbaceous	<1
Developed	...	Developed	<1
California coffeeberry	*Frangula californica*	Native shrub	<1

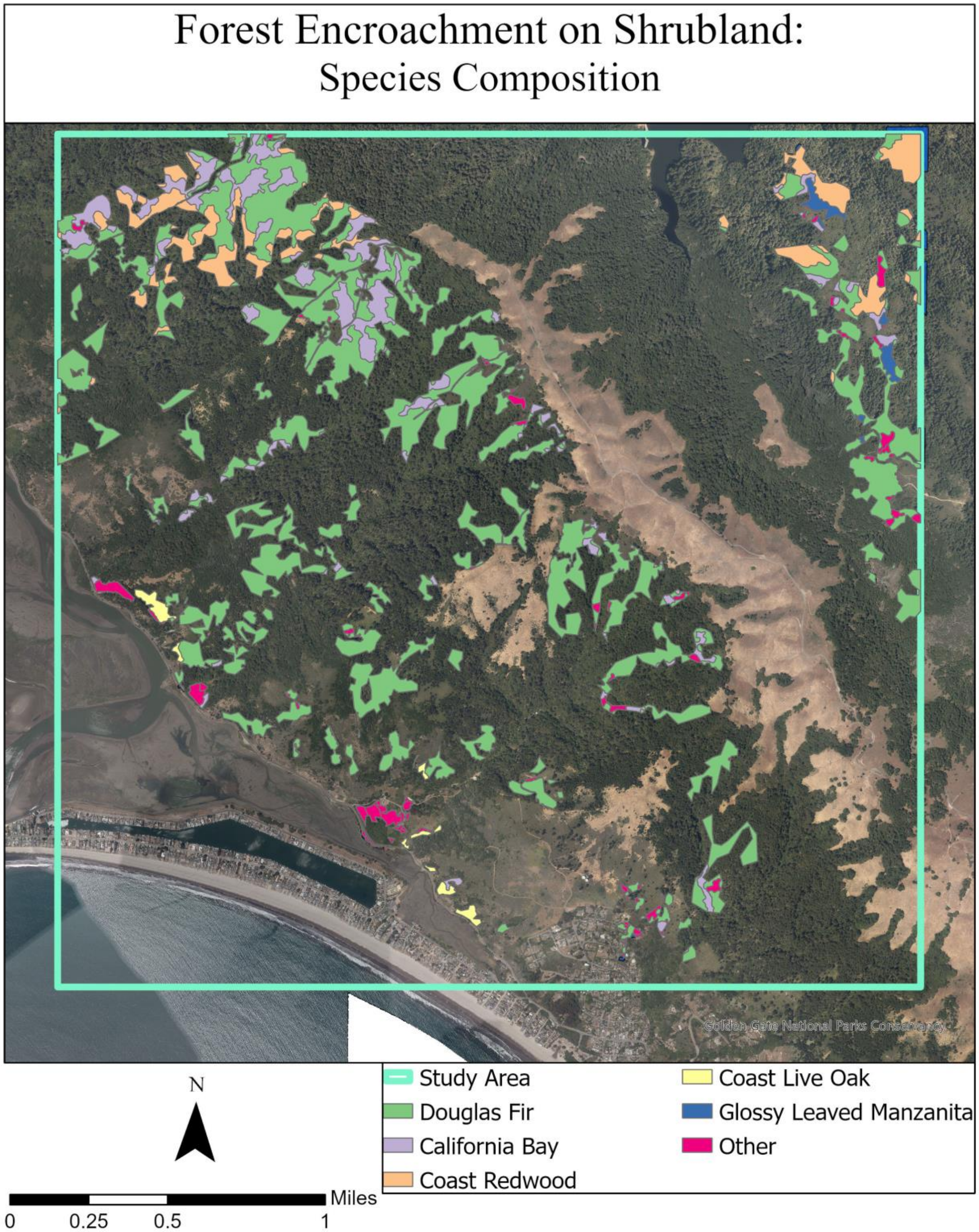

Figure 21. The species composition of forest that replaced shrubland between 1952 and 2018 before correcting for errors.

Of the emerging shrub species since 1952, coyote brush was the most common, covering 59% of the total area. California sagebrush, also a native shrub, was the second most common with 12% cover (Table 13 and Figure 21). Classification of shrub species gained had 77% accuracy with Douglas Fir and herbaceous plants (orange and yellow) accounting for 15% of the misidentified vegetation.

Table 13. Shrubland species that emerged between 1952 and 2018 in order of cover from largest to smallest.

Land cover	Scientific name	Life form	Cover (%)
Coyote brush	*Baccharis pilularis*	Native shrub	59
California sagebrush	*Artemisia californica*	Native shrub	12
Douglas fir	*Pseudotsuga menziesii*	Native forest	10
Annual and perennial grassland	...	Herbaceous	5
Shrub fragment	...	Mixed shrub	2
Pampasgrass and jubatagrass	*Cortaderia selloana, jubata*	Non-native herbaceous	2
Chamise	*Adenostoma fasciculatum*	Native shrub	2
Coast live oak	*Quercus agrifolia*	Native forest	1
Eastwood manzanita	*Arctostaphylos glandulosa*	Native shrub	1
California bay	*Umbellularia californica*	Native forest	1
Poison hemlock	*Conium maculatum*	Non-native herbaceous	<1
Forest fragment	…	Mixed forest	<1
Freshwater wetland	…	Freshwater wetland	<1
Baker’s manzanita	*Arctostaphylos bakeri*	Native shrub	<1
Canyon live oak	*Quercus chrysolepis*	Native forest	<1

Land cover	Scientific name	Life form	Cover (%)
Monterey pine	*Pinus radiata*	Non-native forest	<1
Developed	…	Developed	<1
Coast redwood	*Sequoia sempervirens*	Native forest	<1
Arroyo willow	*Salix lasiolepis*	Native shrub	<1
California coffeeberry	*Frangula californica*	Native shrub	<1
Major road	...	Major road	<1
Glossy leaved manzanita	*Arctostaphylos (nummularia, sensitiva)*	Native shrub	<1

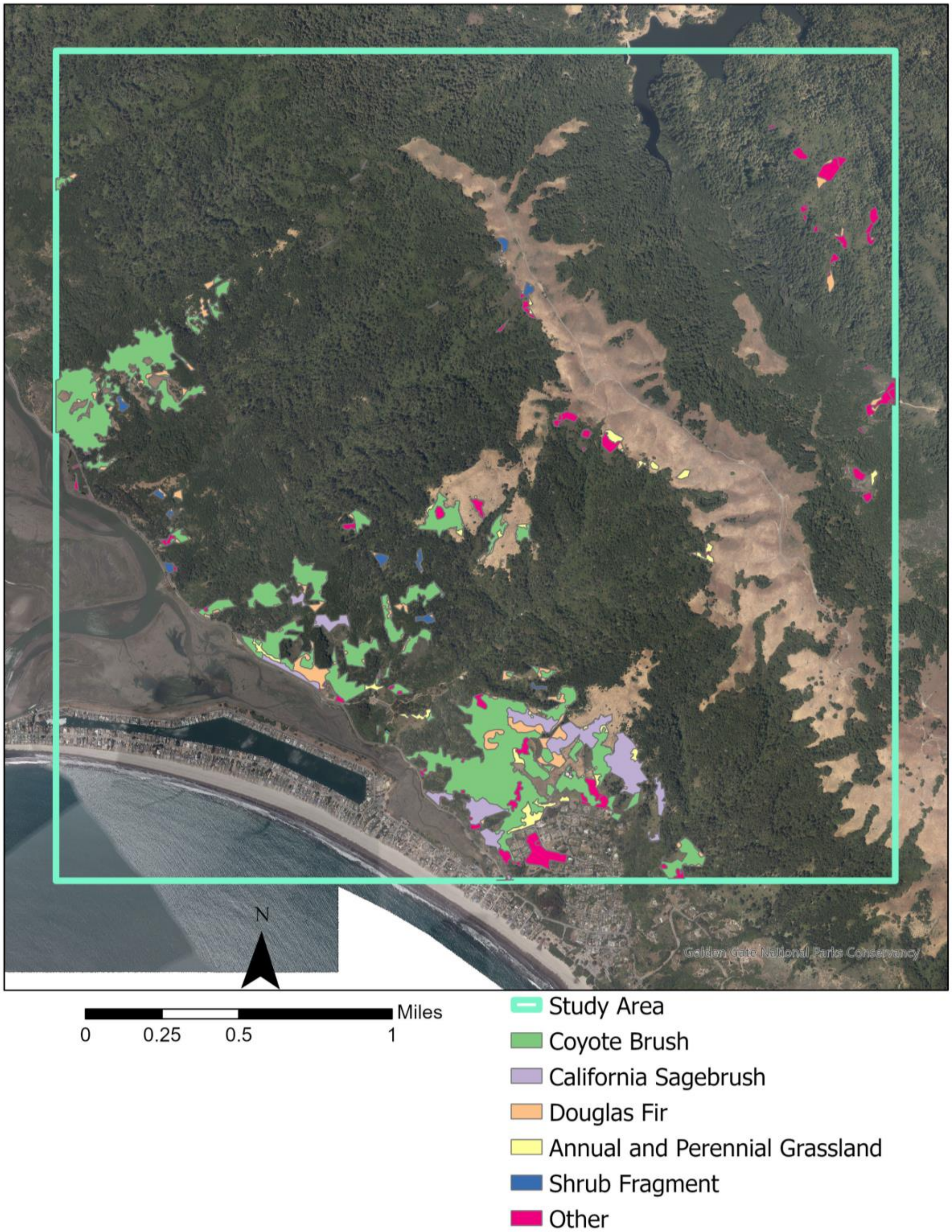

Figure 22. Shrubland species gained between 1952 and 2018 in order of cover.

Shrubland loss was explored as a separate process to see which plant species have displaced former shrubland since 1952 (Table 14 and Figure 23). Before correcting for errors, Douglas fir was the most common species covering 65% of the total area. California bay was the second most common species (12% cover), followed by Coast redwood (10%) and Coast live oak (1%). 1% of shrubs were replaced by water which could be accounted for by the construction of the Seadrift Lagoon (yellow). 1% of shrubland was developed by 2018, reflecting the residential expansion of the town of Stinson Beach (blue). Classification of shrubland lost resulted in 97% accuracy. Various native shrubs were misclassified and removed from the results chapter. These species include glossy leaved manzanita (1%) and coyote brush (<1%).

Table 14. Species and land cover that displaced shrubland between 1952 and 2018 in order of cover from largest to smallest.

Land cover	Scientific name	Life form	Cover (%)
Douglas fir	*Pseudotsuga menziesii*	Native forest	65
California bay	*Umbellularia californica*	Native forest	12
Coast redwood	*Sequoia sempervirens*	Native forest	11
Water	…	Water	2
Developed	…	Developed	2
Coast live oak	*Quercus agrifolia*	Native forest	1
Glossy leaved manzanita	*Arctostaphylos (nummularia, sensitiva)*	Native shrub	1
Californian annual & perennial grassland	...	Herbaceous	<1
Canyon live oak	*Quercus chrysolepis*	Native forest	<1
Coyote brush	*Baccharis pilularis*	Native shrub	<1
Monterey pine	*Pinus radiata*	Non-native forest	<1

Land cover	Scientific name	Life form	Cover (%)
Arroyo willow	*Salix lasiolepis*	Native shrub	<1
Eastwood manzanita	*Arctostaphylos glandulosa*	Native shrub	<1
Major road	…	Major road	<1
Forest fragment	…	Mixed forest	<1
Blue gum and red gum	*Eucalyptus (globulus, camaldulensis)*	Non-native forest	<1
Non-native forest	…	Non-native forest	<1
Bigleaf maple	*Acer macrophyllum*	Native forest	<1
Pacific madrone	*Arbutus menziesii*	Native forest	<1
Mudflat/Dry pond bottom	…	Mudflat/Dry pond bottom	<1
California sagebrush	*Artemisia californica*	Mixed shrub	<1
Shrub fragment	...	Mixed shrub	<1
Pacific willow	*Salix lucida ssp. lasiandra*	Native forest	<1
Freshwater wet meadow & marsh	...	Freshwater wet meadow & marsh	<1
Desert saltgrass	*Distichlis spicata*	Tidal wetland	<1
Chamise	*Adenostoma fasciculatum*	Native shrub	<1
Coastal gumplant	*Grindelia stricta*	Tidal wetland	<1
California coffeeberry	*Frangula californica ssp. californica*	Native shrub	<1

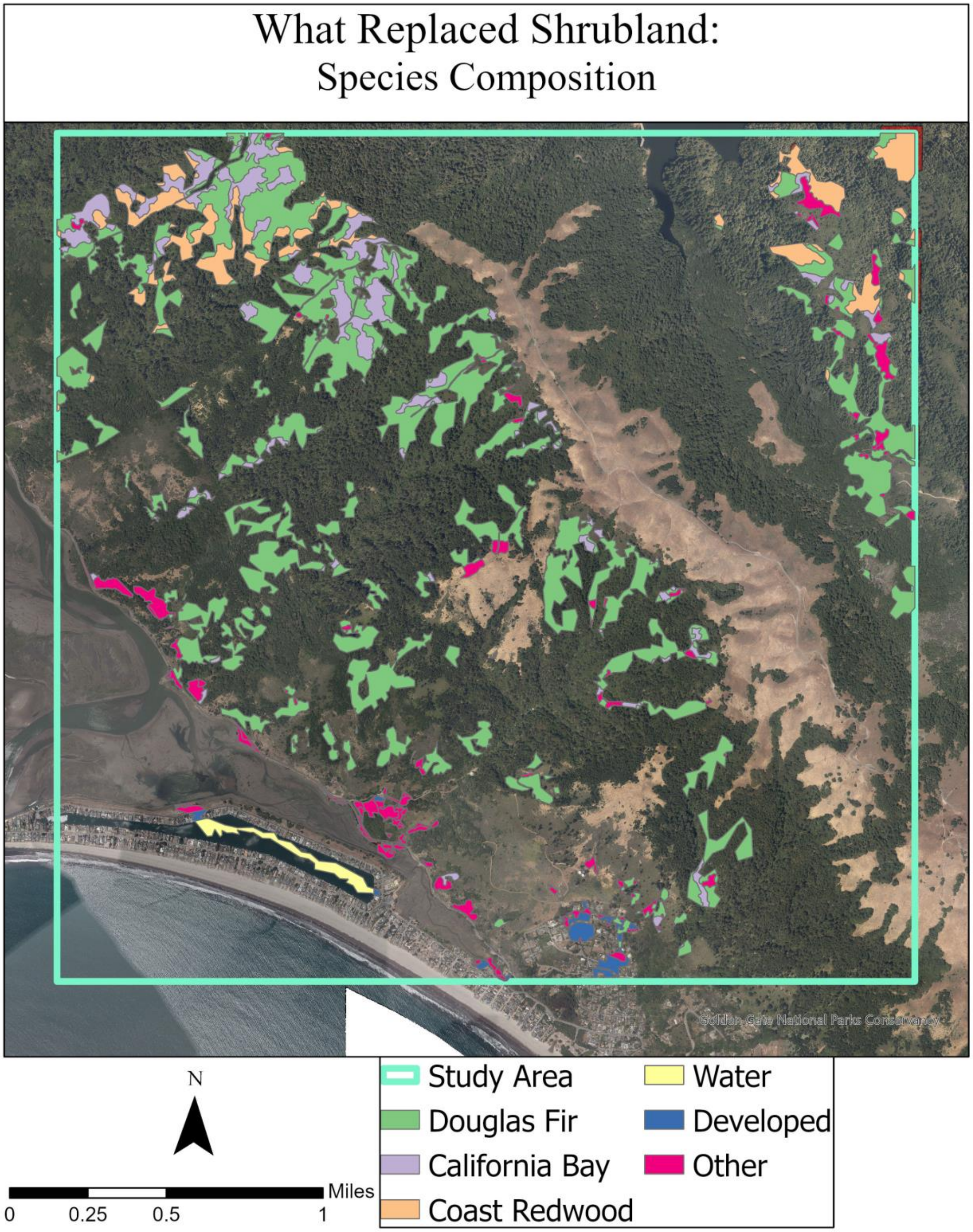

Figure 23. The land cover types and species that displaced shrubland between 1952 and 2018 before correcting for errors.

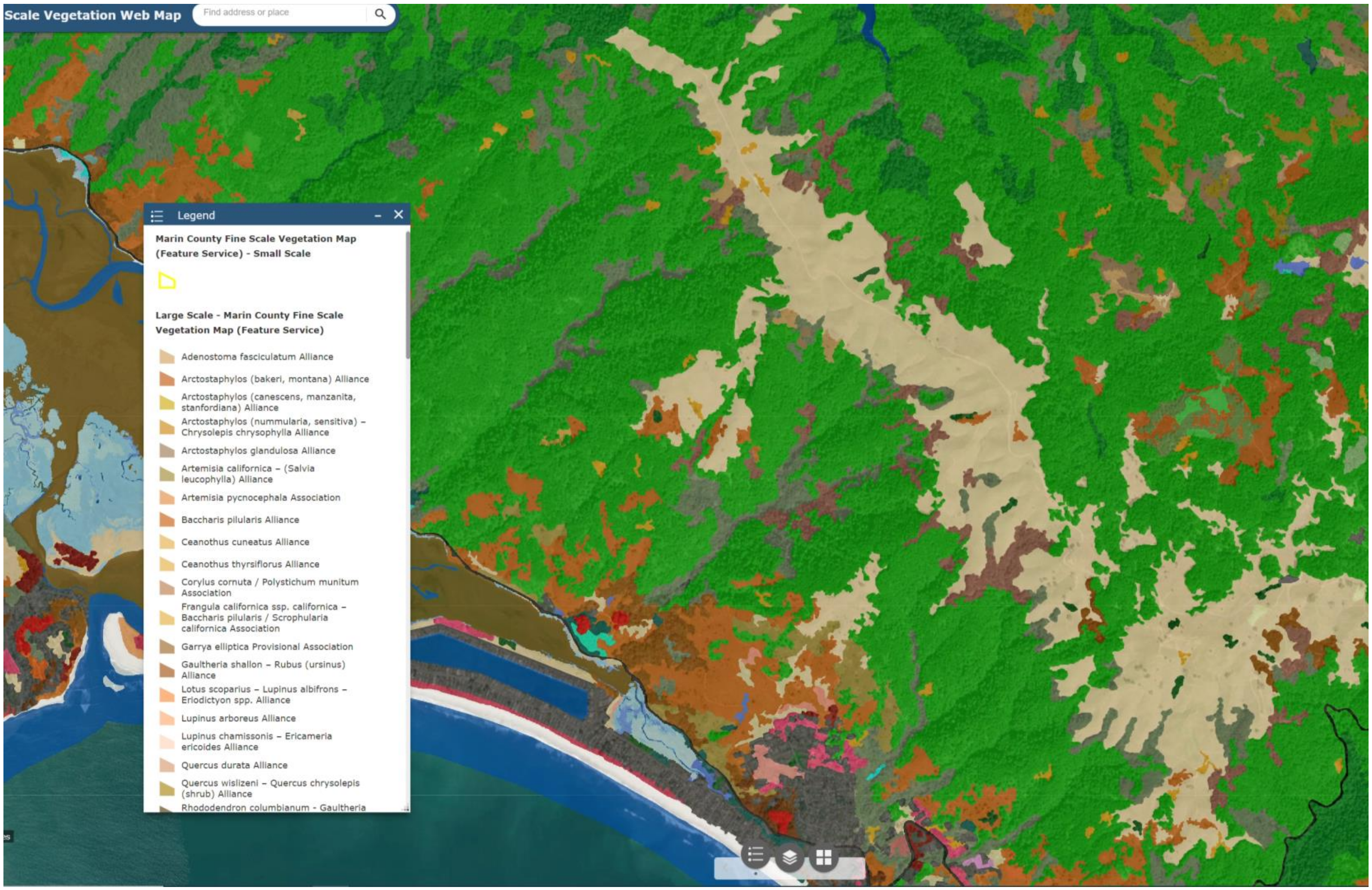

Figure 24. The Marin fine scale vegetation map includes 106 classes of vegetation.
Source: GGNPC et al. 2021.