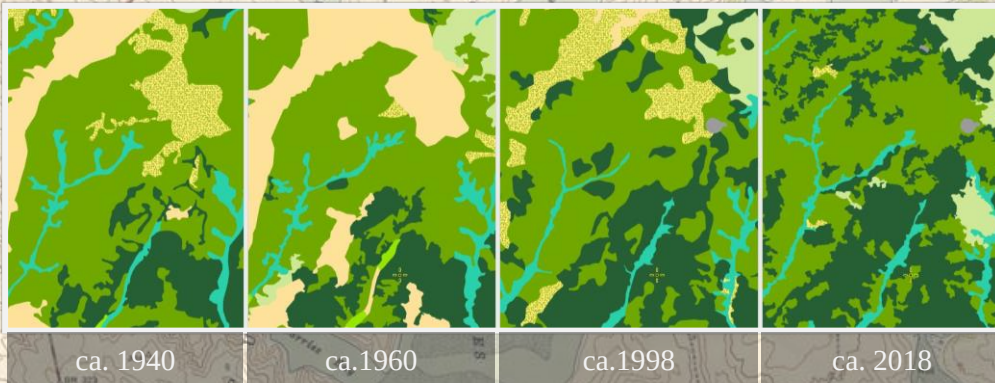




HISTORIC CHANGES IN POINT REYES' VEGETATION COMMUNITIES:

Shifts in the Vegetation Landscape in Response
to Watershed Land Use and Other Changes



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December 1, 2023

ABSTRACT

Vegetation communities are floristic manifestations of forces that are both long-term (geological, climatic) and more immediate (wildfire, flooding). Over geologic millennia, forests and shrublands have expanded during wetter periods while grasslands have expanded during drier ones. With the settlement of western Marin County, the Point Reyes landscape was dramatically reworked by an unprecedented number of disturbance factors, including introduction of livestock and non-native plants, extensive clearing and logging of forests, and suppression of wildfires and prescribed burning by native peoples. Historically, information on exactly how flora has changed in response to natural and anthropogenic influences has been limited. With the introduction of aerial photography and Geographic Information Systems (GIS), detailed analyses of trends in vegetation can now be conducted over broad landscape scales. This type of information is important to conserving vegetation resources in national park units such as Point Reyes National Seashore (PRNS). Starting in 2010, PRNS moved forward with a historic vegetation mapping project that assessed change in broad, structurally based vegetation communities between the 1940's, 1960's, 1990's, and 2018.

Within Point Reyes, the floristic landscape remained relatively stable between the 40's and 60's, except for a 12% increase in Mixed Herbaceous/Shrub habitats. However, dramatic and seemingly contradictory changes in vegetation occurred between the 60's and '18. Between the 60's and 90's, acreage of Grassland (<10% shrub cover) plummeted (48%), while Open Scrub/Grassland (interspersed shrub cover <60%) jumped (96%), only to drop sharply again (23%) between the late 90's and '18, while Grassland climbed slightly (5%). The extent of Dense Coastal Scrub ($\geq 60\%$ shrubs) did not appear to change between the 40's and 90's, although it contracted slightly by '18 (1%). As with Grasslands, acreage of Douglas-fir (*Pseudotsuga menziesii*) and Hardwood Forests remained relatively stable between the 40's and the 60's, although that of Bishop pine (*Pinus muricata*) dropped slightly probably due largely to localized clearing. All three forest types expanded substantially by the late 90's and again by '18 albeit at a much reduced rate. Over the past 20 years, gains by Hardwood Forest have outpaced those of Douglas-fir by four-fold. Over the entire study period (40's – '18), acreage of Herbaceous communities fell 40%, while those of Mixed Herbaceous/Shrub and Native Forests (i.e., Douglas-fir, Bishop pine, Hardwood Forest) climbed 70% and 37%, respectively. Shrub-dominated habitats contracted by 8%.

These floristic changes have undoubtedly been strongly influenced by shifts in the degree of active management of Point Reyes lands during the 1900's with incorporation into the national park system in 1962, as well as by ongoing trends in the local agricultural industry (e.g., gradual shifts from dairy to beef cattle ranching) and sporadic wildfires (e.g., 1995 Vision Fire). With a sharp reduction in logging/clearing in the early 1900's, forests began to re-establish on the Inverness Ridge, particularly Douglas-fir. While many researchers have sounded the alarm about the threat of woody vegetation encroachment, expansion of Douglas-fir and California bay may be less of an unprecedented "encroachment" and more of a recovery response to the unprecedented convergence of impacts associated with Euro-American settlement. Slowing in the rate of expansion of Douglas-fir and hardwood forests in Point Reyes within the past 20 years may be the first sign that forests are coming back into some type of equilibrium. However, disequilibrium is likely to persist and possibly worsen in the future due to new floristic challenges such as disease and climate change that will continue to reshape the landscape of Point Reyes.

EXECUTIVE SUMMARY

Project Purpose and Implementation

Vegetation communities are floristic manifestations of forces that are both long-term (geological, climatic) and more immediate (wildfire, flooding). These forces are often unfolding simultaneously, acting synergistically and, at times, antagonistically to create a unique mosaic of vegetation types across the landscape. The impact of these forces on vegetation can be difficult to detect, at least for less immediate disturbances, because communities may take decades or more to shift in response. And, even then, it can be difficult to link those changes to their proximate cause.

Our information on how flora in the past changed in response to both natural and anthropogenic influences has been limited until recently by technology. Up until the 1930's, most information on historic vegetation communities or disturbances came from palaeoecological studies on pollen and charcoal deposition, fire scar studies on existing trees, or ethnohistorical accounts and maps. With the introduction of aerial photography and continued technological advancements such as personal computers and Geographic Information Systems (GIS), however, a more detailed analysis of trends in vegetation communities could be conducted over broader landscape scales, with the ability to bring in additional information on hydrology, soils, topography, climate, fire intensity, and other factors to tease apart vegetation response to a variety of factors that can influence landscape change.

The National Park Service (NPS) is charged with the mission of conserving and protecting the nation's natural resources, including its vegetation resources. If Point Reyes National Seashore (PRNS, Seashore) is to manage for conservation of some of its unique habitats or plant and wildlife species associated with habitats, it needs to better understand historic and recent trends in vegetation communities and how these trends might be influenced by historic disturbance factors such as logging/clearing, development, grazing, and introduction of non-native species as well as by relatively new factors such as disease (i.e., *Phytophthora*) and climate change.

Between 2010 and 2016, PRNS moved forward with a historic vegetation mapping project that involved manual interpretation ("head's-up digitizing") and classification of broad, structurally based vegetation communities for black-and-white (B&W) aerial photograph sets obtained from the early 1940's (40's) and the early 1960's (60's). Mapping was also already available for the late 1990's (90's) from an earlier 1994 vegetation map (CDFG/AIS) of PRNS that had been revised to reflect changes following the 1995 Vision Fire as part of a dissertation project (Forrestel et al. 2011). PRNS staff had converted the revised 90's map to the classification system used for the earlier mapping periods, but these GIS files had never been fully reviewed for accuracy and finalized. In 2022, PRNS received funding from a NPS Functional Conditional Assessment (FCA) grant and from the Point Reyes National Seashore Association (PRNSA) to fund QA/QC and revision of the three (3) historic mapping periods (early 40's, early 60's, late 90's) and to crosswalk the most recent large-scale vegetation map from 2018 ('18) for Point Reyes (Tukman Geospatial Analysts/AIS).

Poor image quality and spatial resolution for some of the earlier aerial photographs (40's, 60's) hampered fine-scale mapping and classification of vegetation during those periods, particularly for different types of forests and freshwater wetlands, which can be difficult to distinguish or tease apart in B&W. We attempted to account for potential mapping and classification error by introducing confidence limits that factored in image and georectification quality and, to a lesser extent, challenges with

mapping of particular communities (Table 3). Generally, confidence limits increased, and potential mapping error, decreased over time, with newer imagery and mapping datasets judged to have a very low potential for mapping error (e.g., 1% for crosswalked '18 map; Table 3). When potential mapping error exceeded change in acreages between mapping periods, these changes were not formally analyzed, although they could be treated as indicating that those communities were relatively stable during that change analysis period.

Historic Changes in Vegetation Communities at Point Reyes

Pollen studies paint a dynamic landscape in Point Reyes over geologic millennia, with forests and shrublands expanding during wetter periods and contracting during drier ones, thereby encouraging expansion of grasslands (Rypins et al. 1989, Anderson 2005, Anderson et al. 2013). During the late Holocene, a generally cooler climate led to establishment of more mesic vegetation such as the Douglas-fir-mixed conifer-hardwood forests, riparian forests, coastal scrub, and wetlands that had dried up during the drier early Holocene period (Anderson 2005, Anderson et al. 2014).

Settlement of western Marin County area by progenitors of the Coast Miwok tribe introduced the first anthropogenic influences, with native peoples using prescribed burning to expand grassland extent and manage shrublands and woodlands/forests (Stephens and Fry 2005, Keeley 2005, Lorimer et al. 2009, Anderson et al. 2013). With the advent of the Historic Period and Euro-American settlement, an unprecedented number of extrinsic disturbance factors converged and conflated to dramatically rework the Point Reyes landscape, including introduction of livestock and non-native plants, extensive clearing and logging of forests, and suppression of prescribed burning by native peoples (Clar 1959, Duncan 1992, Anderson et al. 2013, Forrestel et al. 2015). While Spanish settlers discouraged prescribed burning by native peoples, fire frequency between the early 1800's and early 1900's increased, approximating that estimated for the pre-Euro-American settlement period (Brown et al. 1999, Anderson et al. 2013). Brown and his colleagues (1999) postulated that clearing for grazing may have been undertaken both through use of mechanical removal and fire. Based on historical accounts, early hand-drawn maps, and paleoecological studies, grasslands expanded considerably under this expansive agricultural management regime, while forests dwindled, with remnant stands possibly restricted to the top of the Inverness Ridge (Russell 1983, Duncan 1992, Brown et al. 1999, Keeley 2005, Anderson et al. 2013).

Agricultural development was soon followed by massive urbanization in California as a whole (Sleeter et al. 2011), with urbanization threats tempered in Point Reyes by establishment of a national seashore in 1962. The development boom in the U.S. and California had particularly severe impacts on specific communities such as salt marsh and freshwater wetlands, with 90% of them being drained or filled (Dahl 1990). At Point Reyes, acreages reported for Salt Marsh were highly influenced by both diking (40's-60's) and subsequent restoration (90's-'18) of a large salt marsh at the southern end of Tomales Bay, along with restoration and continued progradation of estuarine deltas in other Point Reyes watersheds due to sedimentation (Table 7). Trends in Freshwater Wetlands, which includes brackish marshes, are a little more difficult to interpret due to challenges in mapping seasonally saturated or seep-fed features, particularly in B&W imagery. Freshwater Wetlands appeared to decrease between the 60's and 90's (adjusted (adj.) net loss=80 acres), however, some of that may have resulted from re-establishment of Riparian Forest/Shrubland following a reduction in agricultural management intensity or mowing, as riparian habitat increased by 385 adj. acres during that same period after decreasing slightly between the 40's and the 60's (Table 7).

While development constitutes less of a threat to coastal dunes in Point Reyes due to land protection, they have still been impaired by planting and subsequent spread of highly invasive, non-native species such as European beachgrass (*Ammophila arenaria*) and iceplant (*Carpobrotus* spp.). Conversion of more sparsely vegetated native Dune Mat habitat to dense monocultures of European and iceplant is evidenced by the continued increase in Vegetated Dunes between the 40's and the 90's (adj. cumulative net gain=119 acres) relative to the continued decline in Unvegetated Dunes (adj. cumulative net loss=186 acres), despite some conversion of invaded habitats to native Dune Mat through restoration, particularly near Abbotts Lagoon. Vegetated Dune habitat, which also includes native Dune Scrub, also probably continues to climb with expansion of dune depositional features in Grassland and Open Scrub/Grassland inland of the immediate coast.

With a sharp reduction in logging/clearing in the early 1900's, forests began to re-establish on the Inverness Ridge, particularly Douglas-fir (*Pseudotsuga menziesii*). More intensive agricultural practices such as row cropping began to phase out in the early to mid-1900's. These land use trends intensified with incorporation of Point Reyes into the national park system in the early 1960's. Starting in the 1970's, livestock grazing transitioned from more dairy cattle grazing and to less intensive beef cattle grazing (NPS 2020), which favored conversion of open grasslands to ones supporting some level of shrub cover or even dense scrub. Over the next century, rapid expansion or "encroachment" of shrublands and conifers such as Douglas-fir into grasslands in central California areas, including Point Reyes, sparked considerable concern due to loss of grazing, recreation, and biodiversity values of grasslands and increases in potential fire hazards (Biswell 1954, McBride and Heady 1968, McBride 1974, Williams et al. 1987, Dunne and Parker 1999, Russell and McBride 2003, Keeley 2005, Kennedy and Sousa 2006, Zavaleta and Kettley 2006, Hsu et al. 2011, Startin 2022). Douglas-fir has also been documented encroaching into shrublands, oak woodlands, and chaparral (Dunne and Parker 1999, Russell and McBride 2003, Cocking et al. 2014, Startin 2022, GGNPC 2023). There have also been reported incursions of hardwood species such as California bay (*Umbellularia californica*) into grasslands and brushlands in the Berkeley Hills and Santa Cruz Mountains (McBride 1969, Unsicker 1974 *in* USDA n.d.).

A number of vegetation change analysis studies have incorporated sites or areas at Point Reyes or inland portions of Marin (Dunne and Parker 1999, Russell and McBride 2003, Kennedy and Sousa 2006, Hsu et al. 2011, Startin 2022). These studies generally detected somewhat similar patterns of vegetation change in Marin as for other central California areas. For example, detailed analysis of aerial imagery dated between 1985 and 2010 found that herbaceous plant communities and shrubland on the Bolinas Ridge in Marin County shrunk by 62% and 51%, respectively, while forests increased by 307% (Startin 2022). An earlier study that had a Bolinas Ridge site documented similar trends between 1939 and 1997 with shrub and grassland cover decreasing while that of Douglas-fir increased significantly and mixed-evergreen and Hardwood Forest remained stable (Russell and McBride 1983).

Interestingly, temporal trends documented in our study differed somewhat from those in these other studies, although the overall trajectory over time appeared similar. Within Point Reyes, the floristic landscape appeared to remain relatively static between the 40's and 60's, with the exception of a 12% increase in Mixed Herbaceous/Shrub habitats. However, dramatic and often seemingly contradictory changes in vegetation occurred between the 60's and '18. (Acreage for lifeforms was only calculated for upland habitats, not "margin" ones such as Salt Marsh, dune, and Cliffs). Taken from the perspective of the entire study period (40's – '18), acreage of Herbaceous communities fell 40%, while Mixed Herbaceous/Shrub and Native Forests (i.e., Douglas-fir, Bishop pine, Hardwood Forest) climbed 70% and

37%, respectively. Shrub-dominated habitats dropped by 8%. It should be noted that other studies did not incorporate change in mixed shrub-herbaceous communities.

The extent of Grasslands, which includes active agricultural areas, within Point Reyes fluctuated considerably during the study period and even reversed direction at times. Acreage of Grasslands (<10% shrub cover) appeared to be relatively stable between the 40's and the 60's, or at least the relatively small raw acreage change fell within our estimated mapping error (Table 7). However, between the 60's and the 90's, a substantial amount of Grassland transitioned into Open Scrub/Grassland (<60% interspersed shrub cover; 37%) and, to a lesser extent, Dense Coastal Scrub ($\geq$ 60% shrub cover; 11%), causing a 48% loss in acreage (adj. loss acres = 8,917; Tables 6-7, Fig. 10). These floristic changes have undoubtedly been strongly influenced by shifts in the degree of active management of Point Reyes lands with incorporation into the National Park Service, as well as by ongoing trends in the local agricultural industry (e.g., gradual shifts from dairy to beef cattle ranching; NPS 2020). By 2018, these trends seemingly reversed somewhat, with Grassland increasing slightly (331 adj. acres; ~5%) and Open Scrub/Grassland dropping considerably (2,158 adj. acres; 23%), although acreage of mixed herbaceous-shrub communities still exceeded that reported for the 40's and 60's (Table 6). Within the study period, acreage of Dense Coastal Scrub remained relatively consistent between the 40's and 90's (or within estimated mapping error), with a slight drop by 2018 (99 adj. acres; 1%). Between the 90's and '18, a large amount of flux existed between the Grassland, Open Scrub/Grassland, and Dense Coastal Scrub, with both progressive and retrogressive succession evident due probably to continued active management as well as to environmental perturbations such as climatic variations and wildfire (e.g., Vision Fire).

As with Grasslands, acreage of Douglas-fir and Hardwood Forests remained relatively stable between the 40's and the 60's, although Bishop pine dropped by 87 adj. acres, probably due in part to clearing of late successional stands along Pierce Point Road in the 60's (Murphy 2022; Table 7). The geographic extent of all three forest types jumped dramatically by the late 90's, ranging from 996 adj. acres for Hardwood Forest (33%) to 1,290 adj. acres for Bishop pine (59%; Table 7). Following the 60's, Douglas-fir re-established at Firtop where large swaths had been removed between the 40's and 60's and continued to expand into grassland and scrub areas along the coast (Murphy 2022), with gains totaling 1,086 adj. acres by the 90's (Table 7). The 1995 Vision Fire fueled a large-scale expansion of Bishop pine on the Inverness Ridge, particularly in areas west of Limantour Road that appeared previously to be a mix of grasslands and coastal scrub. The fire also sharply reduced (46%) the spatial extent of Douglas-fir within the 13,000-acre burn footprint, while increasing that of Hardwood Forest by 13% (Forrestel et al. 2011). All three forest types continued to expand between the 90's and '18, albeit at a much slower rate. Acreage gains ranged from 123 adj. acres for Douglas-fir to 467 adj. acres for Bishop pine and 569 adj. acres for Hardwood Forest (Table 7). While forests did appear to encroach occasionally into Open Scrub/Grassland and, to a much lesser extent, Grassland, based on our classification matrix analyses, most of the forest expansions resulted from conversion of Dense Coastal Scrub, ranging from 12% (60's) to 32% (90's; Fig. 10). Some of these changes may result from juvenile trees in earlier mapping periods being classified as Dense Coastal Scrub, but especially in later mapping periods, most of these changes probably represent true conversions.

As is evident from the results above, acreage gains by Hardwood Forest have outpaced those of Douglas-fir within the past 20-years by four-fold. The potential expansion of Hardwood Forest over the last two decades is noteworthy, because these forests, along with coniferous forests, have been

devastated by Sudden Oak Death (SOD; *Phytophthora ramorum*). SOD, a water mold which produces spores in humid and moist environments, was first documented in California and Oregon in the late 90's (Rizzo and Garbelotto 2003) and in Point Reyes in 2004 (Forrestel et al. 2015). By 2007, almost 40% of coast live oak (*Quercus agrifolia*) woodland and coast redwood and Douglas-fir forests sampled in Point Reyes and adjacent Golden Gate lands showed evidence of SOD (Moritz et al. 2011). All three forest types support tanoak, which appears to be one of the most susceptible species along with coast live oak and other members of the black oak group, as they are not only hosts, but can also be killed by lethal bole cankers (Moritz et al. 2008, Forrestel et al. 2015). California bay, one of the major components of Point Reyes' Hardwood Forests, does not die from SOD, but it does experience foliar infections and supports a higher level of infection than any other known host, including tanoak (Davidson et al. 2008). As such, California bay has been implicated as one of the major drivers of tanoak mortality, at least in certain habitat types such as coast redwood and mixed evergreen forests (Davis et al. 2010, Cobb et al. 2010, Ramage et al. 2011).

The fact that Hardwood and, to a lesser extent, Douglas-fir Forests expanded even after introduction of SOD perhaps points to this disease currently having more effect on understory and overstory structure, habitat quality, and fuel loading, at least at Point Reyes, than on overall forest habitat distribution. Preliminary findings of several studies pointed to dead tanoak potentially being primarily replaced by California bay in Douglas-fir (Moritz et al. 2008) and coast redwood in coast redwood forests (sensu Kohyama 1993 in Cobb et al. 2010). In this instance, then, competition between canopy species could be driven by differences in disease transmission, as well as disease susceptibility, as Douglas-fir and coast redwood are both considered to have low susceptibility and transmission rates (Cobb et al. 2010) unlike California bay. These disease-related dynamics could ultimately influence distribution of forest types in areas such as Point Reyes. Once established, California bay may be able to gain some competitive advantage over Douglas-fir on xeric sites or in periods of drought. In general, hardwood species are considered more tolerant of drought or establishing on xeric sites than Douglas-fir (Tesch et al. 1992).

A similar phenomenon may have transpired with Bishop pine and Pitch Pine Canker Disease (PPCD; *Fusarium circinatum*). Mortality in the stands that originated following the Vision Fire was striking, particularly once PPCD was documented in 2006. However, recent monitoring results suggest that, while PPCD is continuing to impact Bishop pine forest, it is unlikely to result in loss of local populations in the near term, because changes to stand structure are not widely outside the range of variability for this ecosystem across seral stages (Harvey et al. 2022). This conclusion is supported by the results of our study, which shows that acreage of this community continued to expand between the late 90's and 2018 (15%) despite introduction of PPCD.

While many researchers have sounded the alarm about the threat of woody vegetation encroachment, expansion of Douglas-fir and California bay may be less of an unprecedented "encroachment" and more of a recovery response to the unprecedented convergence of impacts associated with Euro-American settlement. With cessation of logging and a reduction in clearing and other agricultural activities, these tree species may have potentially expanded to re-occupy some of the ecological niches that they occupied prior to European contact, when Point Reyes supported "abundant" Douglas-fir, coast redwood, and hardwood forests (Livingston 1994 in Anderson et al. 2013, Anderson 2005, Anderson et al. 2013).

Researchers have pointed to suppression of both wildfires and the prescribed burning practices of the

Coast Miwok as one of the reasons for Douglas-fir expansion (Dunne and Parker 1999, Brown et al. 1999, Russell and McBride 2003). While recent studies in montane areas point to Douglas-fir being among the most abundant regenerating species under moderate-intensity fire scenarios (Welch et al. 2016, Hankin et al. 2019, Povak et al. 2020), in the coastal ranges of California, Douglas-fir tends to be less of an early seral species than in other areas such that other species tend to colonize first (A. Forrestel, NPS, *pers. comm.*). As noted earlier, following the Vision Fire, Douglas-fir forests contracted by 46% (Forrestel et al. 2011), although this fire burned at a higher severity than the 2020 Woodward Fire in which some Douglas-fir seedling regeneration is evident (Parsons et al. 2023). Fewer acres of Hardwood Forest burned during the Woodward Fire, but both basal resprouting and seedling regeneration of California bay was evident in hardwood stands where it did occur (Parsons et al. 2023). Ultimately, Douglas-fir and perhaps California bay may possess a competitive advantage by exhibiting an extremely adaptable or plastic response to fire – regenerating following both less severe wildfires and also during periods of no fire by infilling underneath the canopy of other tree species (Douglas fir; Welch et al. 2016) or when understory vegetation such as tanoak is impacted by SOD (California bay).

As noted earlier, with the elimination of logging and prescribed burning and the reduction in tree clearing and grazing intensity association with the transition to beef cattle ranching in the 1900's, the Point Reyes landscape may have started to revert back somewhat towards the more forested and brushy conditions present before human settlement. This pace of this ecological recovery probably intensified with establishment of the park, with further easing of development and management pressures. Deceleration in growth of native forested habitats in the last 20 years may point to a slowing in this recovery response, with Douglas-fir and, to a lesser extent, Hardwood Forest, reaching ecological equilibrium or balance as dictated by current physical and environmental conditions. Looking to the future, distribution of these habitats on the Point Reyes landscape may continue to shift in response not only to changes in historic disturbance factors such as agricultural management and fire regimes (e.g., increased potential for wildfires), but to anthropogenically induced changes in climate and introduction or spread of new diseases such as soil-borne *Phytophthora*.

While models for California generally predict a drier and warmer climate (Polade et al. 2017), other models suggest that certain portions of coastal California could become cooler, windier, and wetter (Lebassi et al. 2009, Maloney et al. 2014, Pozo Buil et al. 2021), leaving a high degree of uncertainty about how coastal areas might be impacted. Drier and warmer climate projections form the basis for a number of vegetation community change models developed between 2009 and 2015 that assert that, by the mid-21st century, oak woodland, shrub, and grassland habitats will be favored over coniferous and evergreen broadleaf forested ones, particularly in the San Francisco Bay area (Stralberg et al. 2009, Cornwell et al. 2012, Ackerly et al. 2015). Some of these models depict the Inverness Ridge by mid-21st century as being dominated either by a mix of remaining forest and forest-converted shrubland (Stralberg et al. 2009) or almost entirely forest-converted shrubland (D. Ackerly, 2010, *unpub. data*). These predictions somewhat contrast with findings of other ecological and paleoecological studies, which point to coyotebrush and shrublands other than perhaps coastal sage scrub (typified by California sagebrush/*Artemisia californica*) expanding under wetter climatic regimes (Williams et al. 1981, Williams and Hobbs 1989, Rypins et al 1989, Anderson 2005, Hsu et al. 2011, Sandel et al. 2012, Anderson et al. 2013).

Despite the pervasiveness of climate change, modeling suggests that climatic factors on a regional scale

less govern vegetation community transitions than those occurring on a localized scale, with shifts dependent on the biological threshold of a particular vegetation type in relation to how close the upper or lower bounds of that threshold are to current climatic conditions (Cornwell et al. 2012). A recent study concluded that some portions of the Douglas-fir and Ponderosa Pine (*Pinus ponderosa*) forests in low-elevation areas of the western U.S. may have already crossed a climate threshold such that any stand-replacing wildfire may result in no forest regeneration and instead a lifeform conversion to grasslands (Davis et al. 2019). Edaphic or abiotic factors such as soil type, slope, and aspect as well as biotic variables such as “priority effects” (order/timing of immigration of species); vegetation-environment feedbacks; facilitation; and competition operating on a localized scale can also heavily influence the trajectory and speed of transitions (Fukami and Nakajima 2011, Ackerly et al. 2015).

Transitional thresholds may possibly explain why wetter habitats – Douglas-fir forest – and wetter species – coyotebrush – have been expanding or at least remaining stable in Point Reyes and elsewhere despite the fact that climate change has already been occurring for 50 years or more. As Ackerly et al. (2016) noted, recent trends, especially for Douglas-fir, run counter to the projected impacts of a warmer climate. In many areas of Marin County, Douglas-fir is also displacing oak woodland (GGNPC 2023), while climate change models point to the exact opposite occurring within the next 30 years. In addition to thresholds, vegetation shifts are subject to a natural lag in response of species within communities due to dispersal or growth limitations, effectively creating a disequilibrium between a rapidly changing climate and a (possibly) slowly responding vegetation (Ackerly et al. 2016). Adjustments to climate change may unfold over decades or even centuries (Ackerly 2016). A similar phenomenon of disequilibrium was recently documented for coniferous forests of the Sierra Nevada, where almost 20% were experiencing what researchers termed “vegetation climate mismatch” in which they persisted where climate was currently unsuitable, with 95% of those forests stands occurring at lower elevations (2,356 m; Hill et al. 2023).

Slowing in the rate of expansion of Douglas-fir and hardwood forests in Point Reyes within the past 20 years may be the first sign that forests are coming into equilibrium with a changed climate, but it’s difficult to assert this definitively as Douglas-fir forests continue to expand even in immediately adjacent areas such as Bolinas Ridge (Startin 2022). Ultimately, continued disequilibrium of vegetation communities still recovering from historic disturbances such as logging, agricultural development, and fire suppression with current climatic conditions may make certain communities more vulnerable to drought stress, fire risk, pathogens and disease and to invasion by disturbance-adapted weeds with high dispersal rates and short generation times (Ackerly et al. 2016).

INTRODUCTION

Vegetation communities are floristic manifestations of forces acting over both extended and more immediate time spans. Over millennia, geological forces sculpt landforms such as mountains, valleys, and plains, control soil formation, and influence hydrology. Long-term climatic cycles dictate temperature and precipitation that also govern patterns of vegetation establishment. Juxtaposed against these longer-duration factors are more immediate and transient natural disturbances such as wildfires and flooding, which can act seemingly instantaneously to re-set successional processes and influence vegetation mosaics. In recent times, anthropogenic disturbances have come to exert perhaps an even more dominant role in controlling vegetation community change. Within California, residential, commercial, and agricultural development have dramatically transformed its landscape, driving some communities such as vernal pools to the brink of extinction. Between 1985 and 2010, urban land cover jumped by 37.6% within California and 24.9% within the San Francisco Bay area (Hsu et al. 2011).

Point Reyes has largely been protected from damage to natural resources such as native vegetation inflicted by residential and commercial development, thanks to incorporation in the National Park Service (NPS) system. However, it has not been entirely immune to anthropogenic influences. Starting in the 1700's, Point Reyes was subjected to an unprecedented convergence of highly pervasive and intensive impacts that escalated in the 1800's and dramatically altered its landscape, including logging of forests, introduction of livestock and non-native plants, and suppression of wildfires and prescribed burning conducted by native peoples (Anderson et al. 2013, Forrestel et al. 2015). These disturbances have shifted in nature and intensity somewhat over the past 150 years: For example, logging was sharply reduced, and livestock grazing has transitioned from more intensive sheep and dairy cattle grazing to beef cattle. Regardless, the legacy of these impacts persists on the Point Reyes landscape, greatly influencing its floristic structure, particularly as some disturbances such as spread of non-native species have continued to intensify over time.

While spared largely from the blight of massive development, Point Reyes will not be able to evade the looming specter of climate change, which will wreak impacts as far-reaching as urbanization, although its effects may be, at least initially, more subtle. Striking and unparalleled changes in vegetation are expected in response to climate change. The type and degree of change is a matter of scientific debate, with intensity of change in California expected to be strongly linked to changes in ambient temperature, precipitation, the pattern of extreme climatic events (e.g., drought, El Niño events), and, for coastal communities, sea level rise and wave surge. While most of the predictions for California have called for warming temperatures and less precipitation coupled with more unpredictability and extremes in precipitation and temperature (Polade et al. 2017), some models suggest that certain portions of coastal California could become cooler, windier, and wetter (Lebassi et al. 2009, Maloney et al. 2014, Pozo Buil et al. 2021), leaving a high degree of uncertainty about how coastal areas might be impacted.

Cooler temperatures along the coast, coupled with warming of interior regions, would seemingly favor continuation of the fog "belt" that typically cloaks the coast during the summer when temperatures soar in inland areas. Cool temperatures, high winds, and fog are important drivers of vegetation community structure along California's coast. The iconic coast redwood (*Sequoia sempervirens*) stands are among those considered specifically adapted to the moderating influences of marine air and supplemental water from fog during the dry summer months (Johnstone et al. 2013). The impacts of climate change on these coastal communities could result in a very different landscape. However, it is difficult to tease

apart the effects of climate change on vegetation communities from other variables such as agricultural or other development, catastrophic events such as fire and flooding, effects of pathogens such as Sudden Oak Death and Pitch Pine Canker, and natural trends in plant succession or transition. In the absence of disturbances, progressive successional processes in the Bay Area vegetation mosaics would suggest that grasslands can be colonized by shrubs, which can then be colonized by trees (Sandel et al. 2012). But analyses of sediment and pollen data points to the possibility that “retrogressive” succession can occur during long-term climatic shifts, with, for example, dominant Douglas fir–pine-fir forests of the wetter Pleistocene period transitioning to coastal sage scrub and grassland during the drier early Holocene period (Rypins et al. 1989, Anderson 2005, Anderson et al. 2013).

The NPS is charged with the mission of conserving and protecting the nation’s natural resources, but it is often more difficult to detect potentially alarming changes in resources for those changes that unfold more slowly and are more geographically disparate than it is for changes that occur more rapidly or are more discrete geographically. Changes in distributions of vegetation communities within the park in response to both anthropogenic and natural factors prove difficult to detect for this very reason. If Point Reyes National Seashore (PRNS, Seashore) is to manage for conservation of some of its unique habitats or plant and wildlife species associated with habitats, it needs to better understand historic and recent trends in these habitats and how these trends might be exacerbated – or countered – by factors associated with climate change, as well as other future stochastic and anthropogenic influences.

To better determine historic trends in vegetation community change, Seashore staff collaborated with U.S. Geological Survey (USGS) staff starting in 2010 to georectify historic aerial imagery owned by the Seashore to allow for mapping of historic vegetation communities. Two sets of historical imagery data were used – one set from the 1940’s and one set from the early 1960’s. The intent was to evaluate change in vegetation communities over roughly 30-year intervals from the 1940’s, the 1960’s, and the 1990’s. In 1994, the Seashore and Golden Gate National Recreation Area (GGNRA) collaborated with California Department of Fish and Game (now California Department of Fish and Wildlife/CDFW) and Aerial Information Systems (AIS, Redlands, CA) to develop a vegetation community classification system and detailed vegetation map for the Seashore and portions of GGNRA. Seashore Vegetation Resources staff used a ‘heads-up digitizing approach’ in ArcGIS to map vegetation communities in the 1940’s and the 1960’s and to revise some of the mapping previously conducted for the 1990’s. To simplify comparison between these vegetation community mapping efforts, polygons were mapped to one of 17 vegetation community types that were adapted from the 1994 vegetation map “vegetation management communities” (Schirokauer et al. 2003).

After initial digitizing efforts, the Seashore conducted several rounds of staff review and map revision. A draft memorandum included the mapping efforts completed as of 2016, as well as acreage comparisons between the mapped communities (Ryan 2016; Appendix A). However, a final Quality Assurance/Quality Control (QA/QC) procedure was never performed on the mapping set as a whole due to the project running out of money and staff time, and the Seashore did not have an in-house GIS specialist to assist with more technical aspects of file clean-up and review. Due to these constraints, this seemingly valuable spatial dataset languished for six (6) years.

In 2022, the Seashore received funding from the NPS’s Functional Condition Assessment (FCA) grant source, as well as from the Point Reyes National Seashore Association Madrone Fund to assist with finalizing this dataset. Funding was used to contract with several GIS specialists who provided QA/QC

review and editing of previous mapping efforts, as well as topological cleanup of GIS files. GIS specialists also assisted with change analyses by conducting classification/confusion matrices between mapping periods for key vegetation communities.

An updated vegetation community mapping effort covering the entire County of Marin was undertaken in 2018 by several agencies headed by Golden Gate National Parks Conservancy (GGNPC), which contracted with Tukman Geospatial Analysts (Santa Rosa, Calif.) and AIS. This 2018 map represents roughly an additional 30 years of data in terms of detecting long-term trends in vegetation change. As part of this project, the 2018 map was crosswalked to the vegetation communities included in the historic mapping efforts and reviewed for consistency.

This report summarizes efforts to review and refine the earlier historic vegetation mapping efforts for the 1940's, 1960's, and 1990's and to crosswalk the 2018 vegetation map to the selected vegetation communities. It also presents results of our analysis of change that transpired between the 1940's and 2018 in vegetation communities in Point Reyes and the implications of these results for potential future trajectories of change in Point Reyes' floristic landscape.

MATERIALS & METHODS

2010-2016

Georectification of Historic Aerial Imagery: Characterization of landforms and vegetation communities improved considerably with the advent of remote sensing in the 1940's (40's). Most of the maps available prior to this, at least in Marin County, were hand-drawn maps developed by Spanish explorers or those put together by cartographers during the 1800's such as the U.S. Coast Survey tidal wetlands maps (Duncan 1992). Many of the earliest aerial photographs flown by planes date to the 1930's (Driscoll 1971, Rango et al. 2008, Morgan and Gergel 2013), with more consistent coverage since the 1950's (Morgan and Gergel 2013). Due to technological limitations, aerial photography continued for several decades to be only available in panochromatic black-and-white (B&W) until at least the 1960's (60's), when color photographs were introduced (Driscoll 1971). Color aerial photographs offer the advantage of displaying in both the visible and infrared spectrums, which enhance differentiation of unvegetated and vegetated areas and different types of vegetation communities (Nezlin et al. 2007). Since then, many vegetation mapping efforts have transitioned to use of satellite imagery, which became possible with implementation of the Landsat program in the early 1970's (70's; Woodcock et al. 2002). Historical aerial photographs typically need to be georectified before they can be used for mapping, which involves taking an image that has not been adjusted to be in a known coordinate system and putting it into a known coordinate system using a set of points in the image for which the latitude and longitude or map coordinates are known and then warping the image into a map projection. Modern imagery such as NAIP (National Aerial Imagery Program) has often been orthogonally rectified ("orthorectified"), which takes an image in its original geometry and very accurately adjusts it so that it is in a known coordinate system, with distortions due to topographic variation corrected.

Historical aerial imagery covering many portions of the Seashore were archived in the park's museum, including photographs from the 40's, 60's, and the 70's. Starting in 2010, USGS (Menlo Park, CA) collaborated with the park on scanning and georectifying some of this historic aerial imagery. Unfortunately, the park was not provided with a detailed memorandum or report on the georectification process by USGS, so much of the information below was pieced together from a series of emails between USGS and park staff. The imagery was a collection of black-and-white (B&W) aerial photographs flown in 1943 (Soil Survey) and in 1963 (for park acquisition) and color aerial photographs from 1979 (unknown provenance). The 1943 set includes 58 photos; the 1963 set, 552 photos; and the 1979 set, 25 photos (A. Torregrosa, USGS, *pers. comm.*, August 11, 2010). The 1963 set is comprised of 52 coarse-resolution large photos and 500 higher-resolution small ones, with both sets covering the same ground (A. Torregrosa, USGS, *pers. comm.*, August 11, 2010). All sets roughly cover the same ground, although the 1943 one is missing the very northern portion of Tomales Point, the very southern portion of the park near Palomarin, and intermittent portions of the eastern edge of Tomales Point adjoining Tomales Bay (A. Torregrosa, *pers. comm.*, August 11, 2010). The 1979 photos were the lowest (coarsest) resolution, and the 1963 photos were the highest (A. Torregrosa, *pers. comm.*, August 11, 2010).

By August 2010, the 1943, 1963, and 1979 photographs had been georectified (A. Torregrosa, *pers. comm.*, August 11, 2010). The processing stream involved scanning, cropping, georectifying, and, in some cases, a secondary cropping (Max Taylor, USGS, *pers. comm.*, July 1, 2010). Each photo set contains a metadata file which includes the # of control points, polynomial RMS errors, aerial image that served as

the reference, transformation, and resample type used to georectify (Max Taylor, USGS, *pers. comm.*, July 1, 2010). It should be noted that the Museum also had aerial imagery from 1954 (transportation study), but these were not included in the USGS processing effort.

The 1963 photographs did not cover the entire park, so additional 1965 photographs were purchased by the Seashore to fill in areas of the park not covered, as well as portions of Bolinas Ridge (A. Forrestel, GGNRA, *pers. comm.*, August 26, 2011). The origin of these 1965 photographs is not clear. They may have come from CalTrans, which had a set of 1965 photos that covered all of Marin County at a 1:12,000 scale, or they may be part of some declassified U.S. Department of Defense imagery (A. Torregrosa, *pers. comm.*). Many of the 1965 photographs were mosaicked into tiles that cover the central and southern portion of the Point Reyes mapping area.

Due to inherent technical issues associated with georectifying older, poorer quality historic imagery, the total mapping area in terms of acreage varied between the three mapping periods even when mapping boundaries were adjusted to eliminate areas for which 40's photographs were not available (e.g., northern Tomales Point, Palomarin area). In addition, some of the photographs do not overlay perfectly, creating "alleys" in between imagery tiles, or are often slightly offset physically, such that features visible in the map do not totally align between imagery tiles.

Historic Vegetation Mapping in GIS: Multiple methods currently exist for mapping historic vegetation communities. Prior to the advent of computers, vegetation communities were mostly hand-drawn onto aerial photographs or copies of photographs or outlined on mylar overlays. With introduction of personal computers and geospatial processing software such as ArcGIS, mapping could be conducted digitally by georectifying aerial photographs and using manual or "head's-up" digitizing, consisting of using geospatial software tools to hand-draw polygons on aerial imagery and classify them. Manual interpretation of aerial photography is among the most commonly used methods for ecosystem classification and production of inventory maps for resource management (Leckie and Gillis 1995, Thompson et al. 2007, Morgan and Gergel 2013).

Continued technological advancement resulted in development of automated vegetation mapping methods in the 70's (Woodcock et al. 2002), which greatly improved efficiency of vegetation community mapping over large areas. This is typically combined with some level of manual review and editing. While automated classification can be faster, manual interpretation can produce more detailed and accurate results (Morgan and Gergel 2013), especially when comparative mapping of different time periods is performed using imagery of different types, age, and quality (e.g., B&W, color; Stancioff et al. 2014). Advances in imagery routinely used with satellite imagery, however, has yielded another tool in the last 15 years that could enhance comparability between datasets based on older and newer imagery (Morgan and Gergel 2013). Classification of high spatial resolution black-and-white images has become more common with the commercial availability of Object Based Image Analysis (OBIA) software that allows to use textural and contextual information in classifying single band images (Platt and Schoennagel 2009, Morgan and Gergel 2013, Eitzel et al. 2016, Lydersen and Collins 2018). A comparative study evaluating automated and manual interpretation techniques for forest classification found Using manual interpretations for comparative reference, automated classifications produced overall accuracies ranging from 62% to 86% with per-class accuracies ranging from 0% to 96% (Morgan and Gergel 2013).

Seashore staff primarily employed manual interpretation or “head’s up digitizing” to map historic vegetation communities in the 40’s and 60’s due to differences in image type and quality. For the 1990’s (90’s) and 2018 (’18) map, staff primarily edited existing topology created by earlier mapping efforts. These mapping efforts combined both automated mapping with manual review and editing. Some researchers advocate a “backwards editing” approach in which mapping of more recent imagery is conducted first, with subsequent mapping performed in a reverse chronological order (Podobnikar 2009) to limit the amount of human error inherent in the manual digitization process (Stancioff et al. 2014). While this method would appear particularly advantageous in the Seashore due to the apparent relatively slow rate of change in vegetation communities, staff did not use this approach, because historic vegetation mapping efforts were disjunct (e.g., funded and implemented separately five years apart) and started with the 40’s and then proceeded to the 60’s, the 90’s, and, most recently, the ’18 map.

Prior to initiating historic vegetation mapping efforts, the Seashore conducted two workshops in May and June 2010 with park resource managers to discuss what level of change could be detected between these three different mapping periods – the 40’s, the 60’s, and the 90’s. At least one of these workshops focused on anthropogenic activities or management actions that were likely linked to the vegetation changes such as logging, dairy farming practices, cessation of potato farming, levee or road building, and wetland restoration. Some of the anthropogenic activities were responses to natural events such as floods, fires, and droughts (A. Torregrosa, *pers. comm.*, July 1, 2010). Workshop participants also discussed which vegetation communities would be most easily to detect between all three time periods: For example, non-native grassland might be difficult to discern in B&W imagery, while open scrub-grassland would not. There was also discussion on how much forest types such as Douglas-fir (*Pseudotsuga menziesii*), Bishop pine (*Pinus muricata*), and Hardwood species could be differentiated in B&W imagery. Unlike scrub and grassland communities, forests were often able to be mapped to dominant tree type because the shape of the crowns, coupled with their relative value (gradation from dark to light) were distinctive (Ryan 2016).

To ease comparison between different quality and resolution aerial imagery sets, Seashore staff identified 19 vegetation-based or structural mapping classes that were adapted from either the Superalliance or Mesocluster classifications present in the 1994 vegetation map (Schirokauer et al. 2003). Two Seashore staff took the lead on using a ‘heads-up digitizing approach’ in ArcMap (versions 9.2-10.2 ESRI, Redlands, California, ©1995-2014), a GIS mapping and modeling platform, to map first the 1940’s (1943; Alison Forrestel) and the 1960’s (1963 & 1965; Amelia Ryan), with fellow staff member Lorraine Parsons providing some assistance with wetlands mapping and editing during both mapping efforts. The minimum mapping unit (MMU) was roughly what was used in the 1994 vegetation map (0.5 ha), although the level of splitting versus lumping and adherence to the MMU varied between primary mappers. All three mapping efforts used the 1943 map boundary as described above, thereby excluding the very northern portion of Tomales Point, the southern portion of the park near Palomarin, and intermittent areas along eastern edge of Tomales Point. Staff used GIS data on topography, soils, and wetlands to aid mapping effort (A. Forrestel, *pers. comm.*, March 2012).

Manual interpretation uses a “convergence of evidence” approach in which many traits (tone or color, shape, size, texture, pattern, shadow, local topography, and neighboring contextual cues) are considered in combination (Morgan and Gergel 2013). This was the approach used by the PRNS mappers (Ryan 2016). For example, Grasslands and Active Agriculture were both light in value, but Active

Agriculture had a pattern of regular rows from tilling, brush-cutting, or ripping (Ryan 2016). Dense Coastal Scrub was dark with small crowns, whereas Open Scrub/Grassland had small dark crowns scattered in lighter grassland (Ryan 2016). Development of a characteristic pattern in color and texture of each vegetation type partly relied on knowledge by the mapper of the current plant community of the site, the texture and value of that vegetation from more recent aerial imagery, and some knowledge of the history of the location (Ryan 2016). For example, Bishop pine forests may have occupied a different extent in the 1940's than the present, but that the zone of occurrence probably largely overlapped, such that a stand of round-crowned trees in a location where there are currently round-crowned Bishop pine trees was likely also Bishop pines and not some other tree with a similar crown shape (Ryan 2016).

After the initial 1943 vegetation map was completed, staff undertook two rounds of map review and revision. First, the aerial images were loaded into digital stereo program, and the entire map was reviewed and edited while viewing the images in three dimensions (A. Forrestel, *pers. comm.*, March 2012). This stereo approach aided primarily in improving the staff's ability to discern Douglas-fir from Hardwood Forest species such as California bay (*Umbellularia californica*) and oaks (*Quercus* spp.; A. Forrestel, *pers. comm.*, March 2012). Second, the draft map was reviewed by Seashore employees (e.g., Ellen Hamingson, Sarah Minnick, Amelia Ryan, Dylan Voeller, Lorraine Parsons) with expert knowledge of Point Reyes vegetation communities.

The historic vegetation mapping project received several rounds of funding from the San Francisco Area Network Inventory & Monitoring (SFAN I&M) program to complete the 60's mapping. The 60's hand-digitizing was completed in stages, with mapping of the Lighthouse, Great Beach, Tomales Point, and areas south of Tomales Point occurring in May 2012 and the remaining taking place between May and June 2014 (Amelia Ryan, *pers. comm.* September 7, 2014). Aerial imagery from the 60's was more detailed than the 40's, and often more than one image, separated by a year or two, was available for the same site (Ryan 2016). Where two photos were available, the better rectified image was used, unless the quality was low, in which case the image with greater resolution was used (Ryan 2016). The 60's vegetation maps underwent a somewhat similar round of review, with Ryan using stereoscopic viewing equipment at USGS offices in Menlo Park to better tease apart some of the differences between Douglas-fir, hardwood, and Bishop pine forests. In addition, Ryan used preliminary data results to double-check some of what appeared to be anomalous results between the 40's, 60's, and the 90's maps. However, the draft 60's map was not reviewed by other park staff.

A formal crosswalk between the 90's map and earlier mapping efforts was not performed, but some effort was made by one or both mappers to convert the 90's map to the same vegetation community classification scheme as used for the older mapping efforts. The 90's map, however, was based on mapping of vegetation Alliances and Associations rather than broader structural community classifications, so some amount of interpretation was needed: the "Vegetation Management Communities" class ("Community" field in GIS) did reference "Grassland," "Grassland Open Scrub," "Coastal Scrub" and other more structurally descriptive attributes. In addition, because the Vision Fire occurred in 1995 shortly after the map was produced, Forrestel later amended the map as part of her dissertation project to include updated mapping for the 13,000-acre area near Limantour that burned during the fire (Forrestel et al. 2011). Because the park did not have access to a full set of later 90's aerial imagery, Forrestel used the 2004 imagery for post-fire mapping (Forrestel et al. 2011). This amended map was used for comparison by Forrestel and Ryan to preliminarily evaluate potential

changes in vegetation communities between the 40's, the 60's, and the late 90's/early 2000's (00's).

Ryan produced a preliminary report in October 2016 that included the three draft mapping products as graphics, as well as a summary chart showing changes in acreages of vegetation communities over time (Appendix A). As part of finalizing these draft mapping products, Ryan clipped the 40's and 60's mapping boundaries on the eastern edge of the Tomales Point peninsula adjacent to Tomales Bay to the 90's map: the rationale for this was not provided in the 2016 report, but this left portions of Hardwood Forest, Dense Coastal Scrub, Riparian Forest/Shrubland, and potentially Grassland unmapped for the earlier time periods.

In the 2016 report, Ryan identified some discrepancies that needed to be addressed. These included some Freshwater Wetlands being mapped as Grassland in the 40's and incorrect classification of Grasslands as Active Agriculture and Cliffs as Unvegetated Dunes in the 90's (Appendix A). However, this portion of the project – which had also been funded by SFAN I&M – ran out of money and staff time before the final Quality Assurance/Quality Control (QA/QC) procedure could be performed on the mapping set as a whole. In addition, the Seashore no longer had a dedicated GIS specialist at that point to assist with more technical aspects of finalizing these GIS files.

2019 - 2022

FCA Project Background Information: In fall 2019, the Seashore submitted a grant proposal under the NPS's FY21 Functional Condition Assessment (FCA) funding call to hire GIS contractors to perform QA/QC on these mapping sets and finalize them. This extensive dataset had been languishing since 2016 and was considered an important management tool for the park. The proposal called for QA/QC of the three original mapping periods (40's, 60's, 90's) with specific emphasis on potential mapping issues identified by Ryan in 2016 (Appendix A), as well as other issues raised by evaluation of the summary data (Table 1). For example, acreage of some communities was higher in the 40's and 90's, but lower in the 60's (e.g., Douglas-fir, Active Agriculture, Salt Marsh) or vice versa (e.g., Freshwater Wetland, Hardwood Forest; Table 1). In addition, the FCA project included crosswalking the newest mapping effort (2018) to the vegetation community mapping categories developed in 2010-2011. The FCA project was eventually funded in FY22.

The QA/QC efforts were split between independent GIS contractors and NPS staff. The Seashore arranged with Tukman Geospatial to review mapping of forested areas in the 40's and 60's maps and, to a lesser extent, the 90's and to provide recommendations on improving classification efforts. Tukman also conducted a preliminary crosswalk of the 2018 fine-scale mapping effort, which mapped vegetation based on Alliance, Association, Macrogroup, and other more species-based classes to the broader, largely more structural classes used in the park's historic mapping efforts. Implementation of changes recommended by Tukman in forested areas was undertaken by either NPS staff or independent GIS contractors – Andrew Giacomelli (40's, 60's) and Miriam Golding (90's and '18). QA/QC of the non-forested areas was performed by Parsons, who also tried to improve consistency between all three earlier mapping periods in how non-forested communities were interpreted and designated. Golding, Parsons, and another contractor, Victoria Infante, also reviewed and revised, when necessary, the '18 crosswalked map produced by Tukman to ensure that classification adhered to the standards established for earlier mapping products. There were typically several rounds of iterative review and

revision for at least each of the 40's, 60's, 90's, and '18, with the initial editing round typically being the most intensive.

Once initial QA/QC of all three original mapping sets was completed, Giacomelli performed a final topological clean-up of the GIS shapefiles, removing slivers and duplicate polygons, ensuring that polygon edges aligned properly, and eliminating alleys between imagery tiles. The shapefiles were then combined into a file geodatabase. Maps were produced for all four mapping periods mapping efforts, as well as tables that summarized acreages for all mapped communities and acreage changes between selected communities for all mapping periods.

Imagery Used in QA/QC of 40's, 60's, 90's, and '18: Imagery used in QA/QC of the historic veg mapping GIS files included the 1943 set (40's); a combination of the 1965/1963 photos (60's); the 2004 400 (1-foot) DOQ (90's); the 2018 NAIP imagery from County of Marin ('18); and the standard basemap imagery from ESRI (higher resolution 2014 and coarser resolution 2021; '18).

The 2018 imagery quality was generally very good. Imagery quality for 2004 was also generally good, except in certain areas, including west of Limantour Road and east of Drake's Estero. Also, the 2004 map had gaps in between tiles and appears to have been flown generally late in the day, so sunlight is casting shadows towards the east.

Multiple photos covering some of the same areas existed for the 1943 set. The attribute table did not denote which imagery tile was used for the original mapping effort, so imagery tiles were sometimes rotated through in certain areas to locate the tile most likely used in the original mapping. To assist with future interpretation, a field was added to the attribute table called "Image_Tile," and the number of the imagery tile was noted when a good match was found or when editing was performed using a particular image tile, so that it was clear which tile was used. In a few cases, tiles did not properly overlap each other, creating issues when digitizing features that extended across multiple photographs. This included the Giacomini Ranch and Lagunitas Creek area near Point Reyes Station. In this instance, the tile with the best overlap was selected to review and revise, if necessary, linework.

Perhaps, the most confusing set of photos was those from the 60's, as there were a very large number of photos available from both 1963 and 1965. The 1963 photos included both small and large photos. The 1965 photos were comprised largely of mosaicked images that covered the central and southern portions of the park with some individual photos available as well. While there is some distortion in the 1965 photos, they appear to be of a higher quality than many of the 1963 photos, so these were preferentially used when possible for review and editing. Some of the photos from the 60's appeared to have not been fully georectified, especially along the edges of photos. Additional georectification was performed on 24 of the 1963 photographs for areas of the park not covered by the mosaicked 1965 photos (see below for more details).

For portions of the park not covered by the mosaicked imagery, review and editing was preferentially performed using separate 1965 imagery tiles that had been re-georectified, as they were of higher quality than the 1963 photos. The separate 1965 tiles enabled coverage of the west shore of Drakes Estero and the outer coast to at least Drakes Beach, as well as most of the Tomales Point. Figure 1 shows the areas covered by both the mosaics and the individual 1965 tiles. Missing is the Lighthouse area, the Great Beach from the Lighthouse to Abbotts Lagoon, and two areas along the western edge of Tomales Bay and the eastern edge of Tomales Point.

On Tomales Point, the mapping overlay with the 1965 imagery was highly variable. Some mapping overlaid perfectly, while even immediately adjacent polygons were definitely off-shifted. Some effort was spent to rotate in other tiles, but, most times, an exact match could not be found. For the Lighthouse to Abbotts Lagoon along the Great Beach, there was almost no overlap of mapped polygons with vegetation features, even with a lot of effort to rotate photos to try and find a better match. It is possible, too, that re-georectification caused this offset, although in some instances, linework was compared with features using the original imagery, and no improvement was noticed in overlay. It is also possible that polygons may have been pulled in from the previous 40's mapping effort. Review and editing efforts were also complicated by the fact that individual photographs often had borders and that some of the tiles – just as with the 40's set – didn't completely overlap, complicating efforts to map features that extended across photographs such as Cliffs and Beach.

As with the 40's map, the imagery tile used for reviewing or editing the 60's map was provided in the Attribute table when possible.

Georectification of Historic Aerial Imagery from 60's: For the 60's, the vegetation maps were created using a combination of 1963 and 1965 aerial imagery to cover all of PRNS. The major source of error in vegetation change assessment was due to only 50% of 1963 imagery being properly georectified. Many subsequent polygons were then drawn over improperly georectified 1963 imagery, leading to Type 1 error. Problematic images from the 1963 set were then georectified using 2nd Order Polynomial Transformations using at least 6 control points. Control points referenced static features such as road intersections, standalone singular vegetation (like old growth trees), and infrastructure like culverts and fences. In difficult areas, such as photos dominated by Douglas-fir and Hardwood Forests, ESRI basemaps were used to approximate reference points in features like stream forks. Even with this additional georectification, some of the 1963 imagery is not 100% accurate in places along the edges where the image has been stretched and slightly distorted, as well some areas distorted by the original flight patterns and variations in the topography. In total, 24 of the 1963 images (gsept/63.XX.XX) were further georectified to compliment the 1965 mosaics.

Next, a folder of 1960s imagery was assembled containing 1965 tiles (g53-XX and g73-XX) and mosaics (st_XX), and newly georectified 1963 photos (gsept63.XX.XX) with coverage of the entire PORE area, without poorly referenced overlapping imagery which led to initial errors in mapping. Also included is a metadata .txt file and polygon outlines of each raster with image names.

Topology Cleanup for 40's, 60's, and 90's Shapefiles: Original GIS shapefiles from 2016 were given topology rules (Must Not Overlap and Must Not Have Gaps) to ensure the boundaries and vertices of polygon shape features maintained contiguity. This process pinpointed and corrected over 1,200 misalignments, gaps, slivers, and alleyways in the original shapefiles and were then cleaned up through the creation of features, and subsequent splitting and merging of features with existing polygons. This task referenced the 1943, 1963, 1965, and 2004 imagery to adjust vegetation polygons for the 40's, 60's, and 90's shapefiles.

40's Shapefile: The 40's shapefile was characterized by bisecting slivers across polygon boundaries (like the 90's shapefile) and gaps and overlaps (like the 60's shapefile).

60's Shapefile: The 60's shapefile was characterized many overlapping and gapped polygons that were likely hand drawn. Conversely, the 90's shapefile which seemed to have random slivers bisecting

boundaries versus alleyways between polygons. Polygons and topological errors were checked against 1965 (and some 1963) imagery to “ground truth.”

90’s Shapefile: The 90’s shapefile was characterized by numerous thin alleyways and slivers bisecting polygon perimeters. All errors in topology (breaking no gaps rule) were converted into features and split at boundary lines, and then the resulting polygons were merged with the larger, adjacent vegetation polygons, referenced by the 2004 imagery.

Refinement of Vegetation Community Classification System and Mapping Rules: As noted earlier, the original Vegetation Classification scheme included 19 vegetation-based or structural classes, including ones defined by predominant species (e.g., Douglas-fir, Bishop pine); predominant type of species (e.g., Hardwood Forest); function (e.g., Freshwater Wetland, Riparian Forest/Shrubland); structure (e.g., Dense Coastal Scrub, Open Scrub/Grassland); and management regime (e.g., Active Agriculture). Some of the categories are not necessarily strongly related to aspects of vegetation, including Disturbed, Water, Beach, Cliffs, and Other/unknown.

For review and editing of the mapping products, staff considered it essential to better define the mapping rules for each of these classes. Table 2 shows the improved Vegetation Community Classification System used in review and editing. Community descriptions were improved, and qualitative or quantitative cut-offs between closely related classes were more definitively spelled out where absent previously. For example, Grasslands were areas with <10% cover of shrubs, while Open Scrub/Grassland consisted of areas ≥10% and <60% shrubs, with shrubs generally interspersed through the landscape (Table 2; Figs. 2a-2d). Shrub cover equaled or exceeded 60% for Dense Coastal Scrub (Table 2; Figs. 2a-2d). In addition, one new class was added: non-native Cypress (*Hesperocyparis* sp.) trees or stands.

QA/QC of Forested Areas (40’s, 60’s, and 90’s): Julia Murphy of Tukman Geospatial reviewed the forested areas of the three mapping periods, focusing specifically on those areas or polygons where a forest lifeform or type conversion seemingly occurred. Tukman first overlaid the 40’s and the 60’s and then the 60’s and the 90’s maps (Murphy 2022; Appendix B). Tukman sub-sampled approximately 67% of polygons greater than 1 acre from the 40’s and 60’s and 54% of polygons greater than 1 acre between the 60’s and the 90’s (Murphy 2022; Appendix B). The resulting polygons were then classified according to the type of change (e.g., Bishop pine to Douglas-fir; Murphy 2022). These polygons were then broken out and dissolved according to three categories: 1) apparent forest loss (forest type to non-forest type); 2) apparent forest gain (non-forested type to forest type); and 3) apparent forest change (one forest type to another forest type; Murphy 2022). Polygons exceeding 1 acre in size were then sampled randomly in each of those categories, aiming for spatial and type-conversion representation (Murphy 2022). From these selected polygons, the vegetation type in each mapping period was photointerpreted (Murphy 2022). A point layer was created, and each polygon sampled was assigned a Change Type (the type of error; if any) and a Likely reason for that change or error, along with comments for further clarification (Murphy 2022). Change Type categories included vegetation types being misidentified in one or more of the mapping periods; true change in veg types; error due to imagery alignment issues between years; differences in MMU or lumping/splitting approaches; and difficult calls on the threshold between forest types (Murphy 2022). Likely reasons for these changes consisted of Forest expansion; Forest removal; Slivers due to alignment issues; Large non-border alignment issues; Misclassification of vegetation type by primary mapper; and Riparian corridors added, changed, or misaligned (Murphy

2022).

Tukman recommended using the Point GIS Bookmark layer to revisit and correct the original maps, focusing on the “Misclassified” and “MMU” error type bookmarks and paying particular attention to areas where Douglas-fir and hardwood mix (Murphy 2022; Appendix B). Tukman also advised that different mappers should be calibrated in their mapping instructions (e.g., the minimum mapping unit of vegetation to pull out of a larger contrasting veg type, or threshold calls between hardwood and conifer types; Murphy 2022).

General Editing Techniques for Mapping Review and Revision: The cleaned-up GIS shapefiles provided by Giacomelli were exported to a new shapefile that included the initials of the person conducting the editing and the date of edits. The original MMU as stated in the original mapping effort was 0.5 ha (~1.2 acres), but it was obvious from review of maps that mapping unit size was often smaller than this for certain features such as Freshwater Wetlands and ranch ponds (Water). During review, both the linework and classification were evaluated: Did linework appear to adequately capture distinct vegetation community features in the map, and, if so, was the polygon properly classified based on the revised mapping rules?

If changing classification of polygon without changing boundaries, the new classification was listed in the “Veg_Type” attribute field, and the old classification was listed in “OLDVegType.” For mapping eras involving multiple imagery tiles, all polygons from the 1940s and 1960s shapefiles were assigned an image tile(s) for use in future revisions. The tile number used to make this determination was noted in the “Imagery_Tile” field. In the “Comments” field, editors sometimes noted that the polygon had been edited and the rationale for that change. In instances when editors were uncertain about whether a change should be made, the term, “2ND OPINION,” was written in the “Comments” field, along with the reason for uncertainty.

In some instances, physical changes needed to be made to the map or to the polygons to improve mapping accuracy or ease of review. For the ’18 crosswalked map, the **Dissolve** tool was used in ArcGIS Pro to merge polygons within the vegetation feature class that had the same Vegetation Class and were adjacent to one another, which drastically reduced the total number of polygons present and simplified review and editing. Editing in either ArcMap or ArcGIS Pro involved mainly splitting of polygons; merging of polygons; and creation of new polygons using Autocomplete Polygon. If a mapped stand could benefit from being divided to improve its compositional integrity, the **Split** tool was used to split the polygon. The resulting polygons were either maintained as is after being split with appropriate reclassification of one of them, or one of the polygons could be merged with an adjacent polygon that appears to be more compositionally similar by using the **Merge** tool. In some instances, mapping wasn’t complete with some areas left completely unmapped. The **Autocomplete Polygon** tool was used to create new polygons with vertices that automatically snapped to vertices of the adjacent polygons. This tool was also used to resolve sliver or alley issues where gaps existed between adjacent polygons.

Editors took precautions to ensure that changes did not accidentally create sliver polygons, and, if they did, slivers were merged with an appropriate adjacent polygon. Slivers can also be picked up by checking the attribute table for unclassified polygons with very small areas. Also, in editing, polygons can sometimes shift when the **Hand** tool is used, and the polygon is selected: these usually were evident

from polygons having extra thick lines. When this happened, the **Undo** tool was used to shift the polygon back.

If a topological issue existed that couldn't be resolved directly by the editor, the term, "NEED HELP", was placed in the "Comments" field, so that the issue could be addressed by staff with more GIS expertise during the next round of editing.

Topological issues presented in classes such as Beach, Cliffs, Disturbed, Freshwater Wetland, Hardwood Forest (RF), and Riparian Forest/Shrubland among others. Errors were corrected using the set of topological rules mentioned above to adjust vertices and manage alleyways and overlaps. All topology errors in the 40s, 60s, and 90s shapefiles have been resolved and not gaps or overlaps currently exist lending to more accurate assessments in vegetation change among decades.

Once a round of review and editing was completed, the Attribute Table was reviewed, and any sliver polygons evident as blank rows with very small acreages were merged or deleted. Nomenclature was reviewed for consistency and accuracy, and some of the Comments specifying the need for further review and editing were addressed.

Acreages ("Acres") were calculated in GIS using planar rather than geodesic acreages, because planar better fit with the older imagery sets, which are planar, and maximized our ability to compare our acreage results with those in previous reports (Ryan 2016).

Review and Revision of Forested Areas (40's, 60's, 90's, '18): Using the Tukman Point Bookmark GIS layer as a guide, Giacomelli revised the 40's and 60's forested areas, and Golding and Parsons revised the 90's forested areas. Areas where misclassifications had been identified were prioritized, followed by areas where MMU or Imagery alignment errors had been found. Before changes were made, recommended changes were reviewed by Giacomelli and Golding and compared with forest types identified in other mapping efforts, including the 2018 map, as Murphy at Tukman said that the 2018 map was not necessarily consulted in her QA/QC efforts when reviewing the older mapping products (J. Murphy, Tukman Geospatial, *pers. comm.*).

Of the 435 errors identified in the Tukman Point Bookmark GIS layer between the 40's and 60's, 86 were attributed to class misidentification in the 40's, and 53 were due to misidentification in the 60's. Most of these were due to confusion between Douglas-fir, Hardwood Forest, and Bishop pine due to poor imagery quality in addition to differences in riparian corridor mapping strategies. A total of 101 errors were due to imagery alignment issues between the 40's and 60's, which was reconciled by the further georectification of 1963 imagery. A total of 37 errors were due to MMU and inconsistencies in how vegetation was mapped among decades and mappers. A total of 60 errors were due to slivers due to the misalignment of polygons among decades, and 28 errors due to large misalignment issues. Errors were reconciled using a variety of techniques including the adjustment of boundaries, merging of adjacent polygons, splitting of polygons, reclassification of vegetation types, while referencing imagery from the 60's, 2004, 2018, and modern ESRI basemap imagery. Boundaries were adjusted using the Edit Vertices, Move, and Align Edges tools with the "edges" feature enabled to ensure topology was maintained. Three open maps containing the 40's, 60's, and 90's shapefiles were used with linked cursors with their respective decadal imagery to more accurately align imagery among decades.

Editors spent some time initially trying to become comfortable with characteristic aerial imagery

signatures for Bishop pine, Douglas-fir, and Hardwood Forest and with the mapping rules that were established between 2010 and 2011 (and updated and refined in 2022; Table 2). In this classification system, forest communities are defined as having at least 10% absolute cover of trees (as opposed to 15% cover cut-off used in the 2018 mapping classification; Table 2). In terms of forest types, simple dominance rules (>50% relative cover) are used to classify Douglas-fir and Bishop pine, but Hardwood Forests are defined as stands having > 60% relative cover of hardwood species such as California bay, oaks, madrone (*Arbutus menziesii*), etc. (Table 2).

Interpretation of forest types can be complicated due to mixing of tree species within stands; different signatures for mature versus juvenile trees; and different signatures for stands on north- and south-facing slopes or on valley bottoms vs. slopes. For example, California bay stands can look “shirred” on slopes or flats, but look like much larger trees on valley bottoms, where creeks are located (Fig. 3). In addition, shadows often conflate the size of stands, making it difficult to interpret the true forest boundary. Mapping decisions were guided by use of both the 1994 and 2018 vegetation maps, as change in most areas is expected to be minimal or to be occurring slowly due to the lack of large-scale commercial and residential development within the Seashore, so there is a strong likelihood that species present in these more recent comprehensive mapping efforts were present to some degree in earlier periods. Both the 1994 and 2018 mapping efforts relied to varying degrees on initial automated computer characterization of vegetation to Alliance or Association level followed by subsequent manual review and editing. The expectation would be that current automated classification techniques would be more accurate than those used in the 90’s due to continued evolution of this mapping technique.

Review and Revision of Non-Forested Areas (40’s, 60’s, 90’s, ‘18): In reviewing non-forested areas for the 40’s, 60’s, and 90’s mapping efforts for non-forested areas, the primary reviewer (Parsons) generally started near the Lighthouse and worked towards Tomales Point and then to Chicken Ranch Beach, then covered Pierce Point Road area, and then worked south and eastwards from Home Ranch to Limantour Road to Palomarin and then finally through Olema Valley north to Giacomini/Martinelli.

For the 40’s, 60’s, and 90’s, existing polygons were reviewed for accuracy of linework alignment with observed vegetation features and classification of those features using visual interpretation of the imagery and personal site knowledge of the reviewer aided by several resources. Resources included PRNS field-based wetlands mapping GIS layer, which covers most of the park except the Wilderness; the recently revised U.S. Fish and Wildlife Service National Wetlands Inventory (NWI) map (revised 2021); the vegetation Alliances and Associations mapped in the original 1994 vegetation map; the Alliances, Associations, and Macrogroups in the 2018 vegetation map; and the USGS 10-foot topographic contours GIS layer for PRNS. As its name implies, the field-based wetlands mapping layer includes information on species dominance collected in the field, so it provides another source of “ground-truthed” information. The recent NWI revision incorporated some of the field-based wetlands mapping, although it used other techniques such as color aerial infrared photography and other tools to verify presence of wetland and water features. The PRNS field-based wetlands mapping and NWI resources, along with topographic contours, were particularly invaluable in guide mapping of Freshwater wetlands, which are often difficult to discern in B&W aerial imagery. As the 1994 and 2018 vegetation maps are derived from automated mapping techniques that detect signatures of particular types of vegetation, they provide another source of information, with the assumption change within the Seashore is not necessarily rapid. For example, areas with freshwater or brackish water-adapted hydrophytic or wetland species were often identified in the 2018 map as “Vancouverian Freshwater Wet Meadow & Marsh Group.” The

topographic contour layer was also used in reviewing and mapping Cliffs, Riparian Forest/Shrubland, and the extent of the dune field along the Great Beach.

In addition to reviewing existing features, areas that had been missed during initial mapping were also mapped and classified using aerial imagery interpretation and the resources listed above.

The issues associated with use of this older imagery also meant that the park or “land” boundaries did not exactly overlap with that of the 90’s mapping, leading to generally different land acreages. This was not so much of an issue on the Great Beach, Lighthouse, Limantour, or Palomarin areas as it was along the eastern side of Tomales Point, where the easternmost edge of land in the 40’s and 60’s imagery consistently jutted out further east than that of the 90’s map (Fig. 4). Ryan had trimmed both the 40’s and 60’s maps on this eastern edge to match that of the 90’s map. Assumably this trimming was intended to help minimize the discrepancy in total acreage mapped between the three mapping periods, although the specific rationale was not called out in the 2016 report (Ryan 2016). As discussed earlier, trimming on this eastern edge probably reduced total acreage of Hardwood Forest, Dense Coastal Scrub, and possibly Riparian Forest/Shrubland for the earlier mapping efforts. Ultimately, acreage of trimmed areas is probably very low relative to the overall amount of error present in this type of mapping, so these eastern areas were remapped in both the 40’s and 60’s maps during the editing process.

The ‘18 crosswalked map was also trimmed around the edges of the Peninsula, but unevenly so. There were sections of the coast where all of the Cliffs, Beaches, and some of the Water had been included and other sections where they had been cut off. Within these cut-off sections, it was apparent that polygons from the original, pre-crosswalked map had been greatly reduced as part of the crosswalking process. These Cliff and Beach areas were added back into the ‘18 crosswalked map by Infante and, to a lesser extent, Parsons as part of the QA/QC process.

In reviewing non-forested areas of the ‘18 map, the primary reviewer (Golding) began with the coasts, addressing crosswalk issues for Cliff, Beach, and dune vegetation communities, then worked from north to south on Grassland, scrub, and forested communities. Polygons were reviewed for accuracy of linework and for classification. Because the ‘18 aerial imagery and original linework were highly accurate, most of the review was for errors in crosswalking from the Alliances, Associations, and Macrogroups classifications down to the shorter list of communities used in the 40’s/60’s/90’s, as well as differences in assessment of shrub cover. The 2018 imagery was usually strong enough for analysis, but personal knowledge of the sites, imagery from 2004, and occasionally imagery from ESRI’s recent base maps (estimated dates 2014 and 2021) were used as an additional point of reference if a particular area or feature was blurry or somehow unclear. One of the larger issues that needed to be addressed in refining the crosswalked ‘18 map was that automated mapping approach tended to separate scattered shrub-dominated patches in grasslands into standalone polygons, while earlier mapping efforts took a more structural interpretation, classifying these areas as Open Scrub/Grassland. Considerable effort was made by Golding, Parsons, and Infante to remedy this issue and make results more comparable to earlier mapping efforts. In addition, Parsons also worked at refining the mapping of Freshwater Wetlands, as the crosswalked map largely relied on presence of hydrophytic or wetland-characteristic vegetation (Vancouverian Freshwater Wet Meadow & Marsh Group alliance), which would greatly overestimate the number of wetlands present, as earlier mapping efforts took into account topography and hydrology.

Change Analysis Approach: Accurate analysis of change in historic vegetation communities can be greatly complicated by a number of factors. Use of different types of imagery with varying spatial resolution and quality can limit the number and types of communities and patch size that can be feasibly discerned and introduce a potential for mapping error, particularly with older B&W imagery that has lower spatial resolution and quality (Lydersen and Collins 2018). Forested areas pose perhaps some of the greatest mapping challenges when using B&W imagery, as it can be hard to distinguish between types of forests such as conifers and oak woodlands even with supervised automated classification tools that rely on ground-based data to inform classification processes (Eitzel et al. 2014). Aerial photographs have increasing distortion approaching the edge of the photograph, relative to the center, and that error is magnified when photos were shot with a smaller focal lens length (wider angle; Fensham and Fairfax 2007), which results in trees near the edge of the image appearing larger due to the greater view from the side (Lydersen and Collins 2018). Photoscale can also impact mapping efforts, as photoscales with lower spatial resolution (e.g., 1:80,000) may underestimate vegetation cover relative to those with higher resolution (1:25,000; Fensham and Fairfax 2007). Distinguishing between tree crowns and shadows is also more difficult in B&W photographs, as shadows are highly influenced by the time of day in which photographs were shot (Platt and Schoennagel 2009, Lydersen and Collins 2018). Digitization of historical photographs can also introduce a substantive source of error associated with stretching and distortion of images during the georectification process (Stancioff et al. 2014). Lastly, manual interpretation and classification can be laborious, subjective, and difficult to replicate, yielding inconsistent results (Morgan and Gergel 2013).

Potential sources of error identified for the Seashore's comparative historic vegetation mapping process include the following:

- "Head's-up digitizing" was performed by different primary mappers for the 40's (Forrestel) and the 60's (Ryan) at different periods of time (2010-2011 and 2016, respectively). There were calibration efforts conducted in 2016 between primary mappers to ensure that mapping approaches were consistent. Initial conversion of the 90's map to a classification system consistent with the earlier mapping efforts appears to have been initiated by Forrestel and completed by Ryan. QA/QC of these mapping efforts was also conducted by different combinations of Seashore and contractor staff – 40's (Forrestel, Parsons, Ryan, Seashore staff, Giacomelli), 60's (Ryan, Parsons, Giacomelli), 90's (Forrestel, Ryan, Parsons, Golding), and '18 (Golding, Parsons, Infante).
- Use of older B&W aerial photographs that have lower spatial resolution and are of poorer quality than more recent color imagery. Some of the photos were stretched or distorted during the georectification process. All of these factors (B&W, low resolution, poor quality) inherently favor more detailed and accurate mapping of vegetation from more recent periods (90's, '18) than historic periods (40's, 60's).
- Older photograph sets were often incomplete, not covering the entire park or had gaps or "alleys" between tiles due to photograph borders. This often required using multiple sets of photographs, sometimes from different years (e.g., 1963 vs 1965) to conduct mapping, and these photographs were often of varying quality. In addition, editing efforts for the 60's and, to a lesser extent, the 40's were hindered by the fact that the original mappers did not specify the tile that was used to map vegetation in particular areas.
- Older photograph tiles were sometimes distinctly physically offset from the adjacent tile, such

that features that crossed two different tiles did not line up completely, which reduced accuracy of mapping efforts.

- Due to distortion created in georectifying older imagery, the borders or edges of the mapping areas within the Study Area were different between mapping periods, with the easternmost edge of the Peninsula along Tomales Point extending further east in the 40's and 60's imagery than in the 90's or '18 imagery. As clipping the 40's and 60's to the 90's boundary would impact acreage of Hardwood Forest, Dense Coastal Scrub, Riparian Forest/Shrubland, and some of the wetland communities, the decision was made to not clip the older maps.
- Aerial photographs were flown at different tides and different times of day, which complicates comparison, particularly for communities such as Beach and Forested ones, as the time of day can influence shadows in the photographs that can be mistaken for the edges of forested or scrub stands.
- Vegetation mapping in the 40's and 60's was based on broader, more structurally oriented vegetation communities (e.g., Hardwood Forest, Open Scrub/Grassland) whereas initial vegetation mapping in the 90's and '18 was based more on species or grouping of species such as Alliances and Associations. This resulted in a vastly different number and spatial extent of polygons and complicated efforts to crosswalk between newer maps and older ones, with newer maps generally having double the number of polygons (>5,000).
- Vegetation maps for the 90's and '18 were constructed using an automated method with maps later edited manually, whereas the earlier mapping products were developed entirely using head's up digitizing.
- The 90's map initially produced in 2016 was not derived directly from the 1994 vegetation map produced by CDFW and AIS, but was instead a revised version that included updated vegetation communities present in the Vision Fire area mapped using 2004 aerial imagery for a dissertation project (Forrestel et al. 2011).

All these factors introduce a significant source of bias and error into our historic vegetation mapping efforts, despite our best efforts to greatly reduce this error through this project's extensive QA/QC procedures. As was discussed in Eitzel et al. (2016) regarding forest mapping, misclassification can lead to situations in which cover changes appeared to have occurred that are known to be false, "implying that the classification uncertainty was large enough to conceal the underlying process."

For this reason, analyses that evaluate change in acreages of specific vegetation communities between mapping periods need to be presented – and interpreted -- with considerable caution. Some approaches have been developed to deal with these sources of error, including a method called Intensity Analysis that converts vectors to rasters and then uses a pixel-based change detection approach that can be used to smooth out errors resulting from incorrectly mapped boundaries between communities (Stancioff et al. 2014, Startin 2022). Pixel sizes can vary depending on the mapping project (Stancioff et al. 2014). In general, if two different vegetation communities fall within the same pixel, the community with the largest area will be designated for that pixel (D. Franco, GGNPC, *pers. comm.*). This method was recently used to evaluate changes in Lifeform and Enhanced Lifeforms on GGNRA and PRNS lands in Marin, San Francisco, and San Mateo between a series of maps produced from 1994-2006 and the 2018 map (D. Franco, *pers. comm.*).

An alternate approach proposed by Murphy at Tukman would involve quantifying changes by using a point-based sampling system rather than on total acreages, which would minimize effects of slight

alignment issues and focus on areas of true change (Murphy 2022; Appendix B). Given the amount of effort to produce and revise these mapping efforts, a set of sampling points selected through random stratification would potentially minimize some of the mapping issues identified, but it could also greatly reduce the ability to discern the degree of change between communities, if not the trajectory of change.

Tabular Change Analysis Approach: While scientific studies often employ confidence intervals to convey the degree of certainty or uncertainty in precision of analyses, these are strictly constructed from means or averages calculated from multiple samples, not from sums or totals. Rather than trying to analyze changes in vegetation communities between mapping periods using raw acreage sums, as was done in the preliminary 2016 report (Ryan 2016), we elected to introduce the concept of mapping/classification “confidence limits” that vary depending on mapping period and, to a lesser extent, vegetation community. These confidence limits are based on multiple factors. A primary factor was the level of error found in the initial mapping files for forested areas as evaluated by Tukman (see “Results”), with the assumption that forested areas might pose the highest risk for mis-mapping, particularly for the 40’s and 60’s that relied on coarse and often poor-quality B&W imagery. Because the Tukman QA/QC process was used to identify and later correct mis-mapping errors as described earlier, the assumption is that the degree of error should have improved with the current mapping product, however, some errors will undoubtedly persist due to inherent distortion in the georectified imagery.

Another factor was the relative risk of mis-mapping assigned to communities for various mapping periods based on the best professional judgement of staff and consultants performing review and revision of the mapping products. Mis-mapping risk was influenced by the resolution and quality of imagery used (i.e., innately higher for older B&W sets) and the relative likelihood that certain communities could be mis-classified or mis-mapped. For example, certain communities were less likely to be mis-mapped (e.g., Grassland, Salt Marsh) across all of the at least earlier mapping periods (40’s, 60’s, 90’s) than others (e.g., Douglas-fir, Hardwood Forest, Bishop pine, Riparian Forest/Shrubland). Forest mapping appeared to be very accurate in the ’18 mapping effort.

Also taken into consideration was the potential for initial mappers to have used a different approach for classification. One substantial difference between the ’18 map and earlier versions is that the automated system used tend to map at a finer level than the broad landscape pattern approach utilized for the earlier mapping products, particularly the 40’s and the 60’s. As discussed earlier in this section, mapping of the Freshwater Wetlands community in the ’18 map largely relied on crosswalking of a specific vegetation alliance, Vancouverian Freshwater Wet Meadow & Marsh Group alliance. This is quite dissimilar to wetland-mapping approaches taken in the other maps, which incorporated considerations of topography and hydrology. Also, the ’18 map often grouped grass-dominated wetland features with Grasslands unlike earlier mapping efforts. Because of these issues, a lower confidence limit was introduced, and formal change analysis for Freshwater Wetlands between the 90’s and ’18 was not performed. As was also discussed earlier, similar issues occurred between the ’18 map and earlier mapping efforts for Open Scrub/Grassland, although much of this was addressed through later revisions of the crosswalked map by project staff in efforts to improve compatibility.

Additionally, the ’18 map placed almost all of the paved roads to the Disturbed category, while the other three maps tended to lump most of the roads with adjacent vegetated polygons. For this reason, change analysis is only performed between the 40’s and the 90’s for Disturbed areas. Beaches were mapped initially with varying level of precision – efforts were made to correct this in the three earlier mapping

periods – but Beach acreage is inherently dependent on what tide the photographs were flown, so Beach is omitted from the change analysis. Detailed information on mapping issues with communities that helps to explain confidence limit assigned can be found in Results.

Tabular change analysis was performed for the following communities:

- Douglas-fir
- Bishop pine
- Hardwood Forest
- Riparian Forest/Shrubland
- Freshwater Wetland
- Salt Marsh
- Grassland
- Open Scrub/Grassland
- Dense Coastal Scrub
- Vegetated Dunes
- Unvegetated Dunes
- Disturbed (40's – 90's only)

Table 3 presents the confidence limits established for vegetation communities for the various mapping periods. Confidence limits range from 92% to 99%, with lower limits implying less confidence in acreage totals and a higher percent chance for “noise” in final totals due to issues with imagery quality, georectification, mis-mapping, or mis-classification errors. Potential mapping error, therefore, ranged accordingly from 8% to 1%, respectively. Estimates of potential mapping error for individual communities in each mapping period (e.g., Hardwood Forest in the 40's and 60's) were added for each analysis period (e.g., 40's-60's). If the estimated error total was lower than the raw acreage change for that analysis period, the result for that community would be treated as probably an accurate reflection of “true” change in the system. In these situations, one final analytical step was performed to derive the acreage change estimates that are analyzed in Results: The estimated mapping error potential for that analysis period is subtracted from the raw acreage changes, creating “adjusted” (adj.) gains or losses in acreage. Conversely, if the error total exceeded raw acreage change, no further analysis is performed. Thus, our process creates a moderately conservative estimate of the trajectory and degree of vegetation community change between the 40's and 2018.

Classification/Confusion Matrix Change Analysis Approach: To better define the trajectory as well as the degree of change, Tukman used updated GIS information to create classification/confusion matrices for each comparative mapping period. This approach helped to determine what communities transitioned into during subsequent mapping periods. Tukman created the change analysis matrices by overlaying the updated maps for each time period (40's, 60's, 90's, '18) in ArcGIS, using the Union tool (Julia Murphy, *pers. comm.*, February 3, 2023). The output of this overlay was a single map where every polygon had attributes showing the vegetation communities in each year (Murphy, *pers. comm.*). For instance, a polygon could represent that its particular location was mapped as Grassland in both the 40's and 60's and then Dense Coastal Scrub in the 90's and '18. Though this overlay method does create slivers where lifeform boundaries do not quite line up, these slivers are generally small and do not contribute excessively to the total acreage (Murphy, *pers. comm.*).

Tukman exported the attributes of this overlay map to Excel and created tables to sum up the size of all

of the polygons for each vegetation community of interest across the different time periods. In the change matrices, each row displays a lifeform from the first time period, and each column shows the acreage of how that initial lifeform was mapped in the second time period. For instance, if there were 1,000 acres of Grassland mapped in the 40's, the columns might show that in the 60's, 900 of those acres were mapped as Grassland, 70 as Dense Coastal Scrub, and 30 as Douglas-Fir. This information was then used to produce a graphical depiction of transitions between four mapping periods (40's, 60's, 90's, '18) within key communities, primarily Grasslands, Open Scrub/Grassland, Dense Coastal Scrub, and Native Forest. The three non-riparian forested habitats (Bishop pine, Douglas-fir, and Hardwood Forest) were deliberately lumped into "Native Forest" for the final analysis, because the degree of error in classification of specific native forest type varied so dramatically across the analysis period, thereby clouding interpretation of community type conversions. The diagram shows the percentage of the earlier mapping period community that transitioned to these key communities in the subsequent mapping period. If percentage totals do not add to 100%, then, that community also transitioned to other communities not represented in the diagram.

RESULTS

Accuracy of Original Mapping Efforts

Specific changes for each of the vegetation communities or mapping classes are described in Table 4, and Table 5 displays the estimated time for initial review and revision of non-forested and riparian areas, as well as the number of polygons after initial review/revision.

Forested Areas (40's, 60's, 90's, '18): PRNS staff and contractors agreed with the vast majority of Tukman Bookmarks with a few exceptions, such as threshold calls between Douglas-fir and Hardwood Forest and Dense Coastal Scrub and Open Scrub/Grassland borders. The threshold calls were addressed by classifying vegetation types through a visual approximation and adhering to the guidelines set by the provided PRNS Updated Historical Vegetation Mapping Guidelines document. The 40's shapefiles were characterized by misidentified vegetation types due to some particularly challenging areas that occurred in many of the 1943 images due to poor spectral quality of photo exposure and development. Approximately 17% (1,333 acres) of forested polygons, including Riparian Forest/Shrubland that occurred on the Inverness Ridge and in Olema Valley, were mapped incorrectly in the 40's, mostly due to type confusions between Douglas-fir and Hardwood Forest (Murphy 2022; Appendix B). Bookmarked areas were compared to imagery from the 60's and, in some cases, 2004 if vegetation types looked similar. The 60's shapefile was characterized by many errors due to poorly georectified imagery. For the 60's, 11% of the forested polygons were mapped incorrectly, again largely for the same reason (Murphy 2022). The degree of error for the 60's forested mapping increased slightly in the 60's-90's comparison, climbing to 19% (1,418 acres) with confusion stemming largely from mis-mapping of Douglas-fir, Hardwood Forest, and Bishop pine in the 60's relative to the 90's (Murphy 2022). Due to the overlapping and doubling of imagery in certain areas for the 60's, it appeared that many polygons had been digitized over portions of imagery that were distorted. This was corrected by making a comprehensive set of contiguous imagery and mosaics of the 1960s and then reconciling polygon boundaries in adherence to the Tukman bookmarks.

Many errors in assessing forest change among the earlier decades can be attributed to two issues: image quality, and mapper lumping/threshold/tolerance for defining polygon size. In general, 40's shapefiles contained larger polygons for Douglas-fir and Hardwood Forests due to image quality. Use of the 60's imagery resulted in finer forest mapping, which may have resulted in a simulated change in forest types (i.e., Douglas-fir to Hardwood Forest). While transition to and from Douglas-fir forest between the 40's and the 60's often appeared to represent accurate changes on the landscape – e.g., expansion into grassland and coastal scrub, as well as loss from a large area of removal near Firtop Peak – conversion of Douglas-fir into Hardwood Forest documented in original mapping efforts (Ryan 2016; Appendix A) grossly overestimated the magnitude of this transition, although it did occur (Murphy 2022; Appendix B). There was some expansion of Hardwood Forest, largely through scrub conversion, but the large net increase reported in the 2016 draft mapping analysis can primarily be traced to type confusion between Hardwood Forest and Douglas-fir forests (Murphy 2022). There was also over mapping of Bishop pine forests in much of the 40's shapefile (Murphy 2022; Appendix B). The apparent loss in Bishop pine forest from the 40's to the 60's reported in the draft 2016 analysis (Ryan 2016) was largely due to type confusion between Bishop pine, coastal scrub, and Hardwood Forest, although there were some areas of removal, notably mature Bishop pine along Pierce Point Road (Murphy 2022).

Classification of forest polygons did appear to improve in the 90's, with Tukman estimating that only 6% (441 acres) were mis-classified (Murphy 2022; Appendix B). As with the 40's and the 60's, Hardwood Forest that occurred along drainages or in small stands adjacent to Douglas-fir were often lumped with Douglas-fir. More than 1,000 acres of Hardwood Forest were incorrectly miscategorized as Douglas-fir in the original 90's mapping. Douglas-fir forest extent did increase between the 60's and the 90's largely due to expansion in Dense Coastal Scrub, as well as Open Scrub/Grassland. However, in some cases, areas mapped as Douglas-fir in the original 90's map were actually Dense Coastal Scrub: These were Douglas-fir forest stands that burned during the 1995 Vision Fire, as was evident from dead trees visible in 2004 imagery.

Increases in Bishop pine in the 90's largely reflects true expansion of this species following the Vision Fire (Murphy 2022). The magnitude of this increase may have been underestimated, because young Bishop pine in the 90's map was often misclassified as Dense Coastal Scrub, even if absolute cover of juvenile trees exceeded 10% absolute cover. Linework for Bishop pine and Dense Coastal Scrub near Limantour Road were largely not aligned with what showed in the imagery. We used 2004 imagery, which may account for the difference, but this area was supposedly re-mapped using 2004 imagery by Alison Forrestel after the Vision Fire, which burned approximately two-thirds of this area (Forrestel et al. 2011). In some cases, Bishop pine stands were mis-classified as Dense Coastal Scrub. In other cases, Dense Coastal Scrub patches with standing dead trees or visible dead branches scrub stands potentially dominated by *Ceanothus* appear to have been mis-classified as Bishop pine. This is also true to some extent for the '18 mapping. Use of later imagery (6-inch 2014 imagery) helped to more clearly see Bishop pine that had been very young and harder to identify in the 90's, and overall mapping of Bishop pine in the Vision Fire burn area in the revised 90's mapping has been improved by splitting and merging the polygons to more closely fit the stands. However, there are likely still Bishop pine and Dense Coastal Scrub patches whose mapping could be improved in this area for both the 90's and the '18 maps.

Another area where significant editing occurred was for Riparian Forest/Shrubland. Ancillary sources of GIS information such as 10-foot USGS topographic contours, the recently revised National Wetlands Inventory (NWI) for Point Reyes, the field-based PRNS wetlands mapping, and the 2018 vegetation map were used to ensure that riparian areas were adequately captured by all three mapping periods and that interpretation of Riparian Forest/Shrubland was consistent. There were some significant differences in how the 40's and 60's mapping efforts interpreted "riparian," with the 60's taking a broader, more function-oriented view of any species that bordered drainages or creeks in dense stands even if the dominant species is not considered to be a true wetland or riparian species (e.g., coyotebrush/*Baccharis pilularis*). In efforts to better align all three mapping efforts, coyotebrush areas were converted to Dense Coastal Scrub. Only drainages or creeks that supported hydrophytic or phreatophytic species such as willow (*Salix* spp.), alder (*Alnus rubra*), bigleaf maple (*Acer macrophyllum*), or salmonberry (*Rubus spectabilis*) were mapped as Riparian Forest/Shrubland. After an email conversation with Amelia Ryan, staff also elected to identify stands of Hardwood Forest that directly adjoin creeks or drainages and that are distinct from adjacent vegetation communities such as Douglas-fir and grasslands as Hardwood Forest (Riparian Forest/RF), as they appear to be functioning as riparian habitat (Figs 5a-5b). However, it should be noted that Hardwood Forest (RF) mapping was performed on a limited basis for the 90's map, with Hardwood Forest stream corridors pulled out from Douglas-fir stands, but not specifically labeled as "RF." Hardwood Forest (RF) mapping was not performed for the '18 crosswalked map.

Mapping of forests in 2018 generally appeared to be very good both in terms of linework and

identification. Compared to earlier mapping efforts, mapping of forested (and non-forested) areas was much more precise and conducted at a much finer scale in 2018, as is evidenced by the dramatic increase in the number of polygons relative to earlier mapping periods (Table 5). Very few adjustments (i.e., splitting, merging) were made for forested layers in the '18 map. Unlike earlier mapping periods, there was less lumping of mixed forest types into one category based on the primary dominant species. There were a lot of forest fragments that were crosswalked into the Unknown/other category. When possible, those were updated to reflect the actual forest make-up, which was usually Bishop pine, sometimes Douglas- fir or Hardwood Forest, and, a few times, Dense Coastal Scrub. Most of these were very small polygons, so these changes did not greatly impact overall acreage totals.

Non-Forested Areas (40's, 60's, 90's, '18): For the 40's and 90's, an estimated 60 to 80 percent of existing Non-forested and Riparian Forest/Shrubland polygons were reviewed for accuracy of linework alignment with observed vegetation features and classification of those features. As described below, the amount of review for the 60's map was a bit more variable due to issues with the imagery.

The 40's mapping was difficult to review and edit not only because of the often poor quality of the B&W aerial imagery, but the fact that some of the imagery tiles did not meet up exactly. Also, as noted earlier, it was often difficult to discern which imagery tile had been used for the original mapping effort, which then required rotating through tiles to find the one that provided the best fit. In general, linework for the 40's map was very good, particularly when the right imagery tile was located. Some sloppy linework existed near Palomarin and near Giacomini in southern Tomales Bay, which may have been partly due to use of a different imagery tile for initial mapping. These areas were corrected to the maximum extent practicable.

In general, with the exception of certain areas within the Vision Fire footprint near Limantour Road, linework for the 90's map was good, which is even more impressive given that a different aerial imagery set was used for review than most of the original mapping effort (2004 vs 1994). There was some sloppy linework near Palomarin and near Martinelli Ranch north of Giacomini that was cleaned up. In terms of missing polygons, these occurred mainly on Beaches and Cliffs, particularly near Tomales Point and Palomarin (Table 4). The poor linework in the Vision Fire footprint near Limantour Road affected both forested (Bishop pine) and unforested (Grassland, Open Scrub-Grassland, Dense Coastal Scrub) polygons.

Crosswalking of the 2018 map involved determining the appropriate match between alliances and associations mapped in the original mapping effort and those in the PRNS' vegetation community classifications. Broad community identification was mostly good, however, there were some crosswalking interpretations that required revision (Tables 4-5). For example, the late successional Dune Mat vegetation community, *Eriophyllum staechadifolium* – *Erigeron glaucus* – *Eriogonum latifolium* Alliance, was crosswalked to Open Scrub/Grassland: these areas are mapped in earlier PRNS's maps as Unvegetated Dune, as percent cover is typically very low (<30%). In addition to refining crosswalking classification, polygon assignment was reviewed in specific areas to ensure that mapping approach was compatible with the PRNS's mapping approach. The most significant changes were: 1) many dune polygons mistakenly categorized as Grassland or Dense Coastal Scrub communities; 2) vegetation communities found on cliffs categorized as Grassland instead of Cliffs or Dense Coastal Scrub; 3) channels categorized as Salt Marsh instead of Water, and 4) shrub or forest fragments left as

Unknown/other.

The '18 linework was very good and, in general, required only moderate adjustment. As was noted under forested areas, mapping in 2018 was much more precise and conducted at a finer scale than the earlier mapping periods due to use of automated mapping and much higher image quality. The biggest issue encountered was that the fine-scale mapping approach used by the '18 map tended to split shrub- and grassland-dominated areas into separate polygons in instances where earlier mapping efforts broadly interpreted these mixed grass/interspersed communities as Open Scrub/Grassland. Significant review and editing were performed of Grassland, Open Scrub/Grassland, Active Agriculture, and Dense Coastal Scrub polygons to ensure that classification of these vegetation communities aligned with mapping rules used for other mapping efforts. Also, as discussed under Methods, the '18 map was trimmed around the edges of the Peninsula, but unevenly so. Sections of coast were missing Cliffs, Beach, Water, and forest and shrub communities. These omissions largely occurred on the west side of Tomales Point adjacent to the ocean; in scrub and forested areas on the east side of Tomales Point; and the Cliffs on the southern coastline, near Palomarin. Coincidentally, these are generally the same areas where coastal features had been omitted in earlier mapping efforts, although there was not complete overlap. These areas were not only added into the earlier mapping efforts, but into the '18 crosswalked map, as well.

One other issue with the '18 map involved the occurrence of dozens of linework errors in crosswalked '18 file that were not present in the original '18 mapping file. These were small thin shapes that had been cut out of some of the community polygons, but that were not polygons themselves. They appeared to be artifacts of some GIS process and not a mistake in any actual mapping. They were easy to remove as the map was reviewed. Their removal likely resulted in negligible changes to some of the linework overall, with area of most of these artifacts probably less than 0.1 acre.

The 60's mapping was by far the most challenging to review and revise. Most of this was because it was unclear which imagery was used for some of the mapping in certain areas, particularly for areas not covered by the mosaicked 1965 imagery, even after extensive efforts to rotate through available imagery tiles to find the one used for initial mapping. For this reason, review and editing approaches – and thoroughness -- varied depending on the geographic region.

For areas covered by the mosaics (central and southern portions of the park), review and editing efforts were highly detailed, with an estimated 80% of the non-forested polygons being reviewed. Most of the more minor editing here dealt with converting between Grassland/Open Scrub-Grassland/Dense Coastal Scrub to ensure consistency in classification between all three mapping efforts, as well as double-checking mapping of Riparian Forest/Shrubland (Table 4). The linework in the areas covered by the mosaicked images was generally very good with a few exceptions. Cliff and Beaches were often not mapped between Drakes Estero and Palomarin (Table 4). These were added. A different set of imagery appear to have been used for mapping upland habitats near Palomarin and the southern map boundary, as there was not strong overlap between mapped habitats and habitats in imagery. The overlap of mapping with imagery near Giacomini and southern Tomales Bay was pretty good, but the linework here was not as fine-scale or as detailed and, in some cases, accurate as in others in the central and southern portions of the park. Effort was spent to improve the quality of mapping in these areas.

For areas not covered by the mosaicked images, where there was often moderate to poor overlay, less

fine-scale review and editing was possible. In these areas, effort was spent to try and improve mapping along land boundaries or edges, including adding or splitting out Cliffs and Beaches and trimming land boundaries with Water. As with previous mapping efforts, Cliffs and Beaches were often very under-mapped along the Great Beach, particularly near Tomales Point (Table 4). Also, because of the importance of sensitive vegetation communities such as Freshwater Wetlands, Riparian Forest/Shrubland, Salt Marsh, and Waters (Ponds), some effort was also spent to clean up these areas or add in wetlands that had not been mapped previously, although cleanup was considerably constrained by poor image quality. Much less effort was spent editing boundaries of Grasslands, Open Scrub/Grassland, Dense Coastal Scrub, and Disturbed areas, although they were generally reviewed to ensure that the size of the off-shifted polygons generally looked somewhat congruous with the size of the stand observable on the map. If off-shifted polygons looked like they had been misclassified, those were generally changed, but the poor quality of the 1963 photos made it very difficult to interpret vegetation patterns in general. When in doubt, the polygon was left as is.

Table 5. Time invested into initial review and editing of **Non-Forested and Riparian Forest/Shrubland** areas of historic vegetation GIS mapping layers and number of initial polygons

	40's	60's	90's	'18
Estimated number of hours for INITIAL rounds of review/edits	36	52	70-80	60 ¹
Estimated number of polygons after INITIAL round of review/edits	2,615	3,316	5,295	19,417

¹ An estimated 120 additional hours spent on further mapping revision after initial round.

Below are some additional issues found with all of the mapping layers and the changes made to improve accuracy of these mapping efforts relative to these issues.

Active Agriculture – During review of mapping files, it became apparent that imagery quality, particularly for older B&W imagery, did not allow reviewers to adequately determine whether mowing or other types of active management had, in fact, taken place, particularly when mowing efforts might have been conducted many months previous to when the imagery was flown. Some of the same issues may also occur even with newer, color imagery. For this reason, for reporting and analysis purposes, Active Agriculture was lumped with Grasslands, which includes herbaceous communities with less than 10% shrub cover.

Disturbed – There were not many changes to this category. In general, roads such as Sir Francis Drake or Highway 1 were not initially classified as Disturbed, except for one section of road near Ottinger's Hill. As part of the revision effort, treatment of paved roads was changed for all three earlier mapping periods such that if roads bisected or fragmented an intact stand of habitat, the road was broken out and classified as Disturbed. If the road did not bisect or fragment habitat, it was lumped instead with the adjacent non-sensitive habitat types such as Grassland, Open Scrub/Grassland, or Hardwood Forest. In certain situations, roads bisected wetland swales, particularly on the Point Reyes Peninsula: if the road did not constrict the wetland, and if it represented a small proportion of the overall size of the wetland, it was left as originally mapped. It should be noted that the '18 map classified almost all of the paved roads as Disturbed, so acreages and acreage changes for Disturbed should be interpreted with caution.

Unvegetated Dunes and Vegetated Dunes – The dunefield at PRNS extends some distance inland. There

was some inconsistency amongst all three mapping efforts in how vegetated and unvegetated dunes were characterized. In some areas, stands of bush lupine (*Lupinus arboreus*) and other Dune Scrub species were mapped as Dense Coastal Scrub. To ensure consistency, all areas with >30% vegetation cover that occurred on coastal or inland dune features were mapped as Vegetated Dunes; open, barren sand or Dune Mat areas with ≤ 30% vegetation cover were classified as Unvegetated Dunes. Topographic contours, aerial imagery signatures, and the 2018 map were used to help guide decisions on the furthest inland extent of dune features. In aerial imagery, light-colored sand was often visible within densely vegetated stands that appear to have established on dunes.

Analysis of Changes in Acreage of Historic Vegetation Communities

Current Analysis: Table 6 presents a summary of acreages for all vegetation communities mapped over the four (4) mapping periods (40's, 60's, 90's, '18). Table 7 highlights changes in acreages for selected communities between all four (4) mapping periods based on confidence limits, as described in the Methods section. Figures 6-9 show revised maps for the 40's (Fig. 6), 60's (Fig. 7), 90's (Fig. 8), and '18 (Fig. 9) mapping periods. Figure 10 presents a diagram showing transitions between some of the key vegetation communities between the 40's and '18: forests were condensed into a single category, "Forest," due to varying degrees of type confusion issues between mapping periods.

Based on lifeform, the floristic landscape remained seemingly relatively static between the 40's and the 60's, with the possible exception of a slight increase in Mixed Herbaceous/Shrub communities (12%; Table 8). (Lifeform analysis focused on upland vegetation communities and did not include "margin" habitats such as Salt Marsh, dunes, or Cliffs). Due to higher potential for error for the earlier mapping periods associated with poor image quality and resolution, only 6 of the 12 communities pulled forward for further analysis recorded changes substantive enough between the 40's and 60's to exceed estimated error potential (Table 7). Disturbed areas increased moderately by 205 adjusted (adj.) acres, while Salt Marsh acreage fell by approximately 317 adj. acres (Table 7). Other changes were relatively minor, including slight reductions in Bishop pine, Riparian Forest/Shrubland, and Unvegetated Dunes and a slight increase in Vegetated Dunes (Table 7). Changes in Dense Coastal Scrub, Douglas-fir, Grassland, Hardwood Forest, Open Scrub/Grassland, and Freshwater Wetland were small enough that that they could be accounted for by potential mapping error, which suggests that the spatial extent of these communities remained relatively equivalent between mapping periods (Table 7).

Classification matrix analysis points to Grassland and Dense Coastal Scrub largely persisting intact between the 40's and the 60's (>57%), although a large percentage of Open Scrub/Grassland (50%) converted to Grassland, with 23% remaining as Open Scrub/Grassland and another 18% transitioning to Dense Coastal Scrub (18%; Fig. 10). Approximately 24% of Dense Coastal Scrub in the 40's became Grassland or Open Scrub in the 60's (Fig. 10). Conversely, a modest percentage of Grasslands transitioned into Open Scrub/Grassland (14%) and Dense Coastal Scrub (7%; Fig. 10). Up to 12 percent of Dense Coastal Scrub stands in the 40's was mapped as Native Forest in the 60's. (As noted earlier, forest types were not broken out for presentation of classification matrix results due to potential issues with mis-categorization of Hardwood Forest, Douglas-fir, and Bishop pine for earlier mapping efforts). Conversion of coastal scrub into forest could reflect encroachment of Douglas-fir and Bishop pine into shrub-dominated areas, although potentially a small portion of this change may stem from juvenile Douglas-fir in the 40's being mapped as scrub. Only 3% of Open Scrub/Grasslands showed conversion to Native Forest (Fig. 10).

Table 8. Acreage of Lifeforms in upland areas of PRNS during selected mapping periods. Acreage does not include margin habitats such as Salt Marsh, dune-associated habitats, or Cliffs.

Lifeform	40's	60's	90's	'18
Herbaceous	22,654	23,139	12,731	13,563
Mixed Herbaceous/Shrub	4,858	5,454	10,694	8,240
Shrub	11,475	11,025	10,985	10,561
Native Forest	15,354	14,781	19,277	21,031

By the 90's, changes in vegetation became much more striking (Table 8). Acreage of Herbaceous communities plummeted 45%, while that of Mixed Herbaceous/Shrub associations more than doubled (Table 8). There was a substantial increase in the extent of Native Forest, as well (30%; Table 8). Acreage of shrub-dominated communities declined negligibly (<1%). Reduced potential for error with the 90's mapping resulted in 11 of the 12 communities having changes substantive enough between the 60's and the 90's to exceed estimated error potential (Table 7). The only community that was not formally analyzed was Dense Coastal Scrub (Table 7), which suggests that acreages of this community remained relatively stable within this change analysis period. The largest changes within this analysis period came from dramatic increases in Open Scrub/Grassland (adj. acreage=4,753); Douglas-fir forest (adj. acreage=1,086); Bishop pine forest (adj. acreage=1,290), and Hardwood Forest (adj. acreage=996) and very dramatic decreases in Grassland (adj. acreage=8,917; Table 7). There were also moderate increases in Riparian Forest/Shrubland (adj. acreage=385; Table 7). Disturbed, Salt Marsh, and Vegetated Dune communities recorded modest gains (adj. acreage ranging from 94-148), while Freshwater Wetland and Unvegetated Dunes posted modest losses (adj. acreage ranging from 80 to 131; Table 7).

As might be expected based on these results, classification matrix analyses confirm that most of the loss in Grasslands (37%) came from conversion to Open Scrub/Grassland with a further 11% transitioning into Dense Coastal Scrub (Fig. 10). Very little loss of Grassland resulted from encroachment of Native Forest (<2%). Ironically, a large proportion of Open Scrub/Grassland in the 60's became Grassland in the 90's (26%), so this community did not necessarily remain static during these mapping periods, even if it did increase (Fig. 10). Dense Coastal Scrub in the 60's also transitioned into Open Scrub/Grassland (8%) and, to a lesser extent, Grassland (3%) in the 90's (Fig. 10). In terms of Native Forest expansion, most of the gains came from loss of Dense Coastal Scrub habitat (32%), along with Open Scrub/Grassland (13%; Fig. 10). As noted earlier, some areas with juvenile tree species may have been mapped as Dense Coastal Scrub in the 60's, which may account for at least a small portion of the seeming conversion of scrub into Native Forest.

The degree of change in lifeforms between the 90's and '18 was a bit more muted (Table 8). There were minor increases in Herbaceous (7%) and Native Forest communities (9%) and a noticeable decline in Mixed Herbaceous/Shrub (23%), with no or very little change in shrub-dominated communities (Table 8). However, trajectories for specific vegetation communities showed some striking differences from the previous mapping period. After a substantial increase in Douglas-fir forest between the 60's and the 90's, acreage of Douglas-fir increased only slightly (adj. acreage gain = 123) between the late 90's and '18 (Table 7). Acreage gains of other forest types such as Hardwood Forest and Bishop pine were much higher than Douglas-fir during this period, with adjusted gains totaling 569 and 467 acres, respectively (Table 7). At least a small portion of this change may result more from the much finer-scale mapping

approach taken by the original 2018 mappers (Tukman Geospatial/AIS) than from true shifts in forested communities on the landscape. More splitting was performed initially in mixed forested stands with the '18 map than in earlier versions, although considerable effort was made to break apart lumped Douglas-fir-Hardwood Forest stands for the 90's mapping; to refine mapping of Bishop pine; and to reclassify areas with dead Douglas-fir with the appropriate understory community.

Similarly, while changes in Disturbed acreage was not formally assessed between the 90's and '18 due to differences in mapping approach, raw acreage of Disturbed actually dropped between the 90's and '18 even though more paved roads were mapped as Disturbed in '18, most likely because mapping of Disturbed areas around residential areas, for example, was conducted at a finer scale than in earlier maps (Table 7).

The largest change posted between the 90's and '18 came from dramatic declines in Open Scrub/Grassland (adj. acreage loss=2,158). Conversely, Grassland increased slightly (adj. acreage gain=252; Table 7). There was a very slight increase in Unvegetated Dune acreage (adj. acres=18), as well, that may actually reflect stable conditions within that change analysis period: Acreage of Vegetated Dunes also appeared stable during this period (adj. acres=25; Table 7).

Wetland-related vegetation communities assessed between the '90's and '18 posted modest acreage gains ranging from 185 to 221 adj. acres (Salt Marsh, Riparian Forest/Scrub; Table 7). As was discussed in Table 4, changes between the 90's and '18 for Freshwater Wetlands was not assessed, because crosswalking largely correlated the extent of Freshwater Wetlands with that of the Vancouverian Freshwater Wet Meadow & Marsh Group alliance, which meant representation of Freshwater Wetlands was entirely based on a one-parameter wetland delineation approach based on vegetation. Hydrophytic vegetation can occur, however, in areas that are not true wetlands, particularly in areas that are more mesic due to marine-influenced microclimates. Wetlands mapping for the other mapping periods took this into account and also factored in hydrology and soils factors and used existing field-based wetlands mapping or NWI for mapping of wetlands. While a considerable amount of this wetland over-representation issue for the '18 map was addressed during later editing, full review and editing of Freshwater Wetlands for the entire park could not be completed. Therefore, as these approaches are not comparable, changes in Freshwater Wetland extent were not analyzed for this time period.

Almost two-thirds of the areas mapped as Grassland in the 90's remained Grassland in '18 (Fig. 10). Otherwise, the largest transition to Grassland came from areas mapped as Open Scrub/Grassland (24%) in the 90's (Fig. 10). Similarly, half of areas (50%) mapped Open Scrub/Grassland in '18 was mapped as that community also in the 90's, with additional conversions from Grassland (23%) and Dense Coastal Scrub (10%; Fig. 10). More than two-thirds of Dense Coastal Scrub (67%) also persisted relatively intact between the 90's and '18, with additional acreage coming from Open Scrub/Grassland (16%) and Native Forests (22%) in addition to Grassland communities (4%; Fig. 10). In terms of conversion from non-forested to forested habitats, approximately 18% of Dense Coastal Scrub transitioned to Native Forests (Fig. 10). Transitions to and from forested and Dense Coastal Scrub may have been influenced by misclassification of juvenile Bishop pine, Douglas-fir, and Hardwood Forest species as shrubs in the 90's.

Comparison with Past Analyses: In general, trends documented between the two change analysis periods included in the 2016 preliminary analysis (40's-60's and 60's-90's) at least partially agreed with those documented in the current analysis (Appendix A). Change trajectories for six (6) of the 12

communities (Grassland, Riparian Forest/Shrubland, Salt Marsh, Unvegetated Dunes, and Vegetated Dunes) showed strong agreement with current trajectories. Only two trajectories were markedly different -- Dense Coastal Scrub and Hardwood Forest -- while Douglas-fir, Freshwater Wetlands, Open Scrub/Grassland showed partial agreement, with trends between both 2016 and current analyses similar for the 60's-90's comparison period. As part of map review and process editing, extensive efforts were made to improve consistency of mapping of wetlands between the 40's, 60's, 90's, and, to a lesser extent, '18. The 2016 analysis pointed to Hardwood Forest increasing in the 60's, only to decrease in the 90's, while current analysis suggested stability in Hardwood Forest between the 40's and 60's followed by a sizeable increase in extent during the subsequent mapping period. Based on the 2016 analysis, Douglas-fir acreage dropped moderately in the 60's, only to climb substantially by the 90's. Revised analyses suggest that Douglas-fir extent remained relatively equivalent between the 40's and 60's, although it did increase considerably by the 90's. Lastly, in draft analyses, Dense Coastal Scrub exhibited a minor, but steady, decline in acreage between the 40's and the 90's, whereas the current mapping effort points to no substantive change in scrub extent during that time period.

DISCUSSION

Historical Context in Vegetation Community Change at Point Reyes

Pre-Historic Period: Based on paleoecological studies, Point Reyes' vegetation history appears to have involved a dynamic mosaic of forested, shrubland, and grassland habitats that responded to both long-term climatic and, more recently, fire-related factors. Within much of California, the primary drivers for secondary progressive succession tend to favor grasslands converting to shrublands, which then convert to woodlands or forest (Sandel et al. 2012). However, this successional pathway can be reversed by long-term climatic factors, as paleoecological studies have documented. Many of these studies rely on analyses of pollen within sediments to document trends in vegetation communities and even species over long periods of geologic time. A number of pollen, charcoal, and fire scar (for evaluation of fire frequency), and ethnohistoric studies have been conducted within Point Reyes over the last 50 years (Russell 1983, Rypins et al. 1989, Duncan 1992, Brown et al. 1999, Anderson 2005, Anderson et al. 2013).

Generally, research supports the premise that the distribution of forest, shrubland, and grassland habitats in Point Reyes have shifted over time in response to long-term climatic cycles. In the late Pleistocene area, roughly 14,000 years BP (before present), forests dominated by Douglas-fir and other fir (*Abies*) species dominated on the Point Reyes Peninsula particularly at higher elevation and more inland areas (Rypins et al. 1989, Anderson et al. 2013). At the Coast Trail Pond site, closed conifer forest lasted until ca. 10,500 calendar years ago (Anderson 2005). This has been characterized as a generally cooler time period in which the sea temperature was estimated to be 2- 5 degrees Centigrade lower than the early 2000's (Barron et al. 2003, Anderson 2005). During this time period sea level was ca. 100 m lower in elevation, and further west due to greater amounts of ice in land-based glaciers (Anderson 2005). Paleoclimatic reconstructions (Mock and Bartlein 1995, Bartlein et al. 1998) document greater penetration of Pacific stormtracks to the south during winter as the Jet Stream was diverted to more southerly latitudes by the height of the Laurentide Ice Sheet in the North American interior (Anderson 2005).

During the transition to the early Holocene period (~10,500 years BP), sea levels rose, and ocean and air temperatures became warmer, creating a more arid environment (Barron et al. 2003, Anderson et al. 2005). Climatic conditions within this period may have been more driven by La Niña events with suppression of the El Niño Southern Oscillation (ENSO) and a negative Pacific Decadal Oscillation (PDO) cycle (Barron and Anderson 2011). Summer insolation (amount of solar radiation) may have been higher than today during the early Holocene in the Northern Hemisphere (Bartlein et al. 1998, Anderson 2005). These factors may have intensified Mediterranean conditions along the California coast and inland, with lowered groundwater tables and drying of perennial wetlands (Anderson 2005). Within Point Reyes, forests transitioned to drier communities such as coastal scrub and grassland (Rypins et al. 1989, Anderson 2005). Regionally, pines (*Pinus* spp.) became more important during this period (Barron et al. 2003). Vegetation near Coast Trail Pond appears to have become an open hardwood forest with a large sage scrub component, probably dominated by California sagebrush (Anderson 2005). Some perennially flooded wetlands became either seasonal or even, in the case of one near Creamery Bay, a dry grassland with ferns (Anderson 2005).

By the middle of the Holocene Period (~ 5,000 years BP), a cooler climatic regime re-emerged, fueled

potentially by emergence of a more modern-like ENSO Pacific Ocean (Barron and Johnson 2011). This shift was accompanied by establishment of more mesic vegetation such as the Douglas-fir-mixed conifer-hardwood forests still present in Point Reyes today (Anderson et al. 2013). In addition to these tree species, the abundance of riparian ones such as alder (and hazelnut (*Corylus*) increased, as well (Anderson 2005). Forest gaps were dominated by coastal scrub species such as coyotebrush and California sagebrush. Many of the perennial wetland features once present returned, as groundwater levels rose (Anderson 2005). Around 2,200 years BP, coast redwood and tanoak (*Notholithocarpus*) also expanded into Point Reyes, particularly near Wildcat Lake, Glenmire, and even Coast Trail Pond (Anderson 2005). These vegetation changes are consistent with the trend toward increasing moisture – and perhaps fog precipitation – that would have particularly favored coast redwood and Douglas fir at the expense of pines (Anderson et al. 2013). This transition was accompanied by a more variable, more El Niño-like, and more positive PDO Pacific Ocean during the later Holocene period (Barron and Anderson 2011).

The role of fire in shaping vegetation communities at Point Reyes has intensified in more recent geologic times. Charcoal influx in sediment layers predating 4,000 years BP was minimal. Non-human ignition of wildfires in coastal California environments is believed to be infrequent, with lightning strike frequency estimated currently at approximately 4 strikes per century near Santa Cruz (Striplen 2014) or 3/100km²/year on the central coast (van Wagtendonk and Cayan 2008). Not surprisingly, climatic variation influences wildfire frequency, with more frequent fires occurring in some portions of California at the end of wetter and beginning of drier periods (Mensing et al. 1999, Cowart and Byrne 2013).

Between 4,000 and 2,200 years BP, small amounts of charcoal started to be deposited consistently in sediments, with a higher influx after 2,540 years BP (Anderson et al. 2013). Increasing charcoal deposition during this time may be indicative of the use of fire by the prehistoric communities related to the Coast Miwok, which populated the area during this period (Anderson et al. 2013). Native peoples in California actively used burning to manage vegetation communities (Keeley 2005, Lorimer et al. 2009, Anderson et al. 2013), with Coastal Miwok believed to burn coastal prairie, scrub, foothill woodland, grassland, and coast redwood vegetation to promote abundance of certain species for harvesting (Duncan 1992, Stephens and Fry 2005). The ratio of grass and shrub pollen in sediments at Wildcat Lake varied considerably during the past 1,000 years, although starting around 1850, the grass to shrub pollen ratio climbs, probably due to introduction of livestock grazing (Russell 1983). Charcoal influx increased substantially in the period between 2,200 and 1,000 years BP, when Douglas-fir, coast redwood, and tanoak reached their maximum expansion: This is ascribed to more intense management by native peoples as well as to a more fire-prone forested environment (Anderson et al. 2013). In fact, at Glenmire, six temporal spikes in charcoal influx within this period strongly overlapped with either increases in pollen of either coast redwood or Douglas-fir (Anderson et al. 2013). Moreover, a significant decline by almost an order of magnitude in charcoal deposition around 1,000 years BP coincided with a decline in Douglas-fir pollen (Anderson et al. 2013). Anderson and his colleagues argue that the pollen and charcoal stratigraphies at Glenmire suggest a tight coupling of fire history and vegetation changes (Anderson et al. 2013), which is likely superimposed on a broader scale of vegetation changes associated with long-term climatic cycles.

Historic Period: Some earlier studies have argued that forests at Point Reyes were limited even before the mid-1800's. In a study on fire frequency during the historical period, Brown et al. (1999) points to several historical records as evidence that grassland was much greater in extent than forests even prior

to the 19th century. These include quotations taken from a historical study by Duncan (1992) that described "places of sierra [hills] bare to the sea" (Vizcaíno 1602) and later noted that "the verdure of the plain continued to a considerable height up the sides of the hills, the summits of which ... one could see produced a few trees" (Vancouver 1792 *in* Brown et al. 1999). Ironically, the full quote from Vizcaíno paints a somewhat different picture: "places of sierra (hills) bare to sea and of medium height with some cliffs, but soon the country left on shore becomes massive and wooded until you reach low land at 37½ degrees" (Aker 1965 *in* Duncan 1992). Meanwhile, the full quote from Vancouver clarifies that rocky outcrops near the coast supported a few trees, as the Inverness Ridge would not be within "musket shot" of the shore: "...the summits of which, though chiefly composed of rugged rocks within a musket shot of the land, one could see it produced a few trees" (Wilbur 1953 *in* Duncan 1992). Ultimately, by the time of Euro-American contact and early settlement, Point Reyes probably represented a mix of forested ridges and grassy coastal marine terraces separated potentially by shrublands that were more common at lower elevations of the flanks of the Inverness Ridge.

Intensification of anthropogenic influences associated with accelerated Euro-American settlement in the 1800's would greatly alter this already altered floristic landscape. Livestock grazing controlled shrub species that would have otherwise colonized grassland, thus preventing succession from taking place (McBride and Heady 1968, Duncan 1992, Keely 2005). While agricultural development on the Peninsula expanded in the 1800's, livestock grazing was already impacting portions of the Marin landscape in the late 1700's where missions and, later, ranchos were established, including the present-day Hog's Island (Menziés 1793 *in* Duncan 1992). Duncan (1992) quotes Von Kotzebue (1821) commenting even in 1785 on the over-proliferation of livestock grazing causing "the need for slaughter and the obvious compaction of the soil around settlements." Following the introduction of livestock grazing, non-native species began to appear in the pollen record between 1840 and 1860, although this was later than in other areas of California (Anderson et al. 2013). The use of fire by Coast Miwok to manage vegetation decreased dramatically due to missionization of native peoples and efforts by the Spanish authorities to suppress fires and thereby "uproot this very harmful practice of setting fire to pasture lands" (Clar 1959).

Simultaneous with this increase in non-native species' pollen came a steep decline in conifer pollen, particularly Douglas-fir and coast redwood (Anderson et al. 2013). At the time of Euro-American expansion, abundant forests of these trees plus Bishop pine and others covered much of the east slope of the Peninsula (Livingston 1994 *in* Anderson et al. 2013). The pollen record at Glenmire and other sites in Point Reyes supports the historical accounts, recording the existence of both conifer and deciduous woodland until 1850, when the decline of all tree taxa begins (Anderson 2005, Anderson et al. 2013). In addition, a number of sites suffered a decline in coastal scrub and chaparral species, as well (Anderson 2005).

While Spanish settlers discouraged prescribed burning by native peoples, fire frequency between the early 1800's and early 1900's on the Peninsula and adjacent inland Marin areas actually increased, approximating that estimated for the pre-Euro-American settlement (Finney 1990 *in* Anderson et al. 2013; Brown et al. 1999). Based on charcoal and fire scar data, Mean Fire Intervals (MFIs) for all stands in Point Reyes from the early 1800s to approximately 1900 was 7.7–8.5 years (Brown et al. 1999, Anderson et al. 2013), which is characteristic of a pre-Spanish settlement surface fire regime on the Peninsula (Anderson et al. 2013). Livingston (1994, 1995 *in* Brown et al. 1999) suggested that clearing of brush from grasslands was a frequent occupation of the early ranchers and dairy farmers on the

Peninsula, and some of that may have been accomplished by burning (Brown et al. 1999). A compounding factor in the loss of trees was the introduction of extensive logging also in the mid-19th century (Anderson et al. 2013). Early efforts apparently focused more on harvesting of oaks, but later switched to conifers such as Douglas-fir and coast redwood (Anderson et al. 2013).

Based on historical accounts, early hand-drawn maps, and paleoecological studies, grasslands expanded considerably under this expansive agricultural management regime, while forests dwindled dramatically, with remnant stands possibly restricted to the top of the Inverness Ridge (Russell 1983, Duncan 1992, Brown et al. 1999, Anderson et al. 2013). Perhaps, the most vivid picture of the dramatic impacts of these activities on the historic Point Reyes vegetation landscape comes from some of earlier mapping efforts of the Punta de los Reyes Rancho dating from 1854, which depicts a fairly open landscape for the peninsula with a few tree stands remaining along the coastal mountain range (Anderson et al. 2013).

Recent Trends in Vegetation Change

The pollen record analyses performed by Anderson and other researchers point to gradual recovery in forest species such as Douglas-fir and Bishop pine at least at some sites such as Glenmire in recent decades, although coast redwood has largely not re-established on the Point Reyes Peninsula (Anderson 2005, Anderson et al. 2013). With the advent of aerial photography starting in the 1940's, most analyses of vegetation change reverted to more detailed inventories of communities present at certain periods. Differentiation of communities in historical time periods is limited typically by the poor image quality and resolution of B&W aerial imagery available for the 1940's-1960's, which strongly dictates the degree to which certain types of communities or species can be accurately discerned (Lydersen and Collins 2018). Introduction of color aerial imagery in the 1970's boosted imagery-based historic vegetation mapping efforts, although they continued to be hindered by low-resolution. Vegetation change analyses definitely benefitted from the initiation of large-scale vegetation mapping efforts in GIS starting in the 1990's. Point Reyes and portions of Golden Gate, in fact, were among the pilot parks in California for the first large-scale vegetation mapping effort that was a collaboration between the NPS, CDFW, and AIS.

Recent vegetation change analyses in California, particularly central California, have often focused on encroachment by trees into grasslands and shrublands or encroachment of shrubs into grasslands (Biswell 1954, McBride and Heady 1968, McBride 1974, Williams et al. 1987, Dunne and Parker 1999, Russell and McBride 2003, Keeley 2005, Kennedy and Sousa 2006, Zavaleta and Kettley 2006, Hsu et al. 2011, Startin 2022). Shrub encroachment has been one of the major land cover changes in the last century worldwide (Eldridge et al. 2011), although in northern portions of central California, concerns have also been raised about expansion of conifers, specifically Douglas-fir, into shrublands as well as grasslands (Dunne and Parker 1999, Kennedy and Sousa 2006, Hsu et al. 2011, Startin 2022). In addition, Douglas-fir has been documented encroaching into forested habitats such as oak woodlands (Engber et al. 2011, Cocking et al. 2012, Cocking et al. 2014). There have also been reported incursions of hardwood species such as California bay into grasslands and brushlands in the Berkeley Hills and Santa Cruz Mountains (McBride 1969, Unsicker 1974 *in* USDA n.d.). Between 1985 and 2010, approximately 19% of the vegetation along the central California coast converted from one vegetation type to another, with greater type-conversion north of the San Francisco Bay than in the south (Hsu et al. 2011). Forests and shrublands have generally expanded, with forest expansion generally highest and often at the expense of shrublands (Hsu et al. 2011).

A number of vegetation change analysis studies have incorporated sites or areas at Point Reyes or inland portions of Marin (Dunne and Parker 1999, Russell and McBride 2003, Kennedy and Sousa 2006, Hsu et al. 2011, Startin 2022). These studies generally detected somewhat similar patterns of vegetation change in Marin as for other central California areas. For example, detailed analysis of aerial imagery dated between 1985 and 2010 found that herbaceous plant communities and shrubland on the Bolinas Ridge in Marin County shrunk by 62% and 51%, respectively, while forests increased by 307% (Startin 2022). An earlier study that had a Bolinas Ridge site documented similar trends between 1939 and 1997 with shrub and grassland cover decreasing while that of Douglas-fir increased significantly and mixed-evergreen and Hardwood Forest remained stable (Russell and McBride 1983). Interestingly, this study also included a site in Point Reyes, which they characterized as exhibiting “limited variation within the time period of this study,” although a slight decline in cover of grassland and mixed evergreen forest was discernible (Russell and McBride 1983). This study did not disclose where the Point Reyes site was located, but the fact that oak woodland and savanna increased somewhat as did the cover of “Monterey pine” suggests that it might have been either in Olema or Bear Valley areas, as oaks are less common in other areas of the park. The results of this study, at least for the Point Reyes site, may not be reflective of changes for the Peninsula as a whole.

Interestingly, temporal trends documented in our study differed somewhat from those in these other studies, although the overall trajectory over time appeared similar. While the floristic landscape remained relatively static between the 40’s and 60’s, with the exception of a 12% increase in Mixed Herbaceous/Shrub habitats, dramatic and often seemingly contradictory changes in vegetation occurred between the 60’s and ’18. (As noted earlier, acreage for lifeforms was only calculated for upland habitats, not “margin” ones such as Salt Marsh, dune, and Cliffs). Taken from the perspective of the entire study period (40’s – ’18), acreage of Herbaceous communities fell 40%, while Mixed Herbaceous/Shrub and Native Forests climbed 70% and 37%, respectively. Shrub-dominated habitats dropped by 8%. It should be noted that other studies did not incorporate change in mixed shrub-herbaceous communities.

While the 40’s – 60’s were relatively quiescent in terms of floristic change, the 90’s were marked by a dramatic decline in acreage of Grasslands (8,917 adj. acres) and a substantial increase in acreage of Open Scrub/Grassland (4,753 adj. acres; Table 7). A large percentage of Grasslands in the 60’s transitioned into Open Scrub/Grasslands (37%), and, to a much lesser extent, into Dense Coastal Scrub by the 90’s (11%; Fig. 10), although acreage of Dense Coastal Scrub showed no apparent change (Table 7). A reduction in intensity of active management of Point Reyes lands since establishment of the National Seashore in 1962 may have potentially prompted some of this conversion of Grassland to more shrubby landscapes. In the mid- to late 1900’s, the ratio of dairy to beef cattle ranching started to drop, with the latter typically involving lower cattle densities and a more passive form of land management (NPS 2020). Interestingly, some of these trends appeared to reverse somewhat by ’18, with Open Scrub/Grassland acreage dropping substantially (2,158 adj. acres) and Grassland increasing somewhat (225 adj. acres; Table 7). Acreage of Dense Coastal Scrub fell slightly (99 adj. acres; Table 7).

Based on secondary progressive succession, it might be expected that Grasslands would transition to Open Scrub/Grasslands areas, which would eventually convert to Dense Coastal Scrub, particularly in areas where cattle grazing or land disturbance had been eliminated. Classification matrix analyses point to a varied degree of conversion Grassland to Open Scrub/Grassland over the mapping periods, ranging from 14% (60’s) to 37% (90’s; Fig. 10). Open Scrub/Grassland represented the highest contributor in

terms of acreage to Dense Coastal Scrub (16-27%), followed to a much lesser extent by Grassland (4-11%; Fig. 10). Retrogressive succession was also evident. Open Scrub/Grassland seemingly reverted back to Grassland in quite a few instances, with conversion rates ranging from 24% ('18) to 50% (60's; Fig. 10). To a much lesser degree, Dense Coastal Scrub also transitioned into both Open Scrub/Grassland (8-11%) and Grassland (2-13%; Fig. 10). Retrogressive succession most likely resulted from changes in anthropogenic management, although climatic factors may influence these floristic transitions.

In terms of conversion of non-forested habitats into forested ones, Dense Coastal Scrub appeared more likely to transition into forested types (12-32%) than either herbaceous or mixed herbaceous-shrub communities (Fig. 10). As noted in Results, some of these changes may result from juvenile trees in earlier mapping periods being classified as Dense Coastal Scrub, but especially in later mapping periods, most of these changes probably represent true conversions. Open Scrub/Grassland also converted into forest, but at much lower rates (3-13%; Fig. 10). Direct conversions of Grassland into forested types were almost non-existent, except in the 90's (2%; Fig. 10).

A reduction in active management between the 60's and the 90's may have also fostered expansion of Douglas-fir and Hardwood Forests. Both Douglas-fir and Hardwood Forest communities remained relatively stable between the 40's and 60's, but increased considerably by the 90's, climbing by 1,086 and 996 adj. acres, respectively. Following the 60's, Douglas-fir re-established at Firtop where large swaths had been removed between the 40's and 60's and continued to expand into grassland and scrub areas along the coast (Murphy 2022). Type confusions with Hardwood Forest and with Dense Coastal Scrub (e.g., juvenile Douglas-fir trees) may have inflated Douglas-fir gains by the 90's (Murphy 2022), although this issue should have been substantially rectified by editing efforts undertaken as part of this project. Both Douglas-fir (123 adj. acres) and Hardwood forests (569 adj. acres) continued to expand between the 90's and '18, albeit at a much slower rate (Table 7). It is possible that a small portion of the Hardwood Forest change resulted from finer-scale mapping of mixed forest stands in '18, although forest layers for both the 90's and '18 appeared to be very accurate based on external (e.g., Tukman Geospatial) and internal review, particularly after editing.

Bishop pine showed a relatively small decrease in acreage between the 40's and 60's (87 adj. acres; Table 7). In west Marin, large-scale harvesting of trees for lumber ceased in the early 20th century (Forrestel et al. 2015), so loss of Bishop pine between the 40's and 60's may have resulted from individualized clearing – clearing of late successional stands was evident along Pierce Point Road in the 60's (Murphy 2022) – and, to a lesser extent, from over-mapping in the 40's (Murphy 2022), although efforts were made to correct the latter issue during the map editing process. The 1995 Vision Fire fueled a large-scale expansion of Bishop pine on the Inverness Ridge, particularly in areas west of Limantour Road that appeared previously to be a mix of grasslands and coastal scrub, as evidenced by a net gain of 1,290 adj. acres by the late 90's. Bishop pine forests continued to expand in the next 20 years, albeit more slowly (467 adj. acres), even after introduction of Pitch Pine Canker Disease (PPCD; Table 7).

These results contrast somewhat with that of a GGNPC Lifeform analysis of vegetation communities on the Point Reyes Peninsula performed in 2022 using the original 1994 PRNS map developed prior to the Vision Fire and the un-crosswalked 2018 map, which showed coniferous forest acreage climbing slightly (2%) between these mapping periods, while acreage of Hardwood Forest jumped 64% (Tukman Geospatial 2023). The original 1994 map would reflect the reduced extent of Bishop pine forests that existed prior to the Vision Fire, as well as the expansion of Douglas-fir communities potentially

associated with reductions in the intensity of active management following purchase by the federal government. By 2018, acreage of Bishop pine forests had continued to increase with maturation of stands established post-Vision Fire, while growth of Douglas-fir communities slowed due, in part, to the fire destroying or damaging fir stands, many of which did not successfully regenerate post-fire. These conflicting trajectories appear to have offset each other, leading to only a small increase in coniferous forest. Meanwhile, this analysis pointed to a 16% increase in shrub and a very small decrease (2%) in upland herbaceous communities: mixed Open Scrub/Grassland was not differentiated in this analysis (Tukman Geospatial 2023). As this analysis used the original 1994 files, it is possible that results incorporate some level of type confusion between Douglas-fir and Hardwood Forest trees and between juvenile trees and shrubs. As noted earlier, extensive editing was performed on the revised late 90's map to better break apart mixed Douglas-fir-Hardwood Forest stands and to improve accuracy of identification between forest and shrub communities and types.

Based on both our and GGNPC's results, acreage gains by Hardwood Forest have outpaced that of Douglas-fir within the past 20- to 25 years. The potential expansion of Hardwood Forest over the last two decades is noteworthy, because these forests, along with coniferous forests, have been devastated by Sudden Oak Death (SOD; *Phytophthora ramorum*). SOD, a water mold which produces spores in humid and moist environments, was first documented in California and Oregon in the late 90's (Rizzo and Garbelotto 2003) and in Point Reyes in 2004 (Forrestel et al. 2015). By 2007, almost 40% of forested areas sampled showed evidence of SOD, particularly near the Bear Valley/Limantour, Five Brooks, and Bolinas Ridge areas (Moritz et al. 2011). Coast redwood forests were hardest hit (63%), followed by California bay-coast live oak woodland (*Quercus agrifolia*; 45%), and Douglas-fir (24%; Moritz et al. 2008). All three forest types incorporate some element of tanoak, which appears to be one of the most susceptible species along with coast live oak and other members of the black oak (e.g., *Quercus kelloggii*) group, as they are not only hosts, but can also be killed by lethal bole cankers (Moritz et al. 2008, Forrestel et al. 2015). California bay, one of the major components of Point Reyes' Hardwood Forests, does not die from SOD, but it does experience foliar infections and supports a higher level of infection than any other known host, including tanoak (Davidson et al. 2008). As such, California bay has been implicated as one of the major drivers of tanoak mortality, at least in certain habitat types such as coast redwood and mixed evergreen forests (Davis et al. 2010, Cobb et al. 2010, Ramage et al. 2011).

The fact that Hardwood and, to a lesser extent, Douglas-fir Forests expanded even after introduction of SOD perhaps points to this disease currently having more effect on understory and overstory structure, habitat quality, and fuel loading, at least at Point Reyes, than on overall forest habitat distribution. Preliminary findings of several studies pointed to dead tanoak being primarily replaced by California bay in Douglas-fir (Moritz et al. 2008) and coast redwood in coast redwood forests (sensu Kohyama 1993 in Cobb et al. 2010). A study from the Santa Cruz mountains found that California bay had a higher tendency to spread to other communities than species from those other communities to invade California bay-dominated woodland (Unsicker 1974 in USDA n.d.). In this instance, then, competition between canopy species is potentially being driven by differences in disease transmission, as well as disease susceptibility, as Douglas-fir and coast redwood are both considered to have low susceptibility and transmission rates (Cobb et al. 2010) unlike California bay. These disease-related dynamics could ultimately influence distribution of forest types in areas such as Point Reyes. Once established, California bay may be able to gain some competitive advantage over Douglas-fir on xeric sites or in periods of drought. In general, hardwood species are considered to more tolerant of establishing on xeric sites or

during drought periods than Douglas-fir, which exhibits reduced tree size and higher mortality even after the seedling stage in drier conditions (Tesch et al. 1992). California bay's competitive abilities appear to be enhanced by allelopathic qualities associated with secondary metabolites called monoterpenes – which give this species its characteristic odor – that may act to reduce vegetation growth under bay canopies and insect herbivory (Adornato et al. 2020).

Only a year after SOD was first detected (2006), PPCD was first detected on Bishop pine in Point Reyes (Harvey and Agne 2021). PPCD is caused by the fungal pathogen, *Fusarium circinatum*, which affects multiple host trees in the genus *Pinus* and has been most well-documented on Monterey and Bishop pine populations near the California coast (Storer et al. 1997). Localized infections, often aided by wounds caused by penetration of tree bark from native beetles (Storer et al. 2004), result in cankers, which then girdle conductive tissue and lead to branch or crown dieback (Storer et al. 1997). Ten years after introduction, incidence and severity were 95% and 79%, respectively, in low-density Bishop pine stands and 47% and 23%, respectively, in high-density stands at Point Reyes (Gordon 2017 in Harvey and Agne 2021). Monitoring conducted in 2021 on these plots found that, within mid-seral stands that largely established around the time of the 1995 Vision Fire, nearly all trees had some symptoms of PPCD infection, though resultant visible crown dieback was lower and ranged from 1% to 34% on average across trees (Harvey et al. 2022). Within old-growth stands, many of which occur on or near Tomales Point, visible crown dieback due to PPCD was lower than in mid-seral stands, ranging from 2% to 10% (Harvey et al. 2022). Based on this data, Harvey et al. (2022) concluded that PPCD is continuing to impact Bishop pine forest, but is unlikely to result in loss of local populations in the near term, as changes to stand structure are not widely outside the range of variability for this ecosystem across seral stages (Harvey et al. 2022).

Researchers have speculated that recent increases in acreage of forests have come from suppression of wildfires (Dunne and Parker 1999, Brown et al. 1999, Russell and McBride 2003). With establishment of state programs in the early to mid-1900's to suppress fires, the MFI during the last half of the 20th century became an order of magnitude longer than those estimated for the 1800's (Anderson et al. 2013). Between 1917 and 2020, return intervals climbed to approximately 37.6 years, more than three times the MFI estimated for the 1800's (7.7- 8.5; Brown et al. 1999, Anderson et al. 2013, Dawson 2021). Douglas-fir, in particular, is believed to have prospered from wildfire suppression, as early studies characterized it as fire-intolerant (Agee and Huff 1980 in Gallagher et al. 2021, Ryan et al. 1988, Keane et al. 1990). This assumption has since shifted somewhat in recent decades, as research now points to Douglas-fir showing an intermediate level of tolerance for wildfires, particularly in montane areas, with response seemingly influenced by fire severity (Lazzeri-Aerts and Russell 2014, Mooney and Dawson 2016, Welch et al. 2016, Coppoletta et al. 2020, UCANR 2022). Several studies released in the last 10 years that evaluated species regeneration post-wildfire over broad geographic scales (e.g., North American Mediterranean climate zone) have found Douglas-fir to be among the most abundant regenerating species, with regeneration particularly favored under light- to moderate-intensity fires (Welch et al. 2016, Hankin et al. 2019, Povak et al. 2020).

In the coastal ranges of California, Douglas-fir tends to be less of an early seral species than in other areas such that other species tend to colonize first (A. Forrestel, NPS, *pers. comm.*). Following the 1995 Vision Fire, the spatial extent of Douglas-fir shrunk by 46% -- perhaps because more area burned at a higher severity -- while that of Hardwood Forest increased by 13% (Forrestel et al. 2011). While conifers such as Douglas-fir and Bishop pine rely strictly on seedling establishment following fires, hardwoods

such as California bay utilize both seedling regeneration and basal resprouting to recover, with basal resprouting perhaps more important (Lazzi-Aerts and Russell 2014). Too little time has elapsed to determine vegetation trends following the 2020 Woodward Fire at Point Reyes, but some regeneration of Douglas-fir through seedling establishment is evident in Douglas-fir, some Hardwood Forest, and a few Bishop pine plots within the Woodward Fire area (Parsons et al. 2023). Fewer acres of Hardwood Forest burned during this fire, but both basal resprouting and seedling regeneration of California bay was evident in hardwood stands where it did occur (Parsons et al. 2023). Ultimately, Douglas-fir – and perhaps, to a lesser extent, California bay -- may possess a competitive advantage by exhibiting an extremely adaptable or plastic response to fire – regenerating following both less severe wildfires and also during periods of no fire by infilling underneath the canopy of other tree species (Douglas-fir; Welch et al. 2016) or when understory vegetation such as tanoak is impacted by SOD (California bay).

Effects of fire suppression on forests has been compounded in Point Reyes by introduction of diseases such as SOD and PPCD. Both diseases are likely to increase susceptibility and change response of these forest communities to wildfire by increasing fuel loads (Forrestel et al. 2015, Harvey et al. 2021). Monitoring on forests in Point Reyes affected by SOD documented increases in fuel loads over time, with a strong association between dead tankoak basal area and surface fuels (Forrestel et al. 2015). Fire behavior modeling pointed to the potential for longer flame lengths, higher rates of spread, and more intense surface fire in diseased stands (Forrestel et al. 2015). In addition to creating more fire risk and challenges for firefighters, these fuel-related changes could also result in undesirable ecological impacts associated with more intense fires such as reduced diversity of below-ground communities, changes to soil or increased erosion, decreased plant regeneration, shifts in plant species composition, and negative impacts on wildlife species such as the northern spotted owl (*Strix occidentalis* ssp. *caurina*; Forrestel et al. 2015). While similar research has yet to be conducted on PPCD (Harvey et al. 2021), monitoring in 2021 showed that greater severity of PPCD was on average associated with greater coarse surface fuel loads (Harvey et al. 2022). The most recent disease threat to vegetation communities comes from soil-borne *Phytophthora* species such as *Phytophthora cinnamoni*, which may have even more devastating effects on the Bay Area floristic landscape and fuel loading (Lee et al. 2020).

Considerable attention has been paid to loss of wetlands in the San Francisco Bay area and the nation as a whole. Developed lands in California increased by 37.6% over a 30-year period ending in 2000 (Sleeter et al. 2011). In California, more than 91 percent or 4.6 million acres of wetlands have been lost to development, and estimates for coastal wetland loss are as high as 95 percent (Dahl 1990, NPS 2006). Point Reyes' unique geology has contributed to an abundance and diversity of wetlands within this landscape (NPS 2006). Subsidence and uplift along the San Andreas Fault that borders the Peninsula's eastern edge have created a mosaic of topographic landforms that promotes wetland establishment, including steep ravines, depressional "sag" ponds along the fault, broad floodplains, lagoons, and even isolated lakes (NPS 2006). Unlike the more urbanized San Francisco Bay areas, however, wetland loss has generally been minimized due to the lack of extensive commercial and residential development and eventual protection as a national seashore.

As with many other areas along the outer California coastline, salt marshes are less extensive in Point Reyes due to the generally rugged coastline that constrains their formation, however, they are present in some of the sheltered estuarine areas. Unlike trends in San Francisco Bay, where salt marsh losses mounted exponentially in the late 1800's, vegetated salt marsh within Tomales Bay and probably other estuarine areas in Point Reyes actually increased during this period largely because sedimentation rates

within creeks rose dramatically, resulting in so-called progradation – or bayward extension -- of estuarine deltas (NPS 2006). This increase in sedimentation probably resulted from an increase in logging and other agriculturally related changes in land use practices (PWA et al. 1993, Niemi and Hall 1996) and was undoubtedly exacerbated by the geologic instability characteristic of this region (NPS 2006).

Some of the historic and new salt marshes within Point Reyes and Tomales Bay watershed were lost between the 1890's and the 1940's due to diking for construction of roads (e.g., Levee Road), railroads (e.g., along east side of Tomales Bay), ranches (e.g., Giacomini Ranch near Point Reyes Station), and livestock watering ponds (e.g., Muddy Hollow Pond; NPS 2006). This is evident by the fact that at least 317 adj. acres of Salt Marsh were lost between the 40's and the 60's. As creation of the Giacomini Dairy Ranch involved diking of more than 550 acres, the number obviously would have been even higher if losses weren't offset by deltaic progradation in other Point Reyes' estuaries. After the 60's and formation of the national seashore, diking and conversion of salt marshes slowed considerably in Point Reyes, leading to a net increase (123 adj. acres) by the late 90's. Since the 2000's, a number of former tidal wetland systems within the park have been restored, which is reflected an additional gain of 185 adj. acres of salt marsh between the 90's and '18. While the Giacomini Wetland Restoration Project restored more than 613 acres through reintroduction of tidal action and other activities, some of these areas became brackish tidal wetlands – which are mapped as Freshwater Wetland – once levees were removed.

Freshwater Wetlands have also suffered losses nationwide. While Point Reyes is a coastal park, surrounded by ocean or bay on almost three sides, its geology has fostered a diversity of freshwater wetlands, as well. Abundant groundwater seeps and springs serve as “headwaters” for many of the bay's perennial and seasonal streams and marshes, as well as hydrologic sources for “sag ponds,” seep wetlands, and freshwater marshes (NPS 2006). Many of these seep-fed or seasonally flooded or saturated features are very difficult to discern on aerial imagery, particularly in B&W aerial imagery. Therefore, accurate mapping of freshwater wetlands proved challenging. Potential mapping error constrained analyses of trends in Freshwater Wetlands between the 40's and the 60's. However, acreage did appear to drop by the late 90's (169 adj. acres). As considerable effort was invested as part of this project to make mapping of Freshwater Wetlands consistent between mapping periods and to conservatively estimate change, this loss would appear to be a true change and not one largely attributable to differences in mapping approach, although the degree of actual loss may be influenced by mapping differences. One possible factor accounting for this loss is conversion of Freshwater Wetlands into Riparian Forest/Shrubland (adj net gain=383 acres). With a reduction in agricultural management intensity, Freshwater Wetland areas that had been mowed or cleared or intensively grazed in previous years may have transformed back into Riparian Forest/Shrubland.

Between the 90's and '18, adjusted acreage of Riparian Forest/Shrubland (224) continued to moderately increase, with large gains in northern portions of the Olema Valley such as the Olema Flats due to cessation of grazing and management. As was noted in Results, changes in Freshwater Wetlands during this change analysis period could not be reliably analyzed, because the crosswalk relied exclusively on extent of a particular vegetation group or alliance, whereas mapping for the earlier periods pulled in information from existing wetlands maps (e.g., PRNS field-based wetlands map; NWI) and factored in hydrology and soils, as well as vegetation, to determine historical extent of wetlands.

Another habitat that has been greatly impacted across the U.S. coastline is coastal dunes. Residential and commercial development plays a substantial role in loss of dunes, but even undeveloped dunes have been heavily impacted by deliberate planting or accidental introduction and spread of non-native invasive plant species such as European beachgrass (*Ammophila arenaria*) and iceplant (*Carpobrotus* spp.). By the late 90's, almost 60% of the park's 2,500 acres of coastal bluff, dune, and scrub habitats had been over by these two highly invasive species (NPS 2009), which were believed to have been planted for dune stabilization to protect adjacent ranches and roads sometime in the early to mid-1900's (NPS 2015). Both beachgrass and iceplant can spread relatively quickly, eventually establishing dense monocultures that oust native dune species (NPS 2015). This change is reflected in the conversion over the mapping period of Unvegetated Dunes or dunes supporting native Dune Mat habitat (cumulative loss of 168 total adj. acres), which characteristically is sparsely vegetated ($\leq 30\%$ cover), to Vegetated Dunes (cumulative gain of 412 total adj. acres), largely dominated by either European beachgrass, iceplant, or, in some cases, native Dune Scrub. Native Dune Scrub is a more densely vegetated coastal habitat dominated by a mix of shrub species, including ones associated with dunes such as chamisso lupine (*Lupinus chamissonis*), mock heather (*Ericameria ericoides*), and lizardtail (*Eriophyllum staechadifolium*) as well as more floristically ubiquitous species such as coyotebrush and bush lupine.

As is evident from the acreages, gains in Vegetated Dunes do not seemingly just arise from spread of non-natives into Unvegetated Dunes, as gains in the former are more than double the losses of the latter. Some of the gain, then, may come from misclassification of Vegetated Dunes into Dense Coastal Scrub or even Grassland, as the primary distinction between these communities is whether they occur on sandy dune soils or within dune fields, which must be distinguished visually by mappers on the aerial imagery. In addition, dune fields have not been static over this period. While European beachgrass and iceplant were planted to stop movement of the dunes, the dunes have continued to migrate inland into adjacent Grasslands and Open Scrub/Grassland over the past 60- 70 years despite rapid spread of these species (Johnson 2013). Dune expansion rates during the period 1943-2007 have varied from 16% at G Ranch to 59% at AT&T, with B Ranch estimated at 27%, resulting in average annual dune expansion rates during this period of 0.25% to 0.91% (Johnson 2013). Analysis of historical aerial imagery at 20-year intervals between 1943 and 2007 suggests that this expansion occurred fairly continuously over approximately 65 years rather than in disjunct stages (Johnson 2013). Many of these inland dune features have been colonized by Dune Scrub vegetation, particularly bush lupine, or even by European beachgrass and iceplant.

Some of the losses in Unvegetated Dunes have been countered since the early 2000's by localized dune restoration efforts, particularly at Abbotts Lagoon, where beachgrass was mechanically removed in 2011 (NPS 2015), which may explain why acreage of Unvegetated Dunes increased slightly by 17 adj. acres in 2018. While more than 271 net acres have been restored over the past two decades, some of the more recently restored areas still have not fully transitioned to native dune habitats, partly due to issues with substantially delayed decomposition of standing dead European beachgrass and its litter. In general, the trend of loss of Unvegetated Dunes and gain in Vegetated Dunes is expected to continue due to the inexorable spread of these highly invasive species, albeit at a lower rate, as many Unvegetated Dunes have already been colonized. Inland dune features may also continue to expand within Grasslands and Open Scrub/Grassland, contributing to net gains in Vegetated Dunes. The only factor countering this trend would be continued restoration of invaded coastal dune ecosystems.

Conclusions

Many recent studies have focused on what has been perceived as an alarming trend in loss of grassland and, in some cases, coastal scrub due to shrub or forest encroachment (Biswell 1954, McBride and Heady 1968, McBride 1974, Williams et al. 1987, Russell and McBride 2003, Keeley 2005, Kennedy and Sousa 2006, Hsu et al. 2011, Startin 2022). In terms of grasslands, some of the earlier researchers decried the loss of high value forage for livestock (Biswell 1954) or the loss of public recreational opportunities (McBride and Heady 1968) resulting from shrub encroachment. In a study titled, "*The Brush Control Problem in California*," Biswell (1954) cautioned that shrub encroachment would reduce productivity of the land not only for livestock, but for game, timber, recreation, and water and strongly advocated for recovery of acres lost to shrub incursion. More recently, researchers have highlighted increases in fire hazard (Brown et al. 1999, Russell and McBride 2003) or losses in biodiversity and ecosystem functions (Startin 2022) with increased abundance of woody vegetation or loss of grasslands, respectively.

Meta-analyses of studies conducted on impacts to biodiversity and ecosystem functioning are equivocal: one documented reduced species richness in North American grasslands and savannas with shrub encroachment (Ratajczak et al. 2012), although another found no consistent link between shrub encroachment and ecosystem degradation (Eldridge et al. 2011). However, taken in the context of vegetation change trajectories over the millennia documented by paleoecological studies, the current trends within Point Reyes of an increase in forested habitat and a decrease in upland herbaceous habitats appear to be less of an issue of a historically unprecedented encroachment of woody vegetation and more of an ecosystem recovery response to an unprecedented convergence of multiple landscape-scale disturbances. These disturbances started with the prescribed burning practices of the Coast Miwok and reached their zenith between the late 1700's and early 1900's with expanded Euro-American settlement and land conversion for ranching and agriculture. As Keeley noted (2005), grasslands were probably of limited extent in the region before the arrival of people.

As discussed earlier, paleoecological studies in Point Reyes point to the Peninsula being dominated by mixed-evergreen-hardwood forests through the late Holocene up until the Historic Period, although Douglas-fir extent decreased somewhat 1,000 years ago (Anderson et al. 2013). Up until the late Holocene, long-term climatic conditions represented probably the broadest influence on vegetation community mosaics on the landscape, with grasslands expanding during dry periods and forest and shrublands expanding during wet ones (Anderson 2005, Anderson et al. 2013). Natural wildfire became more prevalent in the late Holocene potentially due to expansion of forests and associated increases in fuel loading (Anderson et al. 2013). Rather than reduce the extent of forests, Anderson et al. (2013) argue that the wildfires were accompanied by expansion of non-fire-dependent species such as Douglas-fir and coast redwood, as evidenced by strong overlapping in pulses of Douglas-fir and/or coast redwood pollen and charcoal deposition in sediment cores (Anderson et al. 2013). Native peoples introduced the first perhaps anthropogenic factor (prescribed burning) to shape vegetation communities, with burning of grasslands, shrublands, oak woodlands, and other forest types for clearing and other purposes (Keeley 2005, Stephens and Fry 2005, Lorimer et al. 2009, Anderson et al. 2013).

The extent to which native peoples' prescribed burning changed the Point Reyes vegetation landscape relative to what would have existed under just long-term climatic controls and natural wildfires is unclear. But it is clear that, by the early to mid-1800's, a number of anthropogenic factors conflated to

cause abrupt and highly extensive changes in vegetation communities. These factors included introduction of livestock grazing and non-native species; logging and clearing of forests; and suppression of wildfire and Coast Miwok prescribed burning practices. Under this onslaught of anthropogenically induced disturbances, Point Reyes seemingly changed relatively abruptly from a landscape supporting a mix of forest, shrub, and grass habitats to one dominated by grasslands that would ultimately become synonymous in many people's minds with what Point Reyes and other central California coastal areas should be.

Within ecology, alternative stable states have come to largely replace succession as one of the primary theories governing ecosystem development, although succession does still have its role. Under traditional progressive successional models, grassland would be expected to convert to shrubland and then to forest, with environmental (e.g., wildfire) and anthropogenic perturbations then causing retrogressive succession back to grasslands (Walker and Del Moral 2008). Under alternative stable states theory, these perturbations do not necessarily result in a linear re-setting of the successional timeline, but can instead result in the system moving into one or more alternative states that remain stable unless subjected to further disturbance (Beisner et al. 2003, Suding and Hobbs 2009). Researchers have argued that these alternative states are inherently transient, not stable, due to the continual recurrence of disturbance events and that they are greatly influenced by the history of community assembly (Fukami and Nakajima 2011). Change trajectories may result in establishment of either environmentally desirable, more natural states or highly disturbed, undesirable ones (Folke et al. 2004). Once in this highly disturbed state, systems may not naturally revert to their previous state even if the factors that caused the initial change are reversed. To revert to previous states, it may require higher levels of that particular factor – for example, excessive amounts of rain following a drought – or application of different factors (Beisner et al. 2003), and even then, changes may end up being irreversible unless some type of active restoration is performed (Folke et al. 2004).

While broad-scale factors such as long-term climatic trends or landscape-scale disturbances may govern transition between states, other much more localized factors can influence these trajectories, as well, leading to alternative vegetation communities even under similar climatic or environmental conditions (Ackerly et al. 2015). These include edaphic or abiotic factors such as soil type, slope, and aspect as well as biotic variables such as “priority effects” (order/timing of species immigration); vegetation-environment feedbacks; disturbance sensitivity; positive and negative feedback cycles for certain plant species; facilitation of one species by another; and intra- and inter-specific competition among species (Fukami and Nakajima 2011, Ackerly et al. 2015). For example, while climatic cycles in the late Holocene may have generally favored establishment of Douglas-fir forests, patterns of Douglas-fir establishment on a localized scale may have been dictated by priority effects, disturbance sensitivity, feedbacks, facilitation, and competition. Anderson et al. (2013) referenced how local controls may have become more important in the middle to late Holocene than climatic controls.

These ecological theories can be used as a framework for understanding long-term vegetation community patterns. Point Reyes can be envisioned as moving between alternative transient states, albeit perhaps very long-term transient ones, over the millennia in response to long-term climatic shifts, the onset of wildfires, and, more recently, prescribed burning by native peoples. However, the conjunction of anthropogenically induced disturbances that started in the late 1700's and escalated in the mid-1800's -- livestock grazing, logging, fire suppression, and non-native plant introduction -- essentially triggered changes severe enough that the Point Reyes vegetation landscape was pushed into

an entirely new alternative transient state.

With elimination of logging and prescribed burning and a reduction in grazing intensity and tree clearing in the 1900's, the Point Reyes landscape may have started to revert back somewhat towards the more forested and brushy conditions present before human settlement. Prior to establishment of the national seashore, these changes might have been subtle, with acreage of vegetation communities generally showing little change between the 40's and the 60's. However, between the 60's and 90's, dramatic changes in upland herbaceous and forested habitats occurred, with decreases in Grassland and increases in Open Scrub/Grassland and Douglas-fir and Hardwood Forests. These changes are likely reflective of continued changes in active management of Point Reyes lands, with a shift from dairy to more beef cattle grazing (NPS 2020) and a reduction in anthropogenic disturbance with the transition from private to public ownership.

The pace of change in the floristic landscape greatly slowed between the 90's and '18. Forested habitats continued to expand, but at a much-reduced rate relative to the previous mapping period. This deceleration in growth of forests after a period of rapid expansion may point to Douglas-fir and, to a seemingly much lesser extent, Hardwood Forests reaching somewhat of a dynamic equilibrium or balance with their ecological niches as dictated by the current physical and environmental conditions, at least in Point Reyes. Disease may also be partially influencing the trajectory of change in forested habitats with SOD-resilient hosts such as California bay shaping community assemblages by being a vigorous transmitter of SOD to less resilient species. In some cases, retrogressive succession appeared to occur, with acreage of Open Scrub/Grassland dropping dramatically and that of Grassland climbing slightly. Retrogressive succession may be fueled by continued active management or long-term changes in climate (e.g., warming) over the study period. Interestingly, unlike results from other recent vegetation community change studies, acreage of Dense Coastal Scrub remained fairly consistent between mapping periods, with the exception perhaps of a very small decrease between the 90's and '18.

This current floristic equilibrium represents a new alternative transient state – one that may still be in a state of flux. For example, based on the trajectory apparent in the last two mapping periods, forests, particularly Hardwood Forests, may continue to expand in coming years. The degree and direction of change in upland herbaceous habitats is less certain. However, ultimately, Point Reyes, is unlikely, to ever totally transform back to what might be considered a truly naturalized state due to the ongoing impacts of fire suppression, introduction and spread of non-native plant species, diseases such as SOD and *Phytophthora*, continued land management, and climate change.

Future Trends in Vegetation Community Change

While the current trajectory of vegetation community suggests potential at least partial recovery of forested habitats within Point Reyes, the future of this trajectory is clouded by the looming specter of climate change and uncertainty over its effects, particularly along the coast. As discussed in the Introduction, while climate change scientists generally predict a drier and warmer climate for California (Polade et al. 2017), there continues to be a higher degree of uncertainty on more regional scales about potential impacts.

By 2021, climate change had already resulted in an increase in ambient air temperature by 1.1 degrees Centigrade relative to temperature patterns during the pre-industrial period and has been predicted to

lead to warming by as much as 3.2 degrees Centigrade by 2100 under current global warming policies (IPCC 2023). Rapidly warming interior areas of California could increase the ocean-land pressure gradient with coastal areas, intensifying winds during warmer seasons and increasing upwelling in oceanic waters (Johnstone and Dawson 2010, Sydeman et al. 2014, Pozo Buil et al. 2021). Stronger winds along the coast during the upwelling season could be accompanied by reduced coastal temperatures in the summer (Snyder 2008, Lebassi et al. 2009). An analysis of temperature data from 253 weather stations in California from 1950 to 2005 (with a focus on the post-1970 warming period) supports this hypothesis, with cooling of maximum temperatures observed in low-elevation coastal areas ($-0.30^{\circ}\text{C}/\text{decade}$) and warming ($0.32^{\circ}\text{C}/\text{decade}$) observed in inland areas (Lebassi et al. 2009).

Some models have suggested that precipitation in central and northern California could actually increase (Maloney et al. 2014, Seager et al. 2014, Polade et al. 2017). Winters could become wetter in certain parts of California, if not in other Mediterranean regions, because, while low- and medium-intensity precipitation events would decline, extreme precipitation events would increase in frequency and intensity, leading to slightly higher rainfall totals (Polade et al. 2017). In general, more variability is expected in rainfall, with potentially larger storms and longer dry periods, including potentially drier fall and spring seasons and wetter winters (Polade et al. 2017).

In past millenia, expansion of Douglas-fir forests and certain types of shrublands such as coyotebrush-dominated coastal scrub have been associated with wetter climates (Anderson 2005, Barron and Anderson 2010, Anderson et al. 2013), while expansion of California sagebrush-dominated sage scrub and perhaps pine forests have been more associated with drier ones (Rypins et al. 1989, Barron et al. 2003). A study evaluating vegetation community conversion in the San Francisco Bay region between 1985 and 2010 found that forests were generally associated with higher mean annual precipitation and July-August evapotranspiration rates, while grasslands were characterized by lower July-August evapotranspiration rates and extremes in summer minimum and maximum temperatures (Hsu et al. 2011). However, researchers acknowledged that evapotranspiration analyses were compromised by the fact that grasslands were dominated by annual species that had largely senesced by late summer, thereby greatly reducing evapotranspirative demand relative to other habitats (Hsu et al. 2011). Conversion to shrubland – documented more in east San Francisco Bay areas in recent decades (McBride and Heady 1968, Williams et al. 1987, Russell and McBride 2003, Keely 2005) – showed similar positive climatic relationships with precipitation, as well (Hsu et al. 2011). Coyotebrush spreads into grasslands most aggressively in unusually wet years or years with unusually late spring rains (Williams et al. 1987, Williams and Hobbs 1989, Sandel et al. 2012).

Given that water availability and precipitation may decrease in the future – or at least become more variable both intra-annually and interannually – it's possible that future trends in vegetation communities may change or shift from the ones documented over the past century. While the climatic water deficit may turn out be lower in Point Reyes than in more inland areas, it has still been projected to increase due to evaporative demand, regardless of whether precipitation goes up or down (Flint et al. 2013, Ackerly et al. 2015). Coastal areas such as Point Reyes have largely been buffered from some of the climatic extremes of inland California due to fog. Fog water deposition has been documented to contribute significantly to the total water input for coast redwood forests (19%–66%; Dawson 1998, Burgess and Dawson 2004) and for coastal prairie grasses during summer drought (28%–66%; Corbin et al. 2005). It also strongly benefits Douglas-fir (Harr 1982, Kennedy and Sousa 2006), Bishop pine (Fischer et al. 2009, Baguskas et al. 2016), and coyotebrush seedlings (Kidder 2015). Even on a scale as localized

as the western portion of Point Reyes, conifers varied dramatically in their reliance on fog, with stands in some areas entirely reliant on fog (e.g., near the Lighthouse), some seasonally dependent on fog during the late summer, and others surviving entirely off groundwater (Ingraham and Matthews 1985).

Cooler temperatures along the coast would seemingly favor continuation of the fog belt that typically cloaks the coast during the summer on days when temperatures soar in inland areas. The frequency of fog closely approximates the temperature differential between coastal and inland weather stations (Johnstone and Dawson 2010). Increased fog frequency in northern California has also been found to be correlated with wind intensification over the northern limb of the California Current (Johnstone and Dawson 2010). However, fog generation can be counteracted by the warming of sea-surface temperatures (SST), which, at least so far, appears to be the prevailing trend off the California coast despite intensification of upwelling that is commonly associated with turnover of colder ocean waters by strong winds (O'Brien 2011). Several studies have shown a decline in fog over the past century (Johnstone and Dawson 2010, O'Brien 2011) that is projected to continue (O'Brien 2011). Over the last 100 years, the range of fog frequencies is estimated to have declined by 33% (Johnstone and Dawson 2010). From 1951 to 1975, fog frequency varied around a mean of 44%, followed by a gradual decline through the 1980's and 1990's, culminating in a record minimum of 27% in 1997: The following decade (2000's) saw a partial recovery to pre-1977 levels with an average frequency of 42% (Johnstone and Dawson 2010). O'Brien (2011) predicts that fog will continue to decline unless upwelling of cold water can counteract globalized warming trends of SST.

These climate projections form the basis for a number of vegetation community change models developed between 2009 and 2015 that assert that, by the mid-21st century, oak woodland, shrub, and grassland habitats will be favored over coniferous and evergreen broadleaf forested ones, particularly in the San Francisco Bay area (Stralberg et al. 2009, Cornwell et al. 2012, Ackerly et al. 2015). The mix of habitats predicted to evolve, though, often vary dramatically, even within the larger San Francisco Bay area. For North Bay regions, warmer temperatures would promote expansion of drier habitats such as chamise (*Adenostoma fasciculatum*) and California sagebrush-dominated coastal scrub and, to a lesser extent, a variety of oak woodlands and constrict or stabilize extent of grassland and hardwood, Douglas-fir, Bishop pine, and coast redwood forests (Cornwell et al. 2012, Ackerly et al. 2015, Ackerly 2016). Some of these models depict the Inverness Ridge by mid-21st century as being dominated either by a mix of remaining forest and forest-converted shrubland (Stralberg et al. 2009) or almost entirely forest-converted shrubland (D. Ackerly, 2010, *unpub. data*). Winter warming along the coast, including in Point Reyes, may also facilitate spread – or continued spread -- of coyotebrush into grasslands (Cornwell et al. 2012) or at least maintain its extent (Ackerly 2016). It is interesting to note that the results of climate change-based vegetation modeling point to coyotebrush and shrublands expanding during warmer and potentially drier climates while paleoecological and other studies suggest that these species and habitats expand under wetter ones (Williams et al. 1987, Williams and Hobbs 1989, Anderson 2005, Hsu et al. 2011, Sandel et al. 2012, Anderson et al. 2013).

While some of these climate predictions appear to portend dramatic reworking of Bay Area landscapes, type conversions would largely involve encroachment from adjacent existing communities rather than establishment of “novel” ones (Cornwell et al. 2012). Modeling suggests that 54 percent of community conversions in the Bay Area would require less than 1 kilometer of movement for the successful (i.e., newly establishing) vegetation type, while only 8 percent of conversions would derive from communities that are not already close by (Cornwell et al. 2012). Broad-brush predictions of vegetation community

change are complicated, though, by localized factors, even at a regional scale (Cornwell et al. 2012). Regional differences in the magnitude of climate change impacts had a relatively small effect on the potential for community transitions within models ($r^2=0.18$), with much more of the among site variance explained by the intrinsic sensitivity of the vegetation (Cornwell et al. 2012). In other words, the fact that different vegetation communities will inherently exhibit unique biological thresholds (e.g., range of solar radiation conditions under which a community will persist) means that the tolerance of communities to change in environmental conditions and the rate at which they change could vary substantially among communities even if they are geographically adjacent and subject to the same regionalized shifts in environmental conditions. Communities with narrower biological thresholds may ultimately be more sensitive to climate change impacts. Surprisingly, sensitivity to climate change is also higher closer to the coast, on north-facing slopes with lower solar radiation and in areas of higher precipitation (Ackerly et al. 2015). While such sites may provide refugia for mesic and cool-adapted vegetation in the face of a warming climate, the model suggests they will still be highly dynamic and relatively sensitive to climate-driven vegetation transitions (Ackerly et al. 2015).

Broader transitional thresholds may possibly explain why wetter habitats – Douglas-fir forests – and wetter species – coyotebrush – have largely continued to expand in Point Reyes despite the fact that climate change is already occurring. As Ackerly et al. (2016) noted, current trends, especially for Douglas-fir, run counter to the projected impacts of a warmer climate. In many areas of Marin County, Douglas-fir is displacing oak woodland (GGNPC 2023), while climate change models point to the exact opposite occurring within the next 30 years. Approximately 8% of coast live oak woodlands – the dominant oak woodland in Marin County – are actively converting to Douglas-fir forest, and another 43% are threatened with conversion due to being directly adjacent to or within 0.25 mile of a conifer seed source (GGNPC 2023). An even higher percentage of canyon live oak (*Quercus chrysolepis*) woodlands are actively converting (27%): PRNS manages 26% of the 735 acres of this habitat in Marin County (GGNPC 2023). The only climate change model that predicted an increase in forests in the North Bay was based on increased precipitation (Lenihan et al. 2003), although this early model was based on very large (100-km²) pixels (Ackerly et al. 2012).

In addition to thresholds, vegetation shifts are subject to a natural lag in response of species within communities due to dispersal or growth limitations, effectively creating a disequilibrium between a rapidly changing climate and a (possibly) slowly responding vegetation (Ackerly et al. 2016). Adjustments to climate change may unfold over decades or even centuries (Ackerly 2016). A similar phenomenon of disequilibrium was recently documented for coniferous forests of the Sierra Nevada, where almost 20% were experiencing what researchers termed “vegetation climate mismatch” in which they persisted where climate was currently unsuitable, with 95% of those forests stands occurring at lower elevations (2,356 m; Hill et al. 2023). Slowing in the rate of expansion in coniferous forest in Point Reyes within the past 20 years may be the first sign that at least certain types of forests are coming into equilibrium with a changed climate, but it’s difficult to assert this definitively, as Douglas-fir forests continue to expand substantially even in immediately adjacent areas such as Bolinas Ridge (Startin 2022). Ultimately, continued disequilibrium of vegetation communities still recovering from historic disturbances such as logging, agricultural development, and fire suppression with current climatic conditions may render communities more vulnerable to drought stress, fire risk, susceptibility to pathogens and disease and to invasion by disturbance-adapted weeds with high dispersal rates and short generation times (Ackerly et al. 2016).

Recommendations for Future Historic Vegetation Mapping Projects

Vegetation mapping projects that rely on comparisons between historical B&W and recent aerial color imagery pose substantive analytical challenges that inherently introduce error and bias into mapping and classification processes. These sources of error and bias can be minimized, but probably cannot be entirely eliminated despite current technological advances. Below are listed some recommendations that may help reduce error for future historic vegetation mapping projects.

- For most historic mapping efforts, use of B&W aerial photographs for mapping dating back to the mid-20th century is probably inevitable. To the maximum extent practicable, these photographs should be mosaicked to create a seamless map on which to perform mapping. In addition to careful georectification (or even orthorectification), other measures can be taken to improve image quality, including adjusting color balance, eliminating photograph edges, applying a radiometric correction to compensate for expected differences in illumination due to the effect of aspect and slope on reflectance, and potentially correcting for tree shadows (Lydersen and Collins (2018)).
- Some mapping efforts have actually converted color imagery into B&W to enhance comparability with older imagery sets (Lydersen and Collins 2018).
- Mappers should consider a semi-automated mapping approach using an Object Based Image Analysis software as discussed in Platt and Schoennagel (2009), Morgan and Gengel (2013), Eitzel et al. (2016), and Lydersen and Collins (2018). Automated mapping can be manually calibrated to improve mapping precision. Review and editing of automated mapping efforts can also be performed manually.
- To the maximum extent practicable, individuals performing manual review and editing should remain consistent between mapping periods, or initial reviewers should closely work with new reviewers to ensure that mapping approach is calibrated and consistent between personnel.
- Vegetation community classifications employed in historic mapping efforts should take into account which differences in vegetation communities can be reliably and consistently discerned in the poorest quality photographs used in the project.
- Scale and minimum mapping unit should be carefully delineated prior to the project and adhered to during the mapping effort.
- A backwards mapping approach in which vegetation communities are mapped first for the newest maps and then move backwards chronologically may improve mappers' ability to distinguish between communities (Podobnikar 2009, Stancioff et al. 2014).
- When using existing vegetation community maps, it is beneficial to use ones that were mapped using a similar approach – broad-based structural communities such as Grassland, Dense Coastal Scrub, and Hardwood Forest versus species or species groupings such as Alliance and Association. The different approaches can yield vastly different number of polygons that can lead to different mapping resolution and can be difficult to manually review and edit.

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Table 1. GIS Assistance/Products and Photointerpretation/QA-QC Needs for PORE Historic Veg Mapping Project			
Community Classification	Comparison of 40's – 60's	Comparison of 60's – 90's	GIS assistance/product needs - Source of product
Active Agriculture	Decreases from 40's to 60's – EXPECTED with reduction in row cropping	Increases from 60's to 90's – NOT EXPECTED. Includes “Managed Pastures” as Active Agriculture	NPS to Provide: Overlay 60's GIS map with modified 90's map to generate GIS file of areas where Active Agriculture mapped in the 90's not mapped as Active Agriculture in the 60's.
Beach	Increases slightly from 40's to 60's – NOT SURE? - Was imagery shot at different tides?	Decreases substantially from 60's to 90's – NOT SURE? - Imagery shot at different tides? Beach/cliff erosion?	NPS to Provide: Overlay 60's GIS map with modified 90's map to generate GIS file of areas where Beach mapped in the 60's not mapped as Beach in the 90's.
Bishop pine	Moderate decrease from 40's to 60's – EXPECTED with no fire regime? Or artifact of imagery quality/mapping interpretation. Alison perhaps stronger with forest interpretation, but working with lower quality product. Amelia less strong on forest than Alison, but working with better imagery.	Large increase from 60's to 90's – NOT EXPECTED? If this reflects the mapping as of 1994, then would expect decrease due to lack of fire. If it includes Vision Fire regeneration, then increase might be expected. Modified 90's map includes Vision Fire changes (AF).	Tukman to Provide: Overlay all three GIS maps to generate GIS file of areas where Bishop pine mapped differently. Conduct QA/QC (but no editing) of mapping of Bishop pine.
Coastal Bluff/Cliff Faces	Minor decrease from 40's to 60's – EXPECTED. Cliff faces have been eroding.	Moderate decrease from 60's to 90's – EXPECTED. Cliff erosion. However, ABR noted that 94 Veg Map often included Dunes in Cliff Faces.	NPS to Provide: Overlay 60's GIS map with modified 90's map to generate GIS file of areas where Coastal Bluff/Cliff Faces mapped in 90's differed from that mapped in 60's.
Douglas Fir	Moderate decrease from 40's to 60's – NOT EXPECTED. The trend has	Large increase from 60's to 90's – EXPECTED.	Tukman to Provide: Overlay all three GIS maps to generate GIS file of areas where

Table 1. GIS Assistance/Products and Photointerpretation/QA-QC Needs for PORE Historic Veg Mapping Project			
	been for Douglas Fir to increase. Large-scale logging, ag development discontinued.		Douglas Fir mapped differently. Conduct some QA/QC of mapping of Douglas fir.
Freshwater Wetland	Large increase from 40's to 60's – UNSURE – If riparian removed for grazing, might map as FW wetland. Could be that ABR as wetlands person also mapped more FW wetlands whereas AF mapped as grasslands?	Large decrease from 60's to 90's – UNSURE – Riparian might be removed for grazing. Feel confident in 60's mapping as ABR very familiar with wetlands. Not as confident with 90's mapping.	NPS to Provide: Overlay all three GIS maps to generate 1) GIS file of areas from the 60's where Freshwater Wetland was mapped but not mapped as Freshwater Wetland in the 40's and 2) GIS file of areas from the 60's that were mapped as Freshwater Wetland but not mapped as Freshwater Wetland in the 90's.
Grassland	Slight increase from 40's to 60's – EXPECTED – ranchers removing shrubs to improve grazing. Dense coastal scrub decreased.	Huge decrease from 60's to 90's – NOT EXPECTED – This is because pasture placed in Active Agriculture. Need to continue to cull out those areas.	NPS to Provide: Overlay 60's Grassland and Open Scrub Grassland with 90's Active Agriculture to enable culling out of pastures labeled as Active Agriculture. GIS file should show areas where Grassland and Open Scrub were mapped in 60's, but mapped as Active Agriculture in 90's.
Hardwood Forest	Large increase from 40's to 60's – UNSURE? – Affected by logging, ag development?	Large decrease from 60's to 90's – UNSURE	Tukman to Provide: Overlay all three GIS maps to generate GIS file of areas where Hardwood Forest was mapped differently. Conduct some QA/QC of mapping of Hardwood Forest
Open Scrub Grassland	Slight increase from 40's to 60's – EXPECTED – Dense coastal scrub did decrease. More agricultural management.	Big increase from 60's to 90's – EXPECTED? – Again, Dense coastal scrub decreased.	NPS to Provide: Overlay all three GIS maps to generate 1) GIS file of areas from the 60's where Open Scrub Grassland was mapped but not mapped in the 40's and 2) GIS file of areas from the 90's that were mapped as Open Scrub Grassland but not mapped as Open Scrub Grassland in the 60's.

Table 1. GIS Assistance/Products and Photointerpretation/QA-QC Needs for PORE Historic Veg Mapping Project			
Riparian Forest Shrubland	Slight decrease from 40's to 60's – EXPECTED – Ranchers reduce riparian to increase forage areas.	Large increase from 60's to 90's – EXPECTED – less removal of Riparian. However, 90's mapping of riparian very broad.	NPS to Provide: Overlay 60's GIS map with modified 90's map to generate 1) GIS file of areas from the 40's where Riparian was mapped but not mapped in the 60's and 2) GIS file of areas from the 90's that were mapped as Riparian but not mapped as Riparian in the 60's.
Salt Marsh	Large decrease from 40's to 60's – EXPECTED – Due to leveeing of Giacomini in 40's, large loss of salt marsh, but acreage not equivalent. However, progradation of other estuarine wetlands might offset Giacomini loss. Feel confident in this mapping.	Large increase from 60's to 90's – NOT EXPECTED – Giacomini not restored yet, but progradation was creating more salt marsh in other estuarine areas. Need to double check 90's mapping. Feel confident in 60's mapping as done by ABR/LP.	NPS to Provide: Overlay 60's GIS map with modified 90's map to generate GIS file of areas from the 90's where Salt Marsh was mapped but not mapped as Salt Marsh in the 60's.
Unvegetated Dunes	Moderate decrease from 40's to 60's – EXPECTED – Due to spread of European beachgrass and iceplant	Small decrease from 60's to 90's – NOT EXPECTED – There should be continued moderate to large decreases due to expansion of clonal invasives. ABR noted that some cliff faces mapped in 94 map as Unvegetated Dunes, especially to the north near Tomales Point.	NPS to Provide: Overlay 60's GIS map with modified 90's map to generate GIS file of areas from the 90's where Unvegetated Dunes was mapped but not mapped as Unvegetated Dunes in the 60's.
Vegetated Dunes	Moderate increase from 40's to 60's – EXPECTED – Due to spread of clonal invasives such as European	Moderate increase from 60's to 90's – EXPECTED - Due to spread of clonal invasives such as European	NPS to Provide: Overlay all three GIS maps 1) GIS file of areas from the 60's where Vegetated Dunes were mapped but not mapped in the 40's and 2) GIS file of areas

Table 1. GIS Assistance/Products and Photointerpretation/QA-QC Needs for PORE Historic Veg Mapping Project			
	beachgrass. Need to double check whether Dune Scrub mapped as Vegetated Dunes.	beachgrass. Need to double check whether Dune Scrub mapped as Vegetated Dunes.	from the 60's that were mapped as Vegetated Dunes but not mapped as Vegetated Dunes in the 90's.

Table 2. Revised Vegetation Mapping Classes				
Category	Notes	Community	Super Cluster in 1994 map	Best crosswalk with 1994 Map
Riparian Forest/Shrubland	Riparian or phreatophytic trees and shrubs directly adjoining creeks, streams, and drainages.	Riparian Forest and shrubland	Winter Deciduous Forest/Scrub	Riparian Forest and shrubland VMC
Hardwood Forest	Wooded areas that are dominated by California bay (<i>Umbellularia californica</i>), oaks (<i>Quercus</i> spp.), and madrone (<i>Arbutus menziesii</i>). The original vegetation community mapping guidelines stated that HF species should need to have at least 60% cover. For the 2018 map, at least 10% of the cover of the plot needs to be trees, and of that tree cover, more than 50% needed to be Hardwood species, unless Douglas-fir is present. If species such as Douglas-fir were co-dominant (30- 60%), then it would key to Douglas-fir instead. To ensure comparability between mapping efforts, we may hold with the original mapping guidelines. Hardwood Forest also includes distinct stands of Hardwood Forest that function as riparian vegetation.	Hardwood Forest	Winter Deciduous Forest/Scrub & Evergreen Forest and Wetland	Hardwood Forest VMC
Douglas-fir	Wooded areas that are dominated by Douglas-fir (<i>Pseudotsuga menziesii</i>). The original vegetation community mapping guidelines stated that the minimum tree cover is 15%. While it is not explicitly stated, the assumption was that Douglas-fir needs to be dominant (relative cover >50%) to be classified as such. The 2018 mapping guidelines steer areas with 30- 60% Douglas-fir cover in relation to hardwoods to being mapped as Douglas-fir. To ensure comparability between mapping efforts, we may hold with the original mapping guidelines.	Douglas-fir/coast redwood	Evergreen Forest and Wetland	Douglas-fir superalliance
Redwood	Minimum tree cover is 15%	Douglas-fir/coast redwood	Evergreen Forest and Wetland	Redwood-tanoak superalliance
Eucalyptus	Minimum tree cover is 15%	Hardwood Forest	Evergreen Forest and Wetland	Eucalyptus superalliance
Cypress	Minimum tree cover is 15%. Added in 2022.			

Table 2. Revised Vegetation Mapping Classes				
Category	Notes	Community	Super Cluster in 1994 map	Best crosswalk with 1994 Map
Bishop pine	Bishop pine (<i>Pinus muricata</i>) can occur in dense forests, particularly on Tomales Point, but in some areas particularly near Home Ranch and stretching to Limantour Ridge, it is seen in the 2004 aerial imagery as scattered trees. The minimum tree cover for the historic veg mapping effort is 15%. This is slightly more than the 2018 map, which specified areas as dominated by trees if 10% cover. The 2018 map states that Bishop pine must have at least 60% relative cover. To ensure comparability between mapping efforts, we hold with the original mapping guidelines, which assumably stipulated more than 50% tree cover.	Bishop pine	Evergreen Forest and Wetland	Bishop pine VMC
Dense Coastal Scrub	≥ 60% cover of shrubs. Includes coyotebrush, bush lupine, Ceanothus, blackberry, salmonberry (in non-riparian corridors), etc. Includes Chaparral. Sometimes occurs on Cliffs.	Coastal scrub	Coastal scrub, Chaparral	Dense coyotebrush and related scrub mesocluster
Open Scrub/Grassland	Shrubs must be equal to or more than 10%, but less than 60% of the polygon to be Open Scrub/Grassland. Shrubs are generally interspersed throughout the polygon.	Coastal scrub	Coastal scrub	Drier coastal grassland and open scrub mesocluster
Grassland	If shrubs appear to be less than 10% of the polygon, it is mapped as Grassland. This includes actively grazed areas that do not appear to be actively managed: if actively managed by mowing, mapped as Active Agriculture.	Grassland	Grassland-herbaceous	Grassland VMC
Freshwater Wetland	This includes freshwater wetlands, as well as brackish wetlands. These were generally incompletely mapped in earlier automated mapping efforts based on vegetation. Auxiliary sources of information used as part of this include National Wetlands Inventory (NWI) maps; field-based wetlands maps produced by PRNS; topographic contours; soil maps; and aerial imagery interpretation.	Herbaceous wetlands	Grassland-herbaceous	Freshwater wetland herb mesocluster
Salt Marsh	These are tidal marshes. Brackish marshes are lumped with Freshwater Wetland.	Herbaceous wetlands	Salt Marsh	Salt Marsh supercluster
Vegetated Dunes	These include areas dominated by non-native vegetation (European beachgrass, iceplant), as well as areas	Coastal Dunes	Coastal scrub	Coastal dunes VMC

Table 2. Revised Vegetation Mapping Classes				
Category	Notes	Community	Super Cluster in 1994 map	Best crosswalk with 1994 Map
	dominated by native vegetation (Dune Scrub) or shrub-dominated areas growing on dune fields, often with a distinct vegetation community (mock heather, chamisso lupine, coyotebrush, bush lupine). Moist Meadows present with dunes are not wet enough to be wetlands, but probably have a moister soil due potentially to higher organic matter: these support a mix of rush (<i>Juncus lescurii</i>), coyotebrush, and sometimes sedge (<i>Carex obnupta</i>). These were pulled out of Freshwater Wetlands and either placed in Vegetated Dunes or Grasslands.			
Unvegetated Dunes	These are areas with less than or equal to 30- 40% total cover, which is in keeping with most native Dune Mat communities.	Coastal Dunes	Coastal scrub	Coastal dunes VMC
Active Agriculture	Areas in active ag, i.e., row crops or mowed pastures. Look for very distinct field edges, striped, or stippled veg pattern			
Water	Open water bodies, including creeks, streams, lakes, lagoons and ranch ponds that are internal to the park boundary, but not generally in Tomales Bay or Pacific Ocean. Included in these are mudflats that are probably routinely submerged.	Water	Water	Water VMC
Disturbed	This includes buildings, barns, corrals, houses, driveways, and parking lots. Paved roads were not mapped generally as Disturbed except in the '18 map.	Built-up Urban Disturbance	Built-up Urban Disturbance	Built-up Urban Disturbance VMC
Cliffs	Cliffs occur along the Great Beach near Tomales Point and near Palomarin. They are defined as highly sloped areas that are largely unvegetated. Densely vegetated areas are included Dense Coastal Scrub. Grassy or light vegetated areas where a lot of white or beige color is evident are mapped as Cliffs. Topography contours are often used to define the break between Cliffs and Beach, although overlays with land edge are often not exact.			
Unknown/other	Areas that cannot be mapped based on available information			

Table 2. Revised Vegetation Mapping Classes				
Category	Notes	Community	Super Cluster in 1994 map	Best crosswalk with 1994 Map
Beaches	Beaches include sandy and rocky beaches and focus on portions of those beaches that look like they are usually not submerged except during higher high tides. On color imagery, this is visible from higher elevation beaches as being more yellow and less dark than more submerged areas of beach. Mudflats are not included in beach. They are mapped as "Water."			

Table 3. Confidence Limits used for Change Analysis					
Vegetation Communities	40's	60's	90's	18	Type(s) of Error
Bishop Pine	92%	95%	98%	99%	Mis-classification with other forest types and Dense Coastal Scrub
Dense Coastal Scrub	92%	95%	98%	99%	Mis-classification with forest; Cross-walking issues
Disturbed	92%	95%	98%	99%	Mapper interpretation/definition; difference in boundaries
Douglas-fir	92%	95%	98%	99%	Mis-classification with other forest types; lumping of mixed Douglas-fir and Hardwood species
Freshwater Wetland	92%	95%	98%	98%	Mapper interpretation/definition; classified as non-wetland type such as Grassland
Grassland	92%	95%	98%	99%	Mapper interpretation/definition; classified as Open Scrub/Grassland
Hardwood Forest (Total)	92%	95%	98%	99%	Mis-classification with other forest types; lumping of mixed Douglas-fir and Hardwood species
Open Scrub/Grassland	92%	95%	98%	99%	Mapper interpretation/definition; classified as Grassland; Cross-walking issues
Riparian Forest/Shrubland	92%	95%	98%	99%	Mis-classification with other forest types
Salt Marsh	97%	98%	99%	99%	
Unvegetated Dunes	92%	95%	98%	99%	Mapper interpretation/definition; classified as Vegetated Dunes
Vegetated Dunes	92%	95%	98%	99%	Mapper interpretation/definition; classified as Dense Coastal Scrub

Table 4. Issues identified with original mapping layers for 1940's, 1960's, 1990's, and 2018 and corrective measures employed to improve accuracy. Initials refer to name of original mapper/reviewer: ABR=Amelia Ryan. AF=Alison Forrestel.					
Community Classification	Issues Identified in Original Mapping Results	QA/QC of 40's	QA/QC of 60's	QA/QC of 90's	QA/QC of '18
Beach	<i>Increases slightly from 40's to 60's – NOT SURE?</i> - Was imagery shot at different tides? <i>Decreases substantially from 60's to 90's – NOT SURE?</i> - Imagery shot at different tides? Beach/cliff erosion?	Beaches were undermapped, particularly near Tomales Point and Palomarin. Beach areas were added using the same strategy as used for the 90's, although, with B&W aerial imagery, it was more difficult to detect high tide lines.	See 40's for discussion.	All areas of coastline evaluated for Beach discrepancies (>98%). Decreases from 60's to 90's probably due to two factors: (1) Imagery for 60's was probably flown at higher tide than that for 94/04 and (2) many sections of Beach were not mapped, even those were probably exposed at higher tides. Mapping of Beach was minimal on both the Great Beach and the Limantour-Palomarin coastline, with some beach sections mapped as sliver water polygons. Sandy beach areas where the sand appeared very light, as if exposed a lot, were mapped as Beach, but not areas that looked like they were submerged regularly (i.e., darker sands). Near the Lighthouse/Drakes, rocky beach was also mapped. Original 90's mapping did NOT include mudflats, even though the original 94 map had category called "Beaches and Mudflat."	In the original crosswalk version, beaches were under-mapped compared to the 90's and 60's due to trimming layer edge on some coastline. This was corrected ultimately during QA/QC of the '18 crosswalk map.
Water		Ensured consistency in mapping approach by lumping mudflats into Water as was done in the 90's mapping. Also pulled out more ranch ponds as Water and noted as ranch ponds in Notes field of attribute table.	See 40's for discussion. Also eliminated water polygons that existed outside of the physical boundaries of the Seashore such as in the Pacific Ocean and Tomales Bay.	Added ranch ponds as Waters when not mapped.	Polygons marked as "Channel" were originally crosswalked to Salt Marsh. These were reviewed, and most were changed to Water.
Cliffs	<i>Minor decrease from 40's to 60's – EXPECTED.</i> Cliff faces have been eroding. <i>Moderate decrease from 60's to 90's – EXPECTED</i> - Cliff erosion. However, ABR noted that 90's Veg Map often included Dunes in Cliffs.	A good percentage of cliffs were either not mapped or lumped into "Unknown/other" or not classified at all. The latter two often had comments about "coastal bluff" in notes. Missing polygons were particularly evident at Tomales Point and near Wildcat/Palomarin. Because imagery quality was challenging, used topography contours to guide mapping as best as possible. Mapping was often greatly altered by which imagery tile was used.	See 40's for discussion	All areas of coastline evaluated for Coastal Bluff/Cliff discrepancies (>98%). Decreases from 60's to 90's are probably due to two factors: (1) Many sections of Cliffs were not mapped along the Great Beach north of Kehoe, near the Lighthouse, and in the Palomarin section of the outer coastline (2) some sections of Cliffs were mapped as Dense Coastal Scrub if cover was high. This latter mapping approach was maintained (Table 2). The 90's revision did also incorporate sections of rocky areas along the base that were attached to the "mainland" at the Lighthouse as Cliffs. Rocks that were not attached were not mapped.	In the original crosswalked version, cliffs were under-mapped. In some cases, the map was trimmed along the coast, which cut off mapping of the cliffs completely. Later QA/QC added in missing Cliff areas. Additionally, many of the lightly vegetated cliffs were captured under vegetation communities that had been crosswalked to Grassland. In revisions, these vegetated polygons were converted to either Cliffs or Dense Coastal Scrub depending on their cover.
Bishop Pine	<i>Moderate decrease from 40's to 60's – EXPECTED</i> with no fire	Bishop Pine was commonly misidentified as Hardwood Forest or	The majority of editing done to Bishop Pine was boundary adjustment and	As noted, the 90's map includes Vision Fire Changes, per Alison Forrestel. Following	A number of Forest Fragments that were crosswalked to Unknown/Other

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	regime? Or artifact of imagery quality/mapping interpretation? Large increase from 60's to 90's – EXPECTED – after Vision Fire	Dense Coastal Scrub due to poor spectral contrast in 1943 imagery, making differentiation between vegetation types challenging. More problematic were differences between in how 40's and 60's boundaries were drawn leading to slivers of vegetation change. These were addressed by adjusting boundaries using side-by-side linked maps and referencing more modern imagery (1963, 1965, and 2004) if no change had likely occurred. Much of this occurred in the Inverness Ridge area and can be attributed to poor imagery spectral signatures and differences in how boundaries were drawn between the 40's and 60's, resulting in slivers of change.	reclassification after being misidentified as Hardwood Forest or Riparian/Shrubland. Much of this was done in the area to the west of the town of Inverness. The imagery here is part of the 1965 mosaic and is of decent spectral quality, but polygons were misclassified.	review of park areas that were not entirely dominated by forest, acreage of Bishop Pine mapped increased greatly, because more Bishop Pine was mapped on lower elevations of the Inverness Ridge ~west of Limantour Road and ~east of Drakes Estero. There were many areas with scattered Bishop Pine that appeared to meet the percent cover requirements (see adjacent column) that were not mapped as such. In general, the polygons in this area seemed very off or dissimilar from what was visible in the 2004 imagery, so it brings into question whether Vision Fire changes were included in this part of the park? In many instances, polygons were cut and re-merged to maintain the designated percent cover. There were also, occasionally, areas of Dense Coastal Scrub that were mistakenly mapped as Bishop Pine – and vice versa -- due to a similar signature.	and later were recategorized to Bishop Pine.
Douglas-fir	Moderate decrease from 40's to 60's – NOT EXPECTED - The trend has been for Douglas Fir to increase. Large-scale logging, ag development discontinued. Large increase from 60's to 90's – EXPECTED.	It appears that at least 500 acres of Douglas-fir was mapped incorrectly as Hardwood Forest in the 40's shapefile, mainly in the Bear Valley area. Much of this was reclassified from HW to DF and boundaries were adjusted based on threshold mapping guidelines and comparison to 60's and 2004 imagery.	At least 100 acres of Douglas-fir were misclassified as Hardwood Forest in the original 60's shapefile, the majority of which occurred in the Bear Valley area. A lot of other change can be attributed to difference in how boundaries of polygons were drawn between the 40's and 60's.	The 90's mapping	Mapping efforts were generally good. No significant edits.
Hardwood Forest	Large increase from 40's to 60's – UNSURE? – Affected by logging, ag development? Issues in differentiation with Douglas-fir? Large decrease from 60's to 90's – UNSURE.	Hardwood Forest throughout Inverness Ridge was misidentified as other vegetation types, mainly Douglas-fir, Dense Coastal Scrub, and Riparian Forest/Shrubland, almost all due to low spectral quality. Adjustments were made based on Tukman recommendations and comparison to 60s and 2004 imagery.	Unsure of reason for increase. It appears that much of the misclassification issues stemmed from confusion between Douglas-fir and Bishop Pine, including threshold calls based on the density of Hardwood Forest tree cover. This occurred throughout the Inverness Ridge. Many fine-scale revisions were made to both 40's and 60's shapefiles to increase consistency in how threshold calls were made. If at least 60% of individual trees were Hardwood Forest species, polygon then classified as Hardwood Forest.		Mapping efforts were generally good. No significant edits.
Hardwood Forest (RF)	New category	In Olema Valley, a number of drainages have California bay functioning as riparian habitat: these areas were classified as Hardwood Forest (RF); see	See 40's discussion	See 40's discussion	California Bay stands functioning as Riparian Forest (RF) were not broken out in the '18 map.

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		discussion under "Revision of Forested Areas."			
Riparian Forest/Shrubland	<i>Slight decrease from 40's to 60's – EXPECTED</i> – Ranchers reduce riparian to increase forage areas. <i>Large increase from 60's to 90's – EXPECTED</i> – less removal of Riparian. However, 90's mapping of riparian very broad.	Mapping of Riparian Forest/Shrubland was checked, but in general, mapping efforts looked good, given the challenges of interpreting B&W aerial imagery. In general, coyotebrush areas along drainages were already labeled as Dense Coastal Scrub, not Riparian Forest/Shrubland, so not many changes were needed.	See 40's for discussion.	In certain instances, there were areas of discontinuity between downstream wetland/riparian and upstream wetland/riparian with areas in between mapped as upland. Features were connected. Coyotebrush areas along drainages were reclassified as Dense Coastal Scrub.	Mapping efforts were generally good. No significant edits.
Freshwater Wetland	<i>Large increase from 40's to 60's – UNSURE</i> – If riparian removed for grazing, might map as FW wetland. Could be that ABR as wetlands person also mapped more FW wetlands whereas AF mapped as grasslands? <i>Large decrease from 60's to 90's – UNSURE.</i>	Freshwater Wetlands were undermapped in the 40's. Much of this has to do with challenging aerial imagery. It is difficult to detect seasonally ponded or saturated wetlands in B&W. Used resources discussed in Materials & Methods to revise wetland mapping, but erred on the side of undermapping if not at all evident in imagery. This meant that much fewer Freshwater Wetlands were mapped in Olema Valley, because imagery in that area was not as good, and it was harder to detect seasonally wet areas.	While Freshwater Wetland mapping in the 60's was more comprehensive, some wetland areas were still missed. Used resources discussed in Materials & Methods to revise wetland mapping, but erred on the side of undermapping if not at all evident in imagery.	A reasonable percentage of non-forested areas (>90%) were reviewed for Freshwater Wetland inclusion in 90's map. Additional Freshwater Wetlands were mapped by using several resources discussed in the Materials & Methods to identify areas where they were missed during first go-around: (1) PORE field-based wetlands GIS map (includes pastoral zone and Tomales Bay); (2) revised National Wetlands Inventory map for PORE (2021); (3) 2018 Vegetation Map (e.g., focusing on Vancouverian Freshwater Wet Meadow & Marsh Group alliances); and (4) best professional aerial imagery photointerpretation judgement/personal site knowledge of the reviewer (Lorraine Parsons). Not sure if additional mapped Freshwater Wetlands will fully address differences between 60's and 90's maps, though.	Mapping of Freshwater Wetlands in the crosswalked version of the '18 map was largely tied to presence of the Vancouverian Freshwater Wet Meadow & Marsh Group alliance, where mapping of wetlands in the other layers was based on other factors such as hydrology and hydric soils. Some effort was made to review Freshwater Wetlands during later QA/QC efforts, but review was not completed. For this reason, Freshwater Wetlands are not included in the change analysis component, as mapping likely overestimated wetland acreage in 2018.
Salt Marsh	<i>Large decrease from 40's to 60's – EXPECTED</i> – Due to leveeing of Giacomini in 40's, large loss of salt marsh, but acreage not equivalent. However, progradation of other estuarine wetlands might offset Giacomini loss. Feel confident in this mapping. <i>Large increase from 60's to 90's – NOT EXPECTED?</i> – Giacomini not restored yet, but progradation was creating more salt marsh in other estuarine areas.	Mapping of Salt Marsh was checked, but in general, mapping efforts looked good, given the challenges of interpreting B&W aerial imagery. There was some adjustment of boundaries in some areas. Mudflat areas north of Giacomini were mapped as Salt Marsh, as they may have supported some low-growing emergent plant species.	See 40's for discussion.	Mapping for Salt Marsh generally looked accurate. Some of the changes for Salt Marshes might result from true changes in intertidal marsh extent since the original mapping in 1994.	Mapping for Salt Marsh looked generally accurate. There is likely some discrepancy between what was and was marked as Water vs Salt Marsh in Tomales Bay, but not a large acreage. "Channel" polygons were originally included in Salt Marsh, but most were shifted to Water after review.

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Active Agriculture	Decreases from 40's to 60's – EXPECTED with reduction in row cropping Increases from 60's to 90's – NOT EXPECTED. Includes “Managed Pastures” as Active Agriculture	Active Agriculture areas were double-checked for accuracy. Generally linework appeared accurate. However, during review, question arose whether mowed areas were distinct enough in B&W aerial imagery to detect all managed areas, particularly if mowing occurred many months before aerial imagery was flown. For this reason, for final analysis, Active Agriculture was lumped into Grassland.	See 40's for discussion.	>98% of all non-forested areas checked. Grasslands or areas that are not visibly tilled, ripped, leveled, or otherwise actively managed moved to either Grassland or Open Scrub/Grassland. Dairy barns, corrals, and other associated ranch infrastructure classified as Disturbed. Because we were uncertain whether signs of mowing and other land management practices would persist over time, for the final analysis, Active Agriculture was lumped with Grassland for Change Analysis.	See 90's for discussion.
Grassland	Slight increase from 40's to 60's – EXPECTED – Ranchers may have removed shrubs to improve grazing. Dense coastal scrub decreased. Huge decrease from 60's to 90's – NOT EXPECTED – This is because pasture placed in Active Agriculture. Need to continue to cull out those areas.	Mapping of grassland areas was checked, but in general, mapping efforts looked good, given the challenges of interpreting B&W aerial imagery. Some changes were made between Active Agriculture, Grassland, and Open Scrub/Grassland.	Minor editing between Grassland/Open Scrub-Grassland/Dense Coastal Scrub to ensure consistency in classification between all three mapping efforts. Some larger Grassland polygons were split and separated into more fine-scale categories such as Open Scrub/Grassland or Dense Coastal Scrub or merged into adjacent appropriate polygons.	A large percentage (>98%) of areas with potential grassland in the 90's re-evaluated. Active Agriculture or pasture areas without obvious signs of active management were moved to either Grassland or Open Scrub/Grassland. Also, there was a lot of movement between Grassland (<10% Shrubs; interspersed) and Open Scrub/Grassland (≥10% and <60% Shrubs). In some instances, polygons were cut and re-merged to maintain the designated percent cover.	Grassland areas mapped in '18 were extensively reviewed and edited to ensure compatibility with past mapping efforts. There was a lot of movement between Grassland, Open Scrub/Grassland, and Dense Coastal Scrub. A large number of polygons originally crosswalked to Grassland were recategorized to either Cliffs (if they were located on steep cliffs that were marked as such in earlier years), Dense Coastal Scrub (if they were on these cliffs but had a higher vegetation cover), Active Agriculture (if mowing is evident), or Open Scrub/Grassland to align with thresholds.
Open Scrub/Grassland	Slight increase from 40's to 60's – EXPECTED – Dense coastal scrub did decrease as well. More agricultural management. Big increase from 60's to 90's – EXPECTED? – Again, Dense coastal scrub decreased.	Mapping of Open Scrub/Grassland areas was checked, but in general, mapping efforts looked good, given the challenges of interpreting B&W aerial imagery. Some changes were made between Active Agriculture, Grassland, and Open Scrub/Grassland.	Minor editing between Grassland/Open Scrub-Grassland/Dense Coastal Scrub to ensure consistency in classification between all three mapping efforts. Some larger Grassland polygons were split and separated into more fine-scale categories such as Open Scrub/Grassland or Dense Coastal Scrub or merged into adjacent appropriate polygons.	A large percentage (>98%) of areas with potential grassland in the 90's were re-evaluated. Active Agriculture or pasture areas without obvious signs of active management were moved to either Grassland or Open Scrub/Grassland. Also, there was a lot of movement between Grassland (<10% Shrubs; interspersed) and Open Scrub/Grassland (≥10% and <60% Shrubs) and Dense Coastal Scrub (Shrubs ≥ 60%). In some instances, polygons were cut and re-merged to maintain the designated percent cover.	Open Scrub/Grassland areas mapped in '18 were extensively reviewed and edited to ensure compatibility with past mapping efforts. There was a lot of movement between Grassland, Open Scrub/Grassland, and Dense Coastal Scrub.
Dense Coastal Scrub		Mapping of Dense Coastal Scrub areas was checked, but in general, mapping efforts looked good, given the challenges of interpreting B&W aerial imagery.	Minor editing between Grassland/Open Scrub-Grassland/Dense Coastal Scrub to ensure consistency in classification between all three mapping efforts. Some larger Grassland polygons were split and separated into more fine-scale categories such as Open	>70% of areas mapped as Dense Coastal Scrub or Open Scrub/Grassland were reviewed in non-forested areas of the park. Many areas of Open Scrub/Grassland were moved to Dense Coastal Scrub. It was less common to move Dense Coastal Scrub to Open Scrub/Grassland. In some instances,	Dense Coastal Scrub areas mapped in '18 were reviewed and edited to ensure compatibility with past mapping efforts. There was a lot of movement between Grassland, Open Scrub/Grassland, and Dense Coastal Scrub. Also, Dense Coastal Scrub likely increased as some Cliffs polygons

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			Scrub/Grassland or Dense Coastal Scrub or merged into adjacent appropriate polygons.	polygons were cut and re-merged to maintain the designated percent cover.	previously crosswalked to Grasslands or Cliffs were recategorized as Dense Coastal Scrub per Cliffs rules (>50% vegetation on a cliff is Dense Coastal Scrub).
Unvegetated Dunes	Moderate decrease from 40's to 60's – EXPECTED – Due to spread of European beachgrass and iceplant Small decrease from 60's to 90's – NOT EXPECTED – There should be continued moderate to large decreases due to expansion of clonal invasives. ABR noted that some Cliffs mapped in 90's map as Unvegetated Dunes, especially to the north near Tomales Point.	Mapping of Unvegetated Dunes was checked, but in general, mapping efforts looked good. These were perhaps among the easier areas to map on B&W aerial imagery. There was some adjustment of boundaries in some areas. Some areas mapped as Dense Coastal Scrub in dune fields reclassified as Vegetated Dunes.	See 40's for discussion.	See 40's for discussion.	Many polygons crosswalked to Unknown/Other were recategorized as Unvegetated Dunes.
Vegetated Dunes	Moderate increase from 40's to 60's – EXPECTED – Due to spread of clonal invasives such as European beachgrass. Moderate increase from 60's to 90's – EXPECTED - Due to spread of clonal invasives such as European beachgrass.	Mapping of Vegetated Dunes was checked, and, in general, mapping efforts looked good. Some areas mapped as Dense Coastal Scrub in dune fields reclassified as Vegetated Dunes.	See 40's for discussion.	See 40's for discussion.	Vegetated dunes were dramatically mis-categorized in the original crosswalk as Grassland, Open Scrub/Grassland, or Dense Coastal Scrub. Upon review, many polygons were re-categorized as Vegetated Dunes. Vegetated dunes included areas invaded by European beachgrass or iceplant as well as Dune Scrub areas occurring on sandier, dune-derived soils.

Table 6. Summary of acreages of primary vegetation communities mapped between the 1940's and 2018. Sums shown in italics for 2018 show areas that were not fully checked for consistency (Freshwater Wetlands).

Vegetation Community	40's	60's	90's	18
Beach	519	600	622	728
Bishop Pine	2,966	2,515	4,011	4,604
Cliffs	767	582	654	399
Cypress	24	23	24	39
Dense Coastal Scrub	11,475	11,025	10,985	10,561
Disturbed	351	614	789	598
Douglas-fir	8,694	8,303	10,004	10,431
Eucalyptus	43	65	89	122
Freshwater Wetland	2,104	2,109	1,886	<i>2,135</i>
Grassland	20,550	21,030	10,845	11,428
Hardwood Forest ¹	3,694	3,963	5,262	5,996
Open Scrub/Grassland	4,858	5,454	10,694	8,240
Riparian Forest/Shrubland	1,430	1,201	1,680	1,954
Salt Marsh	810	460	604	809
Unknown/other	0	0	0	46
Unvegetated Dunes	458	349	197	221
Vegetated Dunes	1,601	1,846	2,074	2,162
Water	3,055	3,159	3,130	2,659
Total	63,399	63,298	63,551	63,132
¹ Subtotal of HF that is riparian	915	658	567	Not mapped

Table 7. Summary of acreage changes between mapping periods based on totals adjusted for potential mapping error (i.e., confidence limits). NA signifies that potential error exceed raw totals for acreage change and therefore is not being quantitatively assessed.

	1940's-1960's			1960's-1990's			1990's-2018		
Vegetation Community	Raw Change	Pot. Error	Adj Change	Raw Change	Pot. Error	Adj Change	Raw Change	Pot. Error	Adj. Change
Bishop Pine	-450	363	-87	1,496	206	1,290	593	126	467
Dense Coastal Scrub	-450	1,469	NA	-41	771	NA	-424	325	-99
Disturbed	263	59	205	175	47	128	-191	22	NA
Douglas-fir	-392	1,111	NA	1,701	615	1,086	427	304	123
Freshwater Wetland	6	274	NA	-223	143	-80	249	80	NA
Grassland	480	2,696	NA	-10,185	1,268	-8,917	583	331	252
Hardwood Forest	269	494	NA	1,299	303	996	734	165	569
Open Scrub/Grassland	596	661	NA	5,240	487	4,753	-2,454	296	-2,158
Riparian Forest/Shrubland	-229	174	-55	479	94	385	274	53	221
Salt Marsh	-350	34	-317	144	21	123	205	20	185
Unvegetated Dunes	-109	54	-55	-152	21	-131	24	6	18
Vegetated Dunes	245	220	25	228	134	94	88	63	25

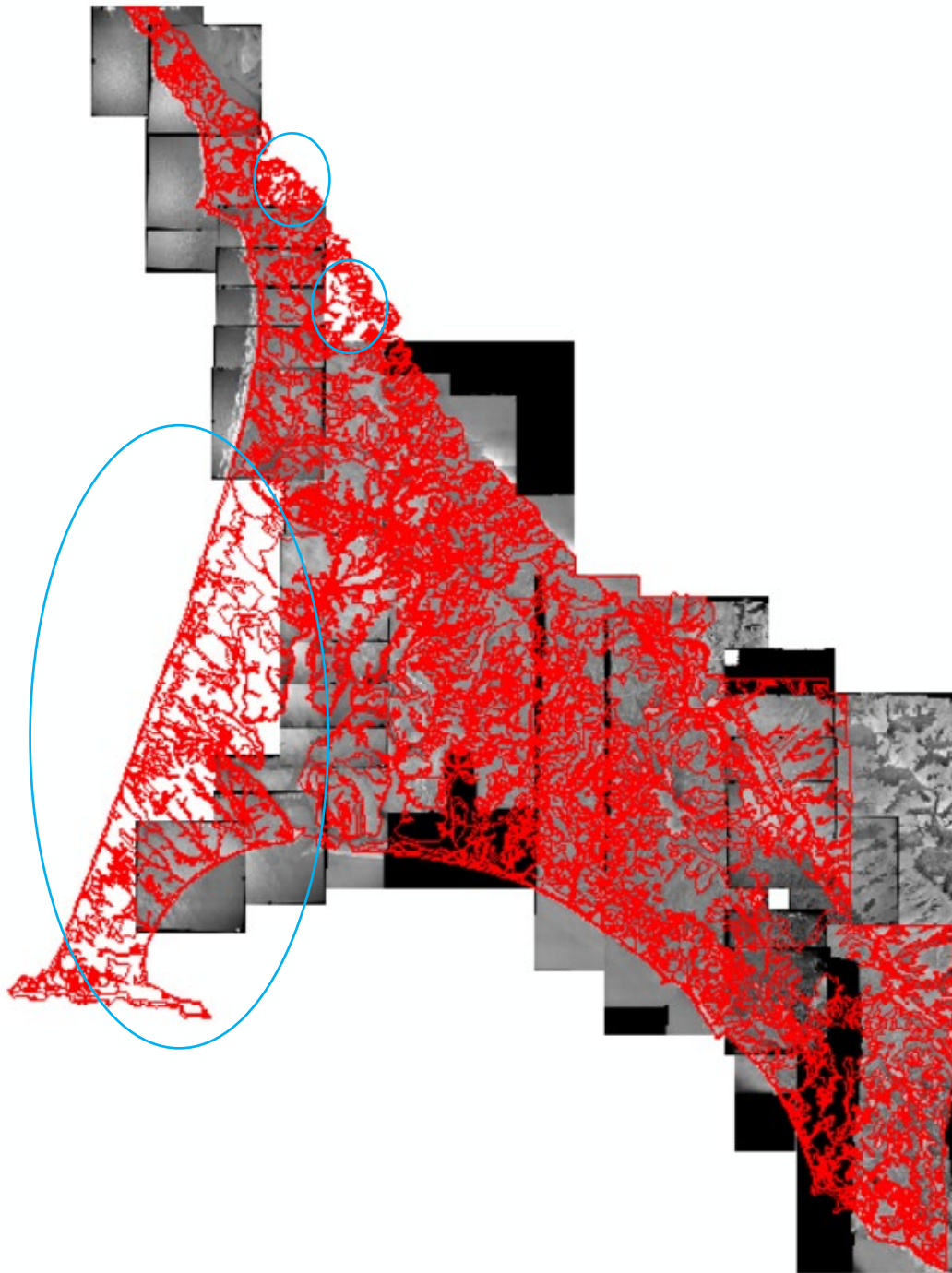


Figure 1. Blue areas denote geographic regions where 1965 aerial imagery was not available.

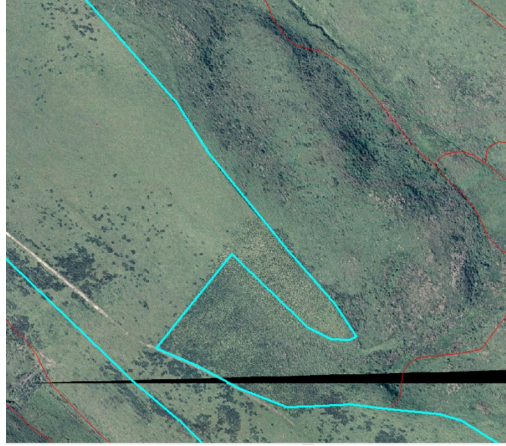


Figure 2a. Dense Coastal Scrub on right and Open Scrub/Grassland on left.

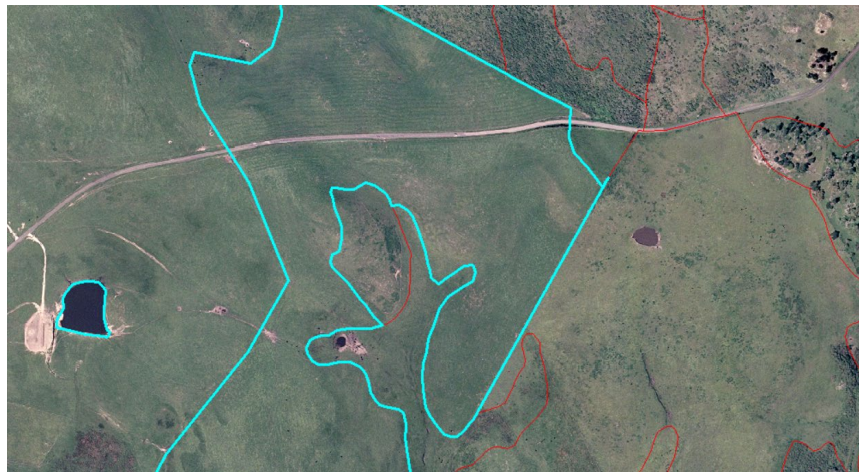


Figure 2b. Grassland (left); Active Agriculture (middle); Open Scrub/Grassland (right). There are shrubs on left, but fewer. Mowing patterns are evident in Active Agriculture.

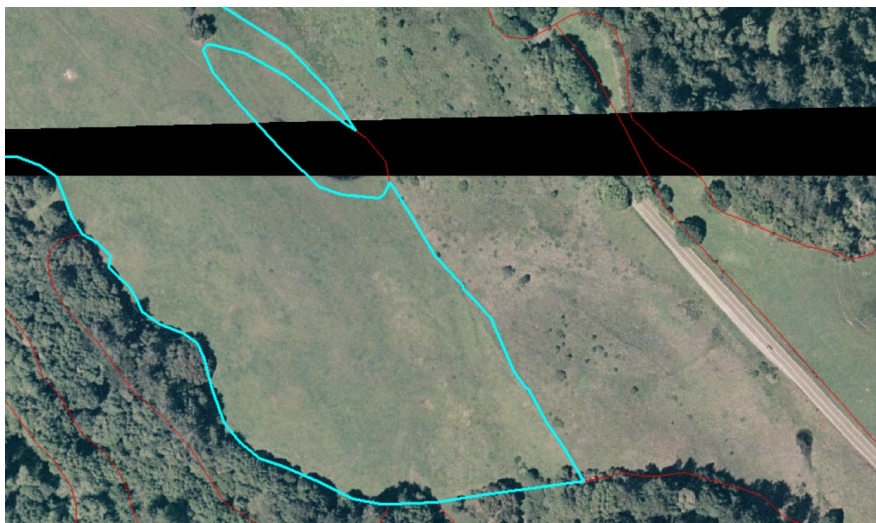


Figure 2c. Grassland (Left); Open Scrub/Grassland (Right)

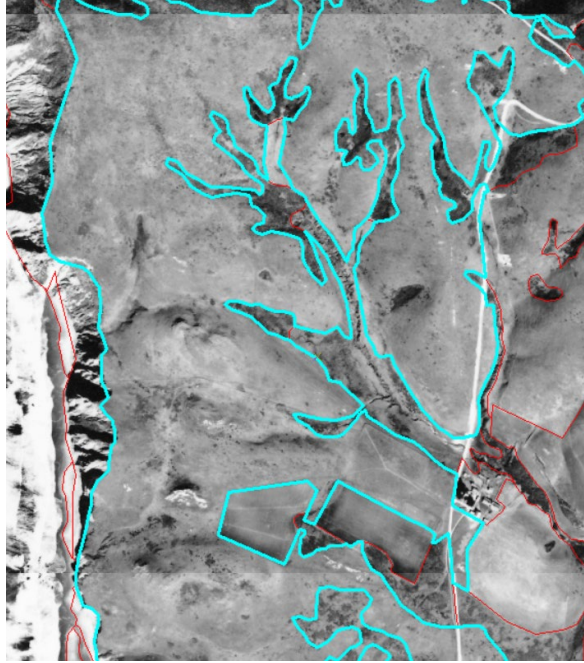


Figure 2d. Area originally mapped as Grassland switched to Open Scrub/Grassland



Figure 3. Bishop pine Forest (left) vs Hardwood Forest (right). California bay trees in Hardwood Forest showed wind-based “shirred” appearance.

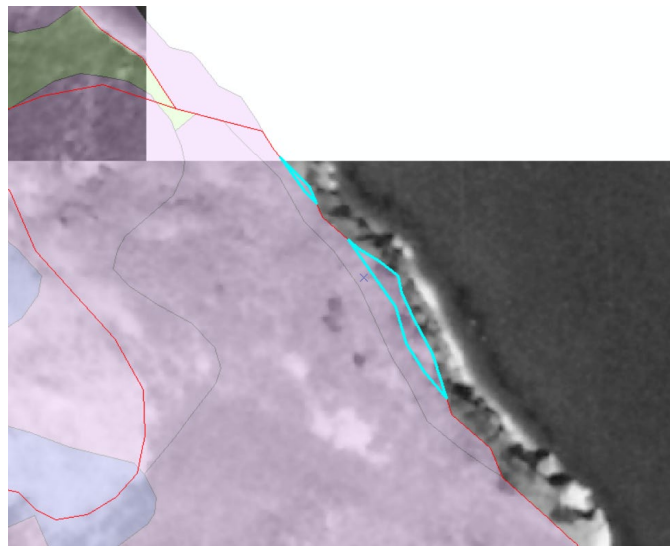


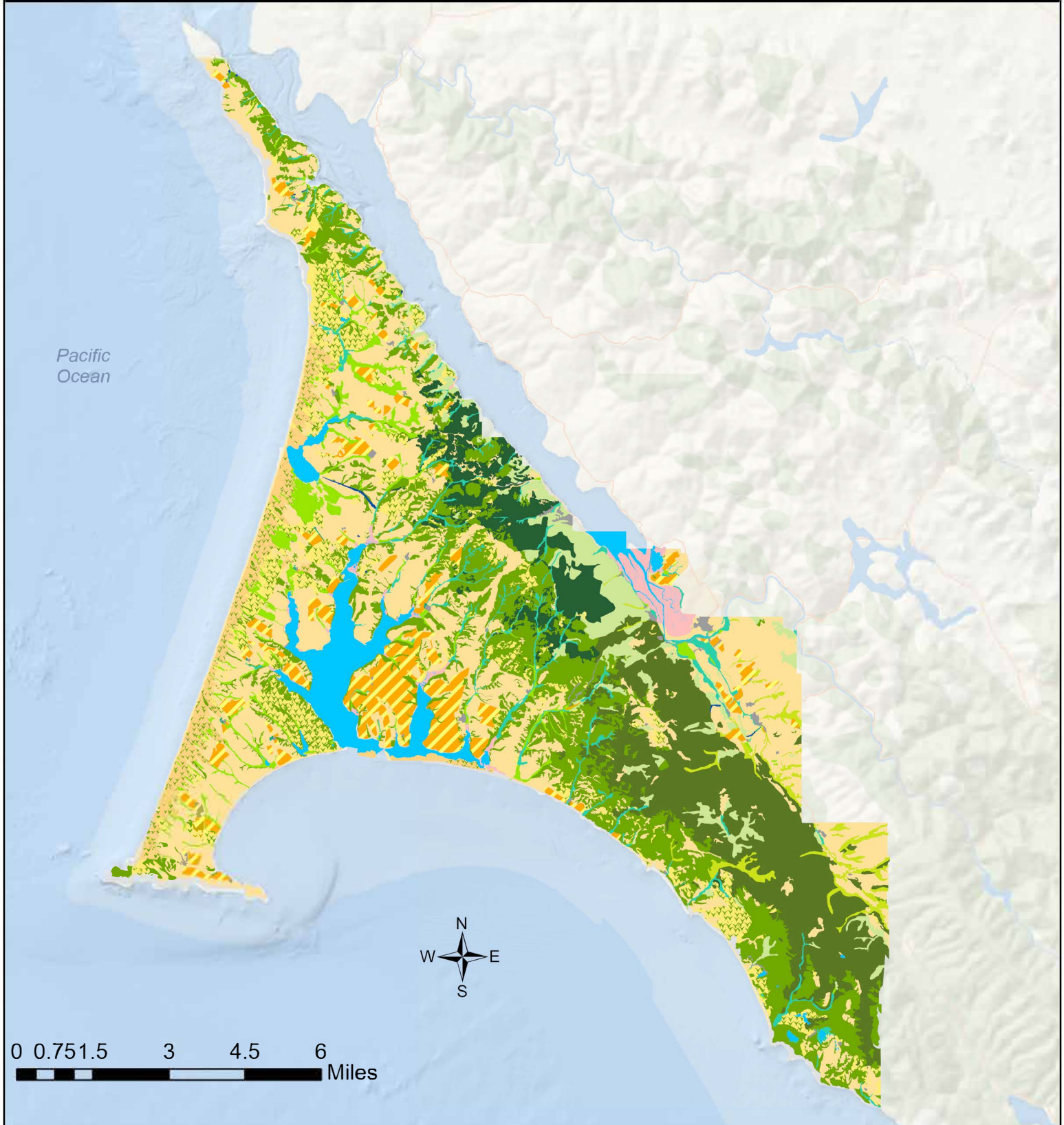
Figure 4. Edge of 40's aerial imagery extends beyond edge of vegetation mapped in 40's (red line) and 90's (colored polygons).



(a)

(b)

Figure 5. (a; Left Photo). Douglas-fir on top; California bay (Hardwood Forest) on bottom. Hardwood Forest stand was mapped as Hardwood Forest (RF), as a creek runs through this stand. (b; Right Photo) Riparian Forest/Shrubland with willow, alder, or maple in blue outline on top right; Below that (bottom right) is thin polygon identified as Hardwood Forest (RF), as it is directly adjacent to creek. To the bottom left is Douglas-fir stand. Top left is Hardwood Forest. Note shirred look to Hardwood Forest, except in creek corridor where trees are generally larger than upland stands.



Vegetation Community (1940s)

Active Agriculture	Dense Coastal Scrub	Grassland	Salt Marsh
Beach	Disturbed	Hardwood Forest	Unknown/other
Bishop Pine	Douglas-fir	Hardwood Forest (RF)	Unvegetated Dunes
Cliffs	Eucalyptus	Open Scrub/Grassland	Vegetated Dunes
Cypress	Freshwater Wetland	Riparian Forest/Shrubland	Water

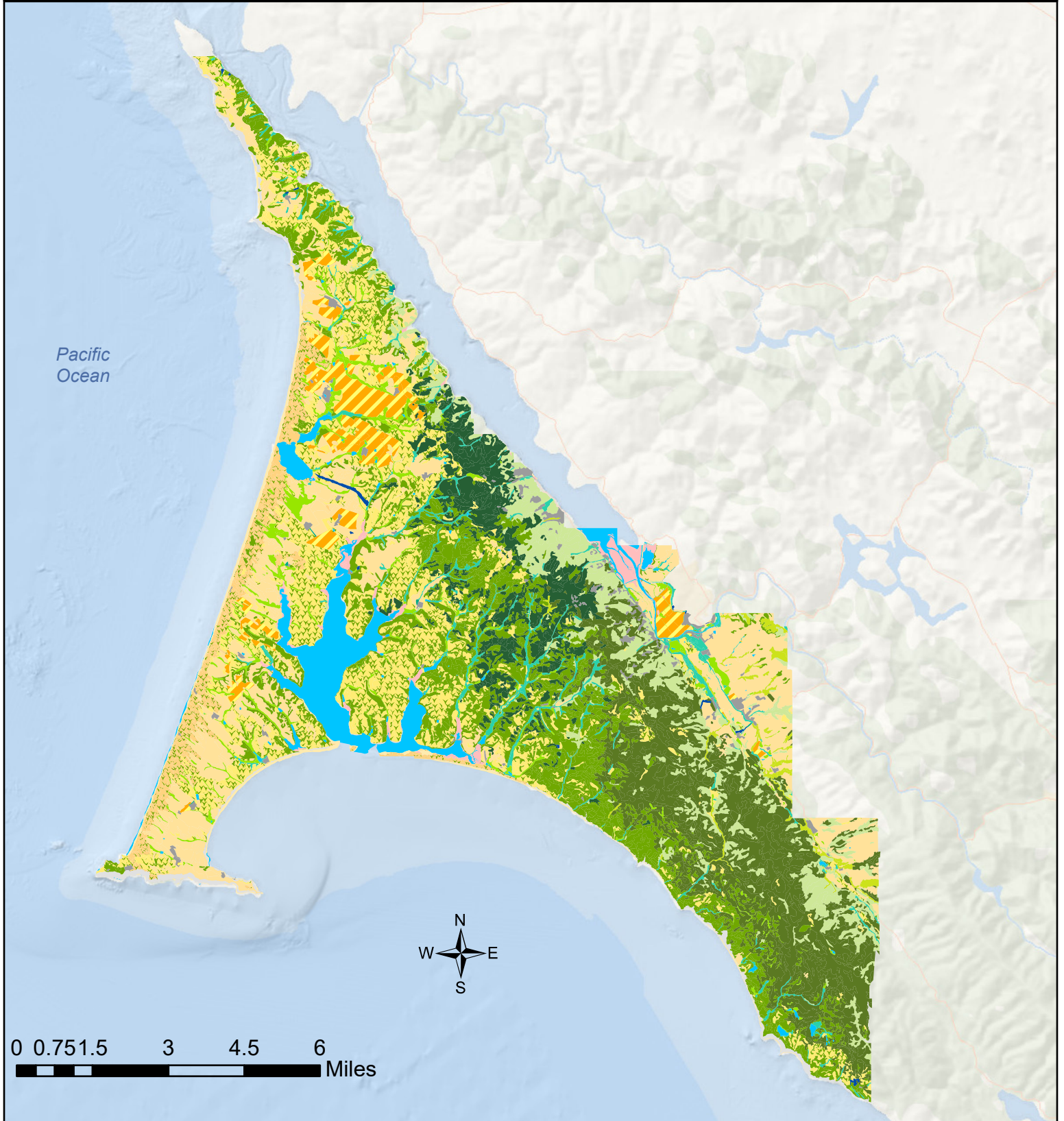
Figure 6 - Vegetation communities and other landcover types mapped using aerial imagery from 1943.



Vegetation Community (1960s)

Active Agriculture	Dense Coastal Scrub	Grassland	Salt Marsh
Beach	Disturbed	Hardwood Forest	Unknown/other
Bishop Pine	Douglas-fir	Hardwood Forest (RF)	Unvegetated Dunes
Cliffs	Eucalyptus	Open Scrub/Grassland	Vegetated Dunes
Cypress	Freshwater Wetland	Riparian Forest/Shrubland	Water

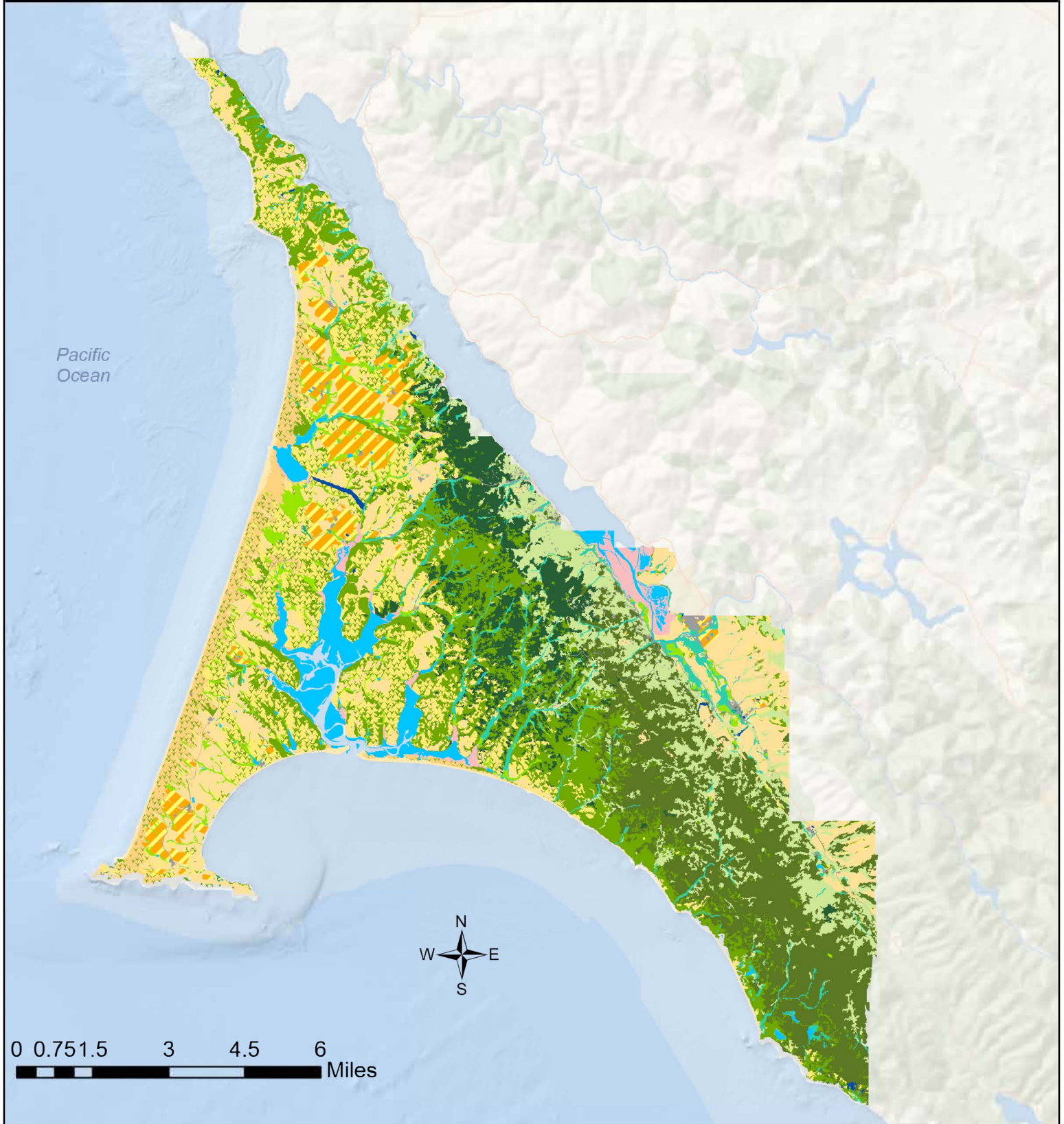
Figure 7 - Vegetation communities and other landcover types mapped using aerial imagery from 1963 and 1965.



Vegetation Community (1990s)

Active Agriculture	Dense Coastal Scrub	Grassland	Salt Marsh
Beach	Disturbed	Hardwood Forest	Unknown/other
Bishop Pine	Douglas-fir	Hardwood Forest (RF)	Unvegetated Dunes
Cliffs	Eucalyptus	Open Scrub/Grassland	Vegetated Dunes
Cypress	Freshwater Wetland	Riparian Forest/Shrubland	Water

Figure 8 - Vegetation communities and other landcover types mapped using aerial imagery from 1994.



Vegetation Community (2018)

Active Agriculture	Dense Coastal Scrub	Grassland
Beach	Disturbed	Hardwood Forest
Bishop Pine	Douglas-fir	Hardwood Forest (RF)
Cliffs	Eucalyptus	Non-native Forest
Cypress	Freshwater Wetland	Open Scrub/Grassland
	Redwood	Unvegetated Dunes
		Vegetated Dunes
		Riparian Forest/Shrubland
		Salt Marsh
		Unknown/other
		Water

Figure 9 - Vegetation communities and other landcover types mapped using aerial imagery from 2018.

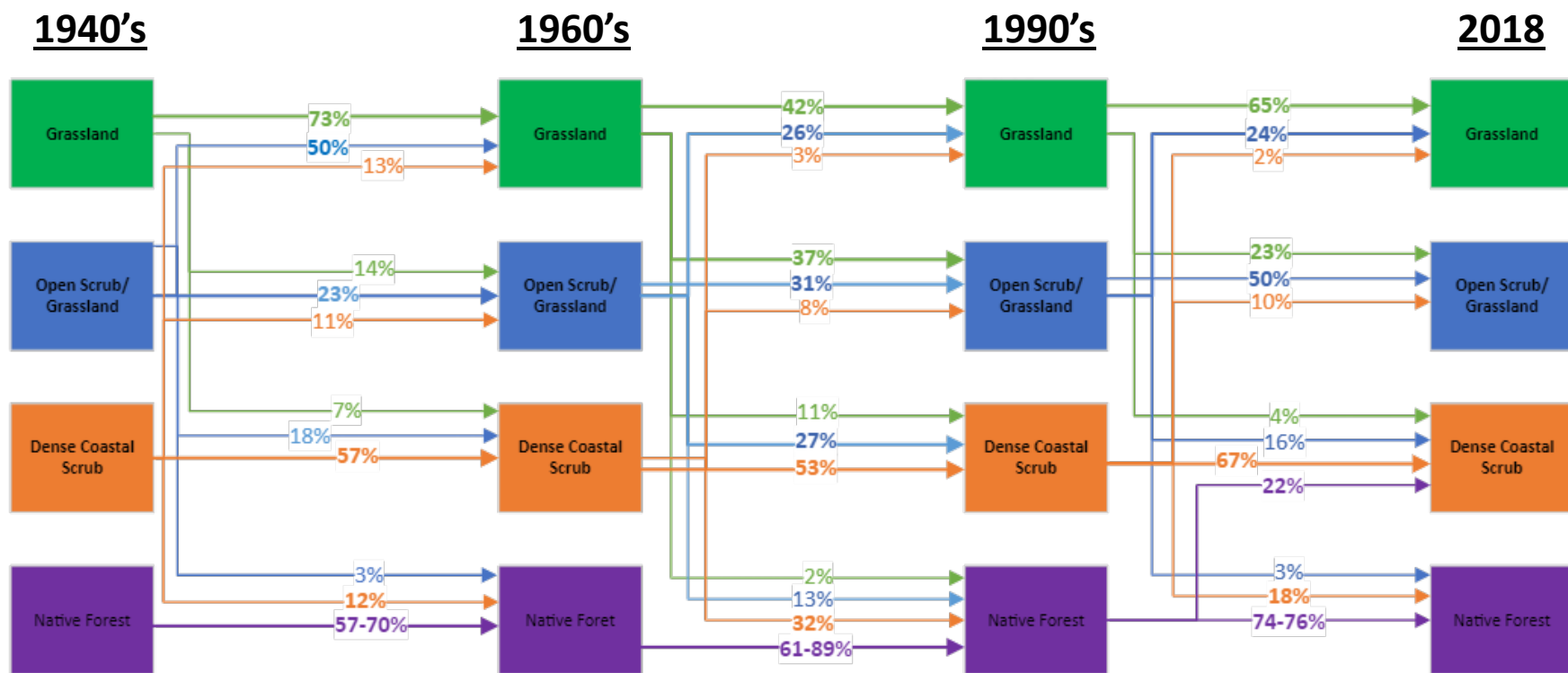


Figure 10. Diagram showing transitions between key vegetation communities between the various change analysis periods. Percentages are derived from classification matrix analyses performed by Tukman Geospatial. Percentages may not necessarily sum to 100%, because not all communities are incorporated into the diagram. Poor imagery quality for earlier mapping periods introduces some error into transitions documented for these communities, particularly between forest types and, to some extent, Dense Coastal Scrub, so transitions between specific forest types such as Douglas-fir, Bishop pine, and Hardwood Forest are not shown. These communities are lumped as “Native Forest.”

**APPENDIX A: HISTORIC VEGETATION MAPPING PROJECT:
PRELIMINARY METHODS, RESULTS, AND NOTES
(AMELIA RYAN, PRNS, 2016)**

Historic Vegetation Mapping Project

Preliminary Methods, Results, and Notes

Background

The Historic Vegetation Mapping Project is a joint project of USGS and NPS. In 2007 ??? USGS approached NPS (?) with a project to scan and georectify historic black and white aerial imagery of Point Reyes National Seashore (Seashore) with the aim of using that imagery to analyze historic resource conditions. In meeting with park managers, several potential uses of the historic imagery were identified as of interest to park managers, in particular, historic land use activities, vegetation communities, and the location and extent of historic roadways. Vegetation Community mapping to the degree possible given the quality of the imagery, with land management activities also noted where feasible, soon rose to the top as something that would be both useful and feasible. This vegetation community mapping would be backcrossed with the existing NPS vegetation map created in 1994 by a combination of using spectral imaging of four color band aerial imagery (remote sensing) and adjustment based on ground truthing. This vegetation map had much more detailed plant communities than was expected to be discernable from historic aerial images, but had multiple, hierarchical levels of plant community classification, including broad ones equivalent to what would be discernable in black and white imagery.

Methods

USGS staff led by USGS scientist Alicia Torregosa scanned and georectified (aligned with real-world coordinates) aerial images of the Seashore. Raw imagery was either owned by NPS or acquired by USGS. Aerial imagery taken in airplane overflights was available for a number of years, but not all sets are complete. The oldest, largely complete, dataset was from 1942 (and 1943). This dataset was scanned and georectified first. A series of datasets were available from the early 1960s, flown between 1962-1965. The datasets overlapped in places and not in others, but together covered most of the seashore. These were also selected for scanning and georectification. Other datasets were designated as lower priority due to less complete coverage, and also a desire to space mapping efforts out over the span of years from the first available imagery (1940s) to the existing 1990s map.

NPS Fire Ecologist Alison Forrestel (now Golden Gate Vegetation Branch Chief) took on creating a vegetation community map of the Seashore from the 1940s aerial imagery. Staff knew from prior experience that some level of vegetation community mapping would be feasible (grassland can readily be distinguished from forest), but were not certain precisely how much detail would be discernable, nor how precise and accurate the results would be. After taking an initial look at the imagery and at the methodology for the 1994 Vegetation Map, Forrestel convened a group of managers experienced in vegetation management to evaluate what level of plant community mapping would be useful and feasible, and would crosswalk with the 1994 map. From this meeting, a list of vegetation communities discernable on this imagery was developed. A list of these communities can be found in Appendix 1. Unlike scrub and grassland communities, forests were often able to be mapped to dominant tree type because the shape of the crowns, coupled with their relative value (gradation from dark to light) were

distinctive. Point Reyes Vegetation Branch Chief/Vegetation Ecologist Lorraine Parsons mapped the salt marsh and most of the freshwater marsh portions of the 1943 vegetation map.

After Forrestel completed the 1943 map, she gave it to other knowledgeable people from the park (Sarah Minnick, Lorraine Parsons, Ellen Hamingson, Dylan Voeller, and Amelia Ryan) and asked them to review specific sections or habitats that they were most familiar with and report back any errors or questions they had. **Forrestel and Ryan also indepentantly mapped a section of the**

NPS Vegetation and Wetland Ecologist Amelia Ryan created a vegetation community map for the 1960s using the categories developed by Forrestel in the earlier mapping effort. Aerial imagery from the 1960s period was more detailed and at time more than one image, separated by a year or two, was available for the same site. Where two photos were available, the better rectified image was used, unless the quality was low, in which case the image with greater resolution was used.

The vegetation map for each of the two periods (1940s and 1960s) was created by hand digitization over the scanned, georectified imagery using ArcMap (versions 9.2-10.2 ESRI, Redlands, California, ©1995-2014), a GIS mapping and modeling platform. Vegetation community boundaries were determined by changes in value and texture. Grasslands and Active Agriculture were both light in value, but Active Agriculture had a pattern of regular rows from tilling, brush-cutting, or ripping. Coastal scrub was dark with small crowns. Open scrub had small dark crowns scattered in lighter grassland. Development of a characteristic pattern in color and texture of each vegetation type partly relied on knowledge by the mapper of the current plant community of the site, the texture and value of that vegetation from more recent aerial imagery, and some knowledge of the history of the location. For example, knowledge that Bishop pine forests may have occupied a different extent in the 1940s then the present, but that the zone of occurrence largely overlapped, such that a stand of round-crowned trees in a location where there are currently round-crowned bishop pines was likely also bishop pines, and not some other tree with a similar crown shape. Forest community dominant were further refined by examining imagery using stereoscopic viewing equipment at USGS offices, Menlo Park, California. Once a boundary was determined, it was outlined in the ArcMap shapefile which contained all other vegetation community polygons for the time period in question. The vegetation community identification was then recorded in the attribute table associated with the shapefile, in the row associated with polygon in question. In that way a map was created of discrete vegetation community patches, with the community designation assigned for each location. In addition to the vegetation community, notes were also recorded about other features observed, including if more detailed vegetation information could be discerned (such as that the dense coastal scrub was Ceanothus and not coyote brush, whether or not there was any uncertainty as to the community designation).

File Pathway

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Table 1. Vegetation Mapping Classes

Category	Notes	Community	Super Cluster	Best crosswalk
Riparian Forest	Will map based on what is visible in imagery. Should include riparian shrubs.	Riparian Forest and shrubland	Winter Deciduous Forest/Scrub	Riparian Forest and shrubland VMC
Hardwood Forest	I think from the veg map hardwoods need to make up 60% of cover.	Hardwood Forest	Winter Deciduous Forest/Scrub & Evergreen Forest and Wetland	Hardwood Forest VMC
Douglas-fir	Mimimum tree cover is 15%	Douglas-fir/coast redwood	Evergreen Forest and Wetland	Douglas-fir superalliance
Redwood	Mimimum tree cover is 15%	Douglas-fir/coast redwood	Evergreen Forest and Wetland	Redwood-tanoak superalliance
Eucalyptus	Mimimum tree cover is 15%	Hardwood Forest	Evergreen Forest and Wetland	Eucalyptus superalliance
Bishop pine	Mimimum tree cover is 15%	Bishop pine	Evergreen Forest and Wetland	Bishop pine VMC
Chaparral		Coastal scrub	Chaparral	Chaparral supercluster
Dense coastal scrub	mimimum for dense scrub cover - 50% based on vegmap field key	Coastal scrub	Coastal scrub	Dense coyotebrush and related scrub mesocluster
Open scrub/grassland	Mimimum scrub cover is 15%; needs to be interspersed with grassland not clumpy	Coastal scrub	Coastal scrub	Drier coastal grassland and open scrub mesocluster
Grassland	includes areas that are grazed	Grassland	Grassland-herbaceous	Grassland VMC
Fresh water wetland	soil types will help with this	Herbaceous wetlands	Grassland-herbaceous	Freshwater wetland herb mesocluster
Salt Marsh	max elevation 5-7', soil types will help with this	Herbaceous wetlands	Salt Marsh	Salt Marsh supercluster
Vegetated dunes	may be some confusion about where dune veg ends and grass/shrubs starts	coastal dunes	Coastal scrub	Coastal dunes VMC
Unvegetated dunes		coastal dunes	Coastal scrub	Coastal dunes VMC
Active agriculture	areas in active ag, ie row crops. Look for very distinct field edges, striped or stippled veg pattern			

Table 1. Vegetation Mapping Classes

Category	Notes	Community	Super Cluster	Best crosswalk
Water		Water	Water	Water VMC
Disturbed		built-up urban disturbance	built-up urban disturbance	built-up urban disturbance VMC
Unknown/other	I think we'll need a catch all for cases we can't figure out			
Beaches				

Preliminary Results

- 1) Increase in open scrub
- 2) Drop in salt marsh coverage for unknown reasons (potential mapper error).
- 3) Slight increase in Douglas-fir
- 4) Slight decrease in Dense Coastal Scrub – but mainly due to change in location (i.e. scrub increased in grasslands, but decreased in areas that were reforested).
- 5) Decrease in freshwater wetland due in part to increase in riparian?

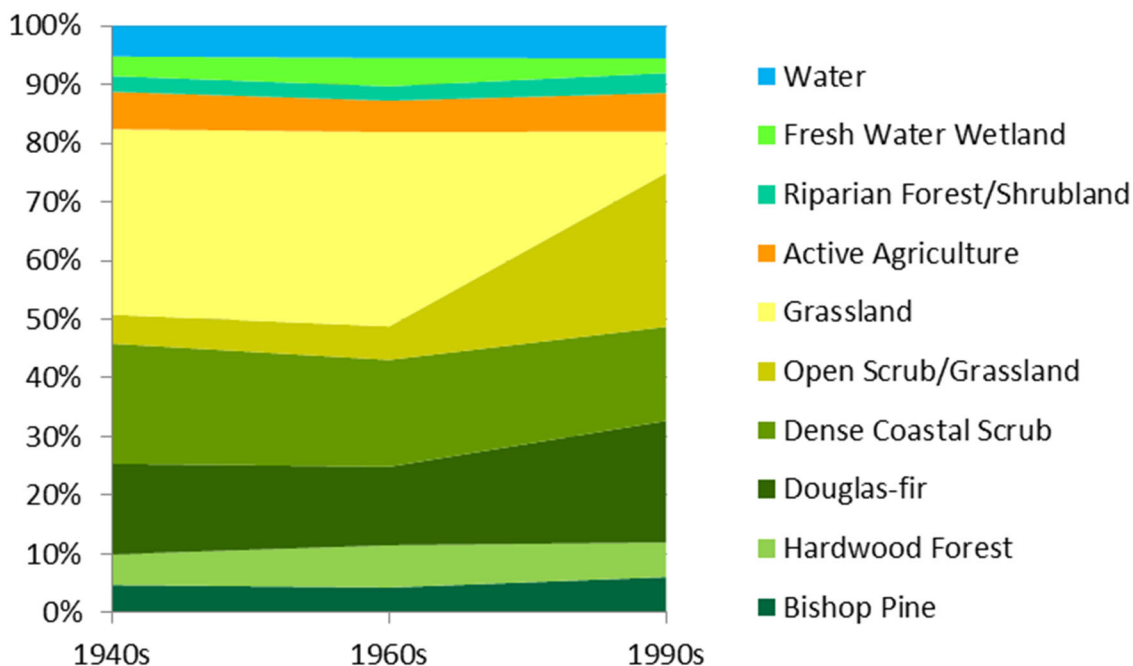


Figure 1. Preliminary Findings of Change in Percent Cover of the Most Common Vegetation Classes

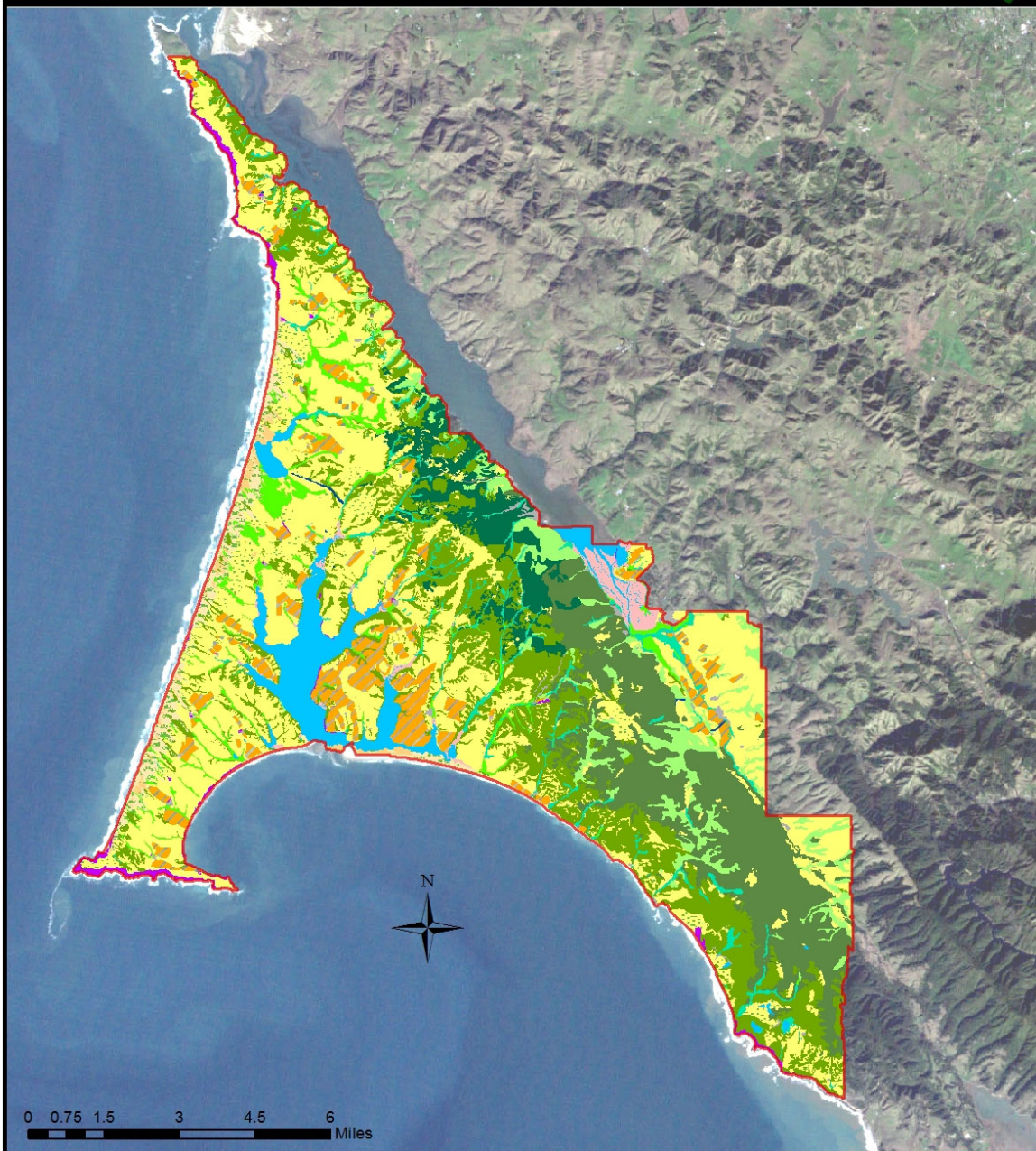
Table 2. Preliminary Comparison of Acreages of Each Vegetation Class in the 1940s, 1960s, and 1990s.

Vegetation Class	1940s	1960s	1990s
Active Agriculture	3770	3139	3802
Beach	525	682	281
Bishop Pine	2789	2525	3532
Coastal bluff/Cliff-Face	588	517	480
Dense Coastal Scrub	12126	10740	9332
Disturbed	328	584	981
Douglas-fir	9143	7889	12076
Eucalyptus	49	63	81
Fresh Water Wetland	1975	2848	1451
Grassland	18718	19535	4136

Vegetation Class	1940s	1960s	1990s
Hardwood Forest	3094	4246	3434
Monterey Cypress	22	20	69
Open Scrub/Grassland	2921	3369	15267
Riparian Forest/Shrubland	1596	1457	1997
Salt Marsh	784	377	674
Unvegetated Dunes	342	240	205
Vegetated Dunes	1384	1780	2134
Water	3087	3219	3225
Grand Total	63240	63229	63157

Historic Vegetation Mapping Project Point Reyes National Seashore

National Park Service
U.S. Department of the Interior



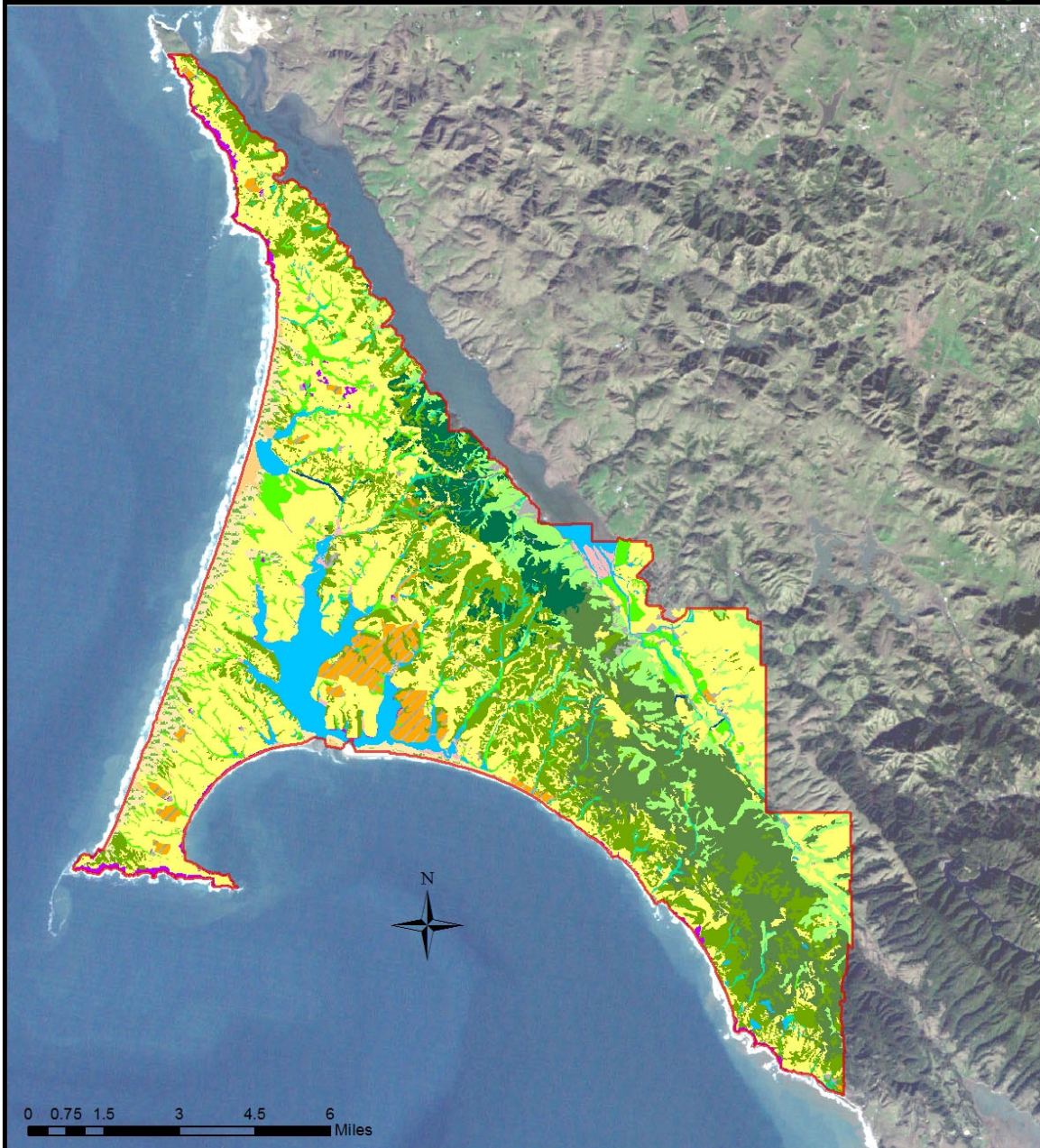
Vegetation Community					
Active Agriculture	Unvegetated Dunes	Fresh Water Wetland	Dense Coastal Scrub		
Disturbed	Vegetated Dunes	Riparian Forest/Shrubland	Hardwood Forest		
Unknown/other	Salt Marsh	Grassland	Douglas-fir		
Beach	Water	Open Scrub/Grassland	Bishop Pine		
			Eucalyptus		

Figure 1
1940s

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Historic Vegetation Mapping Project Point Reyes National Seashore

National Park Service
U.S. Department of the Interior



Vegetation Community

Active Agriculture	Unvegetated Dunes	Fresh Water Wetland	Dense Coastal Scrub
Disturbed	Vegetated Dunes	Riparian Forest/Shrubland	Hardwood Forest
Unknown/other	Salt Marsh	Grassland	Douglas-fir
Beach	Water	Open Scrub/Grassland	Bishop Pine
			Eucalyptus

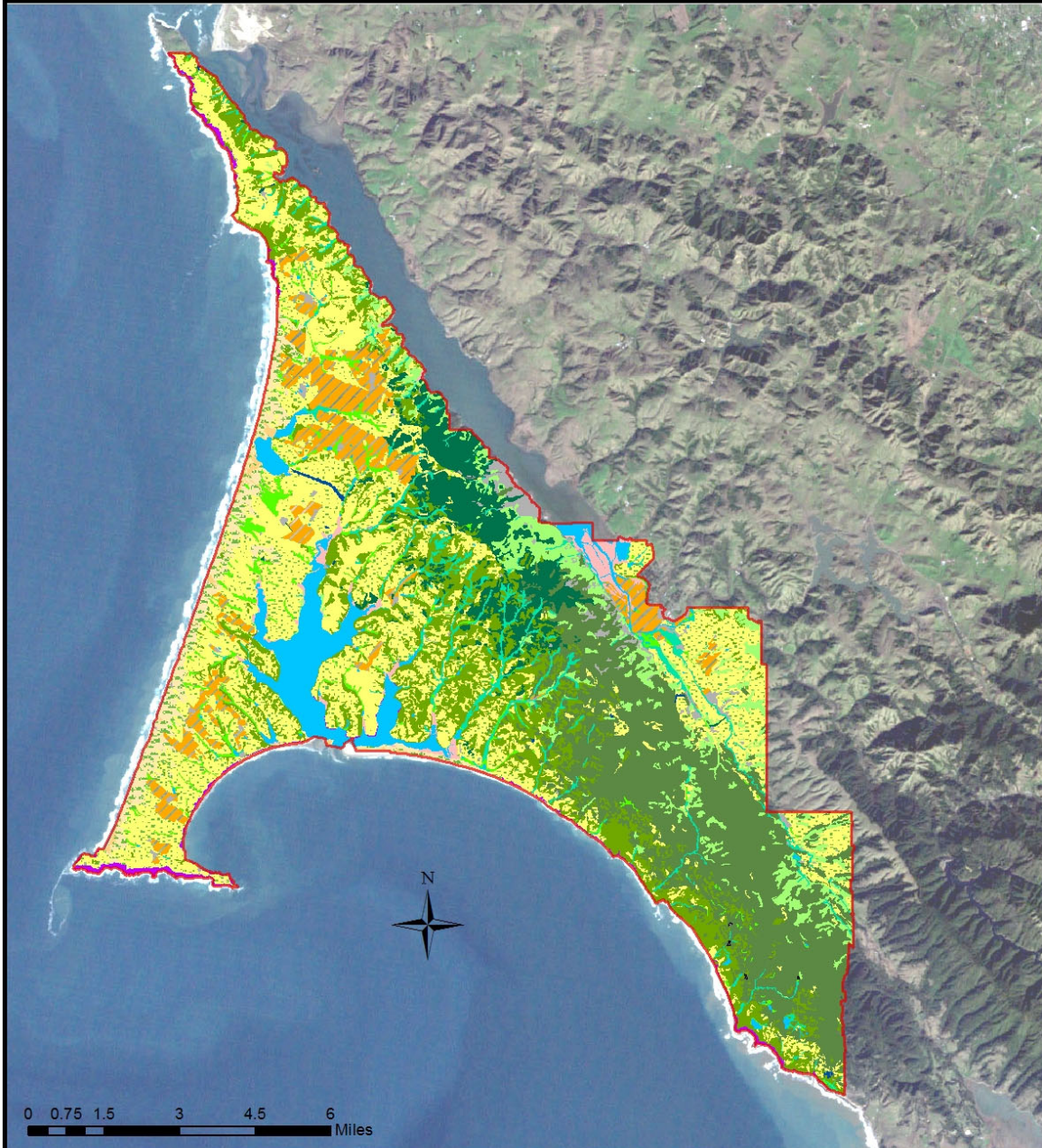
Figure 2

1960s

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Historic Vegetation Mapping Project Point Reyes National Seashore

National Park Service
U.S. Department of the Interior



Vegetation Community

<all other values>	Unvegetated Dunes	Riparian Forest/Shrubland	Douglas-fir
Active Agriculture/Pasture	Vegetated Dunes	Grassland	Bishop Pine
Disturbed	Salt Marsh	Open Scrub/Grassland	Eucalyptus
Unknown/other; Cliff, Cliffs	Water	Dense Coastal Scrub	
Beach	Fresh Water Wetland	Hardwood Forest	

Figure3

1990s

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Problems Observed Between Versions During Mapping

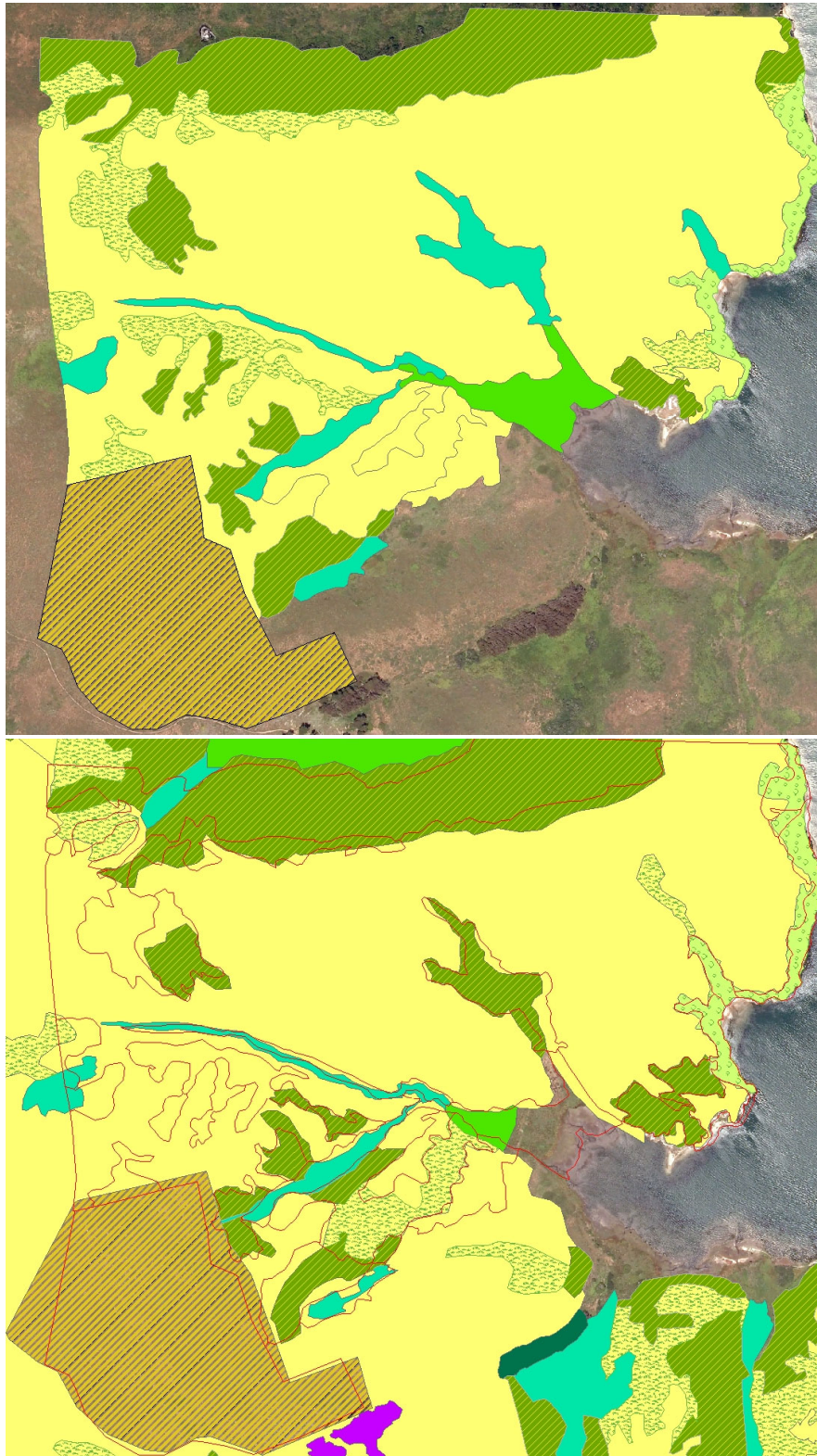
- 1) The 1960s images were higher resolution, which allowed more detail to be distinguished, which sometimes led to different choices of type. The aerials also sometimes have defects (smudges that look like shrubs, etc).
- 2) Differences between mappers effects results, especially in smaller classes (salt marsh, freshwater marsh, veg and unvegetated dunes. When do dunes become coastal scrub? What are some intermediate types? For example, freshwater marsh grades into salt marsh in the lower section, and Ryan, Forrestel, and Lorraine Parsons may have mapped things slightly differently. Also, Ryan, who spent years field mapping wetlands, sometimes recognized wet meadows that had less obvious spectral signatures as wetlands, whereas Alison often mapped them as grasslands. This was exacerbated by the difference in quality between the two image sets.
- 3) Mis-identification of what one is seeing
 - a. For example, I noticed that some white cliff faces (especially to the north near Tomales Point) were mapped as Dunes in the 1994 vegetation map
 - b. In the 1940s vegetation map Alison mapped some areas as scrub that I recognized from experience as thick Pacific reedgrass (*Calamagrostis nutkaensis*) patches. I think she tried to correct this when I pointed it out, but it is possible that some mis-identification still exist.
- 4) Active agriculture. In 1940s and 1960s maps Forrestel and Ryan mapped areas that had signs of regular linear patterns as active agriculture, assuming these were signs of tilling. However, it is not certain whether all of these were active tilling, or simply mowing and brush removal. There were other areas where the smooth, even texture of fields suggested active pasture management (brush removal, perhaps past mowing) but if there was no signs of regular line patterns, they were mapped as grassland. At some point in the process, Ryan notice that some areas that had "lines" in 1963 did not in 1965, so if one year's images were used, the sight would be "active ag" and in another simply "grassland". In the 1994 Vegetation map active ag and managed pasture were lumped, though some effort was made to separate these two classes in the file that was created from the 1994 Vegetation Map and edited to allow comparison between the two years.

Thoughts on accuracy assessment

- 1) One way to go about it might be to sample the center point of polygons in a particular year and then sample the following years to see what percent had changed from the primary year. A subsample of those that had changed could be reviewed to see if the change in type represented a true "change" or reflected differences between mappers or the quality of images (or an artifact of the sampling process)

A random sample of areas could be chosen for careful review between all three years. They could either be entirely random, or stratified into broader areas of interest (for example, a few broad zones could be made based on current or past vegetation patterns and some random places within it could be chosen).

Figure 5. Forrestel vs. Ryan (with Forrestel overlay in red) map of White Gulch in 1960s



APPENDIX B: HISTORIC VEG MAP ANALYSIS – POINT REYES NATIONAL SEASHORE
(JULIA MURPHY, TUKMAN GEOSPATIAL ANALYSTS, SANTA ROSA, CA, 2022)



Historic Veg Map Analysis - Point Reyes National Seashore

9/2/2022

Prepared for the National Parks Service by:

Julia Murphy

Tukman Geospatial, LLC

Summary

The purpose of this assessment was to analyze differences in forest cover between three historic vegetation maps (1940's, 1960's, and 1990's) of Point Reyes National Seashore and determine whether those differences were due to true cover change or errors of interpretation during the mapping process. This report provides: 1) a summary of the changes in Bishop pine, Douglas-fir, and Hardwood Forest cover between each of the historic maps, 2) an analysis of the likely reasons behind those changes, and 3) suggestions on how to address and correct errors in the datasets.

From the 1940s to the 1960s, the net changes in forest types (by mapped area) were: 9.5% decrease of Bishop pine, 14% decrease of Douglas-fir, and 37% increase of hardwood forest.

- **Bishop pine:** There was true loss of Bishop pine due to several areas of obvious removal, but significant areas of apparent Bishop pine loss can be attributed to type confusions between Bishop pine, coastal scrub, and hardwood forest.
- **Douglas-fir:** There were significant areas of accurately mapped Doug-fir transitions, including a large area of Douglas-fir removal, as well as notable expansion/encroachment of Douglas-fir into grassland and coastal scrub areas. There was also high acreage of transitions to and from hardwood forest – some accurate, but largely due to misinterpretation between the two forest types.
- **Hardwood forest:** Though some hardwood forest expansion was due to true type change (scrub transitioning to forest), the large net increase in hardwood forest seemed to be largely an issue of type confusion between hardwood and Doug-fir forests.

From the 1960s to the 1990s, the net changes in forest types (by mapped area) were: 43% increase of Bishop pine, 53% increase of Douglas-fir, and 19% decrease of hardwood forest.

- **Bishop pine:** The 1995 Vision Fire predictably caused an expansion of young Bishop pine in areas of scrub and grassland adjacent to existing Bishop pine.
- **Douglas-fir:** Large increases in Douglas-fir were accurately mapped in both expansion/encroachment of Doug-fir into grassland and coastal scrub areas, as well as re-vegetation of the area where Doug-fir was removed between the 40s and 60s. Type confusions, particularly with hardwood, likely inflated the net increase of Doug-fir acreage.
- **Hardwood forest:** Though there were some true losses of hardwood forest due to development, the majority of apparent transitions were due to type confusions with Douglas-fir.

To address and correct errors in the maps, I suggest the following:

- **Manual edits:** Using the “Misclassified” and “MMU” error type bookmarks as a guideline to revisit and correct the original maps, with particular attention to areas where Douglas-fir and hardwood mix.
- **Calibration:** Ensuring that different mappers are calibrated in their mapping instructions: e.g. the minimum mapping unit of vegetation to pull out of a larger contrasting veg type, or threshold calls between hardwood and conifer types.
- **Change analysis:** Quantifying change analysis using a point-based sampling system, rather than on total acreages of forest types. This could minimize the effects of slight alignment issues and focus analysis on areas of true change.

Methodology

National Parks Service (NPS) provided three historic vegetation map shapefiles (1940s, 1960s, and 1990s), as well as imagery sets from 1943, 1963, 1965, 1994 (not used, due to lack of georeferencing) and 2004. The analysis was conducted with the following steps:

1. Overlay (union) the maps (1940s + 1960s, 1960s + 1990s)
2. Classify the resulting polygons with *Veg_Type_Diff* (e.g. Bishop pine to Douglas-fir)
3. Break out and dissolve those according to three categories:
 - a. *Apparent forest loss*: from a forest type to a non-forested type
 - b. *Apparent forest gain*: from a non-forested type to a forest type
 - c. *Apparent forest change*: from one forest type to another forest type
4. Sample from polygons >1 acre (to eliminate most slivers) in each category, aiming for spatial and type-conversion representation.
5. Photointerpret the vegetation type in each year.
6. Using a point layer, assign a *Change Type* (the type of error) and a *Likely reason* for that change or error, along with comments for further clarification.

The following table shows the attributes for *Change Type*:

Code	Description
Misclassification_40	Veg type misidentified in 40s map
Misclassification_60	Veg type misidentified in 60s map
Misclassification_90	Veg type misidentified in 90s map
Cover Change	Accurate classification, difference is due to true change in veg type
Alignment	Error seems to stem from imagery alignment issues between years
MMU	Minimum mapping unit (MMU) and related issues. These can include lumping/splitting (e.g. small areas of a veg type not pulled out) as well as difficult calls on the threshold between forest types.
Unknown	Not able to assess the reason for veg type change.

To give more clarifying information about the coded Change Types, a *Likely Reason* was assigned with a judgment about the possible explanation for errors or actual land cover changes. The following table shows the attributes of those reasons:

Code	Description
Forest expansion	True forest expansion
Forest removal	Forest loss or clearing
Sliver	Slivers (borders) likely due to alignment issues
Alignment	Large (non-border) alignment issues
True BP	True Bishop pine, misidentified as another veg type
True DF	True Douglas-fir, misidentified as another veg type
True HW	True Hardwood forest, misidentified as another veg type
Other type misclassification	True vegetation is something other than BP, DF, or HW.
Riparian	Riparian corridors added, changed, or misaligned.

	Generally not due to change between years, but rather interpretation and updates as imagery quality improved over the years.
Subjective calls	Lumping/splitting, differences in how mappers draw borders, and threshold calls between forest types where they mix (e.g. where Douglas-fir mixes with hardwood)
Image quality	Image quality issues other than alignment, including warping, shadows, and resolution.

DRAFT

Analysis of 1940s to 1960s

For all forest types and changes, 5255/7876 (67%) acres of polygons greater than 1 acre were assessed and assigned a likely error type and reason for the change:

- **Accurate cover change:** 26% (2058 acres) assessed as accurate cover change. This included notable areas of Bishop pine removal along Pierce Point Rd, Doug-fir removal south of Firtop Peak, as well as Doug-fir expansion into grasslands.
- **Misclassified in 40s:** 17% (1333 acres) assessed as mapped incorrectly in the 40s. This largely consisted of type confusions between Douglas-fir and hardwood forest, and can likely be attributed to the difficulty of interpreting the low-resolution 1940s imagery.
- **Misclassified in 60s:** 11% (886 acres) assessed as mapped incorrectly in the 60s. Again, this was primarily due to type confusions between Douglas-fir and hardwood forest.
- **MMU Issues:** 5% (399 acres) assessed as errors due to MMU/judgement calls. Often, these were due to the 1960s being mapped more finely than the 1940s, e.g. pulling out small patches of grassland within an area of Doug-fir.
- **Alignment:** 5% (386 acres) assessed as errors due to image alignment. This acreage would be higher if polygons <1 acre were included in the assessment, due to clear and consistent mis-alignment between the imagery. Image alignment between the 40s and 60s was a consistent issue that created a high number of slivers.
- **Unable to assess:** 2.5% (192 acres) were areas where I could not determine the true veg type in one of the years, or the source of the error (if erroneous), due to image quality.

The table below is a simplified confusion matrix of the apparent transitions between the three forested types plus “other” non-forested areas. Note that these totals differ from the “assessed” acreages, because these include all polygons rather than only those greater than an acre.

- Of the 2789 acres mapped as **Bishop pine** in the 40s: 57% remained Bishop pine, 0.6% transitioned to Douglas-fir, 13% transitioned to hardwood forest, and 30% transitioned to non-forested vegetation.
- Of the 9143 acres mapped as **Douglas-fir** in the 40s: 62% remained Doug-fir, 2.5% transitioned to Bishop pine, 18% transitioned to hardwood, and 17% transitioned to non-forested vegetation.
- Of the 3094 acres mapped as **hardwood forest** in the 40s: 54% remained hardwood, 6% transitioned to Bishop pine, 24% to Doug-fir, and 16% to non-forested vegetation.

Veg Type 40s, Classified	Veg Type 60s, Classified (Acres)				
	Bishop Pine	Douglas-fir	Hardwood Forest	Other (non-forest)	Total
Bishop Pine	1579.3	18.0	369.2	822.4	2788.9
Douglas-fir	236.8	5656.4	1663.2	1586.2	9142.6
Hardwood Forest	181.2	739.9	1664.2	509.0	3094.3
Other	527.8	1475.0	549.9	45769.9	48322.7
Total	2525.0	7889.4	4246.5	48687.5	63348.4

The table below shows apparent forest gain, areas that were mapped as non-forested in the 40s and forested in the 60s. The yellow highlights show the most common apparent veg type conversions by acreage. These transitions and their accuracy are broken down individually in the following sections.

Veg Type 40s	Veg Type 60s (acres)			
	Bishop Pine	Douglas-fir	Hardwood Forest	Total
Active Agriculture	0.2	0.4	3.7	4.3
Beach	-	-	-	0.0
Dense Coastal Scrub	413.3	1059.9	240.2	1713.3
Fresh Water Wetland	1.7	0.4	7.0	9.0
Disturbed	-	0.8	7.1	7.9
Eucalyptus	-	0.1	0.2	0.3
Grassland	51.0	211.3	178.8	441.1
Open Scrub/Grassland	21.9	68.6	11.9	102.4
Riparian Forest/Shrubland	38.9	132.1	96.7	267.7
Salt Marsh	0.3	-	0.3	0.5
Unknown/Other	-	-	2.8	2.8
Water	-	1.5	0.3	1.9
Total	527.3	1475.0	549.0	2551.3

Bishop Pine Transitions, 40s to 60s

Bishop pine to another type:

56% of 1065 acres (areas >1 acre) were analyzed. The most common reason for transition was misclassification in the 60s (23.5%, 250 acres), then true cover change (18%, 189 acres), then misclassification in the 40s (8%, 86 acres). The table below shows the transitions of Bishop pine to other forest and vegetation types (apparent forest loss or transition), with the most significant end types in the 60s highlighted.

Veg Type Transition from 40s to 60s (all polygons)	Acres
Bishop Pine to Active Agriculture	5.3
Bishop Pine to Beach	0.3
Bishop Pine to Dense Coastal Scrub	378.2
Bishop Pine to Disturbed	48.5
Bishop Pine to Douglas-fir	18.0
Bishop Pine to Fresh Water Wetland	32.5
Bishop Pine to Grassland	176.7
Bishop Pine to Open Scrub/Grassland	58.1
Bishop Pine to Riparian Forest/Shrubland	120.0
Bishop Pine to Salt Marsh	0.4
Bishop Pine to Water	2.4
Bishop Pine to Hardwood Forest	369.2
Total	1209.6

Breaking down the assessed reasons for the most common transition types:

- **Bishop pine to Dense Coastal Scrub (378 acres):** Top reasons were misclassification in the 60s (73 acres), true cover change (46 acres), and unable to assess (14 acres). Misclassification in the 60s largely seemed to be due to challenging imagery and judgment calls, including discrepancies between '63 and '65 imagery.
- **Bishop pine to Hardwood Forest (369 acres):** Top reasons were misclassification in the 60s (153 acres) and misclassification in the 40s (45 acres). Misclassification in the 60s was largely true Bishop pine misclassified as hardwood, likely due to confusion between Bishop pine and tanoak crowns, as well as challenging imagery (warping and alignment issues).
- **Bishop pine to Grassland (177 acres):** This transition was largely accurate, due to heavy removal of mature Bishop pine along Pierce Point Rd.
- **Bishop pine to Riparian Forest/Shrubland (120 acres):** These transitions were largely due to riparian corridors mapped in the 60s that were not mapped in the 40s.

Other veg to Bishop pine:

70% of 836 acres (>1 acre polygons) analyzed. The most common reason was misclassification in the 40s (33%, 275 acres), followed by true cover change (21%, 179 acres), and misclassification in the 60s (11%, 94 acres).

Breaking down the assessed reasons for most common transition types:

- **Dense Coastal Scrub to Bishop pine (413 acres):** Top reasons were true cover change (162 acres) and misclassification in the 40s (61 acres). The quality of the 40s imagery makes it very difficult to distinguish dense coastal scrub from young Bishop pine, which may look very similar. Areas that are coastal scrub in the 40s and Bishop pine in the 60s could either: a) be very young Bishop pine in the 40s, or b) have burned sometime between the 40s and 60s, creating a new cohort of dense young Bishop pine. See Figure 1 for example.
- **Douglas-fir to Bishop Pine (237 acres):** All of the assessed areas of Doug-fir to Bishop pine transition were assessed as misclassification in the 40s, where Bishop pine was mistaken for Douglas-fir due to challenging 40s imagery.
- **Hardwood forest to Bishop pine (181 acres):** Primarily assessed as misclassification in the 60s, areas that should have been hardwood in both years. These polygons were typically large areas of hardwood with pockets of Bishop pine that should have been pulled out in the 60s mapping.

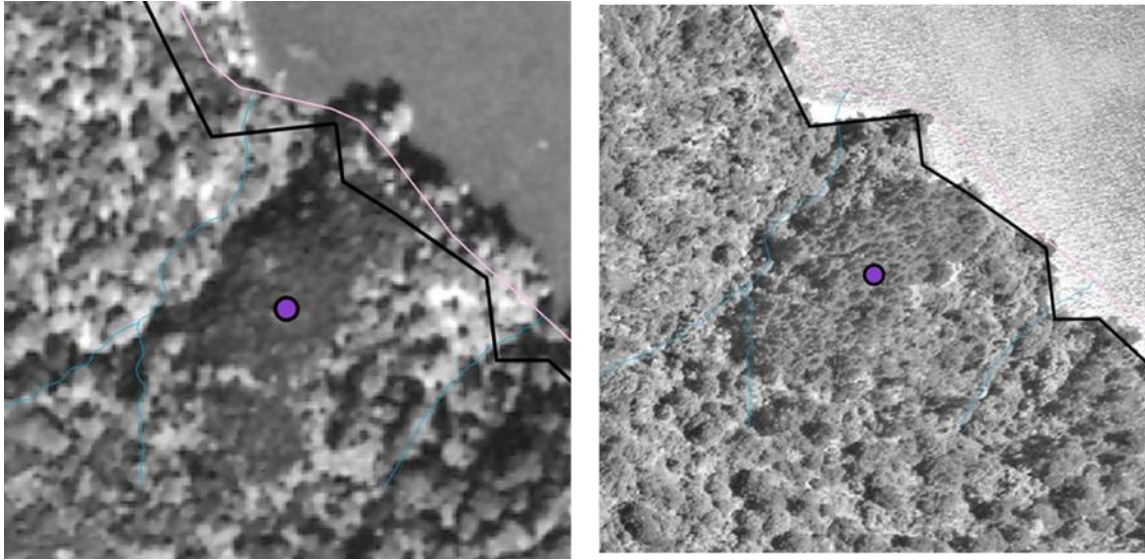


Figure 1: Illustrating the potential for confusion between coastal scrub and young Bishop pine in Tomales Bay State Park. On the left this area is called 'dense coastal scrub' in the 1940s, and on the right (1960s) it is clearly a patch of dense mid-seral Bishop pine. It is possible that the left is early seral Bishop pine, possibly originating from the 1932 Shafter Ranch fire. But without better spatial and temporal accuracy for historic fire perimeters, we can't be sure.

Douglas-Fir Transitions, 40s to 60s

Douglas-fir to Other Veg Types:

76% of 3353 acres (>1 acre polygons) were analyzed. The most common reason for transition was misclassification in the 40s (23.5%, 250 acres), then true cover change (18%, 189 acres), then misclassification in the 40s (8%, 86 acres). The table below shows the transitions of Douglas-fir to other forest and vegetation types, with the most significant end types in the 60s highlighted.

Veg Type Transition from 40s to 60s (all polygons)	Acres
Douglas-fir to Bishop Pine	236.8
Douglas-fir to Dense Coastal Scrub	1105.0
Douglas-fir to Disturbed	60.3
Douglas-fir to Eucalyptus	0.4
Douglas-fir to Fresh Water Wetland	4.3
Douglas-fir to Grassland	197.3
Douglas-fir to Hardwood Forest	1663.2
Douglas-fir to Open Scrub/Grassland	131.3
Douglas-fir to Riparian Forest/Shrubland	81.8
Douglas-fir to Salt Marsh	1.5
Douglas-fir to Water	4.4
Total	3486.2

Breaking down the assessed reasons for the most common transition types:

- **Doug-fir to Hardwood forest (1663 acres):** The large majority of this apparent transition was due to type confusion, either in the 40s (391 acres, 24% of assessed acreage) or in the 60s (473 acres, 29%). MMU issues, often related to mixed forest areas on the threshold between the two forest types, were an additional 280 acres, 17% of the assessed area. No polygons were assessed as accurate cover change. The majority of this transition being erroneous makes sense ecologically, because the transition of Douglas-fir forest to hardwood is unlikely without either large-scale Doug-fir mortality or targeted removal of Doug-fir while leaving hardwoods in place.
- **Doug-fir to dense coastal scrub (1105 acres):** The leading reason for this transition was accurate cover change (720 acres, 67% of assessed acreage). There was a large-scale removal of Douglas-fir in the area surrounding and to the southeast of Firtop Peak.
- **Doug-fir to Bishop pine (237 acres):** See above section “*Other veg to Bishop pine.*”
- **Doug-fir to Grassland (197 acres):** Roughly half of the assessed acreage of this transition type was due to true cover change (32 acres) and half was due to alignment issues like slivers (34 acres).

Other Veg Types to Douglas-fir:

67% of 2106 acres analyzed. The most common reason was true cover change (35%, 730 acres), followed misclassification in the 40s (20%, 427 acres), and alignment issues (6%, 132 acres).

Breaking down the assessed reasons for most common transition types:

- **Dense coastal scrub to Doug-fir (1060 acres):** Top reasons were true cover change (641 acres), MMU issues (77 acres) and misclassification in the 40s (66 acres). The large areas of accurate transition from dense coastal scrub to Douglas-fir occurred primarily along the coast, where clear expansion of Doug-fir into scrub and grassland areas is visible.
- **Hardwood forest to Doug-fir (739 acres):** Top reasons were misclassification in the 40s (339 acres), followed by alignment issues (38 acres). Though this transition type is possible in the form of Douglas-fir overtopping and shading out hardwood in mixed stands, I did not see any clear examples of this transition. Most commonly, areas where hardwood and Douglas-fir mix were misclassified as hardwood in the 40s, often due to challenging and shadowed imagery.
- **Grassland to Doug-fir (211 acres):** Top reasons were alignment issues (40 acres) and true cover change (39 acres).

Hardwood Forest Transitions, 40s to 60s

Hardwood Forest to Other Veg Types:

51% of 1267 acres (polygons >1 acre) were analyzed. The most common reason for transition was misclassification in the 40s map (32%, 410 acres), then misclassification in the 60s map (7%, 91 acres), then alignment issues (4%, 48 acres). The table below shows the transitions of hardwood forest to other vegetation types, with the most significant end types in the 60s highlighted.

Veg Type Transition from 40s to 60s (all polygons)	Acres
Hardwood Forest to Active Agriculture	0.8
Hardwood Forest to Beach	2.7
Hardwood Forest to Bishop Pine	181.2
Hardwood Forest to Dense Coastal Scrub	205.6
Hardwood Forest to Disturbed	29.9
Hardwood Forest to Douglas-fir	739.9
Hardwood Forest to Eucalyptus	1.8
Hardwood Forest to Fresh Water Wetland	12.7
Hardwood Forest to Grassland	139.3
Hardwood Forest to Open Scrub/Grassland	14.1
Hardwood Forest to Riparian Forest/Shrubland	97.1
Hardwood Forest to Salt Marsh	2.8
Hardwood Forest to Unknown/other	0.1
Hardwood Forest to Vegetated Dunes	0.1
Hardwood Forest to Water	1.9
Total	1430.1

Breaking down the assessed reasons for the most common transition types:

- **Hardwood forest to Douglas-fir (740 acres):** See above section *“Other Veg Types to Douglas-fir”*
- **Hardwood forest to dense coastal scrub (206 acres):** With 60/171 acres (of >1 acre polygons) assessed, 31 acres were due to misclassification in the 40s map, and 18 acres were due to alignment issues. The misclassified acres were likely due to shadowing and other challenges in the 40s imagery.
- **Hardwood forest to Bishop pine (181 acres):** See above section *“Other Veg Types to Bishop pine”*
- **Hardwood forest to grassland (139 acres):** Of the assessed areas, the majority were due to true cover change (24 acres, 30%), generally characterized by small-scale removal of trees near developed areas.

Other Veg Types to Hardwood Forest:

68% of 2395 acres (polygons >1 acre) analyzed. The most common reason was misclassification in the 60s map (27%, 635 acres), followed by misclassification in the 40s map (20%, 481 acres), and MMU issues (12%, 280 acres).

Breaking down the assessed reasons for most common transition types:

- **Doug-fir to Hardwood forest (1663 acres):** See above section *“Douglas-fir to Other Veg Types”*

- **Bishop pine to Hardwood forest (369 acres):** See above section “*Bishop pine to Other Veg Types*”
- **Dense coastal scrub to Hardwood forest (240 acres):** Top reasons were accurate cover change (60 acres) followed by misclassification in the 40s (44 acres). The true cover change areas were probably a mix of scrub and young hardwoods in the 40s (difficult to interpret) that matured into more visible hardwoods by the 60s.

DRAFT

Analysis of 1960s to 1990s

An important note about the analysis of 1960s-1990s change: the original maps were drawn to 1994 imagery, and some areas were updated after the 1995 Vision Fire using 2004 imagery. When assessing the forest transitions, I was unable to use the non-georeferenced 1994 imagery and therefore used 2004 imagery to assess all of it. Therefore, there may be discrepancies caused by either: 1) places in the original map that were mapped using different years of imagery, or 2) changes that occurred between 1994 and 2004 that are mistakenly assessed.

For all forest types and changes, 54% (4059/7579 acres, of polygons >1 acre) were assigned a likely error type and reason for the change:

- **Accurate cover change:** 25% (1907 acres) assessed as accurate cover change. This included revegetation in the area of Doug-fir removal in the 60s (near Firtop), Doug-fir expansion into coastal grass and shrublands, and Bishop pine expansion post-Vision Fire.
- **Misclassified in 60s:** 19% (1418 acres) assessed as mapped incorrectly in the 60s. These were primarily type confusions between the three forest types.
- **Misclassified in 90s:** 6% (441 acres) assessed as mapped incorrectly in the 90s. Some of these may be due to the differences between the 1990s and 2004 imagery.
- **MMU Issues:** 3% (242 acres) assessed as errors due to MMU/judgment calls. These were largely judgment calls and threshold issues in mixed stands of Doug-fir and hardwood.
- **Alignment:** 0.7% (53 acres) assessed as errors due to image alignment. Image alignment was much less of an issue between the 60s and 90s compared to the 40s.

The table below is a simplified confusion matrix of the apparent transitions between the three forested types plus “other” non-forested areas. Note that these totals differ from the “assessed” acreage, because these include all polygons rather than only those greater than an acre.

Veg Type 60s, Classified	Veg Type 90s, Classified (Acres)				
	Bishop Pine	Douglas-fir	Hardwood Forest	Other (non forest)	Total
Bishop Pine	2086.8	116.3	178.8	143.2	2525.0
Douglas-fir	25.6	7160.8	440.6	262.4	7889.4
Hardwood Forest	287.7	1522.7	2025.0	411.1	4246.5
Other (non-forest)	1202.0	3276.9	789.5	43419.1	48687.5
Total	3602.1	12076.7	3433.9	44235.7	63348.4

- Of the 2525 acres mapped as **Bishop pine** in the 60s: 83% stayed as Bishop pine, 5% transitioned to Douglas-fir, 7% transitioned to hardwood forest, and 6% transitioned to non-forested vegetation.
- Of the 7889 acres mapped as **Douglas-fir** in the 60s: 91% remained Doug-fir, 0.3% transitioned to Bishop pine, 5.6% transitioned to hardwood, and 3% transitioned to non-forested vegetation.
- Of the 4247 acres mapped as **hardwood forest** in the 60s: 48% stayed hardwood, 7% transitioned to Bishop pine, 36% to Doug-fir, and 10% to non-forested vegetation.

	Veg Type 90s (acres)			
Veg Type 60s	Bishop Pine	Douglas-fir	Hardwood Forest	Total
Active Agriculture	6.0	2.5	0.0	8.5
Beach	0.9	-	3.7	4.6
Dense Coastal Scrub	770.8	2211.5	427.6	3409.9
Disturbed	18.2	27.1	18.1	63.4
Eucalyptus	6.9	0.6	0.7	8.2
Fresh Water Wetland	20.5	4.8	13.7	39.0
Grassland	214.3	544.9	194.7	953.9
Open Scrub/Grassland	81.3	328.0	18.5	427.8
Riparian Forest/Shrubland	76.1	152.7	108.2	336.9
Salt Marsh	0.5	0.1	1.8	2.4
Unknown/other	6.2	0.0	0.1	6.4
Vegetated Dunes	-	-	0.3	0.3
Water	0.3	4.6	2.2	7.0
Total	1202.0	3276.9	789.5	5268.3

Bishop pine Transitions, 60s to 90s

Bishop Pine to Other Veg Types:

67% of 348 acres (>1 acre polygons) were analyzed. The most common reason for transition was misclassification in the 60s map (32%, 113 acres), then misclassification in the 40s map (29%, 99 acres), then true cover change (5%, 19 acres). The table below shows the mapped transitions of Bishop pine to all other veg types, with the most significant end types in the 90s highlighted.

Veg Type Transition from 60s to 90s (all polygons)	Acres
Bishop Pine to Active Agriculture or Pasture	0.3
Bishop Pine to Dense Coastal Scrub	61.9
Bishop Pine to Disturbed	38.0
Bishop Pine to Douglas-fir	116.3
Bishop Pine to Fresh Water Wetland	1.5
Bishop Pine to Grassland	0.9
Bishop Pine to Hardwood Forest	178.8
Bishop Pine to Open Scrub/Grassland	8.4
Bishop Pine to Riparian Forest/Shrubland	31.6
Bishop Pine to Salt Marsh	0.5
Bishop Pine to Water	0.2
Total	438.3

Breaking down the assessed reasons for the most common transition types:

- Bishop pine to Hardwood forest (179 acres):** Primarily misclassification in the 60s map (85 acres) followed by misclassification in the 90s map (10 acres). The misclassification in the 60s were primarily areas where Bishop pine and hardwood stands are adjacent, and Bishop pine was slightly over-mapped.

- **Bishop pine to Doug-fir (116 acres):** Misclassification in the 90s (60 acres), misclassification in the 60s (21 acres). This type confusion occurred in areas where Doug-fir and Bishop pine stands are adjacent, and may potentially be attributed to the discrepancies between the 90s and '04 imagery.

Other Veg Types to Bishop Pine:

61% of 1280 acres (>1 acre polygons) analyzed. The most common reason was true cover change (33%, 424 acres), followed by misclassification in the 60s map (21%, 269 acres), and misclassification in the 90s map (5%, 70 acres).

I also noted and bookmarked several areas in which post-Vision Fire Bishop pine growth was not mapped, possibly due to discrepancies in using 90s and 00 imagery.

Breaking down the assessed reasons for most common transition types:

- **Dense Coastal Scrub to Bishop pine (770 acres):** Top assessed reasons were actual cover change (266 acres) and misclassification in the 60s map (121 acres). The true cover change is due to Bishop pine expansion into scrub areas after the 1995 Vision Fire.
- **Hardwood forest to Bishop pine (288 acres):** Top assessed reasons were misclassification in the 60s map (127 acres), misclassification in the 90s (39 acres) and true cover change (28 acres).
- **Grassland to Bishop pine (214 acres):** Top reasons were true cover change (97 acres), followed by MMU issues (7 acres). True cover change was due to post-fire Bishop pine expansion.
- **Riparian forest/Shrubland to Bishop pine (76 acres):** Largely unassessed, but the only cause assessed was misclassification in the 60s (11 acres). Because the 04 imagery has color, riparian forest classification became much clearer and more accurate for the 90s mapping effort.

Douglas-Fir Transitions, 60s to 90s

Douglas-fir to Other Veg Types:

24% of 597 acres (>1 acre polygons) were analyzed. After the initial analysis, I found that the transition of Doug-fir to hardwood forest was under-assessed, and re-visited the maps to increase the assessment of that transition type. Those assessments are included in the breakdown and the spatial datasets, but the values are not included in the tables.

The most commonly assessed reasons for transition was misclassification in the 60s map (6%, 37 acres), then misclassification in the 90s map (5.5%, 33 acres), then alignment issues (5%, 29 acres). The table below shows the transitions of Douglas-fir to other vegetation types, with the most significant end types in the 90s highlighted.

Veg Type Transition from 60s to 90s (all polygons)	Acres
Douglas-fir to Active Agriculture or Pasture	0.0
Douglas-fir to Bishop Pine	25.6
Douglas-fir to Dense Coastal Scrub	99.6
Douglas-fir to Dense Coastal Shrub*	1.5
Douglas-fir to Disturbed	51.0
Douglas-fir to Eucalyptus	0.6
Douglas-fir to Fresh Water Wetland	17.7
Douglas-fir to Grassland	4.5

Douglas-fir to Hardwood Forest	440.6
Douglas-fir to Open Scrub/Grassland	32.4
Douglas-fir to Riparian Forest/Shrubland	54.8
Douglas-fir to Water	0.2
Total	728.6

*Dense coastal shrub appears in the 90s map, and is assumed to be an error of dense coastal scrub

Breaking down the assessed reasons for the most common transition types:

- **Douglas-fir to Hardwood forest (440 acres):** In the first round of assessments, 95% of the acreage in this transition was unassessed. After a second look, approximately 148 acres were assessed as misclassified in the 60s map, followed by misclassified in the 90s (32 acres).
- **Douglas-fir to dense coastal scrub (100 acres):** Top reasons were true cover change (10 acres) and MMU issues (8 acres). True cover change occurred in a handful of areas where Doug-fir was cleared, while the MMU issues were primarily areas where patches of scrub within Doug-fir stands were not pulled out in one year or another.
- **Douglas-fir to Riparian Forest/Shrubland (55 acres):** Top reasons: Misclassification in the 60s map (22 acres) and alignment issues (12 acres). Because the 04 imagery has color, riparian forest classification became much clearer and more accurate for the 90s mapping effort.

Other Veg Types to Douglas-fir:

54% of 4488 acres analyzed. The most common reason was true cover change (29%, 1316 acres), followed by misclassification in the 60s map (19%, 834 acres), and all other error types less than 5% each.

Breaking down the assessed reasons for most common transition types:

- **Dense coastal scrub to Douglas-fir (2212 acres):** Top reasons were true cover change (1011 acres), then misclassification in the 60s (162 acres). The area (near Firtop) where large swaths of Doug-fir was removed between the 40s and 60s was re-vegetated as Douglas-fir between the 60s and 90s, contributing significantly to the acreage assessed as true cover change. There was also significant continued expansion of Doug-fir into grassland and scrub areas along the coast.
- **Hardwood forest to Douglas-fir (1523 acres):** Top reasons were misclassification in the 60s map (656 acres) followed by MMU issues (116 acres).
- **Grassland to Douglas-fir (545 acres):** Top assessed reason by far was true cover change (201 acres). True cover change is characterized by Doug-fir expansion into grassland and scrub areas, especially along the coast.
- **Open Scrub/Grassland to Douglas-fir (328 acres):** Top assessed reason was true cover change (88 acres), though this acreage was largely unassessed. True cover change is characterized by Doug-fir expansion into grassland and scrub areas, especially along the coast.

Hardwood Forest Transitions, 60s to 90s

Hardwood Forest to Other Veg Types:

59% of 2070 acres (>1 acre polygons) were analyzed. The most common reason for transition was misclassification in the 60s map (41%, 857 acres), then MMU issues (8%, 157 acres), then misclassification in the 90s (7%, 153 acres). The table below shows the transitions of hardwood forest to other veg types, with the most significant end types in the 90s highlighted.

Veg Type Transition from 60s to 90s (all polygons)	Acres
Hardwood Forest to Active Agriculture or Pasture	0.3
Hardwood Forest to Bishop Pine	287.7
Hardwood Forest to Dense Coastal Scrub	37.8
Hardwood Forest to Dense Coastal Shrub	0.3
Hardwood Forest to Disturbed	187.3
Hardwood Forest to Douglas-fir	1522.7
Hardwood Forest to Eucalyptus	1.3
Hardwood Forest to Fresh Water Wetland	1.5
Hardwood Forest to Grassland	4.3
Hardwood Forest to Open Scrub/Grassland	34.6
Hardwood Forest to Riparian Forest/Shrubland	140.6
Hardwood Forest to Salt Marsh	1.2
Hardwood Forest to Water	1.9
Total	2221.5

Breaking down the assessed reasons for most common transition types:

- **Hardwood forest to Douglas-fir (1523 acres):** See above section *“Other Veg Types to Douglas-fir”*
- **Hardwood forest to Bishop pine (288 acres):** See above section *“Other Veg Types to Bishop pine”*
- **Hardwood forest to Disturbed (187 acres):** The top reasons for this transition were misclassification in the 90s (62 acres), MMU issues (41 acres) and true cover change (18 acres). Without knowing the mapping qualifications for ‘disturbed,’ it is difficult to make a judgment call about whether the mapping was erroneous or not. But I observed that ‘Disturbed’ appeared to be over-mapped in the 90s in areas where there was some removal of trees for development, even when plenty of trees remained.

Other Veg Types to Hardwood Forest:

29% of 985 acres (>1 acre polygons) were analyzed. The most common reason was true cover change (10%, 101 acres), followed by misclassification in the 60s (10%, 98 acres), and misclassification in the 90s (5%, 51 acres). Under-assessment of this type was revisited (see above section *“Douglas-fir to Other Veg Types”*)

Breaking down the assessed reasons for most common transition types:

- **Douglas-fir to Hardwood forest (441 acres):** See above section *“Douglas-fir to Other Veg Types”*

- **Dense coastal scrub to Hardwood forest (428 acres):** Top assessed reasons were true cover change (96 acres, followed by misclassification in the 60s (50 acres) and misclassification in the 90s (35 acres).
- **Grassland to Hardwood forest (195 acres):** Top reasons were misclassification in the 60s (14 acres) followed by alignment (8 acres). The sum of area of this apparent type transition was 195 acres, but when eliminating polygons <1 acre for the assessment, the area was reduced to 83 acres. This implies that many of the transitions of this type are likely slivers or differences in how polygons are drawn.
- **Bishop pine to Hardwood forest (179 acres):** See above section “*Bishop pine to Other Veg Types*”

Conclusions

The historical mapping efforts of each year do an admirable job of capturing the state of forested vegetation in time, especially given the inherent challenges of using historic imagery. Significant changes in forest type were accurately captured by this effort: large-scale removals of Doug-fir between the 40s and 60s, the expansion of Bishop pine post-Vision Fire, and Doug-fir expansion over time into coastal shrub and grassland areas. Predictably, mapping accuracy tended to improve over time with the increasing resolution of later imagery.

The most common errors found in this analysis were misinterpretation of forest types, primarily in the 40s and 60s, and with much of the confusion occurring between the Doug-fir and Hardwood forest types. Misclassifications and errors are easier to assess with the benefit of seeing the imagery in both years, knowing the context of how vegetation is most likely to change over time, and having additional layers (creeks, hillshade, and historical fire perimeters) to give context clues.

To address and correct the errors in the maps and subsequent change analysis, I suggest the following actions:

1. **Manual map edits:** Using the “Misclassified” and “MMU” error type bookmarks as a guideline to revisit and correct the original maps, with particular attention to areas where Douglas-fir and hardwood mix.
2. **Calibration:** Ensuring that different mappers are calibrated in their mapping decisions: e.g. the minimum mapping unit of vegetation to pull out of a larger contrasting veg type, or threshold calls between hardwood and conifer types.
3. **Change analysis:** Quantifying change analysis using a point-based sampling system, rather than using total acreages of forest types. This could minimize the effects of slight alignment issues and focus analysis on areas of true change.
4. **Eliminate slivers from analysis:** As done in this analysis, querying the polygons to only consider those of a certain size can eliminate some of the alignment-related issues, but does risk eliminating small areas of true change.

Addressing errors in image alignment would require significant re-mapping with probably minimal gains in accuracy, and is not recommended at this time.