Maui’s Wildland-Urban Interface:

Enhancements for the Unique Vegetative and Agricultural Landscape

by

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To my parents, brother, and grandparents

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Abbreviations

CARs	Communities at Risk
DLNR	Department of Land and Natural Resources
ESA	European Space Agency
HWMO	Hawaii Wildfire Management Organization
LANDFIRE	Landscape Fire and Resource Management Planning Tools
NIST	National Institute of Standards and Technology
NLCD	National Land Cover Dataset
WUI	Wildland-Urban Interface
WUIF	Wildland-Urban Interface (subcategory)
WUIX	Wildland-Urban Intermix

Abstract

In August 2023, Maui experienced a series of massive wildfires, including one that destroyed most of the historic town of Lahaina. Climate change has increased the frequency and intensity of wildfires, and the Maui wildfires exhibit the dangers of living next to wildlands. Identifying an area's wildland-urban interface (WUI) is a crucial part of wildfire management. To provide insight into the relationship between development and the surrounding wildlands in Maui, this thesis studies the spatial distribution of the WUI in Maui before the 2023 wildfires. This thesis creates the first census block-based WUI map of Maui. Standard WUI map creation entails determining census blocks' structural density, vegetation cover percentage, and distance from wildland areas. In census block-based WUI maps, each census block is assigned a WUI classification. This thesis experiments with multiple landcover datasets and a local agricultural dataset to assess their effects on WUI classification and determine the most appropriate datasets for mapping WUI on Maui. For the final WUI analysis, this thesis utilizes 2020 US Census Bureau census block data, European Space Agency 2021 WorldCover landcover data, and Hawaii Statewide GIS Program agricultural land use data to map WUI. The final WUI map product shows the arrangement of Maui in relation to the WUI before the wildfires. The findings of the WUI analysis show that 27.46% of land, 96.82% of buildings, and 99.03% of the population on Maui are in WUI. The final WUI map is developed into an ArcGIS Dashboard that allows users to explore the WUI in relation to other wildfire-related data, while providing transparency into WUI calculation. The findings of this thesis are useful for wildfire management, urban planning, the private sector, and the general public by providing insight into the spatial arrangement of the WUI in Maui, where to target priority areas for wildfire prevention interventions, and the relative safety of buildings and homes in the WUI.

Chapter 1 Introduction

On August 8, 2023, four wildfires began on Hawaii's Maui Island, which together caused terrible loss of life and widespread destruction. The Lahaina wildfire was one of the deadliest wildfires in United States (US) history. The Olinda, Kula, and Pūlehu wildfires did not cause fatalities, but caused building damage and thousands of acres of burned land. One year after these wildfires, at the time of writing this thesis, the Maui landscape and its communities are still recovering. Leading up to the wildfires, many parts of Maui faced wildfire risk factors, including the proximity of homes to wildland areas. Maui is known to have much of its population living in the wildland-urban interface (WUI), a concept created in the 1980s by the department of Forest Fire and Atmospheric Sciences Research to improve mass fire predictions and to improve wildfire protection, wildfire management, natural resource management, and land use planning (Sommers 2008). This thesis creates the first census-block based, Maui-specific WUI map and shares the map publicly in an ArcGIS Dashboard that interactively presents WUI contributing factors and other wildfire management data. This chapter provides background into wildfires in Maui, the Maui 2023 wildfires, and the research goals and objectives of this thesis.

1.1 Study Area

The second largest of the Hawaiian Islands, Maui spans approximately 1,886 square kilometers (or 728 square miles) (Encyclopedia Britannica 2024b). Maui is divided into six geographic regions (Figure 1). Maui is called the "Valley Isle" because of the large valley between the two volcanoes that created it, which lie to the east and west sides of the island (Encyclopedia Britannica 2024b). The volcano on the western side is no longer active and the remnants of the eroded volcano are the West Maui Mountains. On the east, Haleakala is an active volcano over 3,000 meters tall.

Figure 1. Maui, Hawaii study area

Maui is part of Maui County, along with the islands of Lanai, Molokai, and Kahoolawe. As of 2022, Maui County has a population of about 164,000 and a population density of 366 people per square kilometer (US Census Bureau 2022). The communities on Maui developed densely. Maui is significantly denser than the overall US, with a population density of 34 people per square kilometer in 2022 (Macrotrends 2024) The largest demographic group on Maui is White, making up about 29% of Maui County’s population, followed closely by the Asian population at about 28% (Data USA 2022). About 10% of the population is Native Hawaiian or Pacific Islander.

Maui, named after a demigod from Polynesian mythology, has a rich history and cultural significance regarding the Hawaiian Kingdom. King Kamehameha, regarded as the greatest King in Hawaii, united the Hawaiian Islands for the first time in 1810 and he chose the capital of the Hawaiian Kingdom to be in Lahaina (Lahaina Town 2024b). King Kamehameha chose Lahaina because it is said to be the home of the goddess Kihawahine in Native Hawaiian religion (LaPier 2023). Many Hawaiian monarchs are buried in the Waiola Church Cemetery, which is also regarded as sacred (Encyclopedia Britannica 2024a). The capital remained on Maui until the switch was made to Honolulu in 1845.

Before westerners colonized Hawaii, native Hawaiians had a sophisticated land management system that was not based on private land ownership (County of Maui 2008). Islands were divided into sections called ahupua'a, which ran from the mountains to the ocean (County of Maui 2008). The native Hawaiians stewarded the land and carefully managed resources, understanding the interconnectivity of the various ecosystems across an ahupua'a (County of Maui 2010). Complex agriculture and aquaculture systems supported the population. In the 1850s, Maui had 141 ahupua'a, over 300 villages, and about 35,000 inhabitants (County of Maui).

In the 1800s, Maui underwent many changes as western colonizers introduced a new intensive agricultural economy based on private land ownership and greatly changed the vegetative landscape. The native Hawaiians' natural resource management was destroyed as newly introduced crops and livestock depleted native vegetation and westerners cut down forests (County of Maui 2010). Maui continued to change in the 1900s, with a rise in infrastructure and housing after World War II. Hawaii became a state in 1959. Planned communities grew in the latter half of the 20th century, along with large resorts (County of Maui 2008). As Maui developed over time, the diverse native landscape degraded.

Maui's agricultural landcover decreased considerably from 1976-2000s while development increased (Brewington 2020). Agricultural landcover loss was between 46-63%. Contrarily, developed land increased significantly, between 105-273%. Furthermore, grassland on Maui increased between 113-196%, and replaced almost half of agricultural land (Brewington 2020). When sugarcane plantations closed by the late 1990s, the abandoned agricultural plots became unruly and filled with invasive grasses (Harrison 2020; Parsons and Martin 2023). Urban development in Maui has altered the natural landscape, allowing highly flammable invasive plant species to intrude into native vegetation. Homes in the WUI in Maui have an increased wildfire risk due to the prevalence of highly flammable invasive species in the surrounding wildlands.

While agriculture is still prominent today, the largest economy on Maui is the tourism industry (Encyclopedia Britannica 2024b). For attractions, Maui boasts beaches, rainforests, a volcano, waterfalls, and more. Lahaina is the biggest tourist destination on Maui, receiving 80% of the island's tourism and about two million visitors annually (Lahaina Town 2024a). Lahaina has suffered greatly economically after the 2023 wildfires, losing over $13 million in tourism-related revenue per day (Bond-Smith et al. 2023). Tourism to Maui is encouraged to support the island's economy in the aftermath of the 2023 wildfires (Hawai'i Tourism Authority 2024a; Hawai'i Tourism Authority 2024b).

The climate and wildfire susceptibility vary greatly across Maui, and a map of annual rainfall in Maui is shown in Figure 2 (Hawaii Statewide GIS Program 2022b). The northern and eastern parts of the island consist of the windward 'wet' side of the island with rainforests and heavy rainfall (Blum 2024). The southern and western portions of the island are the leeward ‘dry’ side that experience arid and desert-like conditions. West Maui is dry and receives little rain because the prevailing winds from the northeast are blocked by the mountains, producing heavy rainfalls on the eastern side and creating a rain shadow on the western side (University of Hawaii at Manoa n.d.). South Maui and parts of West and Upcountry Maui receive under 20 inches of rain per year. This sharply contrasts other parts of Maui that are rainforests, such as the Big Bog in East Maui, one of the wettest areas on the earth, which receives up to 400 inches of rain per year (Dejournett 2023). The Lahaina and Pūlehu wildfires occurred in dry parts of the island, in areas that receive about 15 inches of rain per year. The area around the Kula wildfire receives more rain, between 25 and 30 inches annually. Of the August 2023 wildfires, the Olinda wildfire occurred in the wettest area, receiving about 65 inches of rain annually.

Figure 2. Rainfall in Maui

1.2 Background

As climate change intensifies, wildfires have become stronger and more destructive (Jones et al. 2022). The top eight largest wildfires in the history of the US occurred in the last 20 years (Earth.org 2024). The state of Hawaii has been ravaged by many wildfires in recent years, and the Hawaiian Islands have experienced some of the highest increases in wildfires in the country (Trauernicht 2019). In the past century, the burn areas of Hawaii have increased drastically, over 400% (Parsons and Martin 2023). Wildfires affect thousands of people each year, and wildfire awareness is a crucial part of the lives of Maui residents.

1.2.1 Wildfire Conditions in Maui, Hawaii

Factors that contribute to wildfire risk in Maui include the rise of invasive species populations and dry weather. Due to the isolation of Hawaii from the rest of the world, native plants on Hawaii lack the ability to defend themselves from invasive species, as they evolved without competition (Hawaii Invasive Species Council 2024b). This background makes Hawaii especially susceptible to the detriments of non-native plant invasions. Native plants in Hawaii did not evolve to adapt to fire because lightning does not normally occur in Hawaii (Parsons and Martin 2023). Only a few native species, if any, can regenerate after a wildfire; only volcanic areas experience wildfires naturally and have vegetation adapted to wildfires (Hawaii Dept. of Land and Natural Resources 2010).

Wildfire risk is exacerbated because of the large number of invasive species that have been recorded invading the Hawaiian Islands for decades (Tunison, D'Antonio, and Loh 2001; Parsons and Martin 2023). About a quarter of Hawaii is overrun by invasive, drought-resistant, highly flammable grasses and shrubs (Parsons and Martin 2023). According to a 2018 USGS report, Hawaii's density of invasive species is 200% when compared to the mainland (Parsons and Martin 2023). When native plant species are destroyed in fires, nonnative dry grasslands populate the islands; the nonnative grasslands in turn are more susceptible to wildfires, therefore furthering the continual destruction of the native biodiversity (Trauernicht 2019; Tunison, D'Antonio, and Loh 2001). Guinea grass and buffelgrass are native to Africa and the Middle East and are some of the most common grasses seen across Maui. Buffelgrass was prominent before the 2023 wildfires occurred; this invasive grass has one of the highest wildfire risks of any in Hawaii (Parsons and Martin 2023). The invasive grasses around Lahaina are known to quickly spread in areas that are disturbed after fires (Romero and Kovaleski 2023). Large open fields of grasslands are dangerous because of their fuel content, especially during drier seasons.

Since the late 1990s, Hawaii has experienced two of its most severe droughts in the past century, which has decreased the moisture in the soil and in plants (Parsons and Martin 2023). The wildfire risk from the invasive grasses that dominate Maui’s landscape increases as they become drier and more flammable. Drought does not deter the growth of the invasive grasses; during droughts, native plants suffer but invasive species are less affected and often replace the native plants (Kunz 2021). Drought conditions are detrimental even after Maui has wet winter conditions; the invasive grasses grow swiftly with rainfall, so there are larger masses of fuel vegetation that dry out when drought returns (County of Maui 2021). Due to Maui’s geography, the southern and western sides of the island are predisposed to have drier conditions, and therefore heightened wildfire risk. When the August 8, 2023, wildfires occurred, Western Maui was split between the drought classifications of Abnormally Dry and Moderate Drought, as seen in Figure 3 (US Drought Monitor 2023). South Maui and parts of Upcountry Maui were in Severe Drought, and East Maui was Abnormally Dry. Maui was under worse drought conditions than all the other Hawaiian Islands, none of which had Severe Drought conditions.

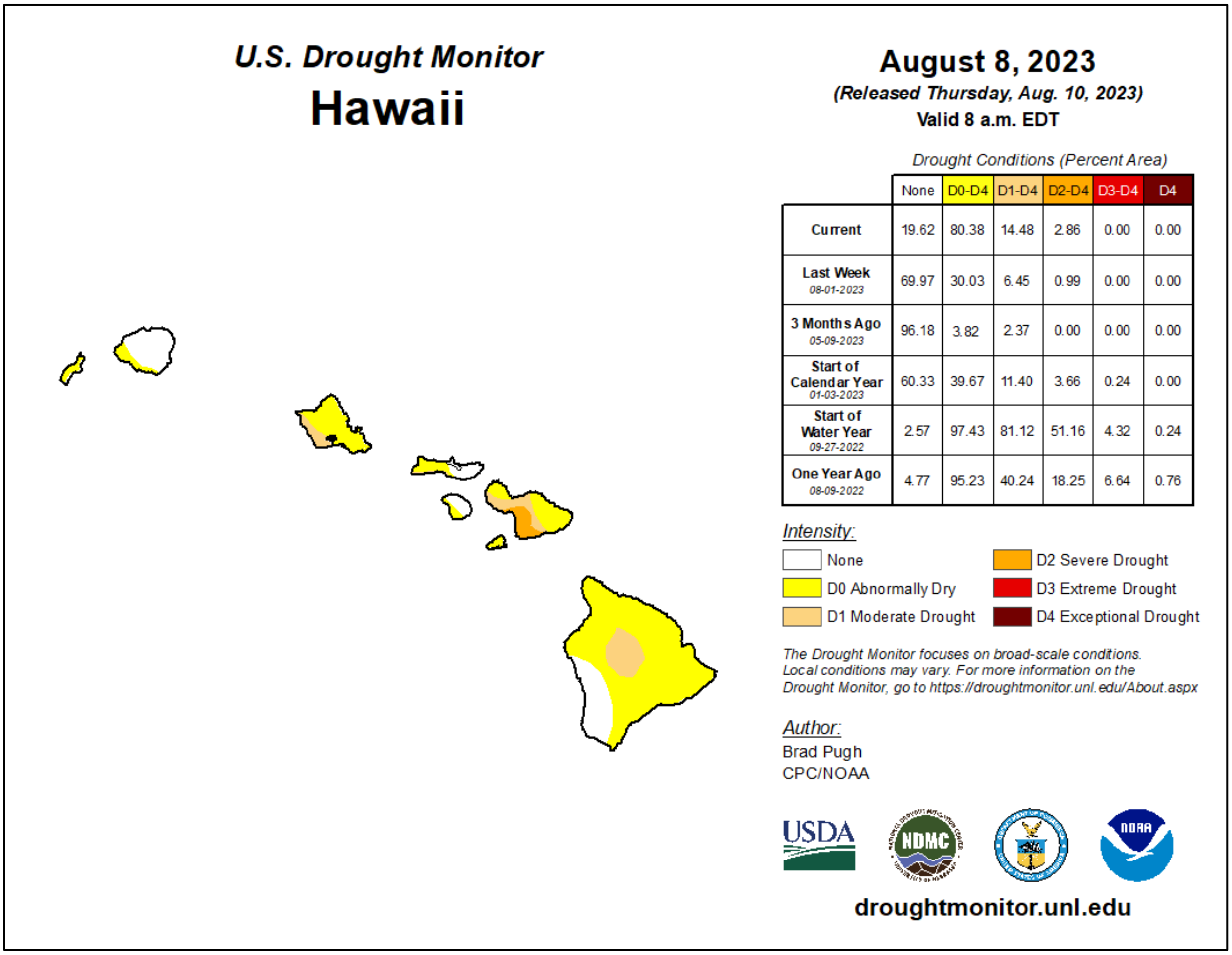

Figure 3. Hawaii drought conditions on August 8, 2023

Wildfires occur across most of Maui. A map with point locations of incidence locations for historical wildfires on Maui between 2005 and 2020 is shown in Figure 4, with less transparency for more recent wildfires (HWMO and Trauernicht 2023). Relatively few fires occur on the wetter parts of the island, including East Maui and the West Maui Mountains. No wildfires have begun on the eastern side of Haleakala, and wildfires in East Maui have only ignited along the coast. Many wildfire occurrences have been in Central Maui, South Maui, and the coast of West Maui. The more recent fires have also been in these densely populated areas, especially around Lahaina and the western side of the North Shore. Wildfire incidents are less dense in Upcountry Maui than in Central Maui and the West and South Maui coasts, but are still numerous, and some recent fires stand prominent in the open land between Upcountry Maui and Central Maui.

Figure 4. Historical wildfires on Maui from 2005-2020

1.2.2 The August 2023 Maui Wildfires

Beginning on August 8, 2023, Maui experienced a disastrous series of wildfires. All the Hawaiian Islands were experiencing an extremely high-pressure system, leading to high winds (Partyka and Erdman 2023). In the early morning hours of August 8, Lahaina experienced winds reaching 60-80mph, and police closed multiple roads due to many electric poles fracturing and falling (Maui Police Dept. 2024). At 6:35am, a fire started near Lahaina Intermediate School, but it was largely contained within two hours and fully extinguished by 2:17pm (Maui Police Dept. 2024). Soon after, at 2:55pm, another fire started at the same location and spread quickly, ultimately destroying most of the town (Kerber and Alkonis 2023). The Lahaina wildfires swept through old, abandoned plantation fields, the slopes surrounding the town, and up to homes, all connected by invasive grasses (Romero and Kovaleski 2023). The fires did not conclude until 8:30am the morning of August 9 (Fire Safety Research Institute 2024). In total, 2,170 acres burned in the wildfire (Maui Police Dept. 2024). Over 100 people were killed, over 2,000 buildings were destroyed, and damages were over $5 billion (US Fire Administration 2024). The Lahaina wildfires were designated a WUI (specifically, Interface) event by the National Institute of Standards and Technology (NIST) (Link 2024).

Many historical sites in Lahaina with cultural significance were destroyed (Hawai'i Tourism Authority 2024a). Lahaina's historic district is compared before the fire, on March 24, 2023, to soon after the fire on August 11, 2023, in Figure 1Figure 5 (Google Earth 2023a; Google Earth 2023b). These maps show some of the most popular landmarks. In Lahaina, some historic landmarks trace back to the 1800s when the first missionaries and whalers arrived, and others trace back to the Hawaiian Kingdom. The wildfires swept through the historic Front Street, around which many historic sites are located. The famous Banyan tree, planted in 1873, was damaged but not destroyed. However, the Lahaina Public Library, Masters Reading Room, Baldwin Home, Pioneer Inn, and Old Lahaina Courthouse were destroyed. Many artifacts and archives were lost from the destruction of the Lahaina Public Library and the Old Lahaina Courthouse. Slightly north, the Wo Hing Temple Museum was destroyed. Slightly to the south, the Waiola Church was destroyed, and its cemetery was damaged. As of writing this paper, most of these landmarks are still closed.

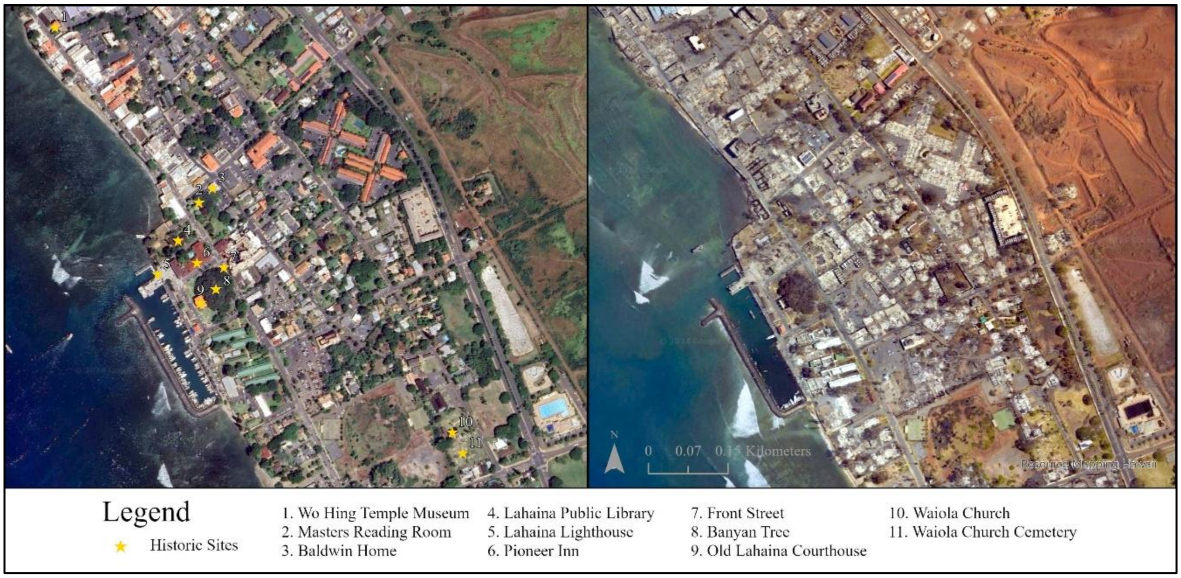

Figure 5. Historical sites in Lahaina before and after the wildfires

Three wildfires occurred in other regions of Maui, with the Olinda and Kula wildfires in Upcountry Maui, and the Pūlehu wildfire in South Maui (Maui Police Dept. 2024). These wildfires were not reviewed by the NIST or assigned WUI event classifications. The burn extents of the wildfires are shown in Figure 6, covering thousands of acres (County of Maui GIS 2024). The Olinda wildfire started on a residential street shortly after midnight, at 12:22am on August 8, spreading quickly and leading police to evacuate residents in the middle of the night (Maui Police Dept. 2024). The Olinda wildfire burned 1,081 acres. The Kula wildfire started at 11:27am on a small street off Route 377 (Kerber and Alkonis 2024). The Kula wildfire burned 202 acres and damaged 25 homes (Maui Police Dept. 2024; Yamane 2024). At 5:59pm, the Pūlehu fire started on a small residential road and burned mostly ranch land (Maui Police Dept. 2024; Kerber and Alkonis 2024; Hawaii Dept. of Land and Natural Resources 2023). This fire burned the largest area, covering 3,240 acres. These three wildfires affected mostly ranch land and had no casualties. The wildfires were not completely contained until September 30, well after a month after they began (Federal Emergency Management Agency 2023).

Figure 6. Maui August 2023 wildfire burn extents

The Maui wildfires made news headlines around the country and brought widespread attention to Lahaina, as well as globally reviving conversations on the danger of wildfires and importance of emergency management (Synolakis and Karagiannis 2024). Resources poured in from all around the world. As of the writing of this paper, the parts of Lahaina that were impacted most from the wildfires are still closed to the public, and tourists are asked not to visit those areas and not to take photos.

1.3 The Wildland-Urban Interface

WUI is defined as the area where developed areas meet or mix with wildland areas (Radeloff et al. 2005). While WUI has a broad, qualitative definition, thresholds are standardized to quantitatively classify WUI. WUI definitions mostly stem from the definitions set by the Federal Register in 2001 (Federal Register 2001). There are two subtypes of WUI, wildland-urban interface (from here on, WUIF) and wildland-urban intermix (from here on, WUIX), and when referred to collectively, they are called WUI. WUI has two main components, structures and vegetation. Commonly implemented thresholds regarding structural density and vegetation cover are in Table 1 (NIST 2023; Federal Register 2001). An additional threshold regarding distance from wildlands is included, which is derived from vegetation cover data. Both WUIF and WUIX have a structural density threshold of over 6.18 structures per square mile (NIST 2023). WUIX has a vegetation cover threshold of over 50%, while WUIF is less than 50% vegetation cover, so WUIF areas tend to be more developed than WUIX areas. WUIX does not have a defined relation with wildlands, but WUIF areas are under 2.4 km from wildlands (NIST 2023). In WUI literature, wildlands are areas of 5 square kilometers or more with greater than 75% vegetation cover (Bar-Massada 2021).

Table 1. WUI definitions

	Wildland-Urban Interface	Wildland-Urban Intermix
Structural density threshold	≥ 6.18 structures per sq km	≥ 6.18 structures per sq km
Vegetation cover threshold	< 50% vegetation	≥ 50% vegetation
Relation with wildland threshold	< 2.4 km from land (≥ 5 sq km) with ≥ 75% vegetative cover	N/A

Source: NIST 2023

WUI was first proposed as a US Forest Service research initiative in 1987 due to wildfire management challenges where urban areas and wildlands met (Sommers 2008). Concerns at the time included water resource conflict and post-war concerns about wildfires caused by bombings (Sommers 2008). Additional intent in conceptualizing WUI was to quantify wildfire-related issues along with demographic information, and to combine information on both structural and wildland fuels (Sommers 2008).

WUI became crucial for wildfire management and policy and is widely used in wildfire management efforts today. WUI maps can be used to identify areas of high wildfire risk and target educational efforts. The maps assist wildfire management in prioritizing where to evaluate and thin fuels in and around urban areas, and where to conduct controlled burns. Targeting where to implement defensible space policies is informed by WUI maps. WUI maps assist urban planners in choosing where to enforce fire-resistant building codes, as well as evaluate proposed developments. WUI maps inform the allocation of firefighting resources and support the design of evacuation routes.

1.4 Research Goals and Objectives

The goal of this thesis is to use cartography and spatial analysis to support wildfire management and wildfire-related research in Maui, creating a WUI map made specifically for Maui and sharing the map publicly in an ArcGIS Dashboard. The overarching research questions for this thesis are, where does WUI exist on Maui and what changes should be made to standard WUI mapping practices to best answer this question given the climate and landscape of Maui? To answer these questions, this thesis first finds the most appropriate datasets to represent the vegetative and agricultural landscape of Maui by assessing how different landcover datasets affect WUI classification. WUI maps of Maui with standard WUI classifications and enhanced microclimate-related subclassifications are created. The information is presented in an interactive, dynamic ArcGIS Dashboard that showcases the factors affecting WUI classification alongside other wildfire-related data for additional context. The analyses conducted and datasets created provide insight for planners in Maui concerning the community's relationship with the WUI to inform wildfire management planning decisions, as well as provide insight for other stakeholders invested in wildfire issues such as Maui County, Maui fire departments, insurance agencies, homebuyers, homeowners, real estate developers, and the public.

1.5 Thesis Organization

The remainder of this thesis consists of five chapters. Chapter 2 provides an overview of related works regarding studies on wildfires in Maui, WUI mapping practices, and existing WUI maps that include Maui. Chapter 3 covers the methodology of this thesis by detailing the data used, the steps for mapping the WUI in Maui, and the experimentation with different landcover datasets that led to the final methodology. Chapter 4 contains the final WUI map products for Maui and the WUI maps from the landcover dataset experimentations. Chapter 5 focuses on the creation of the ArcGIS Dashboard, which showcases the WUI mapping results alongside other wildfire-related data. Chapter 6 is for discussion of the final products and findings of this thesis, as well as limitations and additional research going forward.

Chapter 2 Related Literature

WUI mapping efforts have increased in the last decade and scholars have created WUI maps for many areas that have frequent wildfires. WUI studies in the US are mostly concentrated in the 48 conterminous states, thereby excluding Hawaii. This chapter covers existing wildfire studies on Maui, the many WUI mapping methodologies present in the literature, and existing WUI studies that include Maui.

2.1 Wildfire-Related Studies on Maui

Before the August 2023 wildfires, wildfire-related studies covered a variety of topics including drought and wildfire mitigation, but few were specific to wildfire events. Trauernicht and Lucas (2016) record historical wildfire ignition points for all of Hawaii, but this is the exception in the literature. Some research is on Maui specifically, but research on Maui is more frequently part of studies on the state of Hawaii. After August 2023, research poured into Maui. The 2023 wildfires and their causes and effects were studied extensively.

2.1.1 Maui Drought and Wildfire Studies

Drought was frequently studied on Maui before August 2023. Frazier et al. (2019) find that the impact of drought on agricultural land is dire, specifically in non-irrigated pastures. Over half of Maui's pastureland receives little rainfall, and the agricultural industry suffers heavy financial losses through cattle (Frazier et al. 2019). Heavy financial losses are also felt in Upcountry Maui during drought because many profitable vegetables are grown in that region (Frazier et al. 2019). Dolling, Chu, and Fujioka (2005) find correlation between a drought index and wildfires on Maui. Studying the various effects of drought on Hawaii, Kunz (2021) gathers knowledge from wildfire experts across the Hawaiian Islands on the different tactics for wildfire mitigation. Before drought, emphasis is put on fuels management, road management, training, and taking steps to preserve biodiversity after fires; during drought, emphasis is much higher on active wildfire prevention and preparation (Kunz 2021). Hawaii is in fire season throughout the entire year, and this is exacerbated in the drier southern and western regions (Parsons and Martin 2023).

Since wildfires are expected, many mitigation efforts are taken and researched on Maui and Hawaii as a whole. Maui County has an extensive hazard mitigation plan that covers wildfire risk, hazard mitigation, implementation plans, and more (Maui Emergency Management Agency 2020). Ritchey (2022) explores the potential benefits of controlled burns in wildfire-prone regions of the Hawaiian Islands. The study determines that for Maui, the most appropriate locations for controlled burns would be rural, flat, and dry (Ritchey 2022). Harrison (2020) explores the potential of mitigating wildfire risk through the untapped strategy of cattle grazing targeted at invasive grasses. Although the case study is on the island of Hawaii, the applications extend to all the Hawaiian Islands, especially Maui due to its extensive pastureland and ranching. De Roode and Martinac (2020) research and select three potential sites for resilience hubs on Maui that would support communities during emergencies. Corlew (2015) creates a handbook for community preparedness in Maui, for wildfires, drought, and disasters and hazards.

2.1.2 August 2023 Wildfire Studies

Wildfire susceptibility analysis and mapping has been conducted for the island of Maui after the 2023 wildfires. Using remote sensing data, Ramayanti et al. (2024) include a multitude of wildfire factors and use machine-learning techniques to develop a categorical map of wildfire susceptibility levels across the island. The study also creates an inventory map of Maui wildfires from 2017-2023, including the August 2023 wildfires.

Several studies model the path of the August 2023 wildfires and create maps of the wildfires' spread. Roy et al. (2024) use MODIS, VIIRS, and PlanetScope satellite data to track incidences of the Maui wildfires and characterize their intensities over time. Several map products are created, including maps of active fires and their extents, symbolized by day and/or time. This is significant for showing exactly where the fire reached and at what times during the days that the fire was active. With the Lahaina 2023 wildfire as a case study, Zhou (2024) creates a fire spread model for WUI wildfires and estimates monetary damage to wildlands and structures based on their material type. Juliano et al. (2024) use the Weather Research and Forecasting model and the Streamlined Wildland-Urban Interface Fire Tracing model to model the predicted path of the Lahaina wildfire at timed intervals and compare the predictions to the actual extent.

Many studies on the Maui wildfires focus on topics other than the fire itself. The August 2023 wildfires occurred under extreme wind conditions, and the meteorological aspect of the event is studied (Mass and Ovens 2024). Several studies assess the response to the fire and provide critiques for emergency planning and how the local government handled the situation (Byren and TESA Tech Team 2023; Voda 2023). One study uses vector data to create map products for network analysis from fire stations and cost analysis of damage from parcel data in Lahaina (Mengote 2024). Balmes and Holm (2023) research how wildfire smoke affects human health and mentions that WUI fires, such as the one in Lahaina, are especially dangerous because of the synthetic materials that burn and add toxic substances into the smoke. Averett (2024) studies contaminants and pollutants around the burned areas of the Lahaina wildfires and notes that Lahaina stands out amongst WUI fires because of the high density of homes adjacent to the burned areas.

2.2 WUI and Mapping Practices

Many WUI maps have been created on local, national, and global scales, but choices in WUI mapping methodology vary. The definition of structural density can be altered, either building density or housing unit density. There are two main methodology frameworks for mapping WUI: zonal-based and point-based (Bar-Massada 2021). Many studies focus on editing the standard density and vegetation cover thresholds from the Federal Register WUI definitions to be more appropriate for local study areas. The type of agricultural land included in WUI analysis can also be changed.

2.2.1 Building Density vs Housing Unit Density

Whether a study uses buildings or housing units for its structural density metric is an important distinction. Building footprints include non-residential structures, while housing units are based on census data and may count multiple structures within the same building, such as in an apartment complex. Many studies perform multiple iterations, testing the effect of either choice. Montana has a large history of wildfires, and Ketchpaw et al. (2022) compare three methods of calculating structural density: local Montana address data, the Microsoft building footprint dataset, and census housing units. The study found that the census housing unit method outputs the least WUI territory, and that using buildings results in more WUI coverage. The study recommends using the Microsoft building footprint dataset for assessing defensible space around structures (Ketchpaw et al. 2022). Carlson et al. (2021) compare using the Microsoft building dataset for structural density to using census housing units for structural density. Carlson et al. (2021) also find that the choice of building data results in more WUI area than census housing units. The study finds that using building data provides insight into the effect of non-residential structures on the WUI and recommends using building data in study areas without reliable census data.

2.2.2 WUI Mapping Frameworks

Bar-Massada (2021) compares point-based and zonal-based WUI mapping methods across California (Figure 7). The point-based approach is based on pixels. Structural density is calculated as the number of points within a specified buffer distance around the centroid of each pixel. The percentage of vegetation cover is calculated as the percentage of pixels with vegetation cover within a radius around each pixel centroid as well. Each pixel is determined to be inside or outside of the buffer around wildland areas. Alternatively, the zonal-based approach uses census block polygons to determine structural density and the percentage of vegetation cover. For distance from wildlands, the census block polygon is determined to be inside or outside of a buffer around wildland areas. The census block is used in zonal-based WUI mapping because it is the finest resolution of census data available, smaller than both census tracts and census block groups. A benefit of the point-based approach for calculating density is that the varying size and shape of census block polygons are not an issue, as in the zonal-based approach. However, there are no standards for how far of a radius should be used for calculating density in the point-based approach.

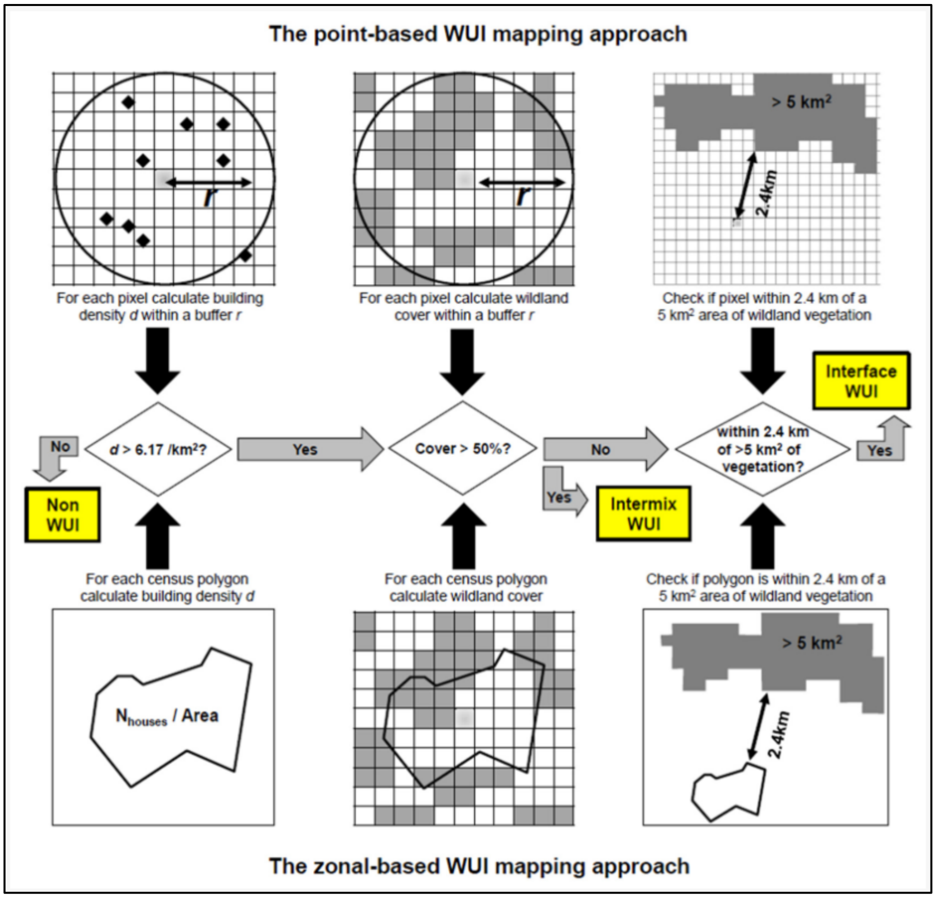

Figure 7. Diagram of two WUI mapping approaches. Figure by Bar-Massada 2021.

2.2.2.1 Point-based

Some WUI maps cover a continental or global extent, and they use point-based WUI mapping practices. Mapping across national boundaries and beyond the extent of consistent census data makes the point-based scale appropriate. Schug et al. (2023) use the point-based approach to map WUI globally with a 500m search radius. Johnston and Flannigan (2018) create the first WUI map for Canada and use a pixel-based approach. With a building location dataset and a 30m resolution LANDSAT landcover dataset, the study calculates density in hexagonal grid cells of 3,400 square kilometers. Johnston and Flannigan (2018) show that almost 4% of Canada is WUI and the WUI maps pave the way for future wildfire-related research. Carlson et al. (2021) create a WUI map of the conterminous US; this study uses 30m 2016 NLCD data and Microsoft building footprints. Carlson et al. (2021) calculate building density and vegetation cover per pixel using a moving window method, with thresholds determined by the Federal Register. The project tests radii of 100, 250, 500, 750, 1000, and 1500m. Density is more controlled in the pixel-based method than when using census blocks of various sizes in the zonal-based method, but results change significantly based on the radius used; the area counted as WUI increases when the radius increases. After testing the various radii, Carlson et al. (2021) choose and recommend the 500m radius as the most appropriate for WUI mapping across the conterminous US because this radius captures WUI around development next to wildlands and excludes WUI around isolated buildings.

2.2.2.2 Zonal-based

Using the zonal-based approach, Radeloff et al. (2005) mapped WUI for the 48 conterminous states in one of the earliest WUI mapping efforts. This study is one of the most significant and commonly cited papers in WUI mapping literature. The zonal approach is popular due to the availability of census block data across the country. The study uses decennial census housing unit counts and NLCD landcover to calculate housing unit density and vegetation cover per census block. While using standard WUI threshold definitions, Randeloff et al. (2005) perform a sensitivity analysis to determine how much the threshold adjustments affect results. The study tests housing density thresholds of 3.09, 6.17, and 12.34 housing units per square kilometer. Vegetation cover thresholds are tested at 25, 50, and 75%. The wildland buffer is tested at 1.2, 2.4, and 4.8 kilometers. Furthermore, wildland vegetation cover classifications are part of the sensitivity analysis. Standard wildland classifications, classifications excluding woody and emergent wetlands, and forest classifications alone are tested. The results of the sensitivity analysis show that the housing density threshold affects WUI area the most, WUIF is especially sensitive to the buffer distance, WUIX is especially sensitive to the vegetation cover threshold, and shrublands should not be excluded from vegetation cover because fires are frequent in chaparral ecosystems. Overall, the ranking of WUI area remained consistent across states regardless of the thresholds used, showing the reliability of WUI analysis (Radeloff et al. 2005). Radeloff et al. (2018) use the same zonal-based methodology to compare WUI in 1990 and 2010.

2.2.3 WUI Definition Thresholds

While many studies use the Federal Register definitions for density and vegetation cover thresholds, some studies alter these thresholds to be more suitable for a study area. Li et al. (2022) map the WUI in California, emphasizing the need for WUI maps to be continually updated in such a fire-prone state, and the study tests the definition thresholds of vegetation cover percentages and the distance between structures and wildland. The study tests vegetation cover percentages in 10% increments, and tests 1.2-, 2.4-, and 4.8-kilometer buffers. Ultimately, a standard buffer of 2.4 km is chosen because the other tested buffers do not significantly change results. A vegetation cover threshold of 40%, slightly lower than the standard 50%, is chosen because the study finds that change in WUI area is stable under this threshold.

Slaton (2022) explores the most appropriate WUI definition for the study area of the Oregon-California border, emphasizing the importance of custom thresholds for small-scale studies. The study tests vegetation cover thresholds between 0 and 75%, and tests housing density thresholds of 1 home per 20, 40 (standard), 60, and 400 acres. A 25% vegetation threshold is chosen for the study area to represent WUI near urban cores. Slaton (2022) chooses a 1 home per 400 acres (approximately 0.6 homes per square kilometer) density threshold, finding that a lower density threshold than national definitions is critical to properly identify WUI in the study area because there are many sparsely populated areas that must be represented.

2.2.4 Agricultural Mapping in WUI

In WUI mapping practice, agricultural land is not considered to be vegetation cover (Radeloff et al. 2005; Schug et al. 2023; Slaton 2023). The most important characteristic of agricultural land that removes it from vegetation cover classification in WUI mapping is its lower level of flammability; agricultural land is typically maintained and irrigated. Agricultural plant species vary in their level of flammability, and some pasture grasses have low wildfire risk (Pagadala et al. 2024). Pastureland is considered agricultural land and removed from vegetation cover calculations in Radeloff et al. (2005). Fu et al. (2023) find that irrigated, low-flammability crop species serve well as fire buffers. Specifically, the study highlights bananas. Fu et al. (2023) recommend banana buffers as a profitable method of fire mitigation, especially in WUI.

2.3 WUI on Maui

Mapping WUI is a popular subject in literature, however not for the study area of Hawaii. Broadly, WUI estimates about Maui have been made, but without detailed WUI mapping. No WUI map has been made specifically for the study area of Maui, but insight into Maui's WUI can be gleaned from WUI maps of larger study areas, of the world and of Hawaii, that include Maui. Furthermore, WUI studies of other fire prone areas provide insight into what may be expected for WUI outcomes. Centered around WUI, many guidelines and community plans have been created for Maui.

2.3.1 Maui WUI Estimations

Nominal WUI assignments have been attributed to Maui without the support of WUI analysis. Per the HWMO and Maui County in a 2014 report, all Western Maui is broadly considered to be WUI and share a wildfire protection boundary (Pickett, Grossman, and HWMO 2014). However, this map is not detailed and does not give insight into the spatial distribution of the island in relation to WUI. Based on field reconnaissance after the 2023 wildfire, the NIST declared the Lahaina wildfire to be an interface event, in a WUI subclassification of intermix or interface (Link 2024). However, a full case study was not conducted by the NIST for Lahaina, so there is no map or further description of this classification. The other 2023 Maui wildfires in Olinda, Kula, and Pūlehu were not reviewed by the NIST or assigned WUI event classifications.

2.3.2 Maui in Global WUI

The SILVIS Lab at the University of Wisconsin-Madison released a global WUI map based on the year 2020 at 10m resolution (Schug et al. 2023). The global WUI map provides a detailed WUI map of Maui, shown in Figure 8. The map does not follow the standard building density threshold of 6.18 buildings per square kilometer because it uses a global building density dataset, rather than building footprints. The study uses the Global Human Settlement worldwide built-up surface estimate 10m raster dataset to calculate building density for pixels with a 500m radius. Unable to follow the Federal Register building density threshold, the study considers pixels as potentially qualifying as WUI if they have at least 0.5% aggregated building density of pixels in the 500m radius around them. The paper claims that because this threshold is higher than the Federal Register definition, the WUI estimates are conservative, so there are likely more WUI areas on Maui than designated in this map.

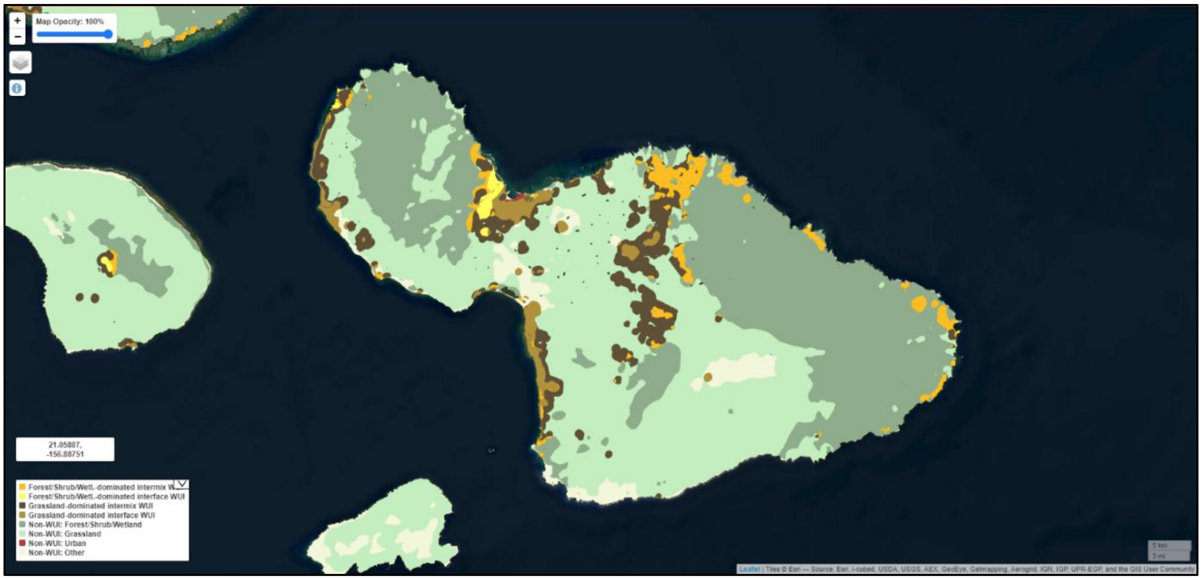

Figure 8. SILVIS Lab – Maui WUI map

For landcover and vegetation data, the study uses the European Space Agency WorldCover 2020 dataset, reclassifying the data into wildland and non-wildland vegetation. Following standard WUI definitions, the study finds wildland areas that are greater than 5 square kilometers of ≥ 75% vegetation cover and considers pixels within 2.4 square kilometers of these wildlands as potentially WUIF. Whether grassland cover, or forest, shrubland, and wetlands cover is greater determines if a WUI pixel receives a grassland or forest subclassification.

The target audience for the global WUI map is other researchers, and map interpretation is done for large areas such as countries and biomes. In continental summaries, Schug et al. (2023) disclose that under 5% of land area and over 60% of people in Oceania are in WUI, and that forest-dominated WUI is more prominent than grassland-dominated WUI in Oceania. While viewable on a web application and accessible through ArcGIS Online, this dataset is exceedingly large and downloadable at continental levels.

2.3.3 Maui in Hawaii WUI

The Hawaii Dept. of Land and Natural Resources (DLNR) has created its own definition of WUI for Hawaii based on Communities at Risk (CARs), which are communities of varying wildfire risk identified by the Hawaii Department of Forestry and Wildlife (DOFAW). The CARs are designated based on vegetation type, climate, and wildfire history, and organized into High, Medium, or Low Risk classifications (Hawaii DLNR 2010). The state of Hawaii defines WUI for Hawaii as areas within 1-mile of CARs. The CARs and WUI defined by Hawaii are shown in Figure 9Figure 6 (Hawaii DLNR 2010). These assessments were begun in 2005 and were published in 2010. The WUI definition does not conform to the 2001 Federal Register definitions of WUI, which are based on density and vegetation cover. The polygon outlines do not align with census-defined community boundaries. The intended audience of the Hawaii-specific CAR and WUI designations is Hawaii-based wildfire management and planning professionals.

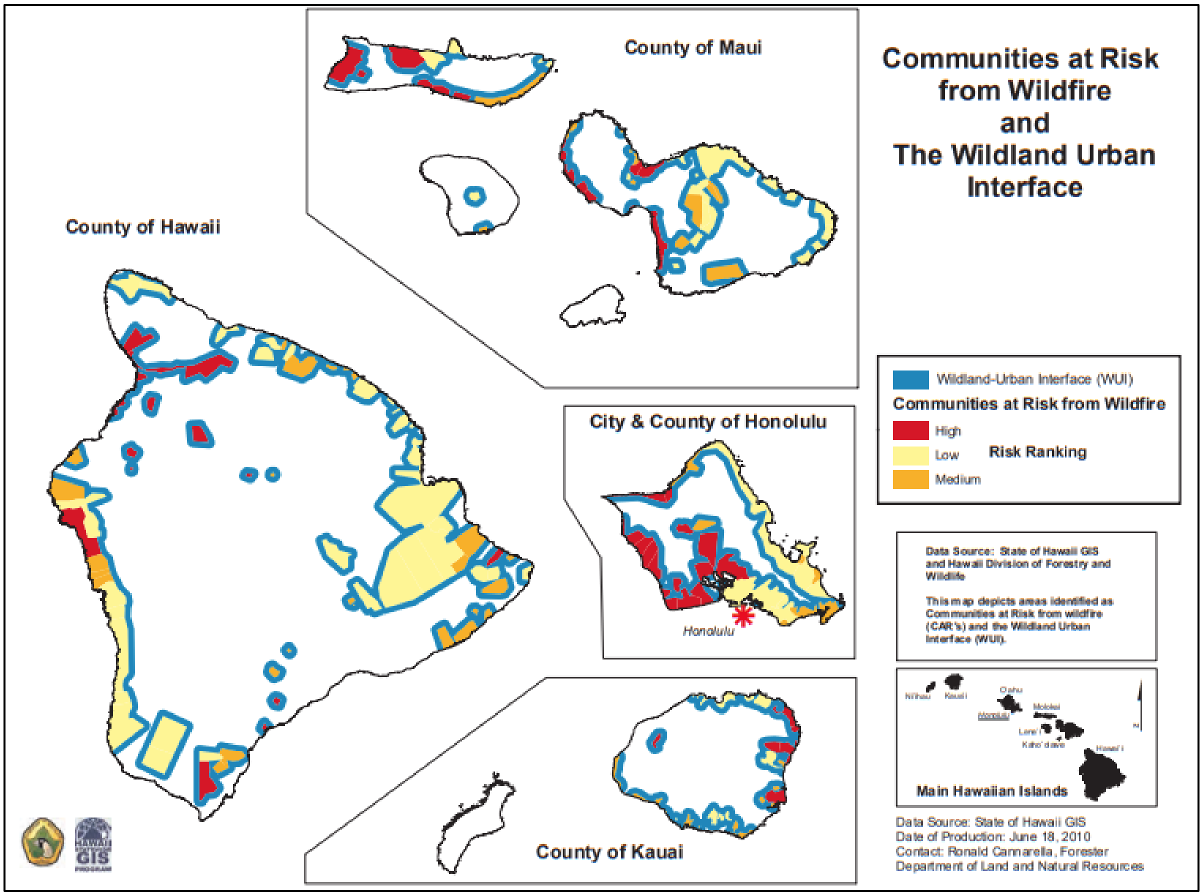

Figure 9. Hawaii state-defined CARs and WUI. Figure by Hawaii DLNR 2010.

2.3.4 Comparison to WUI in Fire-Prone Western US

WUI studies are common in the conterminous US. Radeloff et al. (2023a) provide WUI statistics for the conterminous US for the year 2020, and WUI information on the fire-prone western states can be gathered. While percentages of land area in WUI are quite low for all the fire-prone western states, ranging from 0.9% in Nevada to 8.2% in Washington, the percentage of housing within the WUI is significantly higher, ranging from 32.5% in Washington to 80.1% in Wyoming. The national average for housing percentage in WUI is 31.6%, and many of the western states do not stray far from this average. Notably, while only 1% of Wyoming's land area is within WUI, 80.1% of housing is within the WUI, the highest of the western states. These statistics highlight the disproportionate amount of development within the WUI in fire-prone states.

2.3.5 Maui WUI Guidelines and Community Protection Plans

Designing communities with WUI consideration is addressed in literature to protect communities from fires in nearby wildlands. Calkin et al. (2023) address WUI fires, such as the Lahaina fire, and place the responsibility on individual communities to prevent major wildfire spread in densely developed areas. Specifically, Calkin et al. (2023) take the position that communities must have proper landscaping, construction site, and material guidelines that are designed to prevent the spread of wildfire. Since the greatest risk of wildfire spreading from structure to structure is within 100 ft, the immediate surroundings of buildings should not connect flammable materials together, whether by fences or otherwise (Calkin et al. 2023). Necessary precautions must be taken by homeowners and local governments to prevent wildfires from spreading between structures at such a rapid rate (Calkin et al. 2023). The extension of utility networks in WUI areas increases ignition risks, as in the case of the Lahaina wildfire (Mahmoud 2024), and utility planning must consider WUI as well. All these steps are necessary for WUI areas to coexist with wildland fires and prevent the fires from spreading amongst dwellings.

Maui has many wildfire protection plans such as the West Maui Community Wildfire Protection Plan and the Maui County Multi-Hazard Mitigation Plan Update. Fire management requirements include that projects must have defensible space around them and keep up with maintenance per Maui Fire Dept. guidelines (Maui County Department of Planning 2022). Plans to develop firebreaks with multipurpose recreational functions around and between communities are encouraged. The plan mentions that the transportation system needs to be improved to better address wildfire hazards and that a wildfire information campaign should be held to encourage native plant landscapes and firebreaks.

In a 2021 report, Maui County identified alien grasses as a dangerous wildfire fuel source on the island that must be removed (County of Maui 2021). A strategy recommended for wildfire prevention is replacing invasive grasses with native plants, especially in abandoned sugarcane plantations. The report also recommends an assessment program that identifies properties with hazardous overgrown vegetation and supports their development of proper firebreaks. Furthermore, the report suggests that increasing the required width of firebreaks countywide can reduce the spread of wildfires (County of Maui 2021).

The Maui Fire Department has released a Community Risk Reduction Program for WUI on Maui County's website. The plan has general guidelines for reducing hazards but is not spatialized (Purdy 2018). The plan recommends self-assessment for fire code violations, fire hazard inspections, removing vegetation deemed to be a hazard by the fire department, keeping highly flammable vegetation fuels more than 30 ft away from buildings (or 100 ft, depending on circumstance), and incorporating fuel breaks.

Chapter 3 Methods

This chapter details the data as well as the zonal-based methodology used in this thesis for mapping Maui's WUI. A WUI map is created with standard WUI classifications, and then this map is refined to create a WUI map with Maui-specific WUI subclassifications. To arrive at this methodology, several landcover datasets were compared before choosing the most appropriate dataset to use for vegetation consideration. Furthermore, agricultural data was also incorporated before finalizing the WUI methodology, and these enhancements are discussed.

3.1 Workflow Overview

A workflow diagram of all steps in this thesis's final analysis is shown in Figure 10. The analysis in this thesis is entirely replicable. The only data needed to complete the WUI map are a building footprint dataset, census block data, landcover data, and agricultural data. This thesis project falls into six steps: Step 1 is calculating building density, Step 2 is calculating vegetation cover with agricultural enhancements, Step 3 is identifying wildlands, Step 4 is creating a standard WUI map, Step 5 is calculating grassland and forest cover, and Step 6 is incorporating the forest cover to enhance the WUI map by distinguishing WUI and wildlands that are forest-dominated.

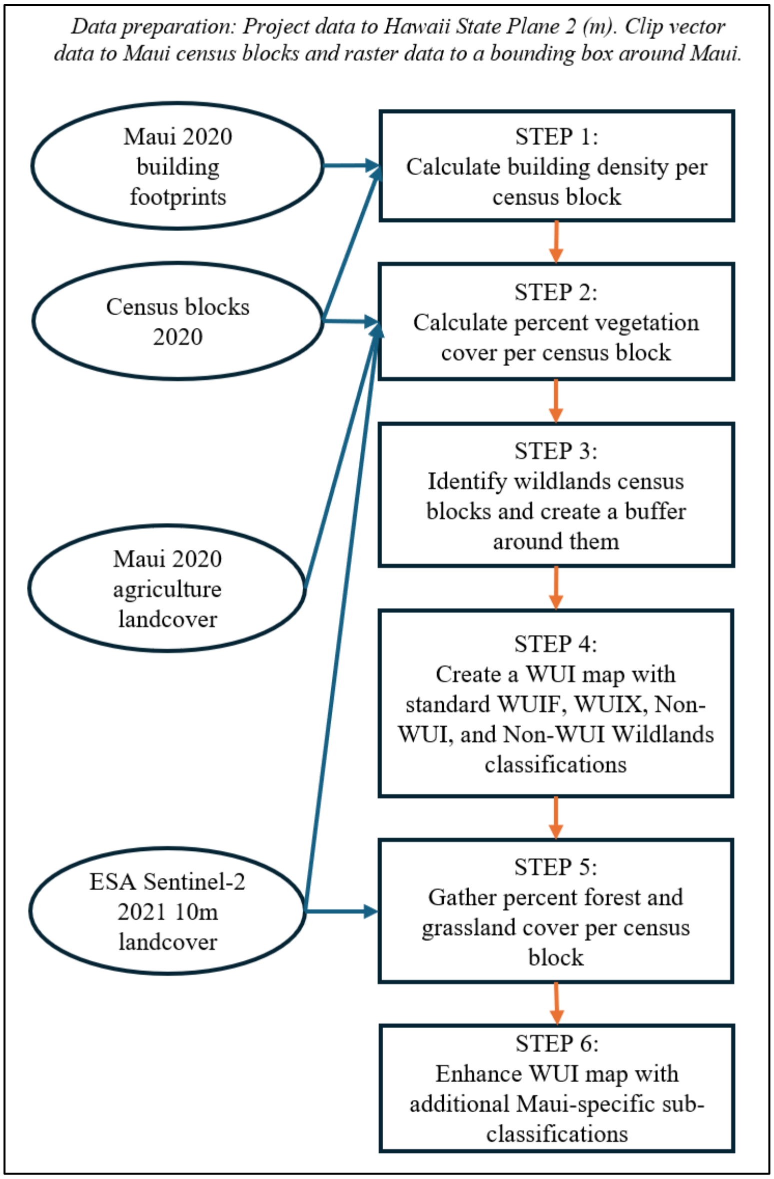

Figure 10. Workflow diagram

3.2 Data Description

The multiple facets of WUI analysis require data products from the Census Bureau, the Hawaiian government, Maui County, and more. The data and relevant characteristics are portrayed in Table 2. Data for WUI mapping includes building footprints, census block boundaries, landcover, and agricultural landcover. More landcover datasets are included in the data table than are used for creating the final WUI map; these extra datasets are used in WUI mapping experiments to compare how vegetation and agricultural classifications affect WUI classification outcomes. The data sources are all free and publicly accessible. All data is projected to Hawaii State Plane 2 (m), per Hawaii government standards (Hawaii DLNR 2013). Raster data is cropped to a bounding box surrounding Maui and vector data is cropped to Maui before analysis begins. All analysis is completed in ArcGIS Pro.

Table 2. Data descriptions

Data	Source	Year	Resolution	Use	Data Description
Building Footprints	Maui County GIS Dept.	2020	N/A, vector	Calculate building density	Building footprint polygons for Maui
Census Blocks	Esri Federal Data, sourced from US Census Bureau	2020	N/A, vector	Boundaries for WUI mapping and zonal analysis	Census block polygons
Hawaii Existing Vegetation Type	LANDFIRE	2022	30m	Vegetation cover dataset experimentation	Per pixel, the type of vegetation cover
Hawaii Fuels Cover	LANDFIRE	2022	30m	Vegetation cover dataset experimentation	Per pixel, the % coverage of flammable fuels
WorldCover Landcover	European Space Agency Sentinel-2	2021	10m	Designate developed/non-wildland areas vs vegetation/ wildland	Raster of landcover classification
Agricultural Land Use	Hawaii Statewide GIS Program	2020	N/A, vector	Eliminate appropriate vegetation types from vegetation cover	Polygons of existing agricultural lands categorized by crop/use

3.2.1 Development-Oriented Datasets

Census blocks are nationally available with information from the 2020 decennial census (Esri US Federal Data 2024) and building footprints for the year 2020 are provided by Maui County (County of Maui GIS 2020). There are over 1,400 census blocks and over 70,000 buildings on Maui, and they are shown in Figure 11. Census blocks vary in size across the island, small in densely developed areas and large in unpopulated wildlands. Buildings are distinctly concentrated in West Maui, Central Maui, South Maui, and parts of Upcountry Maui. Clusters of development are present but sparser in the North Shore and East Maui regions.

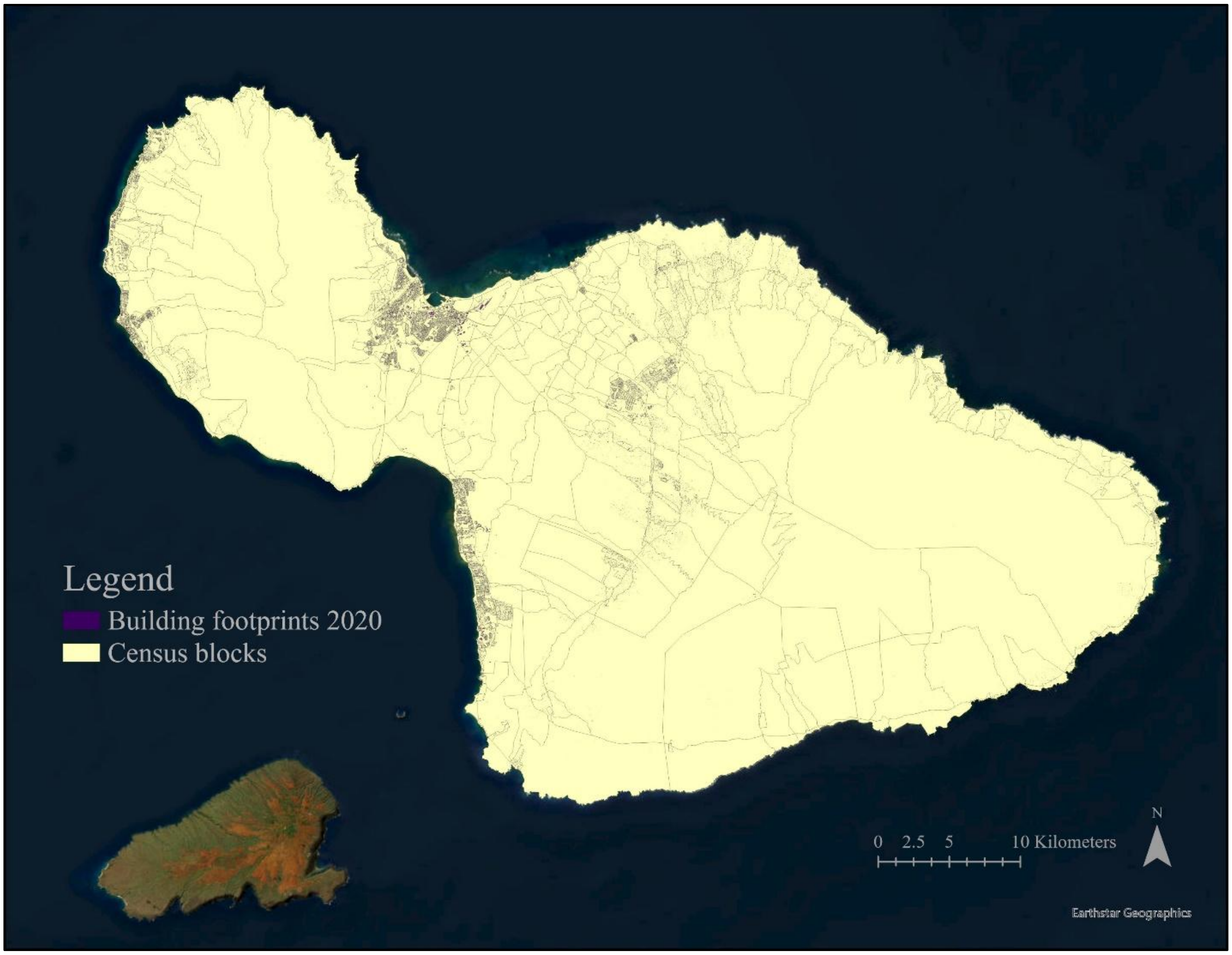

Figure 11. Census blocks and distribution of buildings

3.2.2 Landcover Datasets

The included landcover datasets for mapping vegetation cover are LANDFIRE Existing Vegetation Type (EVT), LANDFIRE Fuel Vegetation Cover (FVC), and European Space

Agency (ESA) WorldCover. The National Land Cover Dataset (NLCD) is the standard dataset for WUI vegetation cover in the US because of its wide coverage, relatively fine resolution (30m), and its timely updates (the most recent being 2021). However, the NLCD updates do not regularly include Hawaii, and the last Hawaii Land Cover dataset is from 2011, so NLCD is not considered in this analysis.

LANDFIRE is a national government program from a collaboration between the US Department of Agriculture Forest Service and the US Department of the Interior, and the datasets are specifically intended to support wildfire management. LANDFIRE datasets are included because of their wildfire-oriented nature, and they have local datasets that are Hawaii-specific. Hawaii has unique vegetation, so Hawaii-specific datasets are advantageous. They are also 30m resolution, like NLCD, and are based on the year 2022, one year more recent. The data is created from field-referenced data, biophysical layers, and machine learning. LANDFIRE datasets have been used in WUI literature (Li et al. 2021).

The EVT dataset is considered for the WUI mapping vegetation cover dataset because it has detailed, vegetation-specific vegetation classifications. The EVT dataset is shown in Figure 12. This dataset has many distinctions, with over 50 existing vegetation type classifications. Whether the vegetation is Hawaiian or Polynesian is distinguished, and the Polynesian classifications are mostly dominated by invasive species. The EVT dataset has multiple agriculture classifications, including cultivated crops, pasture/hay, and orchards. There are also multiple subclassifications for grassland, forests, shrubland, and development. The dataset has significant agricultural misclassifications, especially around Central Maui and West Maui.

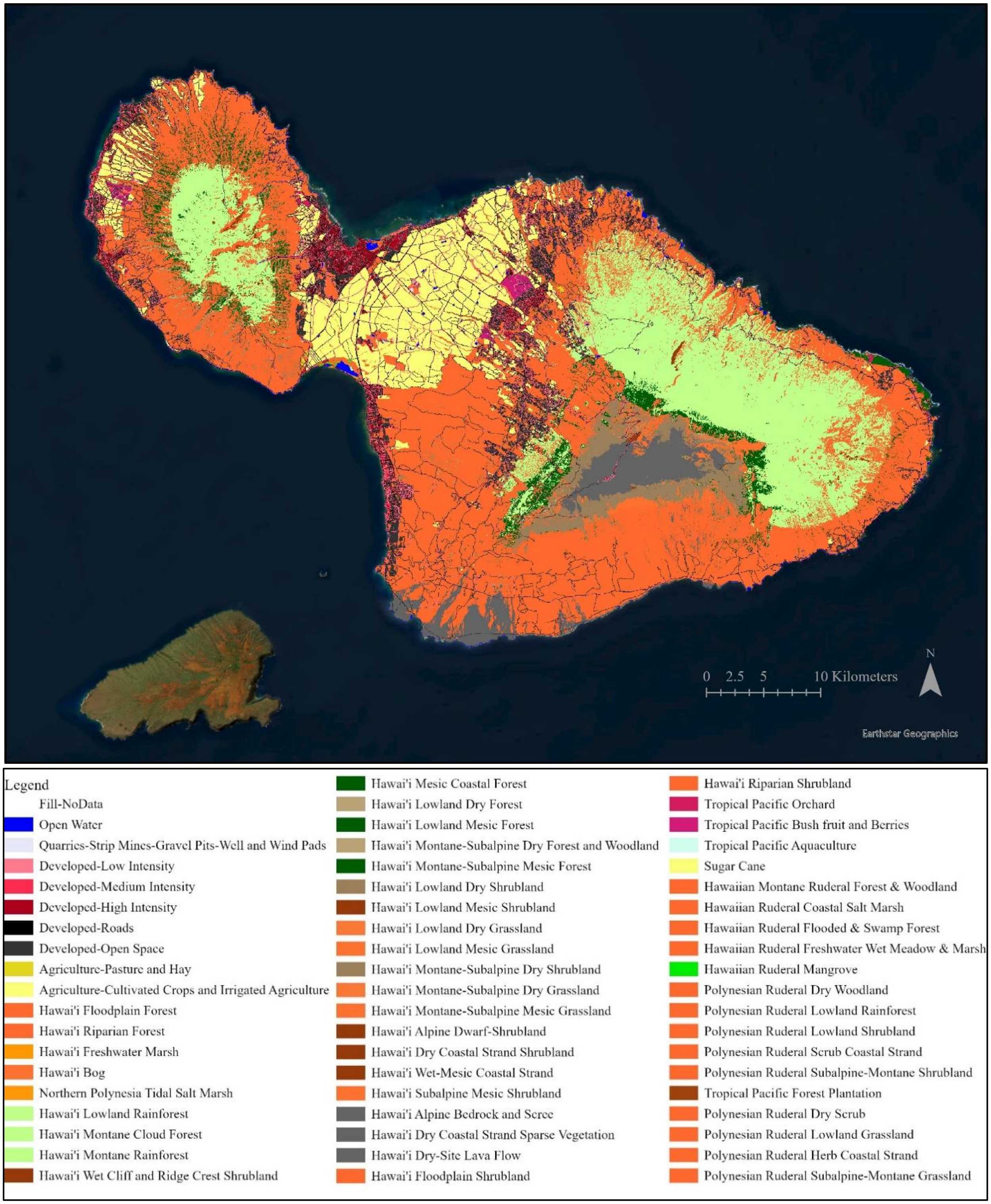

Figure 12. LANDFIRE EVT dataset

LANDFIRE also has a wildfire fuels landcover dataset. The FVC dataset is considered for mapping WUI in Maui because it bases its landcover classification on flammability rather than vegetation type, and vegetation cover classification based on flammability may be beneficial in a WUI context. The FVC dataset is shown in Figure 13 and contains over 30 classifications. This dataset does not detail the specific vegetation type, as in the EVT dataset, but generalizes flammable fuel cover into three categories: tree cover, shrub cover, and herb cover. Within these three categories, the data distinguishes the vegetation cover in increments of 10%. There is one agricultural classification, and it covers significantly less land than the agricultural classifications in the EVT dataset. Like the EVT dataset, this dataset has five development distinctions, but the FVC dataset differs by having only one agricultural classification, cultivated crops. Most of the land area that is classified as agricultural land in the EVT dataset is classified as shrub- or herb-covered land in the FVT dataset. However, large areas of West Maui are still classified as agricultural.

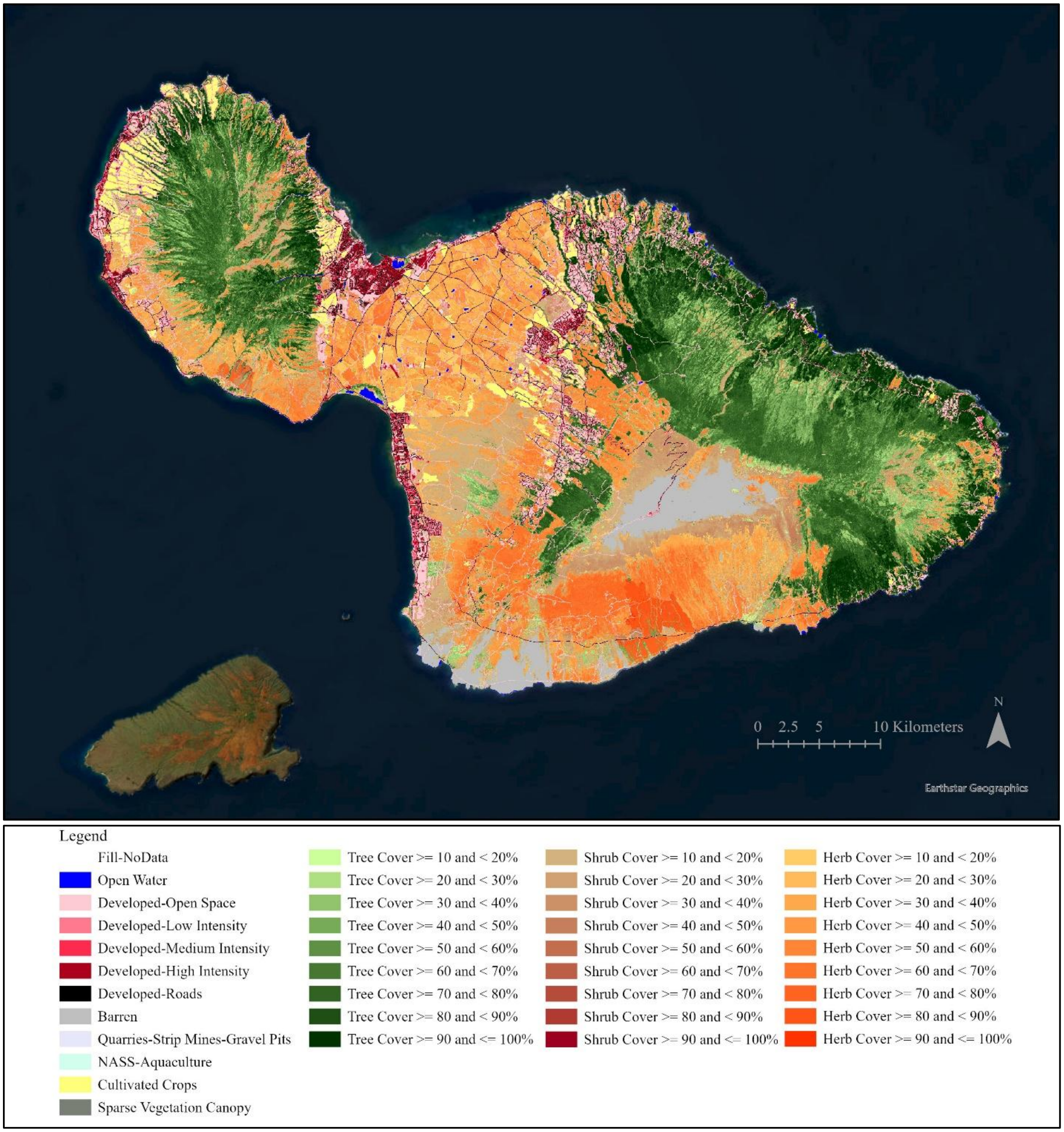

Figure 13. LANDFIRE FVC dataset

The ESA Sentinel-2 global landcover dataset has a higher resolution than the other datasets, with a fine, 10m resolution. This ESA dataset is based on 2021, the same year as the most recent NLCD release that did not include Hawaii. It is also used by the SILVIS Lab in the WUI map of the world, although the SILVIS Lab used 2020 WorldCover data. This dataset is shown in Figure 14. With nine classifications, the ESA dataset has significantly fewer vegetation distinctions than either LANDFIRE dataset. All tree cover, shrubland, grassland, development, and agriculture are represented by one classification each. Compared to the LANDFIRE datasets, almost no land on Maui is classified as agricultural. While the LANDFIRE datasets identified croplands in West Maui and around Central Maui, the ESA dataset classifies these areas as grassland. Only small patches of land around Central Maui are classified as agricultural by the ESA dataset. The ESA dataset recognizes significantly less developed land, most notably in Upcountry Maui. The resolution of the ESA dataset is much finer than the LANDFIRE datasets, which brings higher accuracy; however, some parts of the communities in Upcountry Maui are underrepresented in their development coverage, and more landcover in Upcountry Maui is classified as vegetation cover.

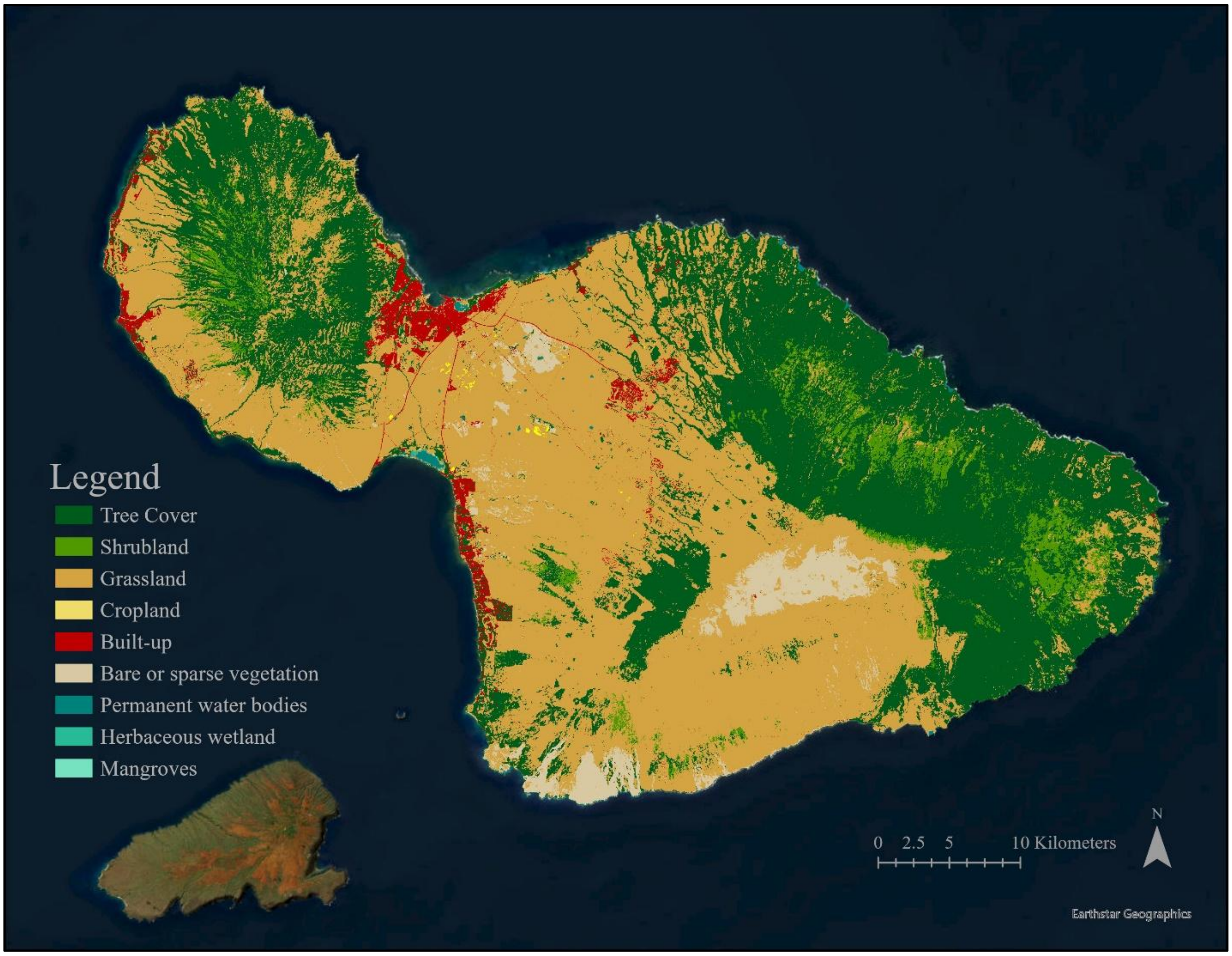

Figure 14. ESA WorldCover dataset

The three datasets that can be used to calculate vegetation cover vary greatly and show that agricultural land is difficult to classify on Maui, whether from remote sensing or predictive modeling. Notably, the EVT dataset presents a great swath of agricultural land in Central Maui, whereas this is mostly grassland in the FVC and ESA datasets. Historically, this area was sugar cane cropland, however it is no longer agricultural. The ESA dataset classifies little area of Maui as agricultural.

The Hawaii Statewide GIS Program is the source for an authoritative agricultural landcover dataset. The agricultural land use data for Maui for the year 2020 is shown in Figure 15 (Hawaii Statewide GIS Program 2022a). Maui has many different agricultural land uses: seed production, pasture, commercial forestry, banana, tropical fruits, pineapple, flowers, taro, diversified crop, macadamia nuts, and coffee.

Figure 15. Agricultural land use dataset

By area, pastureland is the most prevalent agricultural land use, covering about 25% of the land area of Maui. As seen in Table 3, pastureland consists of about 466 square kilometers out of Maui's almost 500 square kilometers of agricultural land. The second most prominent agricultural type is Diversified Crop, covering about 14 square kilometers. The remaining nine agricultural types all cover less than four square kilometers.

Table 3. Maui's agricultural land area by agriculture type

Agriculture Type	Area (square km)
Banana	0.26
Coffee	3.82
Commercial Forestry	0.15
Diversified Crop	13.77
Flowers / Foliage / Landscape	0.62
Macadamia Nuts	3.20
Pasture	465.83
Pineapple	3.88
Seed Production	2.62
Taro	0.46
Tropical Fruits	2.44

Source: Hawaii Statewide GIS Program 2022a

3.3 WUI Mapping

This thesis sources its definition of the WUI from the Federal Register and its methodology from WUI literature. This thesis follows zonal-based WUI mapping techniques, as outlined in Bar-Massada (2021). Structural density, sourced from building footprints as in Carlson et al. (2022), and vegetation percentages, sourced from ESA as in Schug et al. (2023), are calculated within census blocks to map WUI classifications.

According to the Federal Register, WUIX areas are areas with over 50% vegetation and structural density above 6.18 structures per square kilometer. WUIF areas have under 50% vegetation, structural density above 6.18 structures per square kilometer, and are located less than 2.4 km away from wildland areas. Building density, vegetation cover, and wildland areas are calculated to map WUI and classify WUIX, WUIF, Non-WUI, and Non-WUI Wildlands. After these standard classifications are mapped, vegetation cover metrics are enhanced by calculating grassland and forest cover. The new forest cover percentages are used to further classify Non-WUI Wildlands and WUIX into Non-WUI Wildlands Forest and WUIX Forest.

3.3.1 Building Density

Building density is chosen as the structural density metric for WUI calculation in this thesis because this metric is suitable for Maui. Commercial areas were destroyed in Lahaina and received extensive media attention. Housing and commercial areas are in close proximity in Maui and fire spreads between buildings, regardless of how many residential units are within them. Excluding non-residential buildings in WUI analysis would neglect a major aspect of the wildfires' impact in Maui. After investigation, although the density metrics changed significantly (because housing unit density is significantly higher than building density in Maui), most census blocks are far above the density threshold whether the metric is housing unit or building density. So, the different density types will not affect the WUI classification, and building density remains the chosen metric.

Census block polygon data and building footprints are needed to calculate building density for Maui as part of WUI classification because WUI areas have a structural density of ≥ 6.18 structures per square kilometer. WUI mapping with census blocks is precedented by the foundational study, Radeloff et al. (2005). This thesis uses the zonal-based WUI mapping approach, and structural density calculations per census block are the foundation of zonal-based WUI mapping (Bar-Massada 2021).

Calculating building density follows Step 1 of the workflow diagram, and a detailed workflow diagram of this step is shown in Figure 16. To calculate building density in ArcGIS

Pro, the Summarize Within tool is used to create an attribute field of the number of buildings in each census block. The Maui census blocks are the Input Polygons, and the building footprints are the Input Summary Features; the output feature class with the new attribute field for the number of buildings is used for further analysis. The Calculate Geometry tool is used to gather the area of each census block in square kilometers in a new attribute field. The Calculate Field tool is used to divide the number of buildings in each census block by the area in square kilometers of each census block to gather each census block's building density per square kilometer.

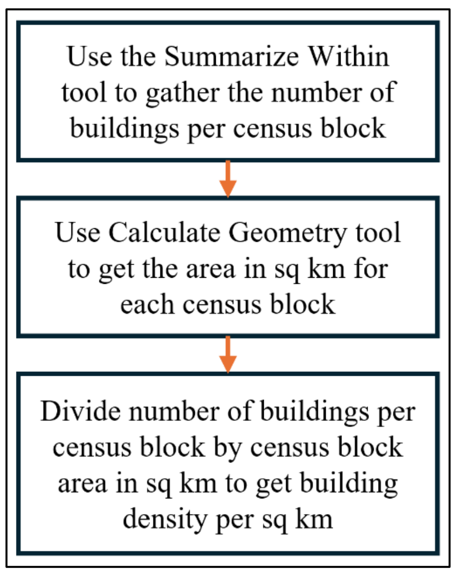

Figure 16. Workflow diagram for calculating building density

A map of the building density on Maui is shown in Figure 17. The threshold value of 6.18 buildings per square kilometer is used as one of the symbology cut-offs. The vast areas in white are census blocks that do not qualify for WUI designation because they do not meet the building density threshold. Most areas that do meet the building density threshold of 6.18

buildings per square kilometer have a much higher density than this minimum. The densest development on the island is in West Maui, Central Maui, and South Maui.

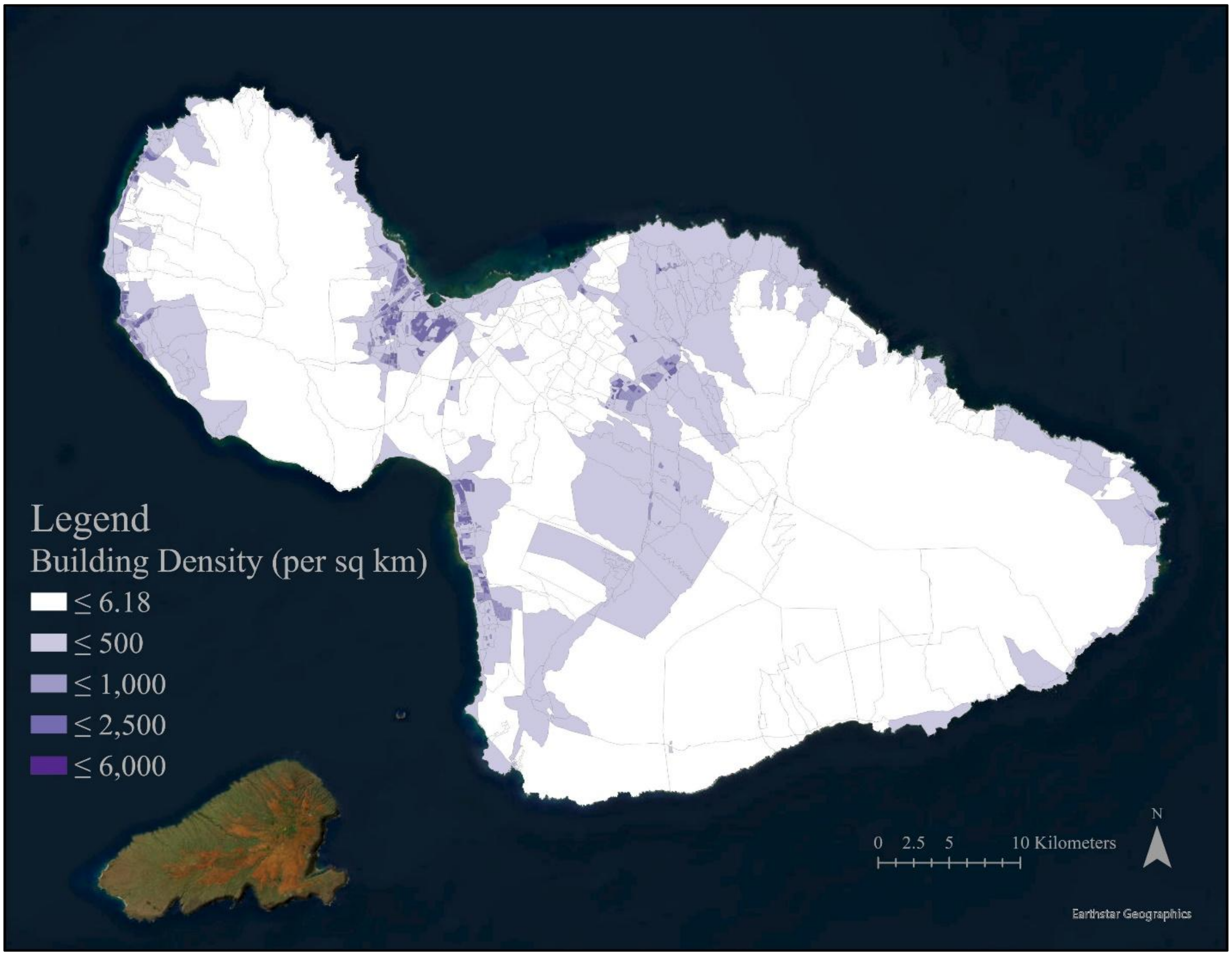

Figure 17. Building density

The building density distribution on Maui is heavily skewed to the right, as shown in the histogram in Figure 18. A large proportion of Maui's landcover has very low building density, but the fewer highly populated areas are incredibly dense. The minimum building density is 0, the maximum is over 5,700 buildings per square kilometer, and the average building density is about 574 buildings per square kilometer. Out of 1,447 total census blocks on Maui, 1,131 have a building density above the threshold of 6.18 buildings per square kilometer. These census blocks reach the building density threshold to qualify as WUI census blocks.

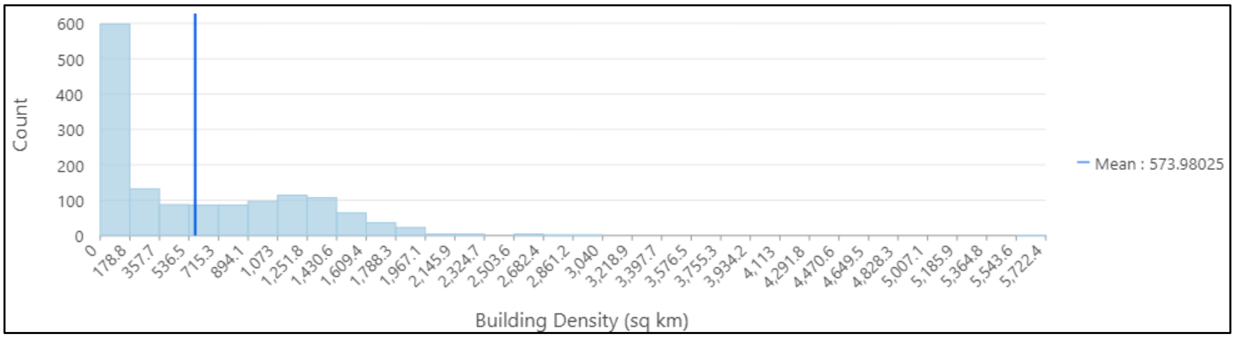

Figure 18. Building density distribution

3.3.2 Vegetation Cover

The percent vegetation cover is also calculated per census track, consistent with standard zonal-based WUI mapping (Bar-Massada 2021). This thesis uses ESA WorldCover 2021 as the source of vegetation cover. Calculating the percentage vegetation cover per census block follows Step 2 of the workflow diagram, and a detailed workflow diagram of this step is shown in Figure 19. The vegetation cover calculation methodology stems from Slaton (2023). The ESA dataset comes in nine classes originally: tree cover, shrubland, grassland, cropland, built-up, bare/spare vegetation, permanent water bodies, herbaceous wetland, and mangroves. These are reclassified with the Reclassify tool to represent either vegetation cover (1) or non-vegetation cover (0). The tree cover, shrubland, grassland, herbaceous wetland, cropland, and mangroves are assigned to 1. Built-up, bare/sparse vegetation, and permanent water bodies are assigned to 0. Cropland is typically assigned as non-vegetation in WUI literature; however, it is initially assigned as vegetation in this step because authoritative, accurate agricultural plots will be removed from vegetation cover in a later step and be assigned as non-vegetation landcover.

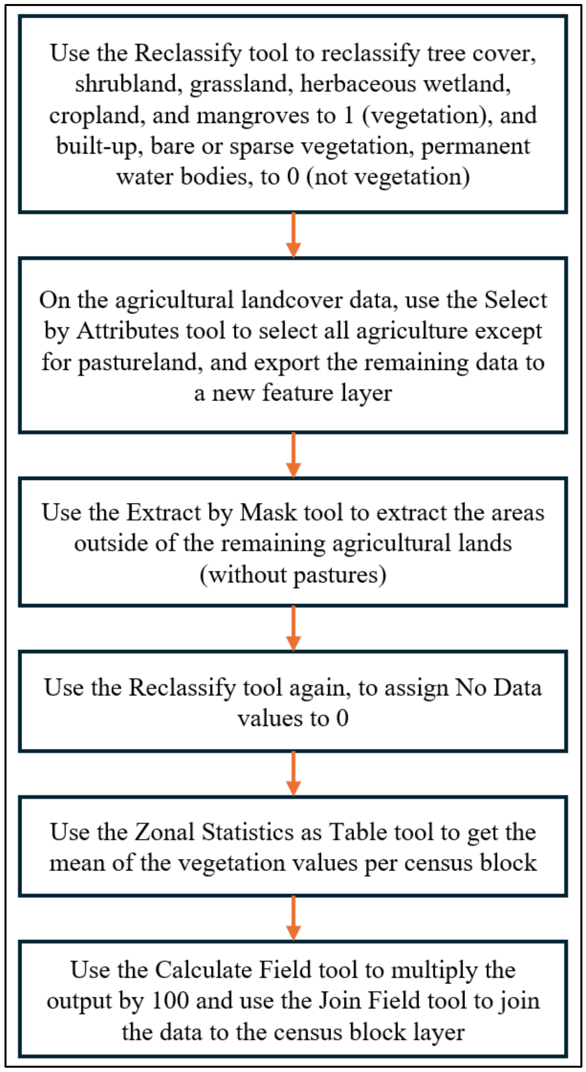

Figure 19. Workflow diagram for calculating vegetation cover

The results of the initial reclassification are shown in Figure 20. By area, most of the island is covered by vegetation. The developed communities of West Maui, Central Maui, and South Maui are distinguishable as areas with high concentrations of non-vegetation cover. Furthermore, the area around the volcano is notable as non-vegetation, as well as the tip of the southern coast.

Figure 20.Vegetation cover before agricultural enhancements

Agricultural land other than pastures is removed from the vegetation cover before further calculations are run. Using the Select by Attributes tool, the included agricultural land without pastures is gathered by selecting the inverse of agricultural plots that are equal to the pastureland classification. After they are selected, these less-flammable agricultural plots are exported to a new feature layer, as is shown in Figure 21. Without pastures, the total area of agricultural land decreases significantly, and the remaining agricultural plots are small and scattered. While they span across the whole island, the largest concentrations of large agricultural plots are in Central Maui and Upcountry Maui.

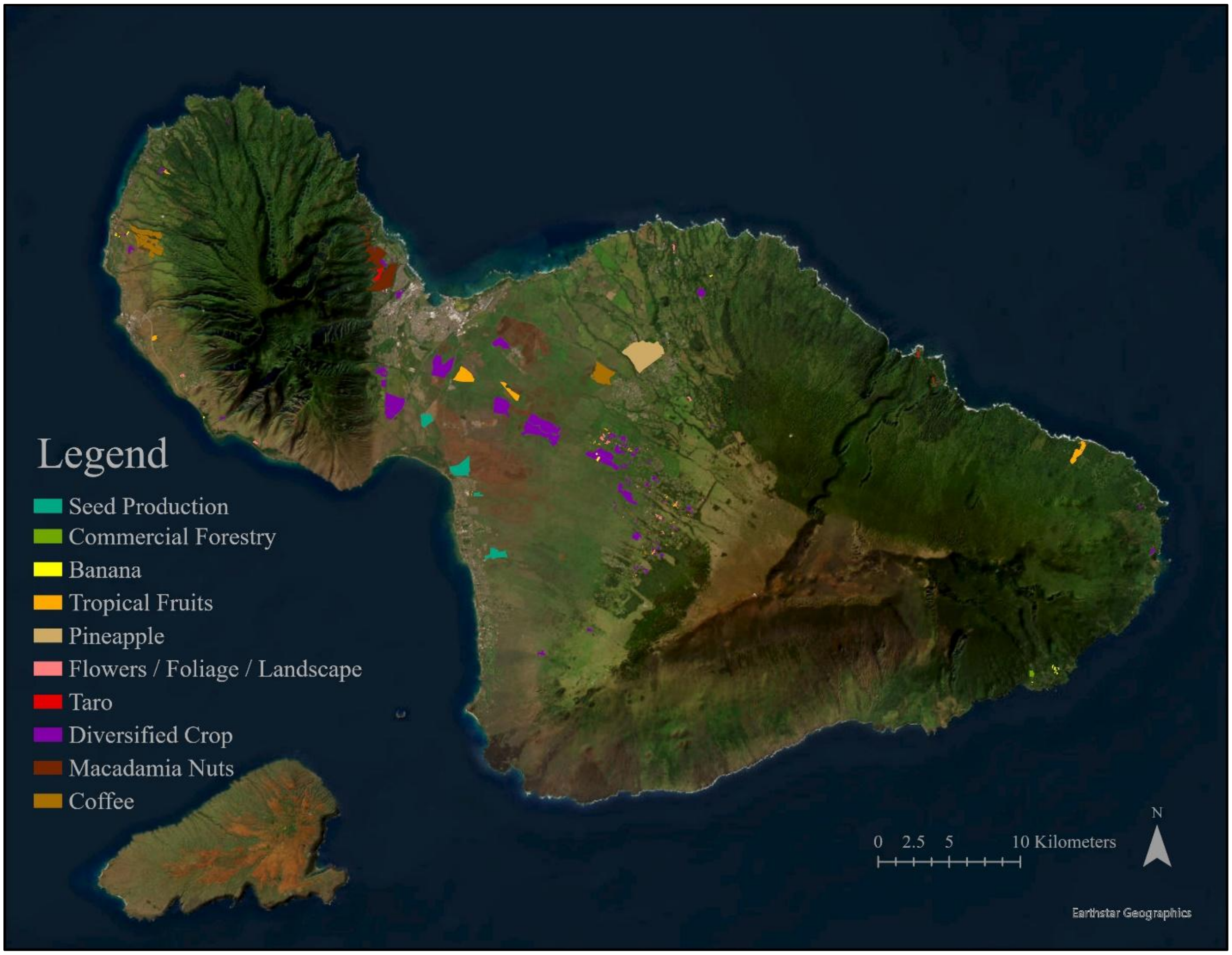

Figure 21. Included agricultural plots

The remaining agricultural land (without pastures) is removed from vegetation cover classification. The Extract by Mask tool is used on the reclassified vegetation raster to extract the areas outside of these agricultural plots. The Extraction Area must be set to Outside, and the Feature Mask Data Input is the feature layer of agricultural plots without pastures. The Analysis Extent must be set to the extent of the island. The output from this tool shows gaps where the plots were. The Reclassify tool is run again so that the no data values are also assigned to 0 (non-vegetation cover). The output can optionally be cropped to the extent of Maui by using the Extract by Mask tool again. The final vegetation raster with appropriate agricultural considerations is shown in Figure 22. Compared to the previous vegetation raster, the amount of non-vegetation cover increased. The shapes of the agricultural plots removed from vegetation cover calculations are seen across the island but are especially noticeable in Central Maui and Upcountry Maui. The agricultural adjustment shifts the vegetation cover classifications in census blocks that have agricultural plots in them. These are the final vegetation cover classifications.

Figure 22. Vegetation cover with agriculture considered

The final vegetation cover classifications are used to calculate the percent vegetation cover per census block. The Zonal Statistics as Table tool is used to get the mean of the vegetation values (0s and 1s) within each census block, as in Slaton (2023), representing the percentage of vegetation cover. The Input Feature Zone Data is the census block layer, the Zone

Field is the Geographic Identifier, and the Input Value Raster is the vegetation raster. The Statistics Type is set to Mean. The values in the output table are multiplied by 100 to get the true percentage value. Then, this attribute field is joined back to the census block feature layer with the Join Field tool. The Input Table is the census block feature layer, the Join Table is the table, the Input Field is the Geographic Identifier, the Join Field is GEOID, and the attribute field holding the percentage vegetation cover is the Transfer Field. The census block layer then contains the vegetation cover attribute field.

The percent vegetation cover for census blocks in Maui is symbolized and shown in Figure 23. The vegetation cover ranges from 0 to 100%, and most of the island is highly vegetated. The map includes a symbology break at 50% vegetation cover, so the distinction is clear between census blocks that may qualify for WUIF (< 50%) or WUIX (≥ 50%) per the vegetation cover aspect of their definitions. Most census blocks on Maui have greater than 50% vegetation cover, with the exceptions being in the most developed areas. Another symbology distinction on the map is the 75% vegetation cover threshold, which is used to determine areas that qualify as wildlands. Most census blocks that have ≥ 50% vegetation cover also have ≥ 75% vegetation cover. The ≥ 75% range covers most of the island.

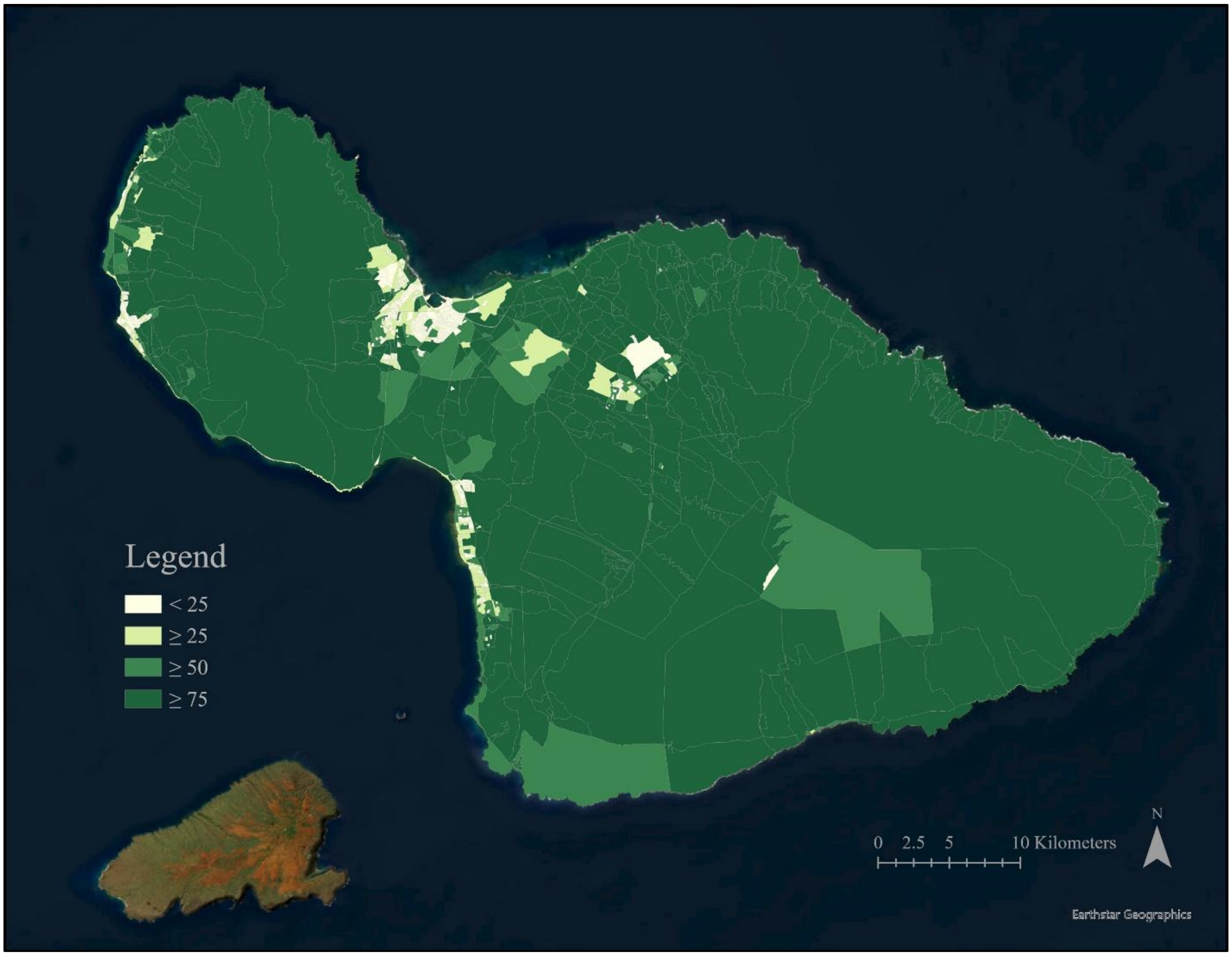

Figure 23. Vegetation cover per census block

3.3.3 Wildland Areas

Wildlands are mapped after vegetation cover is calculated. Part of WUIF classification requires the census block to be within 2.4 kilometers of wildlands, which are greater than 5 square kilometers (Bar-Massada 2021). In this thesis, the vegetation cover data is also used to determine the wildland areas. Per Federal Registrar definition, the wildland areas must be ≥ 75% vegetation cover. Identifying wildlands census blocks and creating a buffer around them follows Step 3 in the workflow diagram, and a detailed workflow diagram of this step is shown in Figure 24. The Select by Attributes tool is used to select census blocks that have ≥ 75% vegetation cover and the Export Features tool is used to export these census blocks to a new feature layer. The Dissolve tool is used to dissolve the newly exported census blocks with ≥ 75% vegetation cover into continuous polygons. The Create Multipart Features option is unchecked. In the dissolved output feature layer, the Calculate Geometry tool is used to calculate the area in square kilometers of each continuous, ≥ 75% vegetation cover polygon. The Select by Attributes tool is used to select polygons that are < 5 square kilometers. These selected polygons are deleted because they do not qualify as wildland areas.

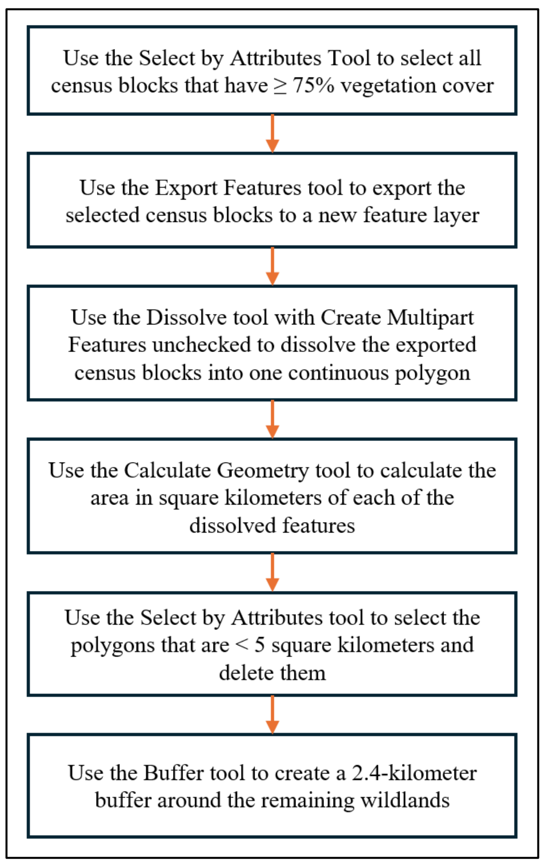

Figure 24. Workflow diagram for identifying wildlands and creating a wildland buffer

The remaining census blocks areas that are ≥ 5 square kilometers of area with ≥ 75% vegetation cover qualify as wildlands, and they are shown in Figure 25. Maui has 1,649 square kilometers of wildlands; wildlands cover most of the island. Few census blocks were removed for not meeting the ≥ 5 square kilometer threshold. The areas that do not qualify as wildlands are developed areas, some areas that contained agricultural plots, and the southern coast and volcano, which did not have high vegetation cover classification. The wildlands layer is used later for Non-WUI Wildlands classification in WUI mapping.

Figure 25. Wildland areas

The wildland areas layer is used to create the 2.4-kilometer buffer that is a part of the WUIF definition. The final wildlands layer is exported with the Export Features tool to make a copy, and the Buffer tool is used on this layer to create a 2.4-kilometer buffer around the wildlands. This buffer is shown in Figure 26. The 2.4-kilometer buffer covers almost the entire island, except for two barren areas (the southern coast and volcano), and extends into the ocean. This buffer is used later in WUI mapping to impact WUIF classifications.

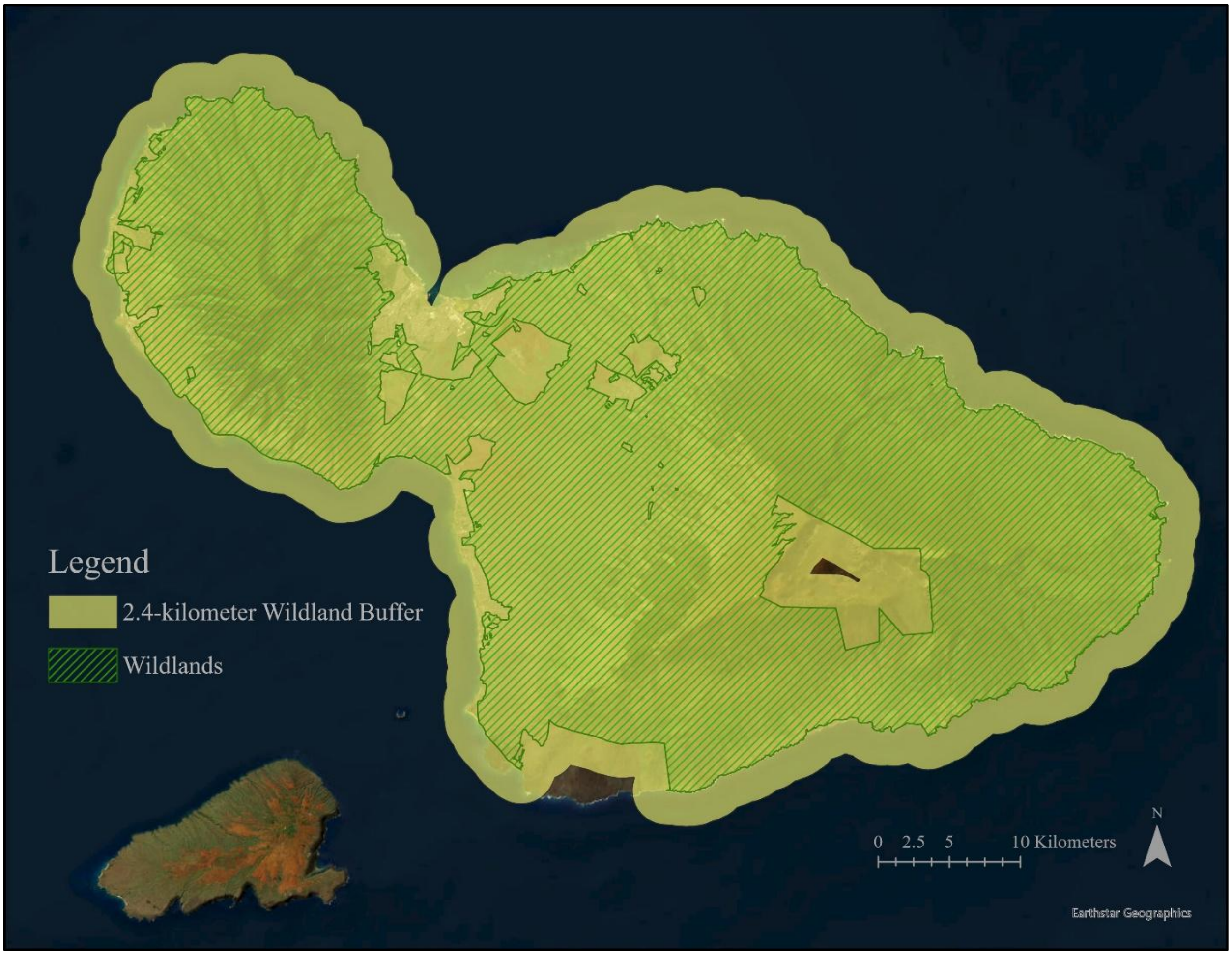

Figure 26. Wildland buffer

3.3.4 Standard WUI Map

Standard WUI maps have four classifications: WUIF, WUIX, Non-WUI, and Non-WUI Wildlands. Initial WUI mapping is Step 4 of the workflow diagram, and a detailed workflow diagram of this step is shown in Figure 27. A new empty text attribute field is added to the census blocks layer to hold WUI classifications. WUIF and WUIX census blocks are identified first. The Select by Attributes tool is used to select census blocks that fit the WUIF definition, with ≥ 6.18 buildings per square kilometer and < 50% vegetation cover. The selected census blocks are assigned “Interface” in the new attribute field with the Calculate Field tool. The WUIF census blocks are exported with the Export Features tool to a new layer to be compared with the 2.4-kilometer wildland buffer. None of the WUIF census blocks fall outside of the buffer, so the wildland buffer aspect of the WUIF definition does not affect WUIF classification on Maui. All census blocks labeled “Interface” maintain their classification. If there were WUIF census blocks outside the buffer, they would be assigned “Non-WUI.” The WUIF selection is cleared, and the Select by Attribute tool is used to select census blocks that fit the WUIX definition, with ≥ 6.18 buildings per square kilometer and ≥ 50% vegetation cover. The selected census blocks are assigned “Intermix” with the Calculate Field tool, and the selection is cleared again.

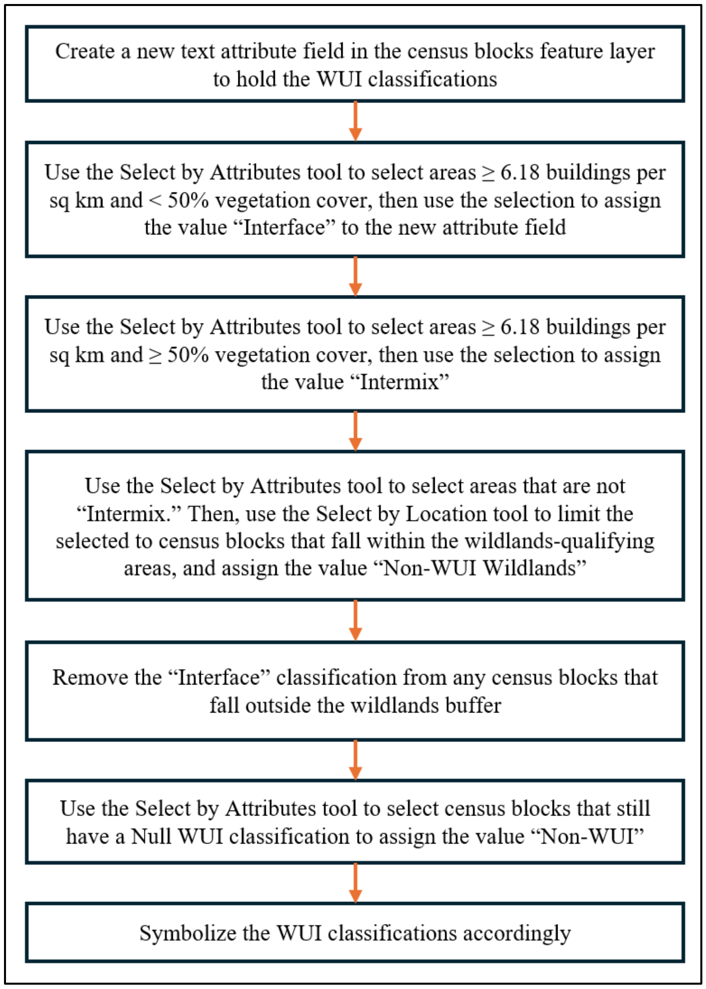

Figure 27. Workflow diagram creating a standard WUI map

The non-WUI classifications are assigned after the WUI classifications. Identifying wildland census blocks requires multiple steps and the use of the wildlands layer created previously. The Select by Attributes tool is used to select census blocks with ≥ 75% vegetation cover and where the WUI classification is Null. Then, to ensure these selected areas qualify as continuous wildlands that are ≥ 5 square kilometers, the Select by Location tool is used with the census blocks layer as the Input Feature, the Relationship as Within, and the Selecting Feature as the dissolved wildlands layer with unqualified areas removed. The Selection Type is set to Select Subset from the Current Selection. The updated selection (although nothing changes in this scenario) is assigned to “Non-WUI Wildlands” using the Calculate Field tool. After the selection is cleared, the Select by Attributes tool is used to select census blocks that have a Null WUI Classification attribute field, and these selected census blocks are assigned to “Non-WUI” with the Calculate Field tool. The initial WUI map product consists of these four classifications that strictly adhere to the Federal Register WUI definitions. Cartographically, WUIF and WUIX are symbolized in WUI literature with warm tones that are associated with fire. Non-WUI Wildlands are shown with green tones and Non-WUI is shown with white tones.

3.3.5 Forest and Grassland Cover

Distinctions between the dry, grassland ecosystems and the wet, rainforest ecosystems on Maui are crucial because rainforests have lowered wildfire risk due to high moisture content and higher rainfall. Rainforest census blocks have less fire risk than other wildland census blocks; buildings in WUIX census blocks that are dominated by rainforest are at less wildfire risk than their counterparts that are amidst highly flammable, dry vegetation. Representing all WUIX census blocks on Maui as being equal with each other, through one classification, is misleading and disregards the varying climate and regional biomes of Maui, and the same applies to Non-WUI Wildlands census blocks. Critical distinctions are necessary to communicate the varying fire risk within the original standard WUI classifications. To show the critical distinctions between areas of Maui that have vegetation of varying levels of flammability, the percentage of forest cover per census block is calculated and used to create a more detailed WUI map with vegetation subclassifications. The forest cover is representative of Maui’s rainforests. The percentage of grassland coverage is also calculated for additional context regarding Maui’s flammable landscape.

Calculating the percent forest and percent grassland cover per census block is Step 5 in the workflow diagram, and a more detailed workflow diagram of this step is shown in Figure 28. To calculate forest and grassland cover, several of the steps for vegetation cover percentage calculation are repeated two more times, for both forest and grassland cover, based on the original ESA landcover dataset. The ESA dataset is reclassified so that only tree cover receives a value of 1 and all other classifications are assigned a 0. This is repeated for grassland cover as well. The agricultural plots are removed from the results of both. Then, the Zonal Statistics as Table tool is used twice, to gather both the mean forest and grassland cover values per census block. The values of each are multiplied by 100 to calculate percentages. The target attribute fields from the grassland table and the forest table are joined to the census block feature layer with the Join Field tool.

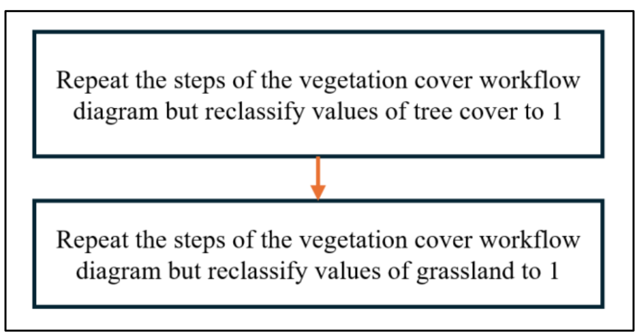

Figure 28. Workflow diagram for forest and grassland cover

The forest and grassland cover are shown in Figure 29. The island's shrubland cover is not represented on this map because of its relatively proportion, but it fills in many vegetation cover gaps. Together, forest and grassland cover almost the entire island. For census blocks that qualify as Non-WUI Wildlands, vegetation cover per census block on Maui is dominated either by grassland or forest cover. East Maui is dominated by forest cover, as well as the mountainous parts of West Maui. These two areas are Maui's large rainforests. The rest of the island is dominated by grassland.

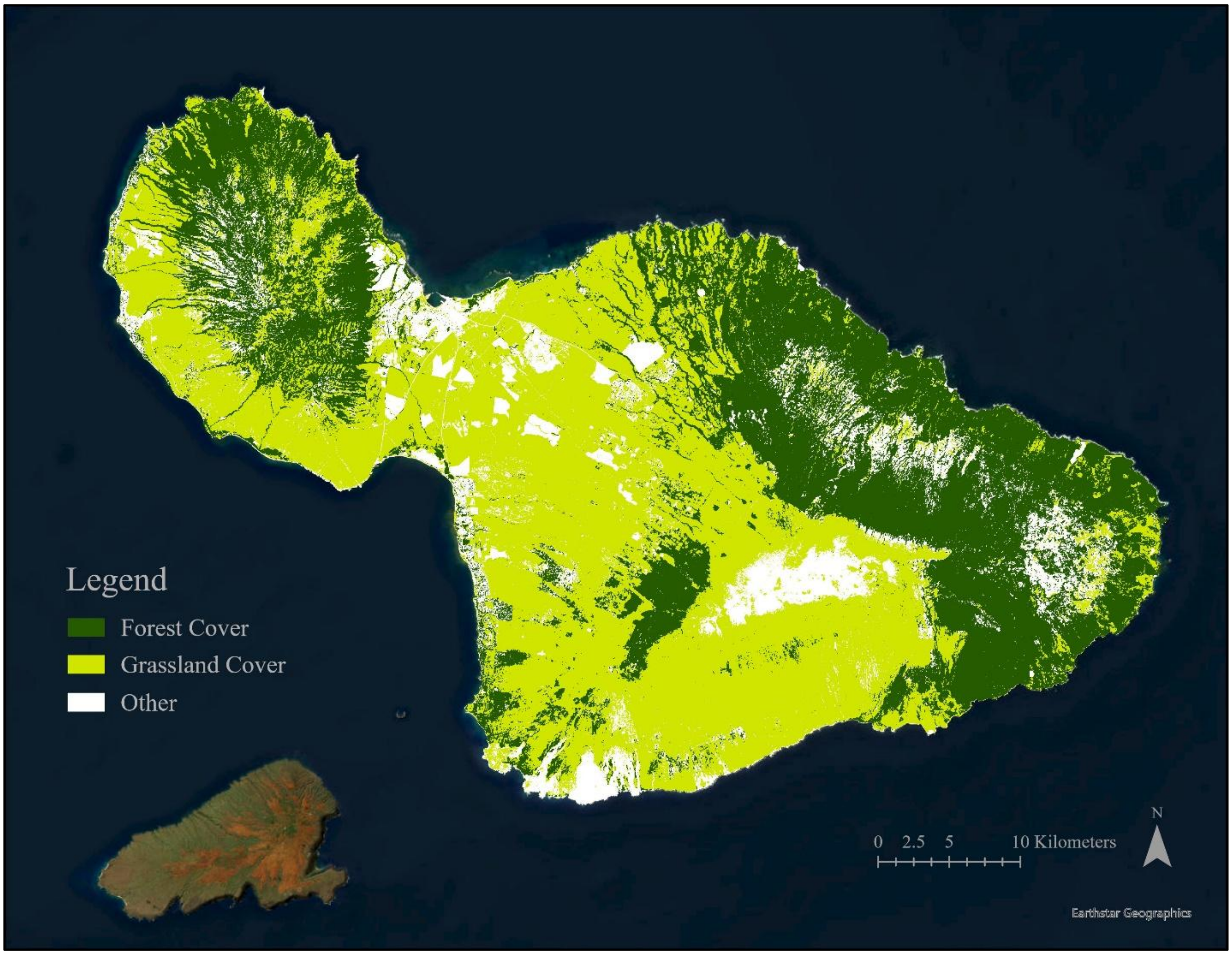

Figure 29. Forest and grassland cover

The newly calculated forest cover is used to alter WUI classifications in the enhanced WUI map product. Census blocks that are dominated by forest cover are renamed to show that their qualities stray from the assumption of flammability. WUIX is divided into WUIX and WUIX Forest, and Non-WUI Wildlands is divided into Non-WUI Wildlands and Non-WUI Wildlands Forest; these classifications are divided because they already have ≥ 50% vegetation cover, and the other classifications are unaffected. Census blocks that are ≥ 50% forest cover receive the additional “Forest” descriptor, indicating that they are majority forest-cover and that they have less wildfire risk compared to their counterparts.

3.3.6 WUI Map Enhancements with Forest Cover

The process of incorporating the forest cover data to enhance the standard WUI map with vegetation subclassifications is Step 6 of the workflow diagram, and a detailed workflow diagram of this step is shown in Figure 30. The Select by Attributes tool is used to select census blocks where the WUI classification is “Intermix” and the forest cover is ≥ 50%. With the Calculate Field tool, this selection is assigned to “Intermix Forest.” The selection is cleared, and the Select by Attributes tool is used to select census blocks where the WUI classification is “Non-WUI Wildlands” and the forest cover is ≥ 50%. This selection is assigned to “Non-WUI Wildlands Forest” with the Calculate Field tool. The grassland cover percentages are not used to affect classification because grassland on Maui matches the standard assumption that WUI areas are highly-flammable. The Non-WUI Wildlands and WUIX census blocks that are not dominated by forest are dominated by grassland, and they keep their “Non-WUI Wildlands” and “Intermix” classifications. The WUIX Forest classification is symbolized with a browner tone of orange than its WUIX counterpart. The Non-WUI Wildlands classification is symbolized with a paler green to represent grassland, and the Non-WUI Wildlands Forest classification is symbolized with a darker green to represent forest.

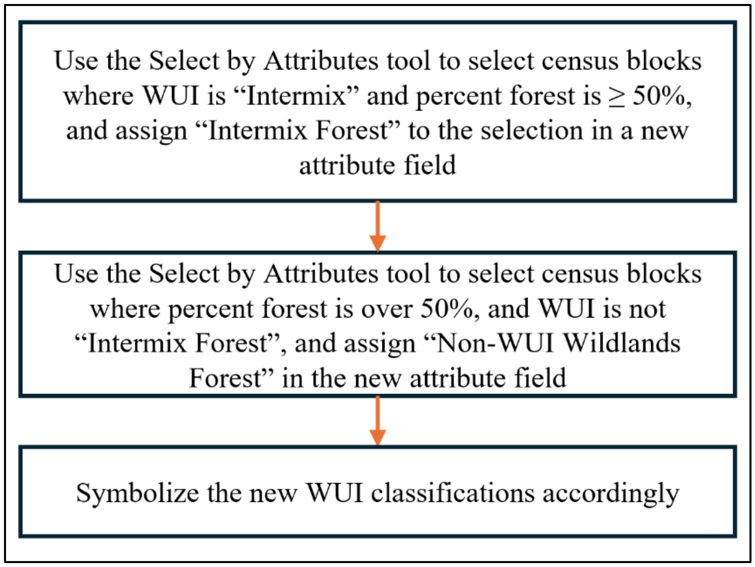

Figure 30. Workflow diagram for enhancing the WUI map

3.4 Refining Landcover Mapping

Refining the WUI methodology to be suitable for Maui required landcover dataset experimentation. Standard WUI mapping practice uses one landcover dataset to gather both agriculture and vegetation landcover information and removes all agricultural classifications from vegetation cover calculations due to their relatively lower flammability. However, these standard practices are inappropriate for the study area of Maui due to its unique agricultural landscape. Choosing the most accurate landcover dataset and appropriately incorporating agriculture is critical. In this thesis, different landcover datasets are tested to assess see how their use affects WUI classification outcomes. Three landcover datasets are tested to assess their WUI outputs, then the chosen landcover dataset is tested with different agricultural landcover classification refinements.

A WUI map is created from each of the EVT, FVC, and ESA datasets with their original agricultural classifications to compare the effect of their use on WUI mapping outcomes. The three datasets show large discrepancies in agricultural landcover classification. Due to the disagreements among landcover datasets in agricultural classification and the potential of the agriculture classification to affect WUI outcomes, authoritative agricultural data from the Hawaii Statewide GIS Program is incorporated into the analysis to increase accuracy in the vegetation cover aspect of WUI calculation. The agricultural plot boundaries from the authoritative dataset do not align with the agricultural classifications in the EVT, FVC, or ESA datasets. Because of the strong agricultural past in Maui and the overrunning of many old croplands with invasive grasses, the difference between historic agricultural lands and current agricultural lands can be difficult to distinguish in remote sensing.

The ESA dataset is chosen as the landcover dataset for further analysis and enhancement over the LANDFIRE datasets due to its finer 10m resolution, its worldwide coverage, and remote sensing source. However, comparing the agricultural classification in the ESA dataset to the authoritative agricultural dataset shows that the ESA classification is inaccurate. Where the ESA-classified agriculture does not overlap with an existing agricultural plot, the misclassified land is mostly likely grassland, due to Maui's history of abandoned agricultural plots being overrun with grasses. For this reason, the land that is classified as agriculture by the ESA dataset is initially set to vegetation in the final methodology, so it is effectively disregarded. Then, the official agricultural land (some of which does overlap with the ESA classification) is removed from vegetation and wildland calculations.

Removing pastureland from vegetation cover calculations along with other agricultural land uses as in standard practice is inappropriate for Maui, and pastureland should be separated from other agricultural land use types in the Hawaii Statewide GIS Program dataset. Pastureland stands out among the other agricultural land uses in the dataset because it is not highly maintained or irrigated. For example, in Figure 31, land growing taro (left) and macadamia nuts (center) is lush, upkept, and green. In sharp contrast, pastureland (right) is dry, untamed, unirrigated, flammable grassland. Although different agricultural species have varying levels of flammability, and some grasses used for pastureland have low flammability (Pagadala et al. 2024), this is not the case on Maui because of the nature of the flammable invasive grasses present in the pastureland. Kikuyu grass is the most important pasture grass on Hawaii (Fukumoto and Lee 2003), but kikuyu grass is one of the highly flammable invasive grasses that threaten the Hawaiian Islands, along with buffelgrass, fountain grass, and others that dominate the landscape in Maui (Hawaii Invasive Species Council 2024a).

Figure 31. Taro, macadamia, and pasture agricultural land

The ESA dataset is used to make two more WUI maps. The second ESA WUI map is made using all agricultural land use classifications from the Hawaii Statewide GIS Program agricultural dataset, including pastures. Removing all agricultural plots from vegetation cover calculations alters the WUI classification outcomes negatively and is inappropriate for Maui, so the agricultural considerations are refined. The third ESA WUI map excludes all agriculture plots except for pastureland from vegetation cover calculations, and this map is used as the final WUI map with standard WUI classifications.

This thesis's methodology and final WUI map products, using the ESA landcover dataset, the Hawaii Statewide GIS Program agricultural dataset, and including pastures in vegetation cover, stem from these experiments. The agricultural landcover classification from the ESA landcover dataset is disregarded and the Hawaii Statewide GIS Program agriculture dataset determines the agricultural classifications in this study's final WUI mapping analysis. Pastureland is classified as vegetation cover due to its high flammability, while the other 10 agricultural land uses are removed from vegetation cover calculations, as is typical for agricultural land.

Chapter 4 Results

This chapter describes the results of this thesis. The standard WUI map and the final WUI map with additional Maui-specific subclassifications are shown. Then, the WUI mapping results from the landcover dataset and agricultural data experiments that were conducted while developing the final WUI mapping methodology are presented. Each WUI map is symbolized in accordance with common practices from WUI literature and followed by a summary statistics table and pie chart of the WUI cover in each map. Map figures are shown with 40% transparency on the WUI feature layer to show the additional context of the terrain.

4.1 Final WUI Map

The WUI analysis in this thesis results in two WUI maps. The first map has four standard WUI classifications: WUIF, WUIX, Non-WUI, and Non-WUI Wildlands. The second WUI map builds off the first and adds a Forest subclassification to WUIX and Non-WUI Wildlands based on their vegetation content. This addresses Maui's unique multi-climate landscape, which contains both grasslands and rainforests. The additional WUI subclassifications show the nuances within the standard WUI classifications.

4.1.1 WUI Map with Standard WUI Classifications

Created with the ESA landcover dataset and improved with the Hawaii Statewide GIS Program agricultural dataset, the standard WUI map with agricultural enhancements is shown in Figure 32. Most of Maui's area is covered by Non-WUI Wildlands. The only Non-WUI areas are around the volcano, by the tip of the southern coast, around some agricultural plots in Central Maui, and in small census blocks around the coast. The most densely developed areas are WUIF, and WUIX is found in more rural areas around the island. This WUI map is highly intuitive and meets assumptions about WUI on Maui based on its geography.

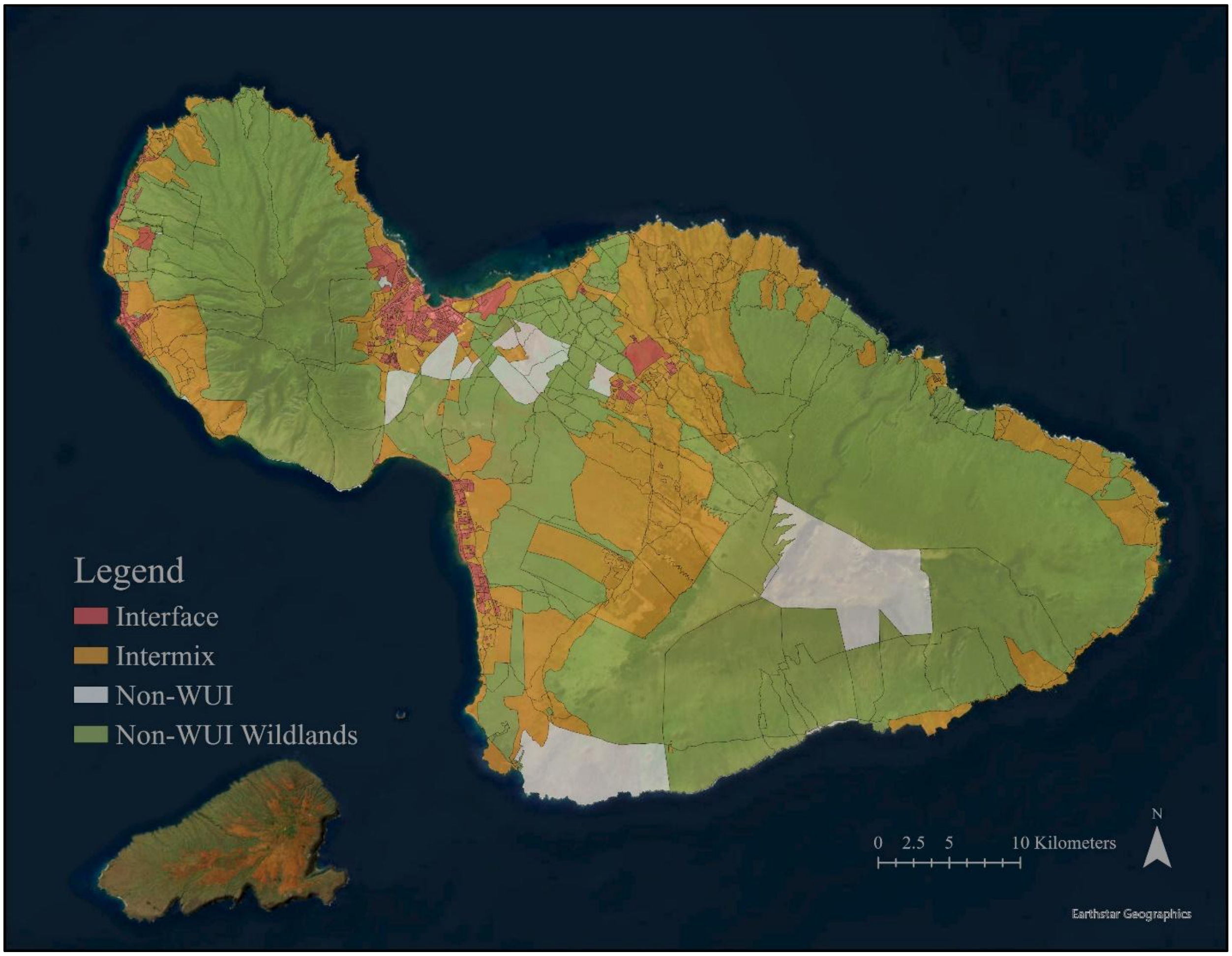

Figure 32. Standard WUI map with agricultural enhancements

The standard WUI classification results are shown in Table 4, compared to about 7% in the ESA WUI map.

Table 10. The results indicate that WUIF covers under 3% of Maui's area, while Non-WUI covers about 8%. WUIX covers about 25% of the land, and Non-WUI Wildlands cover

about 65%. The number of census blocks in each classification is misleading in regard to area coverage because urban census blocks are smaller than rural and wildland census blocks.

Table 4. Standard WUI classification outcomes

WUI Classification	Area (square km)	Percentage of Maui (by area)	Number of Census Blocks
Interface	48.3	2.56%	712
Intermix	469.8	24.91%	419
Non-WUI	148.9	7.89%	76
Non-WUI Wildlands	1,219.3	64.64%	240

A pie chart of the WUI makeup of the standard WUI classifications is shown in Figure 33. WUIF and Non-WUI cover the smallest portions of Maui's area, while WUIX and Non-WUI Wildlands cover large swaths of land. Altogether, WUI areas cover a little over a quarter of Maui.

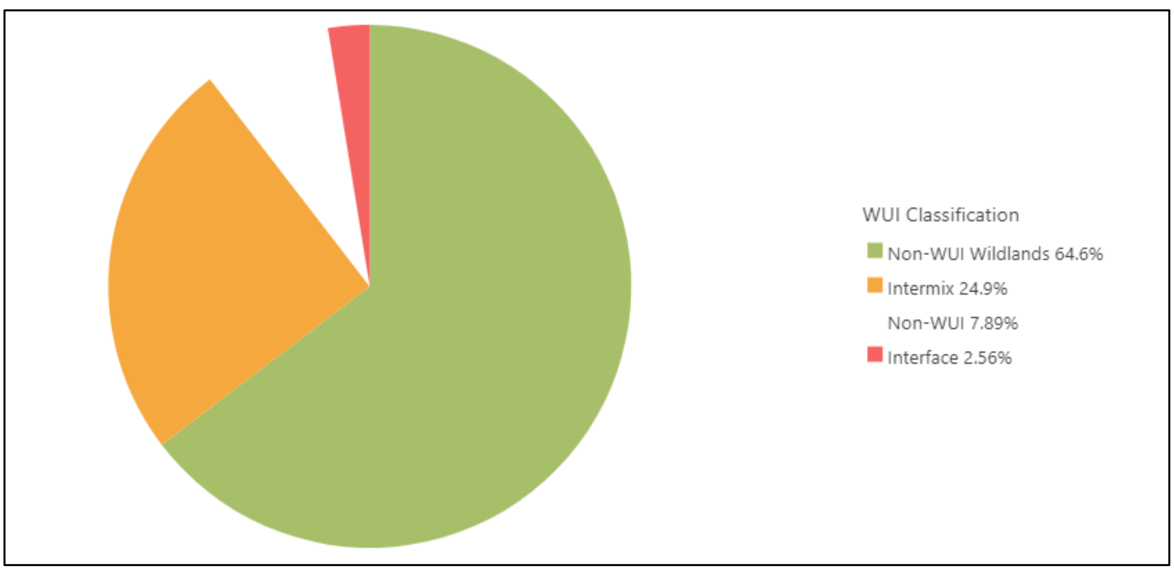

Figure 33. Standard WUI classification makeup

4.1.2 Final WUI Map with Enhanced WUI Classifications

Enhancing the standard WUI map with vegetation cover information culminates in the final WUI map with Maui-specific subclassifications, shown in Figure 34. The WUIX subcategories are represented in two shades of orange, with the WUIX Forest classification having a slightly greener tone. The Non-WUI Wildlands subcategories are shown in two shades of green, with Non-WUI Wildlands having a lighter tone and Non-WUI Wildlands Forest having a darker tone. Compared to the standard WUI map with only four classifications, the six classifications shown in the final WUI map exhibit significantly more nuance across the island.

Rainforest coverage is distinct in East Maui and West Maui; the regional differences in grassland and rainforest cover are now clear. Many previously WUIX census blocks are now WUIX Forest, especially around the Non-WUI Wildlands Forest census blocks in East Maui, the North Shore, and West Maui. Intuitively, the grassland-dominated census blocks of WUIX and Non-WUI Wildlands classifications are grouped together, and the rainforest-dominated census blocks of WUIX Forest and Non-WUI Wildlands Forest are also found together. This final WUI map succeeds in incorporating the vegetation variations within Maui’s landscape, and the WUI classifications reflect these differences accordingly.

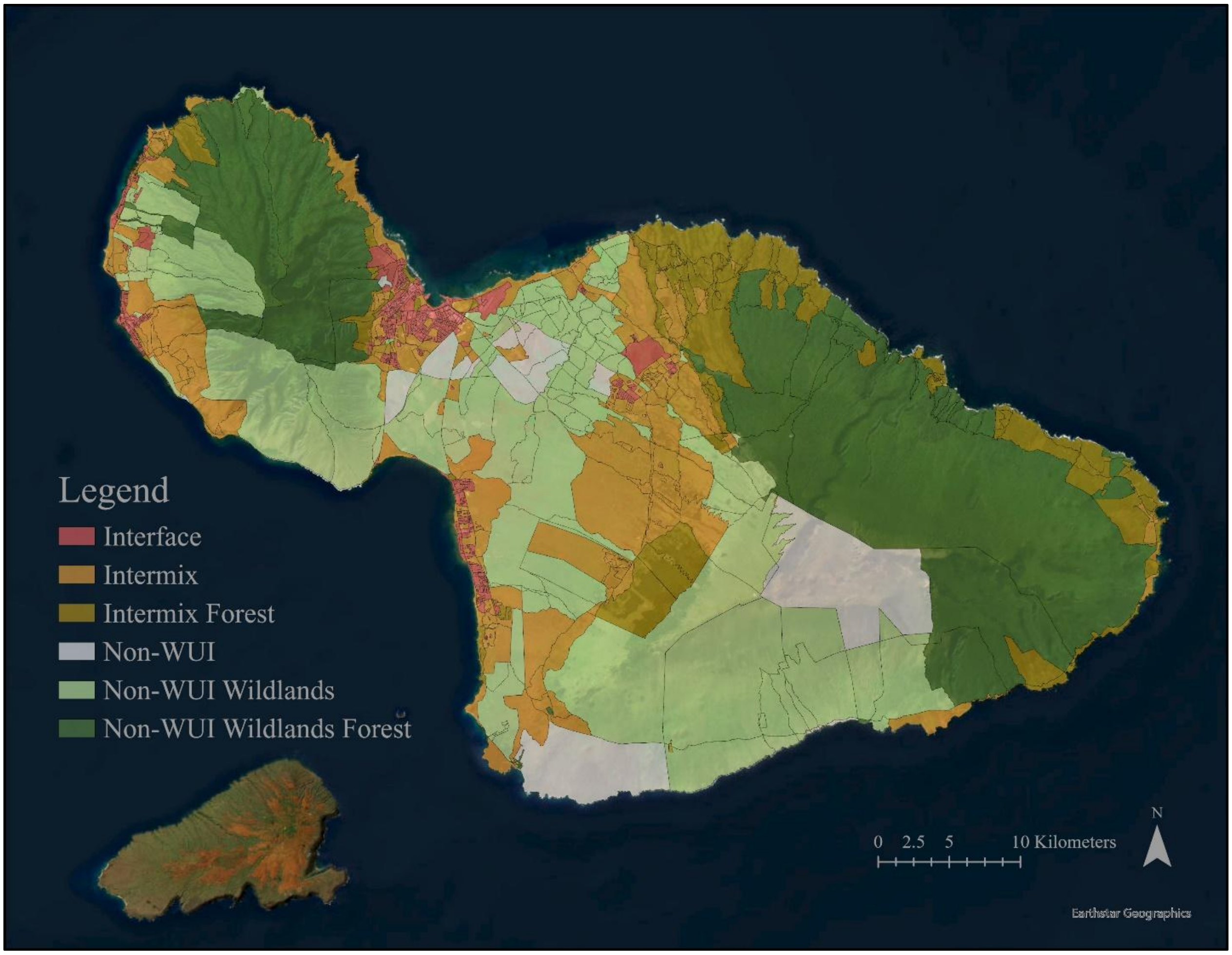

Figure 34. Final WUI map with Maui-specific subclassifications

The WUI classification coverage outcomes for the WUI map with subclassifications are shown in Table 5, subdividing the previous WUIX and Non-WUI Wildlands classification coverages. WUIF and Non-WUI are not affected because these census blocks are not dominated by vegetation; the WUIF and Non-WUI percentages of Maui's land area remain at about 3% and 8%, respectively. WUIX, which overall covers almost a quarter of Maui, is divided into the new WUIX, which covers about 16% of Maui's land area, and WUIX Forest, which covers about 9%. Non-WUI Wildlands is divided into the new Non-WUI Wildlands, which covers about 33% of Maui, and Non-WUI Wildlands Forest, which covers about 31%. Both rainforest subclassifications cover less land area than their grassland-dominated counterparts.

Table 5. ESA WorldCover WUI classification outcomes

WUI Classification	Area (square km)	Percentage of Maui (by area)	Number of Census Blocks
Interface	48.3	2.56%	712
Intermix	300.9	15.95%	263
Intermix Forest	168.9	8.95%	156
Non-WUI	148.9	7.89%	76
Non-WUI Wildlands	625.9	33.18%	174
Non-WUI Wildlands Forest	593.4	31.46%	66

This thesis's final WUI classification outcomes are displayed in a pie chart in Figure 35, which accurately represents the WUI coverage of Maui and its nuances. While wildlands cover most of Maui, they are split almost evenly between grassland-dominated and forest-dominated. The same is true for WUIX classifications.

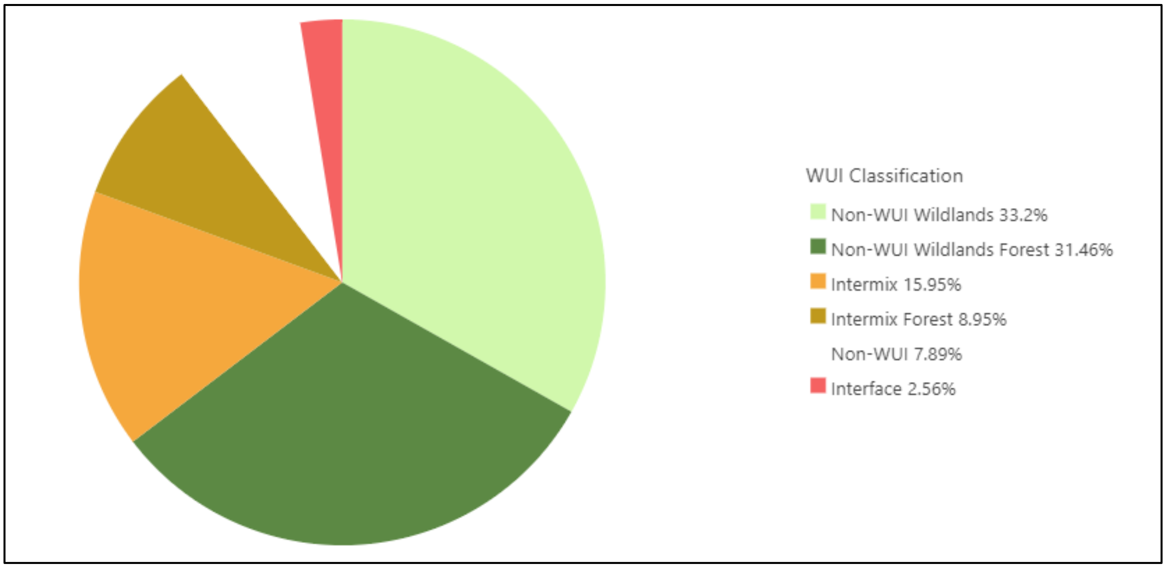

Figure 35. Final WUI classification makeup

There are about 63,000 buildings and 154,100 people on Maui, and the pie charts in Figure 36 reveal the proportion of buildings and people within the WUI. The pie charts show that most buildings and people are in WUIF census blocks, followed by WUIX, then WUIX Forest. The results of this thesis prove that over half of Maui's population is in WUIF. Very few buildings and people are in Non-WUI, Non-WUI Wildlands, and Non-WUI Wildlands Forest census blocks. When viewed altogether, the pie charts reveal that while the WUI covers a small part of Maui by landcover, almost all buildings and people in Maui are situated in the WUI.

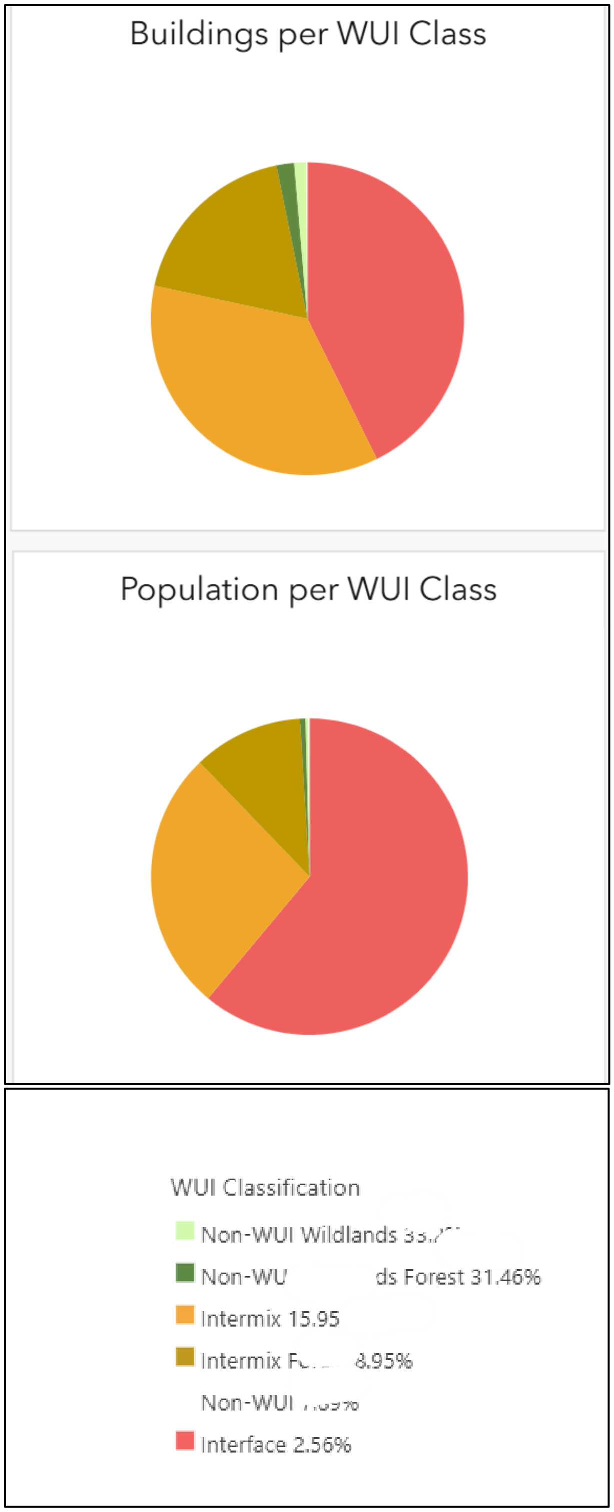

Figure 36. Buildings and population by WUI classification

The percentages of buildings and population in the WUI, with distinctions between Forest WUI and Non-Forest WUI, are shown in Table 6. Forest subclassification significantly alters the distribution, and shows nuance within the land, buildings, and population in the WUI. While 27.46% of Maui's land area is in WUI, 18.51% is in Non-Forest WUI. Showing an almost 20% difference, 96.82% of buildings are in WUI, while 78.4% of buildings are in Non-Forest WUI. Almost all people, 99.03%, are in the WUI, but this drops to 87.82% when WUIX Forest is excluded. While almost all buildings and people are in WUI, 18.42% of buildings and 11.21% of people are in WUI areas with less wildfire risk than their WUI counterparts because they are within the rainforest ecosystem on Maui. Forested WUI covers about 9% of Maui's land area.

Table 6. Land, buildings, and people in WUI

	In WUI	In WUI (Non-Forest)	In WUI (Forest)
Land	27.46%	18.51%	8.95%
Buildings	96.82%	78.4%	18.42%
People	99.03%	87.82%	11.21%

4.2 Landcover Dataset Refinement WUI Maps

Multiple WUI maps resulted from comparing the effect of the vegetation and agricultural landcover classifications from different landcover datasets on WUI mapping results, and then adding a separate authoritative agriculture dataset. WUI classification results change significantly based on vegetation cover designations. The difference in agriculture classification is the most impactful aspect of vegetation cover for this study area.

4.2.1 LANDFIRE EVT Dataset WUI Map

The most stand-out quality of the EVT WUI map, shown in Figure 37, is that the region connecting Central Maui and Upcountry Maui is overwhelmingly classified as Non-WUI. Furthermore, many coastal areas in West Maui are also designated as Non-WUI. The large swath of classified agricultural land in the dataset disqualifies many census blocks that may have been classified as Non-WUI Wildlands by lowering their vegetation cover percentages, instead leaving them as Non-WUI. The 2.4-kilometer wildland buffer affects WUIF classification in this map. The buffer does not cover the whole island, missing most of Central Maui and a small portion of West Maui's coast. Hundreds of census blocks initially meet the WUIF definition by vegetation cover and building density but are classified as Non-WUI because they are outside 2.4-kilometers from wildlands. For West Maui, Central Maui, and Upcountry Maui, their Non-WUI classifications are inconsistent with expectations because these regions have dense populations, frequent wildfires, high wildfire risk, and are generally regarded as WUI areas. The barren qualities of the volcano and part of the southern coast are evident in this map, as they are shown as Non-WUI. The coastal communities in East Maui are mostly WUIX, while the coastal communities on West Maui are mostly WUIF until they transition to WUIX closer to Non-WUI Wildlands. Upcountry Maui has an East to West pattern of Non-WUI Wildlands, WUIX, WUIF, then Non-WUI.

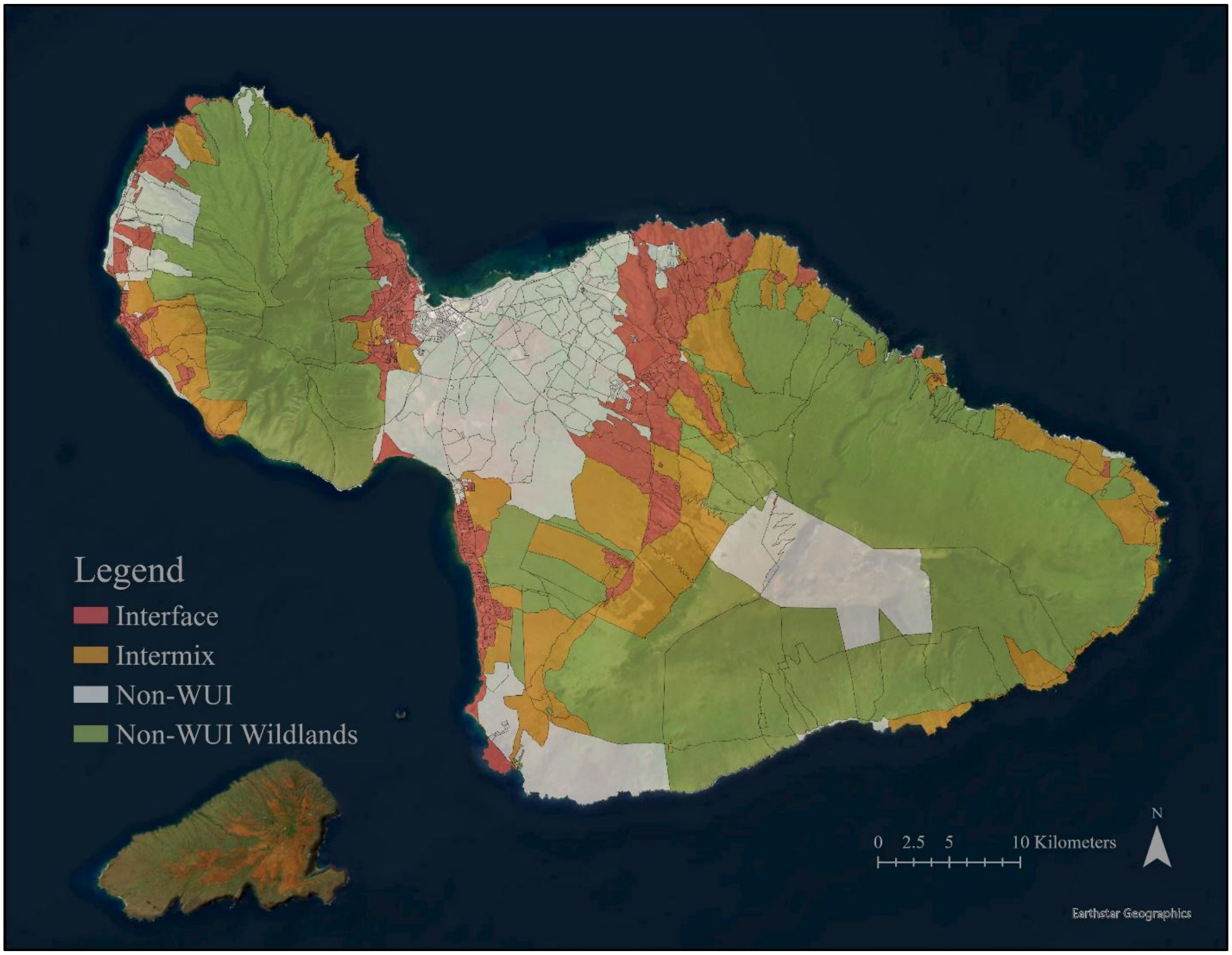

Figure 37. LANDFIRE EVT WUI map

A summary statistics table of the EVT WUI map is shown in Table 7, and shows that Non-WUI Wildlands cover about half of Maui. Per these results, Non-WUI Wildlands cover about 53% of the island, while Non-WUI covers about 22%. WUIX covers about 15% and WUIF covers about 10%. With almost a quarter of the island's area, the EVT WUI map has more Non-WUI areas than expected and its legitimacy is questionable.

Table 7. EVT WUI classification outcomes

WUI Classification	Area (square km)	Percentage of Maui (by area)	Number of Census Blocks
Interface	184.9	9.80%	691
Intermix	283.2	15.01%	108
Non-WUI	414.5	21.98%	563
Non-WUI Wildlands	1,003.6	53.21%	85

4.2.2 LANDFIRE FVC Dataset WUI Map

The biggest differences in the FVC WUI map, shown in Figure 38. LANDFIRE FVC WUI mapFigure 38, are the classification changes to Central Maui and Upcountry Maui. Central Maui is shown as mostly WUI with Non-WUI Wildlands census blocks on the outskirts. Upcountry Maui has Non-WUI Wildlands census blocks to the west of its WUI census blocks. The newly classified Non-WUI Wildlands are in an area classified as Non-WUI in the EVT WUI map. The 2.4-kilometer buffer also did not cover the entire island and affected WUIF classifications. The classifications of the communities in East Maui, West Maui, and South Maui appear nearly identical to the EVT WUI Map.

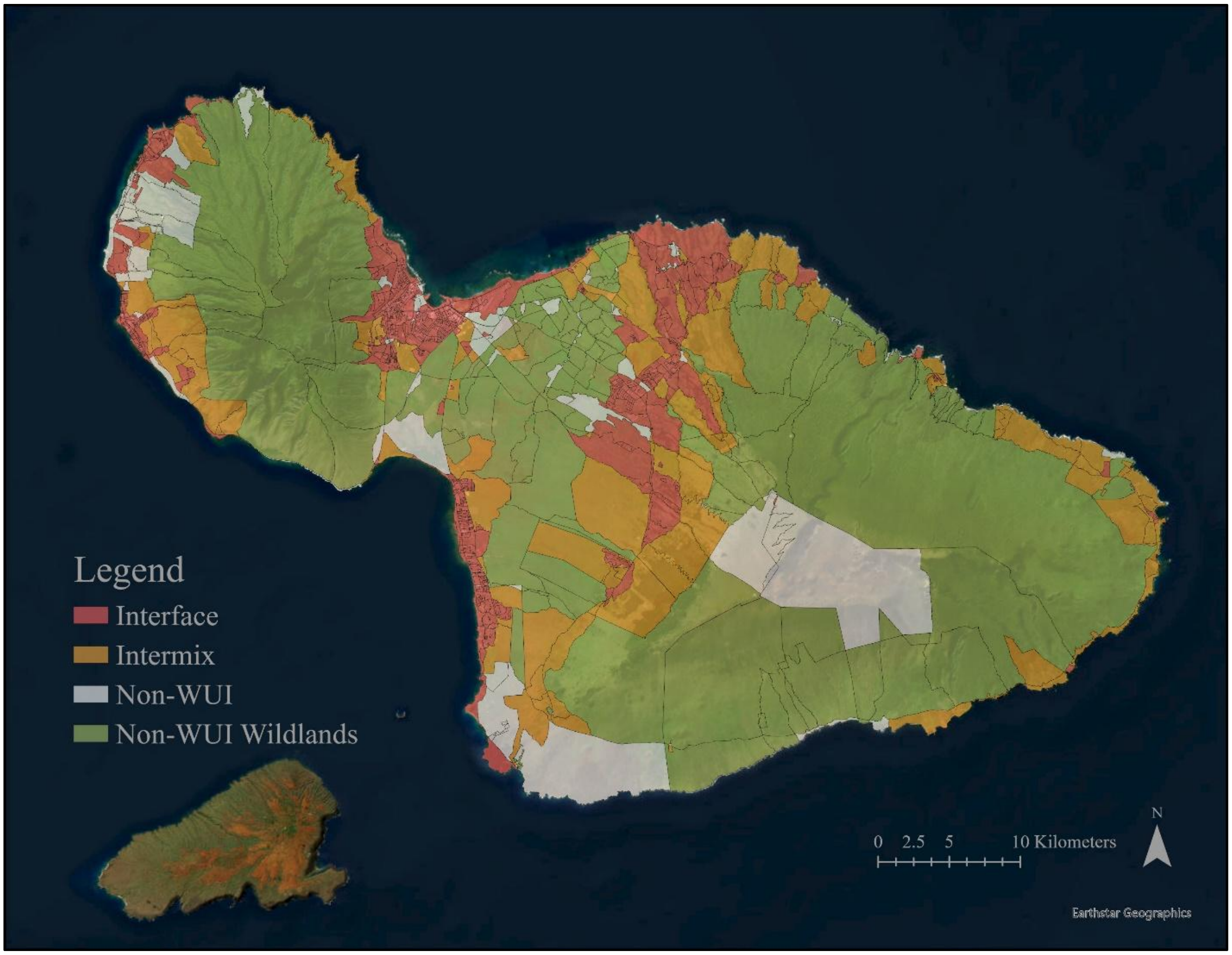

Figure 38. LANDFIRE FVC WUI map

As seen in Table 8, the largest shift in classifications from the EVT WUI map to the FVC WUI map is from Non-WUI to Non-WUI Wildlands. Non-WUI Wildlands account for about 61% of Maui's area, an increase from the 53% in the EVT WUI map. The WUIX classification increases to about 17% of Maui, while Non-WUI decreases to about 11%. While the number of WUIF census blocks increases drastically, the percentage of Maui does not vary significantly; WUIF remains at about 10%.

Table 8. FVC WUI classification outcomes

WUI Classification	Area (square km)	Percentage of Maui (by area)	Number of Census Blocks
Interface	188.3	9.98%	961
Intermix	325.3	17.25%	131
Non-WUI	215.4	11.42%	202
Non-WUI Wildlands	1,157.2	61.35%	153

Demonstrated by the results, usage of the FVC dataset for WUI mapping is an improvement because Central Maui is shown as WUI, and the Non-WUI Wildlands designation fits the vegetative landscape between Central Maui and Upcountry Maui more accurately. However, there are still concerns with agricultural accuracy. The large swath of Non-WUI census blocks in West Maui is also still note for concern.

4.2.3 ESA WorldCover Dataset WUI Map

The ESA WUI map classification results are significantly different than the WUI maps produced by the LANDFIRE landcover datasets, and the ESA WUI map is shown in Figure 39. Upcountry Maui is largely WUIX, rather than WUIF. This is due to the higher vegetation cover assignments within these census blocks because less land is classified as developed. Furthermore, the number of census blocks classified as Non-WUI significantly decreases. This reduction is most noticeable in West Maui and Central Maui. Since more land is classified as grassland instead of agriculture, the vegetation cover in these areas rises. Also, the 2.4-km wildland buffer extends to cover almost the entire island. Therefore, no census blocks that met the WUIF definitions for building density and vegetation cover are assigned to Non-WUI for falling outside the buffer, as occurred in the LANDFIRE WUI maps.

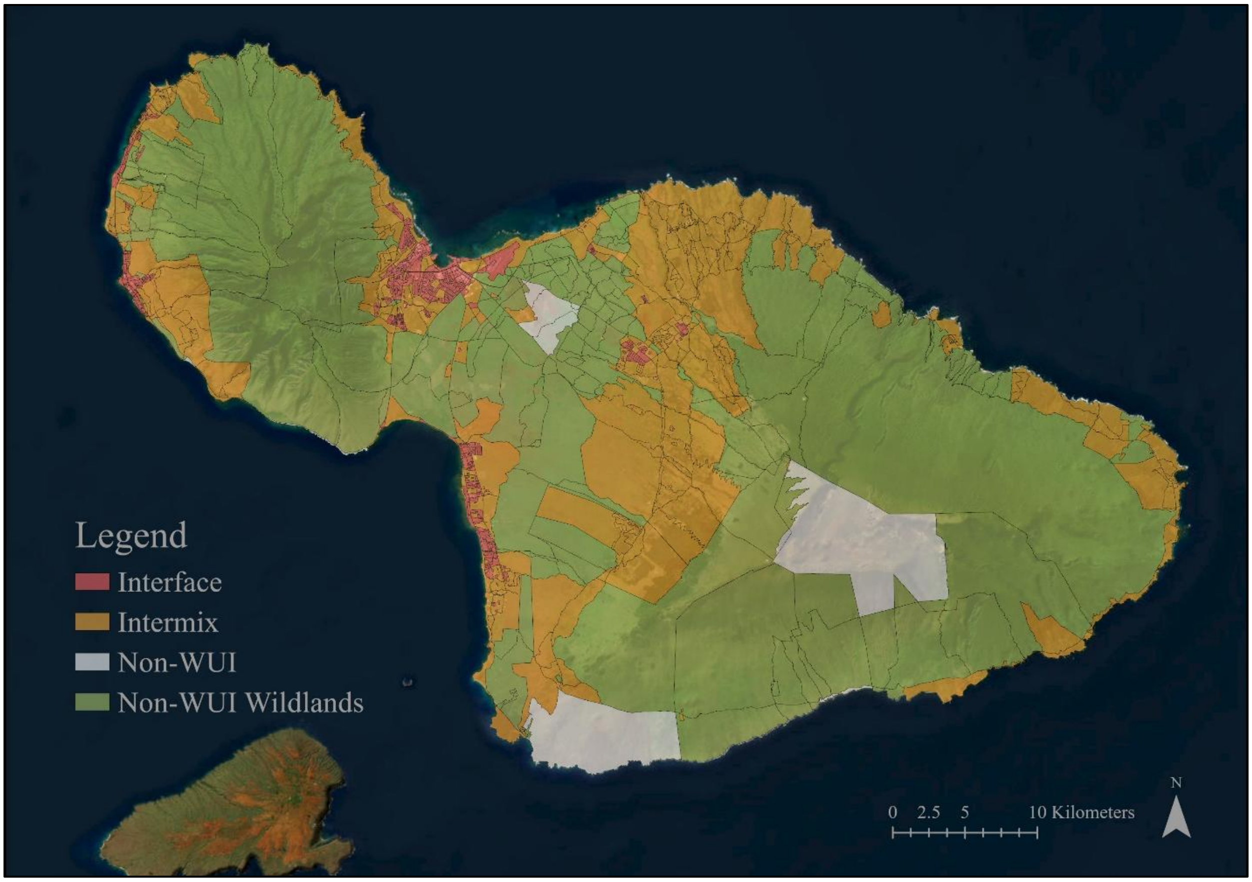

Figure 39. ESA WUI map

As seen in Table 9, WUIF and Non-WUI classifications are at their lowest area coverage, while WUIX and Non-WUI Wildlands are at their highest. WUIF coverage drops from about 10% of Maui's area in the LANDFIRE WUI maps to about 2%. Non-WUI covers about 7%, a decrease from the 10s and 20s. WUIX covers about 25% of Maui, when it was less than 20% in the LANDFIRE WUI maps. Non-WUI Wildlands cover about 66%, an increase from the low 50s and 60s.

Table 9. ESA WUI classification outcomes

WUI Classification	Area (square km)	Percentage of Maui (by area)	Number of Census Blocks
Interface	38.1	2.02%	702
Intermix	480.0	25.45%	429
Non-WUI	125.6	6.66%	66
Non-WUI Wildlands	1,242.6	65.87%	250

The ESA WUI map product proved the most intuitive of the three landcover dataset experimentation results. Few census blocks on Maui are classified as Non-WUI, communities in West and Central Maui fall under WUI classifications, communities in Upcountry Maui are WUIX interwoven with Non-WUI Wildlands, and Non-WUI Wildlands coverage is high. Each of these observations is consistent with patterns in Maui's development and vegetation. Although ultimately enhanced with Hawaii Statewide GIS Program agricultural data, these classification distributions are similar to the standard WUI map.

4.2.4 Landcover WUI Comparisons

The WUI mapping experimentation with different landcover datasets exhibits that vegetation and agriculture cover landcover designations drastically alter WUI classification results. The area, percentage of Maui, and number of census blocks in each WUI classification vary between the three WUI maps created from the EVT, FVC, and ESA landcover datasets. The percentage of Maui's WUI makeup by area is shown in a pie chart for each of the three landcover datasets in Figure 40. WUIF coverage ranges from 2-10%, WUIX ranges from 15-25%, Non-WUI ranges from 7-22%, and Non-WUI Wildlands ranges from 53-66%. The distribution of WUI classifications is most evenly spread in the EVT WUI map. In the FVC WUI map, the proportion of WUIF, WUIX, and Non-WUI are the most similar. The ESA WUI map shows a more unequal WUI classification distribution, with each classification covering a distinctly different proportion of Maui; this WUI map has the largest range of area coverages, from 2-66%.

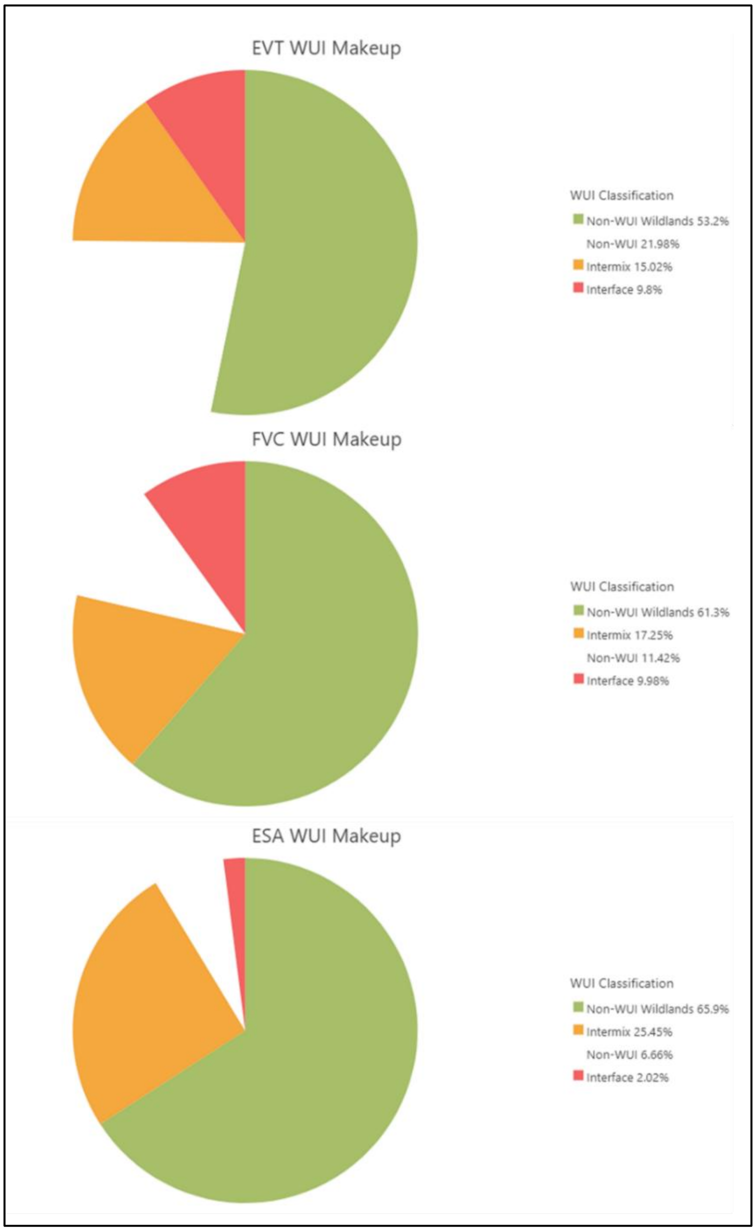

Figure 40. WUI classification makeup per landcover dataset

4.2.5 ESA WorldCover and All Hawaii Statewide GIS Program Agricultural Data WUI Map

The WUI map created from the ESA landcover dataset and Hawaii Statewide GIS Program agricultural dataset, which removes all 11 classes of agriculture from vegetation cover calculation, is shown in Figure 41. Pastures are over 90% of the agricultural land in the agricultural dataset and cover over a quarter of the island, so removing the pastures from vegetation cover calculations affects WUI classification calculations drastically, compared to the previous ESA WUI map. The differences are especially noticeable in Upcountry Maui and around the southern coast. While the tip of the southern coast has Non-WUI classification in the ESA WUI map, the number of Non-WUI census blocks in this map increases drastically and extends into South Maui, Upcountry Maui, and East Maui. More Non-WUI census blocks appear in Central Maui and the North Shore as well. In every region, many census blocks classified as WUIX in the ESA WUI map are switched to WUIF. The trend is most apparent in Upcountry Maui, where there appears to be an evenly distributed mix between WUIF and WUIX.

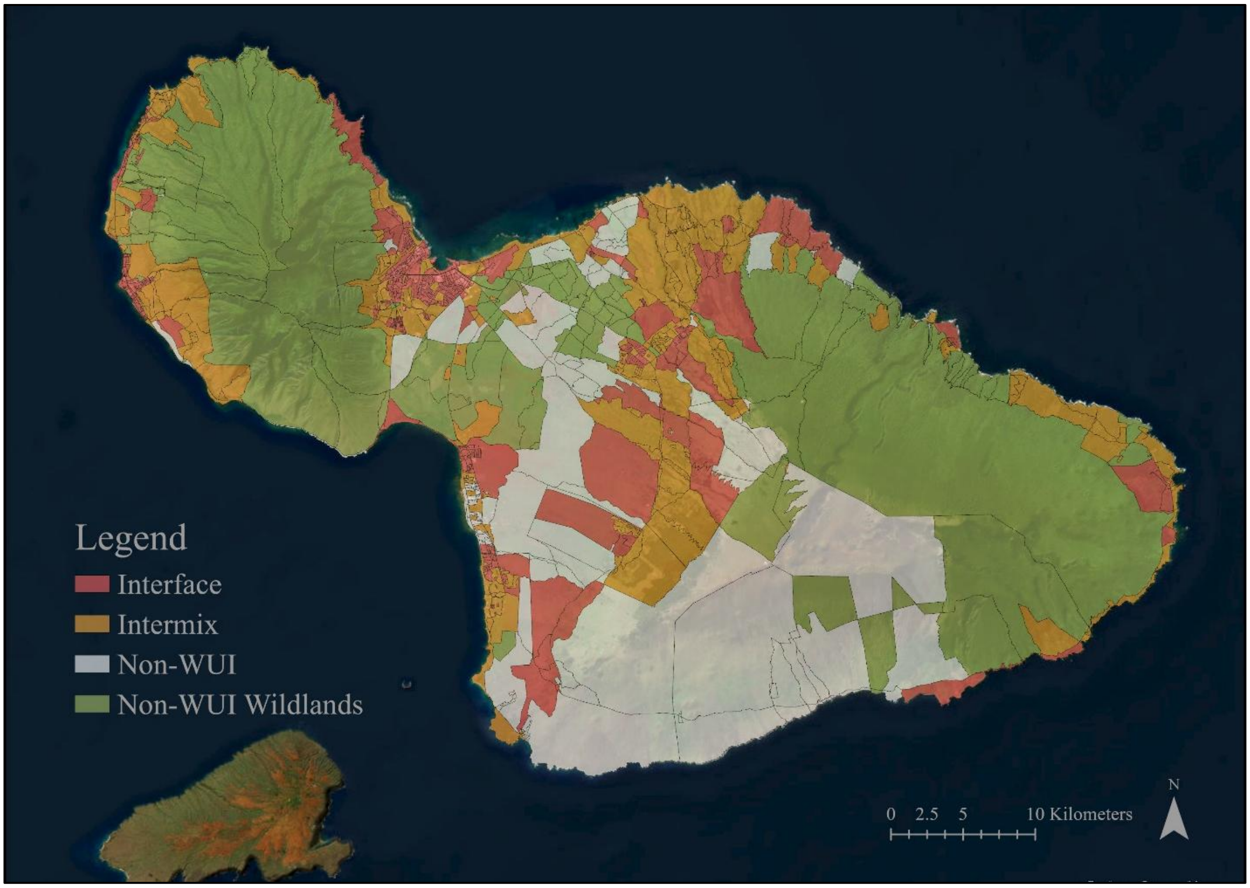

Figure 41. ESA and all agriculture WUI map

The WUI classification outcomes from the WUI map using ESA and all Hawaii Statewide GIS Program agricultural data are shown in Table 10, and this is the first WUI map in which Non-WUI Wildlands covers less than half of the land area of Maui. While the Non-WUI Wildlands cover 2/3 of Maui in the ESA WUI map, the Non-WUI Wildlands in this map decrease to about 46%. The WUIF coverage increases to about 12%, and the WUIX coverage decreases to about 15%, significantly closing the 23% gap between WUIF and WUIX in the ESA WUI map. Non-WUI increases greatly to about 27%, compared to about 7% in the ESA WUI map.

Table 10. ESA and all agricultural data WUI classification outcomes

WUI Classification	Area (square km)	Percentage of Maui (by area)	Number of Census Blocks
Interface	218.6	11.59%	717
Intermix	290.2	15.38%	343
Non-WUI	505.2	26.78%	237
Non-WUI Wildlands	872.4	46.25%	150

A pie chart of the ESA and all agricultural data WUI classifications is shown in Figure 42, and these classifications are very misleading. These classifications show a significant proportion of census blocks as Non-WUI instead of Non-WUI Wildlands, although many of them are highly flammable. The large amount of land removed from vegetation cover calculations also causes the shift to higher WUIF classifications, which is inaccurate in Upcountry Maui because the communities are interwoven with flammable wildlands.

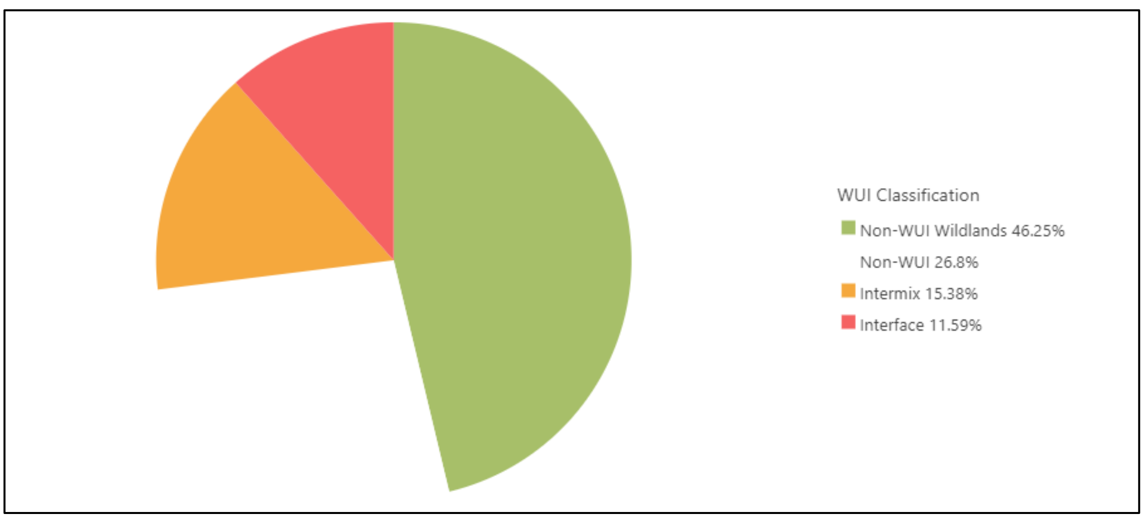

Figure 42. ESA and all agricultural data WUI classification makeup

Chapter 5 Dashboard Creation

This chapter describes the creation of a publicly available ArcGIS Dashboard built around this thesis's final WUI map with Maui-specific subclassifications. The Dashboard is the final product of this thesis. The Dashboard combines the findings of this thesis with supplemental WUI-related and wildfire management-related data to promote a well-rounded perspective on WUI and its relation to other measures of wildfire risk. Existing WUI web applications are discussed, the Dashboard-building methodology is described, and then the Dashboard product is shown. The Dashboard can be accessed at the following link: https://uscssi.maps.arcgis.com/apps/dashboards/c6be46ed9b5549bd89c32a47137cd5b4.

5.1 Web-Sharing Related Literature

Many WUI maps are shared as web applications to communicate WUI information with the public in an accessible and engaging manner for exploration. The global WUI map created by Schug et al. (2023), discussed in Chapter 2.3.2, is viewable on a web application. On the web application, the WUI layer transparency can be adjusted. The WUI data can be viewed over other basemaps and data, including the Global Human Settlement data and the ESA WorldCover data. From the products of Radeloff et al. (2023a), discussed in Chapter 2.3.42.2.2.2, the 2020 zonal-based WUI map of the 48 conterminous US is shared by the US Forest Service as an ArcGIS tile layer map service (Radeloff et al. 2023b). An ArcGIS StoryMap supported by the USDA further introduces readers to the WUI and explores the data from Radeloff et al. (2023b) on the WUI from 1990-2010 from different angles (Mockrin et al. 2023). The findings of Ketchpaw et al. (2022), described in Chapter 2.2.1, are shared in an ArcGIS Dashboard, where the different WUI map products of Montana that are calculated by different methods can be explored side-by-side.

5.2 Dashboard Methods

An ArcGIS Dashboard is used for this product because the ArcGIS platform seamlessly integrates maps from ArcGIS Online. The interactive Dashboard allows viewers to explore the multiple facets of WUI classification, as well as assess their relation to other wildfire-related content. The methods are overviewed, the data is described, and the steps of the methodology are detailed.

5.2.1 Dashboard Workflow Overview

A workflow diagram of the steps for this thesis's Dashboard creation is shown in Figure 43. Creating the Dashboard product from this thesis's final enhanced WUI map entails four steps: Step 1 is adding more attributes to the census blocks in the final WUI map for additional context, Step 2 is publishing all map layers and creating a Web Map from them, Step 3 is creating the Dashboard and centering it on the Web Map, and Step 4 is creating the widgets for the Dashboard. The Dashboard is configured with dynamic and static widgets that highlight the various elements of the WUI analysis and summarize its final results, as well as present other wildfire-related information.

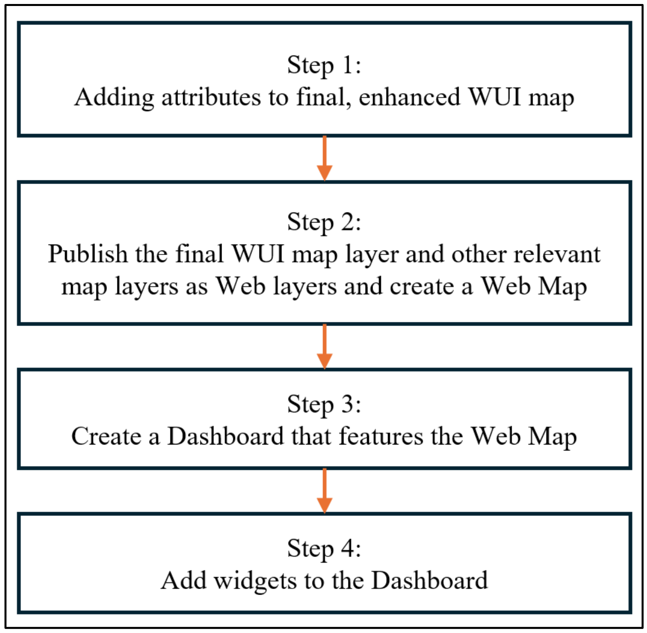

Figure 43. Workflow diagram creating ArcGIS Dashboard

5.2.2 Dashboard Data Description

Data used in WUI analysis, data created from this thesis, and additional wildfire-related data are used in the Dashboard and are portrayed in Table 11. Most of the data presented in the Dashboard is used in WUI analysis; the Maui building footprints, census blocks, and agricultural land use are used and described in Chapter 3. Further utilizing the census block data, housing unit data and population data within census blocks are used in the Dashboard. The 2023 wildfire extents are shown in Chapter 1.2.2 and are included in the Dashboard. The final enhanced WUI map created from this thesis, shown and described in Chapter 4.1.2, is presented as the focal point of the Dashboard. The remaining datasets to be described in this section are the Maui fire station locations and the State of Hawaii-defined CARs.

Table 11. Dashboard data descriptions

Data	Source	Year	Resolution	Use	Data Description
Building Footprints	Maui County GIS Dept.	2020	N/A, vector	Context for building distribution	Building footprint polygons for Maui
Census Blocks with housing unit and population census data	Hawaii gov, sourced from US Census Bureau	2020	N/A, vector	Census data for population and housing unit counts, click on census blocks to update dynamic widgets	Census block polygons
Extents of August 2023 wildfires	Maui County GIS Dept.	2024	N/A, vector	Context for locations of 2023 wildfires	The extent of the wildfires
Agricultural Land Use	Hawaii Statewide GIS Program	2020	N/A, vector	Context for agricultural land distribution	Polygons of existing agricultural lands categorized by crop/use
Enhanced WUI	This thesis	2020	10m	Centrally featured, contains many attributes for each census block, including WUI classification	The final WUI layer with six enhanced WUI classifications from the results of this thesis
Maui Historic Wildfires	Pacific Fire Exchange	2005-2020	N/A, vector	Summarize the number of historic wildfire points per census block	Wildfire ignition points from 2005-2020
Maui Fire Stations	Hawaii Statewide GIS Program	2017	N/A, vector	Context for fire station distribution	Point data of the 10 fire stations located on Maui
CARs	Hawaii Statewide GIS Program, sourced from Hawaii DLNR	2017	N/A, vector	Compare WUI classification results with State of Hawaii's CAR assessments in Dashboard	Polygons of communities at risk of wildfires, with classifications of Low/Medium/High risk

Maui fire station locations are included in the Dashboard for additional context and are shown in Figure 44 (Hawaii Statewide GIS Program 2021). The ten fire stations on Maui are spread across the island. Only one fire station is in East Maui. Fire stations are more concentrated in West Maui, Central Maui, and South Maui. Exploring the relationship between fire station locations, historical wildfires, WUI classifications, and other map layers is insightful for viewers. Many relationships can be observed between the various map layers provided in the Dashboard.

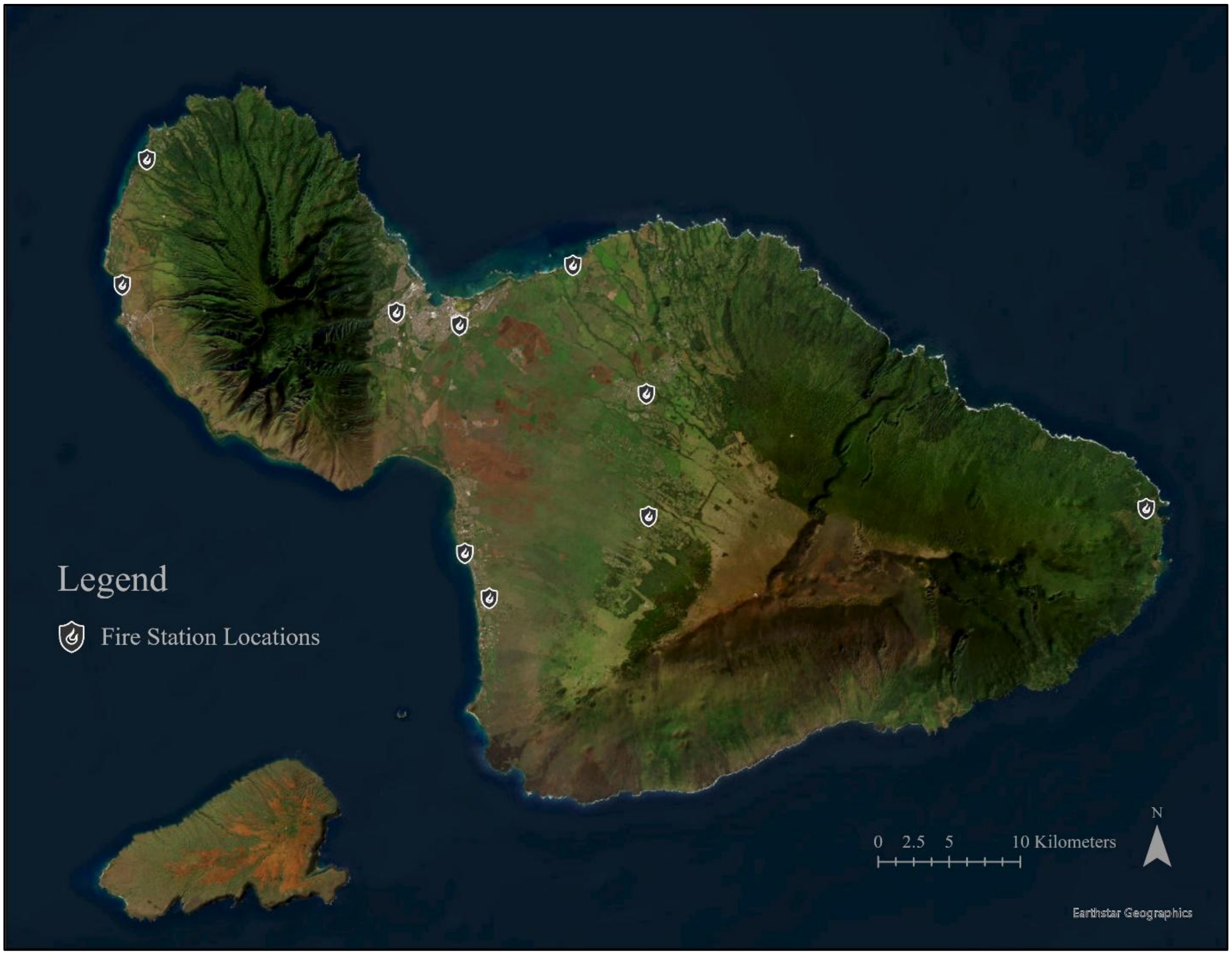

Figure 44. Maui fire stations

State of Hawaii-defined CARs are described in Chapter 2.3.3 and CARs on Maui are shown in Figure 45 (Hawaii Statewide GIS Program 2024). The high-risk CARs are in West Maui, Central Maui, and South Maui. Medium-risk CARs are in Upcountry Maui and parts of West Maui and Central Maui. Low-risk CARs are in East Maui, the North Shore, and Upcountry Maui. Most of the land area of Maui does not receive CAR designation.

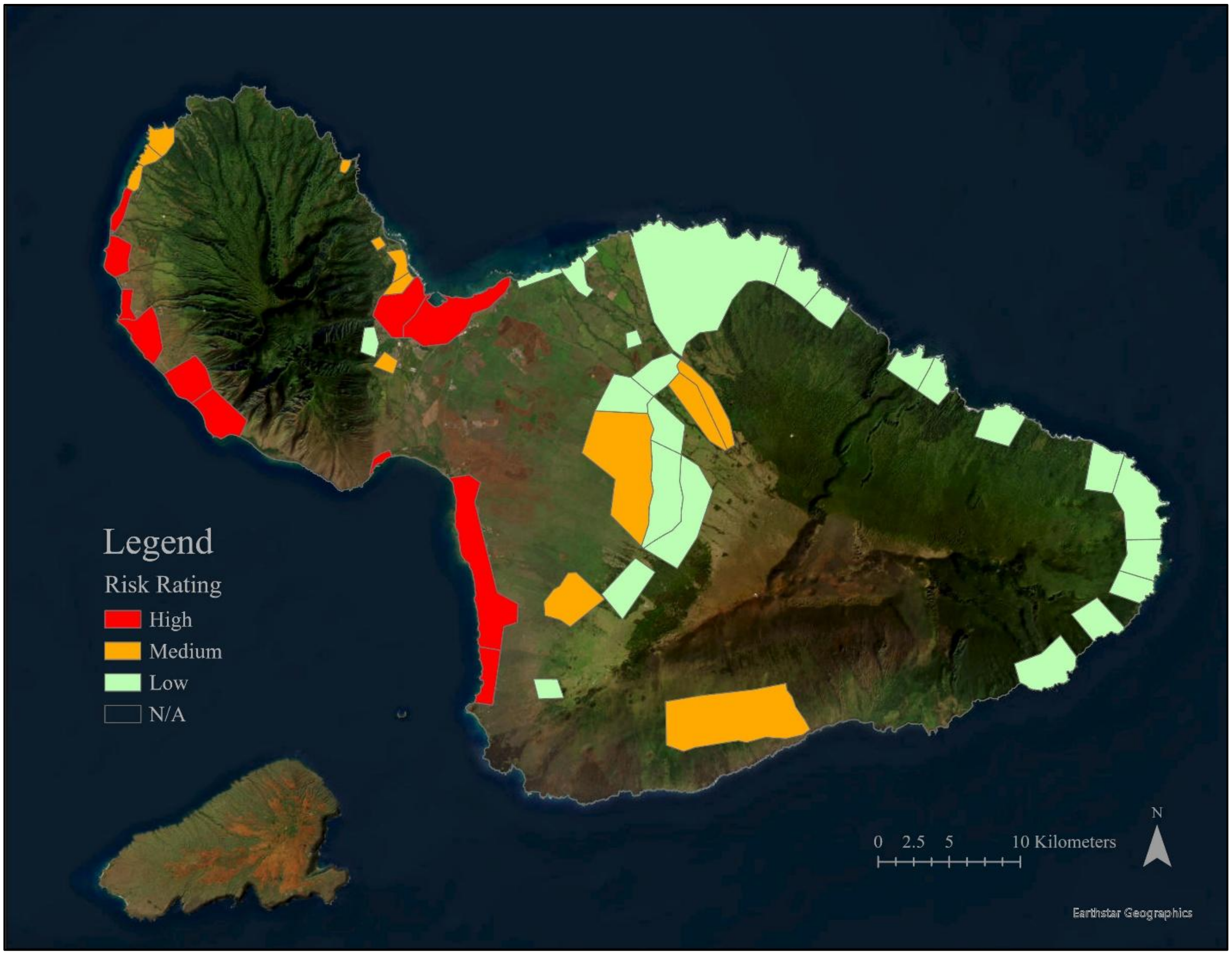

Figure 45. CARs on Maui

5.2.3 Adding Attributes to Census Blocks

While the final WUI map layer contains many attributes from WUI analysis, each census block's number of historic wildfires, agricultural area (not including pastures), and CAR risk rating are added as attributes, following Step 1 of the workflow diagram. To obtain the number of historic wildfires per census block, the Summarize Within tool is used. The Input Polygons are the census blocks, and the Input Summary Features are the fire incidence points. Using the Join Field tool, the output counts are added to the census block layer. The census blocks are the

Input Table, the summarized wildfire counts are the Join Table, and the Input and Join Fields are the Geographic Identifier. The Transfer Field is the wildfire counts.

To calculate the agricultural land per census block, the Summarize Within tool is used. The Input Polygons are the census blocks, the Input Summary Features are the agricultural plots without pastureland, and the Shape Unit is square kilometers. Then, the Join Field tool is used to add the agricultural area attribute to the census blocks. The Input Table is the census blocks, the Join Table is the summarized agricultural areas, and the Input and Join Fields are the Geographic Identifier. The Transfer Field is the agricultural area.

The Spatial Join tool is used to assign each census block its CAR risk rating. The Target Features are the census blocks, the Join Features are the CARs, the Join Operation is Join One-to-One, and the Match Option is Largest Overlap. The output is joined to the census blocks layer with the Join Field tool. The Input table is the census blocks, the Join Table is the output from the Spatial Join, the Input and Join Fields are the Geographic Identifier, and the Transfer Field is the risk rating.

All census data attributes are removed except for block number, decennial population count, and decennial housing count. Attributes from analysis that are kept are the Geographic Identifier, WUI classification, census block area in square kilometers, building density (per square kilometer), number of buildings in census block, percent vegetation cover, percent forest cover, and percent grassland.

5.2.4 Preparing Web Map

All map layers to be featured in the Dashboard are added to a Web Map that becomes the basis of the Dashboard, following Step 2 of the workflow diagram. The layers are first published, and then added to a Web Map. From ArcGIS Pro, the final WUI feature layer is published as a

Web Layer to ArcGIS Online. Other layers that are published are fire stations, wildfires, building footprints, the August 2023 wildfire extents, the State of Hawaii's designated CARs, and agricultural land use. All layers are added to the Web Map. The chosen basemap is the Terrain with Labels basemap and the WUI classification layer has a transparency of 35% so the terrain is visible through the data for geographic context. The Web Map is designed with the layers in the following order: Fire stations, Wildfires 2005-2020, Buildings 2020, August 2023 Wildfire Extents, Communities at Risk – per State of Hawaii, Agricultural Land Use 2020, and Maui Wildland-Urban Interface. All layers are initially turned off, except for the WUI layer. The WUI layer is last so other data layers can be viewed on top of it. Point layers are arranged above polygon layers for optimal viewing.

5.2.5 Dashboard Structure Formatting

Creating a new ArcGIS Dashboard is Step 3 of the workflow diagram. ArcGIS Dashboard design revolves around arranging elements. The ArcGIS Dashboard builder includes 11 element options, shown in Figure 46. The options include map, map legend, serial chart, pie chart, indicator, gauge, list, table, details, rich text, and embedded content. A header and sidebar are also options. The Dashboard for this thesis includes a map, map legend, pie charts, indicators, details, as well as a header and sidebar. The pie charts and indicators are the most frequent elements in this Dashboard; the pie charts are used for presenting summary information and the indicators are used to present various WUI and wildfire-management related metrics. As seen in Figure 46, elements can be placed on top, below, or to the left or right of other elements. The arrangement of the Dashboard in this thesis project is designed to maximize the amount of information presented at once, while still being easily digestible for viewers outside of the scientific community.

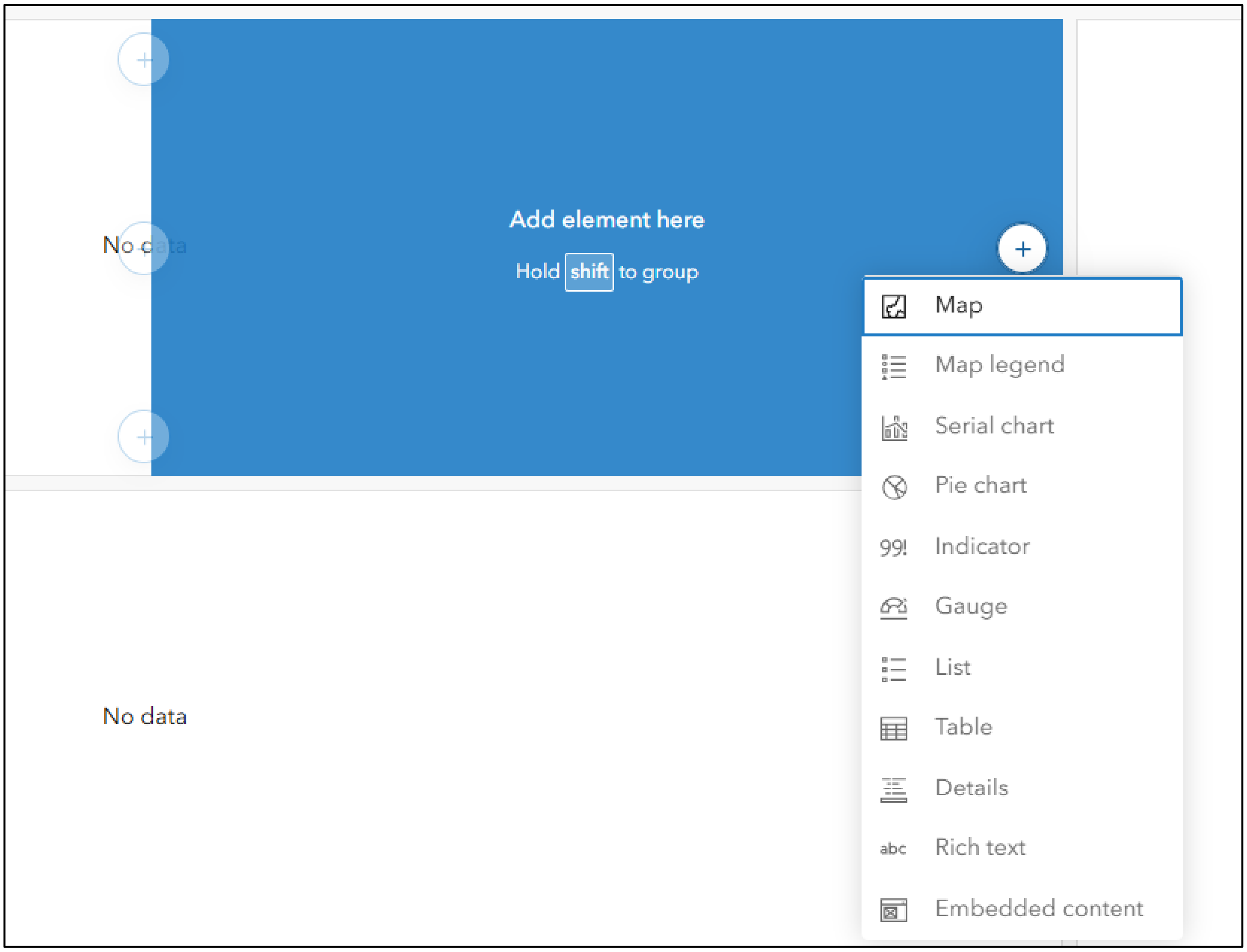

Figure 46. ArcGIS Dashboard elements

The central element of the Dashboard is the Web Map that holds the WUI classification layer and other data layers. The additional data layers are available to toggle and overlay on top of the WUI layer to see their relationships with each other and with the WUI classifications. The user has the option to change basemaps.

A panel is added to the far left of the Dashboard that explains the Dashboard and provides context into Maui and its unique relationship with the WUI. The panel has the following sections: Background, Purpose of the Dashboard, This Project's WUI Definitions, Maui-Specific Adjustments, and Additional Reference Data. The Background introduces what WUI is and the Maui August 2023 wildfires. The Purpose of the Dashboard section describes the

Dashboard and WUI map, their novelty and contribution, and instructions on use. The panel helps the reader to interpret the information presented by the Dashboard. The project-specific WUI definitions overview the six classifications on the central WUI map. The Maui-Specific Adjustments section overviews the agricultural adjustments made in the WUI analysis and the forest subclassifications. The last section addresses the additional data used in the Dashboard and provides links to the original data sources.

5.2.6 Static and Dynamic Widgets

The Dashboard has static information displays as well as interactive functionality. Adding static and dynamic widgets is Step 4 of the workflow diagram. Static information is gathered on the right side of the Dashboard’s central Web Map. Dynamic metrics are aligned above the Web Map, across the top of the Dashboard. Supplemental elements are placed to the Web Map’s left side, between the panel and the Web Map.

The static information on the map summarizes major findings of the WUI analysis. Pie charts are shown statically and are always visible because their data encompasses the entire island and provides critical insights into the WUI on Maui as well as the distribution of people and buildings within the WUI. The WUI classification pie chart is sized largely because this distribution is one of the most important results of the WUI analysis. Two smaller pie charts showcase the portion of total buildings and population distributed within the WUI classifications, respectively. The total buildings and population on Maui are shown as indicator numbers so viewers grasp the content of the pie charts. The pie charts can be hovered over with a mouse to reveal the percentage and number of buildings or population for each WUI classification.

The dynamic nature of the map allows metrics to update based on each census block’s WUI classification and other attributes. The Dashboard allows users to click on any census block in the WUI map of Maui, and the building density, percent vegetation cover, percent grassland cover, percent forest cover, agricultural area, and number of historic wildfires in that census block will appear. With these metrics, viewers can assess how each census block's metrics relate to the WUI definitions. These metrics change every time the viewer clicks on a different census block. Of the metrics, building density and total percentage vegetation cover are presented most prominently because they are the two most important factors of standard WUI mapping. The metric for percentage of forest cover is displayed smaller because it is a Maui-specific metric and not part of standard WUI definitions. The agricultural area in square kilometers for the census block (which does not include pastureland) is shown because it is removed from vegetation cover calculations and impacts the percentage vegetation cover in WUI analysis. This metric also provides insight into the agricultural makeup of the different areas around Maui. The percentage of grassland and the number of historic wildfires from 2005-2020 in the selected census block are displayed relatively small because they do not affect WUI analysis but are included for additional context. The percent grassland and percent forest cover do not always add up to the total percent vegetation cover because shrubland also counts towards vegetation cover, but shrubland is not given a dynamic metric on the Dashboard because of its relatively small contribution.

To the left of the Web Map are supplemental elements, the WUI classification legend and additional census block attributes. The legend is necessary to interpret the six final WUI classifications and subclassifications: Interface, Intermix, Non-WUI, Non-WUI Wildlands, Intermix Forest, and Non-WUI Wildlands Forest. The attributes are the WUI Classification, Census Block Area (sq km), Building Density (sq km), Number of Buildings, Decennial Housing Count, % Veg Cover, % Forest, % Grassland, Agricultural Area (sq km), # Wildfires 2005-2020, and Fire Risk Rating, per HI Gov. Above the attributes, the title that pops up for each census block is the block number and its WUI Classification. The attributes update dynamically each time a new census block is clicked.

5.3 Dashboard Results

A screen capture of the Dashboard is shown in Figure 47. As the user explores the WUI map and clicks on different census blocks, many metrics on the Dashboard update dynamically. Dynamic metrics are shown from a selected WUIX census block in Upcountry Maui. The selected census block is highlighted in blue. At the top of the Dashboard, the viewer can see that the census block has a building density of 18.6 buildings per square kilometer and 95.4% vegetation cover; these metrics explain why the selected census block is classified as WUIX.

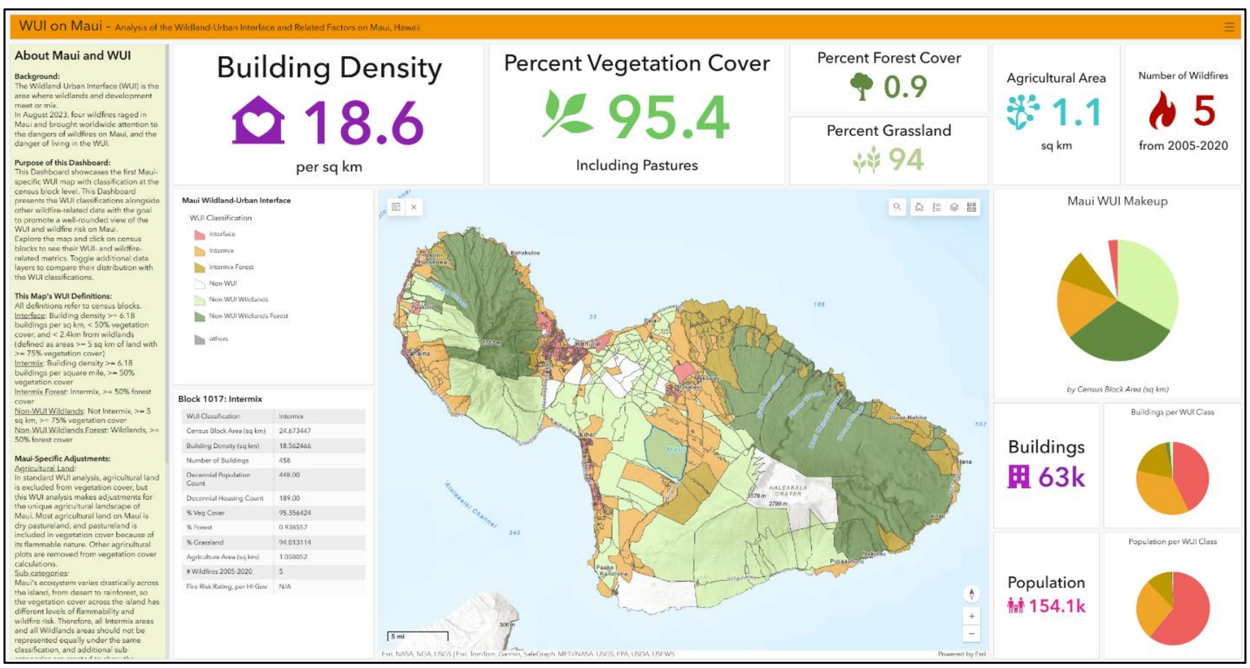

Figure 47. Maui WUI ArcGIS Dashboard

Through the dynamic metrics, the Dashboard highlights the nuances in building density and vegetation cover in census blocks that fall under the same WUI classification. The dynamic portion, which stretches across the top of the Dashboard, is shown in Figure 48. The metrics in this screenshot correspond to a different selected census block than the one in Figure 47, showcasing the dynamic nature of these elements. The building density of 845 buildings per square kilometer in this census block far surpasses the WUI threshold of 6.18, and the vegetation cover is well below 50%, indicating that this census block is WUIF. The census block has 13.6% forest cover and 8% grassland cover. There is no agricultural land in the census block, and there were 10 wildfires from 2005-2020.

Figure 48. Dynamic metrics on Dashboard

Providing a summary overview of the WUI conditions on Maui, the static data on the Dashboard is shown in Figure 49. The static portion of the Dashboard, on its right side, holds pie charts from Figure 35 and Figure 36 that summarize findings from the final WUI map. The three pie charts are discussed in Chapter 4.1.2. The large pie chart on top represents the thesis project's final WUI classification makeup of Maui. The total number of buildings and the total population of Maui are shown as static indicator numbers; next to the indicator numbers are smaller pie charts for building and population distributions within WUI classifications.

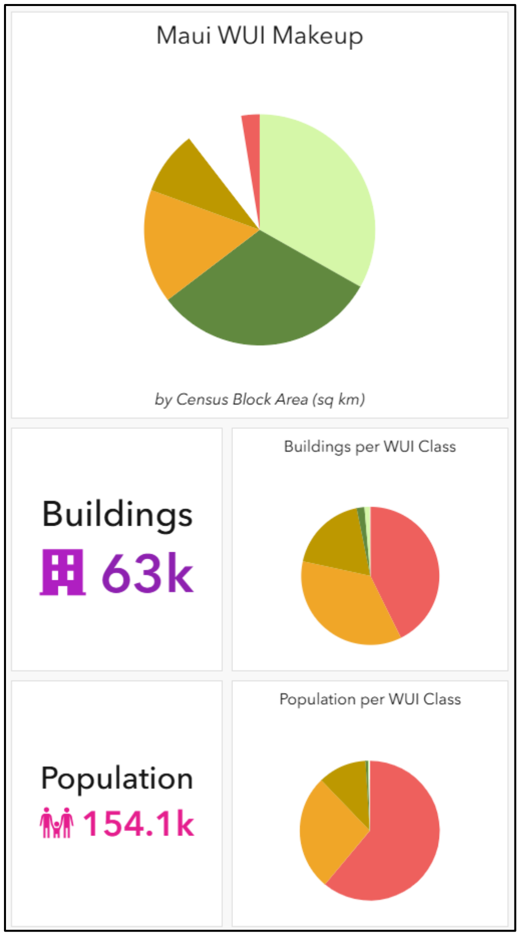

Figure 49. Static portion of Dashboard

The additional WUI-related and wildfire management data layers in the Dashboard are shown in Figure 50, when the layers button is clicked on from inside the Dashboard's central WUI map. These layers contain valuable supplementary information that enhance the WUI classification map and provide context into wildfire risk around Maui. All layers are initially all turned off, but each can be toggled as the viewer desires.

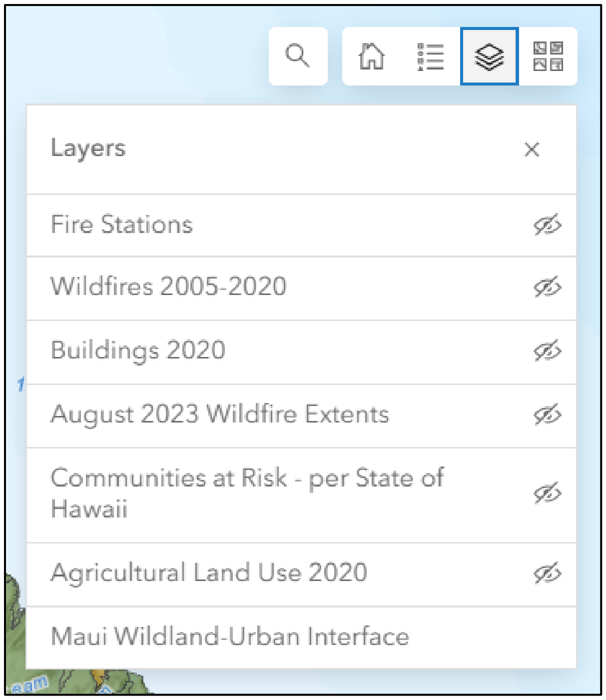

Figure 50. Data layers for additional context

Chapter 6 Conclusions

This chapter discusses the contributions this thesis brings to WUI literature, the findings of this thesis project, and the significance of studying WUI in Maui. The broad audience and applications of the Dashboard product are examined. This thesis project is compared to existing Maui WUI projects and the limitations of the project are addressed. Finally, steps to maintain the Dashboard and future research opportunities are discussed.

6.1 Contributions

As an applied research project, this thesis first provides a WUI map as an intellectual contribution to WUI literature and wildfire management body of knowledge for Maui. Then, this work is applied and drives the development of the final ArcGIS Dashboard product. The methodology and enhancements to standard WUI mapping practice and web-based WUI sharing in this thesis contribute to theoretical and methodological practices, and to technological applications.

6.1.1 Theoretical Contributions

This thesis advocates for WUI maps to be created for local fire-prone areas such as Maui. Wildfire management strategies must be done on a local level, emphasizing the need for local WUI mapping. Fire-prone areas should also develop WUI management plans based on shared common WUI classifications, not other geographic or political boundaries. Maui is divided into six community plan districts and seven Maui County Council districts, which loosely align with the Maui geographical regions. However, each district and region contain a variety of WUI and Non-WUI classifications that must be treated differently in terms of wildfire management. Areas under the same WUI or Non-WUI classification should have similar approaches for wildfires due to their comparable density and vegetation makeups. Furthermore, while many wildfire management plans are made for community districts on Maui, a more collaborative approach to wildfire management and land use planning can be taken by connecting communities across the island that have similar WUI classification and similar wildfire histories.

This thesis project highlights the importance of scale-dependent WUI mapping in local wildfire management and planning, particularly when analyzing small study areas. While this thesis assesses WUI at a regional scale by calculating WUI summaries across Maui, this thesis also analyzes WUI properties at the detailed census block level. Insights at multiple scales can be gathered from this research. Small, local projects that identify locations for wildfire mitigation interventions might find the census block level of analysis with detailed density and vegetation attributes useful. Alternatively, larger community-wide and regional WUI summaries can be useful for more regional and countywide land use policies. Accounting for local assessment is impossible on national and international WUI mapping scales, so mapping WUI at local scales is beneficial for local wildfire management and planning.

6.1.2 Contribution to Methodology

The WUI mapping enhancements in this thesis contribute to WUI scientific literature. This thesis promotes testing input landcover datasets on WUI map results before choosing the most appropriate for the study area, to improve accuracy in WUI results. Choice of dataset is very impactful for the study area of Maui; WUI classification land coverage results changed by up to 20% based on the datasets used. The WUI classifications from each landcover dataset were compared to observations of Maui, as well as historical, developmental, and geographic context about the island, to determine the best choice of landcover dataset. Landcover classifications mostly erred in distinguishing agricultural land from grassland. The initial agricultural classifications from the chosen landcover dataset were treated as vegetation cover. Then, the appropriate agricultural plots, sourced from a local and authoritative agricultural dataset, were removed from vegetation cover calculations. Accurate agricultural representation was also determined by testing and comparing agricultural classifications with the vegetative conditions on Maui, resulting in the separation of pastureland from other agriculture types. Other studies can implement these landcover dataset testing strategies to ensure that the selected landcover datasets and vegetation cover classifications used are the most accurate and representative for their study areas.

This thesis develops zonal-based methods to classify ecosystem-specific vegetative landcover for the study area, separating forest- and grassland-dominated WUI and Non-WUI Wildlands, and interprets the impact of vegetation type for the study area of Maui. While distinguishing forest- and grassland-dominated areas is precedented in Schug et al. (2023) in point-based analysis, this thesis defines census blocks as forest-dominated if they have forest cover ≥ 50%. Furthermore, reinterpreting the impact of vegetation type is critical for study areas. Because the forest on Maui is rainforest, and not high-wildfire risk, woody forests, such as are found most places around the world, the distinction between forest- and grassland-dominated WUI is necessary and changes the interpretation of wildfire risk in Maui. In other places, forests have higher wildfire risk than grasslands, but this is not the case in Maui. Based on the principle that WUI areas and Non-WUI Wildlands are inherently flammable, this project does not rename census blocks as “Grassland” WUI or Non-WUI Wildlands, because grassland in Maui matches these assumptions. Census blocks receive the “Forest” modification because rainforests stray from this principle. These methods support the WUI mapping practice of separating vegetation types based on the varying wildfire risk of vegetation in study areas.

6.1.3 Contribution to Technology

The ArcGIS Dashboard platform summarizes WUI information, additional wildfire management data, and communicates information through spatially enabled widgets. The improvements to sharing WUI knowledge through the web that were developed in this thesis support technical advancements in WUI literature. The design of the Dashboard promotes combining WUI information with other wildfire-related information. Data such as locations of historic wildfires and fire stations are not part of WUI mapping practices, but the supplementary information gives viewers a well-rounded view of wildfire risk and wildfire management alongside WUI. This thesis supports the notion that WUI map products are more helpful when viewed with other wildfire management information than viewed in isolation, and that Dashboards should be used to share WUI-related information broadly and publicly.

Furthermore, the Dashboard improves upon the standard mapping practice that areas under the same WUI classification are presented equally. WUI-contributing factors of building density and vegetation cover are different across census blocks, even when they fall under the same classification. Maui has a very high population density, and WUI census blocks vary greatly over the threshold of 6.18 buildings per square kilometer. The over/under threshold of 50% vegetation cover also holds significant ranges that are glossed over in static map products. By creating a dynamic product that shows the individual building density and vegetation cover components for each census block, the Dashboard discloses the black box of each census block's WUI-contributing factors. The WUI-related factors are presented with transparency so viewers can see the differences within WUI zones, allowing them to make their own assessments on the varied danger each census block faces. By being able to explore the components that go into a census block's WUI classification, viewers have a deeper understanding of the wildfire-related issues that an area faces.

6.2 Findings

The statistics produced in this study allow the prevalence of WUI on Maui to be compared to other locations and reveal the high prevalence of WUI on Maui, even relative to other fire-prone areas. The results of this thesis project demonstrate that the prominence of buildings, people, and land within the WUI in Maui far exceeds that of the fire-prone western states or Oceania. Shown in Table 1Table 6, over a quarter of land in Maui (27.46%) is in WUI, and almost all buildings (96.82%) and people (99.03%) are in WUI. As discussed in Chapter 2.3.4, Radeloff et al. (2023a) reveal that the average percentage of housing units (although different from building density, compared here as a close proxy) for the conterminous US is 31.6%, the average for the fire-prone western states is 48.7%, and the highest in the western states is 80.1%. Maui far exceeds these metrics, with 96.82% of buildings in WUI. The average land area in WUI for the conterminous US is 9.4%, the average for the fire-prone western states is 3.5%, and the highest in the western states is 8.2%. Again, Maui far exceeds these metrics with 27.46% of land in WUI, about triple the conterminous US average.

As stated in Chapter 2.3.2, Schug et al. (2023) provide continental summaries of its worldwide WUI study, including Oceania. In Oceania, less than 5% of the total land area is WUI, and over 60% of people are in WUI; Maui exceeds each of these proportions significantly. Furthermore, the proportion of forest-dominated WUI is higher than grassland-dominated WUI across Oceania, which contrasts the results in Maui, where grassland-dominated WUIX (15.95%) is almost double the land area of forest-dominated WUIX (8.95%). The prevalence of WUI in Maui is greater than other study areas it may be compared to in literature.

The distribution of land, people, and buildings within WUI classifications vary in proportionality. Most development and population in Maui are concentrated in WUIF. As gathered from the pie charts in the Dashboard, the buildings and people in both WUIX and WUIX Forest are relatively proportional to their land area coverages, when compared to the distribution of WUIF. WUIX covers about 16% of the land area, holds about 36% of buildings, and 27% of people. WUIX Forest covers about 9% of land area, 18% of buildings, and 11% of people. Contrarily, WUIF covers the smallest land area, less than 3%, and yet holds the highest percentages of buildings and people, with about 43% and 61%, respectively.

The results show significant nuance in WUI coverage when including or excluding forest-dominated areas. For example, 99.03% people are in WUI and therefore appear to be at imminent wildfire risk. Without WUIX Forest, the percentage of people in the WUI is about 88%, revealing that the danger to people in the WUI is not as drastic as it first appears. The WUI outcomes show that a large portion of land, buildings, and people in WUI are at lower wildfire risk, being surrounded by rainforest, rather than grasslands.

6.3 Comparison to Existing Maui WUI Maps

This thesis builds on efforts from the SILVIS Lab and State of Hawaii to comply more with national standards and create a Maui-specific product. When compared to the existing WUI maps of Hawaii created by Schug et al. (2023) and the Hawaii DLNR, the WUI map and Dashboard created from this thesis have many benefits.

6.3.1 Comparison to SILVIS Lab's Global WUI

While the goal of this thesis is to accurately assess WUI at a local scale in an area that recently experienced disastrous wildfires, and the goal of the global WUI analysis from the SILVIS Lab is to observe WUI trends at global and continental scales, this thesis product shows the benefits of using a WUI map created for a specific study area when studying a small location, rather than using the product from a global analysis. The building and agriculture locations are more accurate for Maui in this thesis's WUI analysis than those of the worldwide WUI analysis, because local datasets are used and landcover is adjusted, rather than using only global datasets. This thesis uses an accurate building footprint dataset, an improvement on the built-up surface estimate dataset used in Schug et al. (2020) that does not contain building footprints. The ESA landcover dataset used in this thesis is one year more recent than the ESA landcover dataset used in Schug et al. (2023).

The overall trends are similar; while the product of Schug et al. (2023) shows less WUI area, Schug et al. (2023) claim to likely be a conservative estimate, so this is to be expected. Both show WUIX Forest around forests in East Maui, WUIX in Upcountry Maui, and WUIX and WUIF in West Maui, Central Maui, and South Maui. However, Schug et al. (2023) show Non-WUI areas around Lahaina and in Kahului, which are both densely developed areas with frequent fires and high wildfire risk. The WUI map created in this thesis is more accurate in and around these communities because they receive WUI classification.

The Dashboard product has additional functionality when compared to the web map product created from the results of Schug et al. (2023) because the attributes of census blocks are revealed when clicked on. The analysis in this thesis is simpler than the analysis conducted in Schug et al. (2023), and the calculations are transparent for viewers in the Dashboard. Furthermore, the Dashboard and WUI map from this thesis use colors that symbolize grassland-dominated WUI to be more flammable than forest-dominated WUI, which is appropriate for the vegetative conditions of the Maui study area. The opposite is true in Schug et al. (2023); the global map symbolizes forest-dominated WUI as more dangerous than grassland-dominated WUI because this condition is true in most other study areas that have woody forests, not rainforests.

Schug et al. (2023) create the global WUI map with the point-based approach, while this thesis uses zonal-based analysis. The zonal-based results are more easily transferable to government boundaries because they are based on census blocks. Although the results of the point-based approach appear smoother, the results of the zonal-based approach in this thesis are easier to interpret because census blocks divide the study area into manageable units. Furthermore, additional attributes can be attached to the census block polygons, unlike pixels from the point-based approach that cannot carry attributes other than classification.

6.3.2 Comparison to State of Hawaii's WUI Definition

Compared to the WUI designations by the Hawaii DLNR, the WUI results of this thesis show greater cohesion with WUI products created around the country and the world, as the WUI calculations are based on Federal Register density and vegetation cover thresholds. By following the census block practice, the WUI map created from this thesis is also more easily overlaid with other GIS data and census-based information, while the community boundaries in the State of Hawaii product do not align with census data.

The low levels of risk in the CARs correspond with the WUIX Forest designations in East Maui and parts of Upcountry Maui in this thesis, further supporting the notion that these WUI areas are at less risk than other types of WUI. The notion that CARs are at highest risk in West, Central, and South Maui aligns with the results of this thesis as well. However, the Hawaii DLNR defines WUI as a buffer around communities, while the WUI mapped in this thesis is an improvement by including the communities themselves in WUI classification, giving greater accuracy to the land area covered by WUI. For transparency and so viewers can make their own assessments comparing the classification from this thesis and from the State of Hawaii, the

Hawaii CARs map is overlaid on the WUI map in the final ArcGIS Dashboard for visual comparison.

6.4 WUI Significance

Increasing research into the 2023 Maui wildfire events supports the affected communities and spreads awareness, respecting areas with so much historical and cultural significance. Creating more WUI knowledge supports wildfire management. Spatializing the WUI on Maui supports existing Maui County spatialization efforts.

6.4.1 Awareness

The one-year post-fire marker is a significant milestone for Maui. The wildfires are no longer receiving media attention like they were in the weeks following the disaster, although the affected communities, especially Lahaina, are nowhere near back to normal. The affected communities on Maui need to not be forgotten by the public but remain in the public mind out of respect for the great loss the communities suffered and for collective support in the recovery process.

6.4.2 Supporting Maui and Maui County Mapping Efforts

This study contributes to the knowledge base of Maui decision makers. A significant amount of data used in this thesis is sourced from the Maui County GIS Department. This thesis can support Maui County’s efforts in spatializing information and using maps as a tool to communicate with residents, as the final WUI and Dashboard products inform Maui residents about the relationship between the communities they know and love and the surrounding wildlands. Maui County has put significant efforts into creating map products to convey wildfire-related information to the public, and this research will diversify and extend these mapping efforts that are already being conducted.

The organization Maui Recovers is devoted to environmental protection and is assessing many environmental qualities in Lahaina (Maui Recovers 2024a). The air quality is being monitored because of the ash and dust released into the air, the coastline and watersheds are being monitored because the debris from the wildfire must be stopped from entering runoff, and soil quality is being measured carefully because of the negative effects of ash and other toxic materials that leach into the ground after wildfires (Maui Recovers 2024a). Maui Recovers provides mapping resources such as smoke maps, maps showing re-entry zones, the safety of built structures, areas under unsafe water advisories, and more (Maui Recovers 2024b). The community is very active and engaged in recovery efforts, yet there is room for further assessments that provide spatialized insight into the relationship between Maui and the WUI.

6.5 Dashboard Audience and Applications

The Dashboard is a creative and innovative way to present data related to the WUI. The Dashboard format presents a large variety of data in one place while being digestible and not overwhelming to viewers. Gathered in the Dashboard, the Maui WUI overview and census-block level WUI detail can aid a variety of stakeholders in Maui. The Dashboard is useful for finding areas that are the least fire-prone, the Non-WUI Non-Wildlands, but due to the small land area of this classification, the Dashboard results are also useful for stakeholders interested in determining the relative safety of census blocks within WUI areas. Dashboard viewers can see the relative building densities within census blocks, the number of housing units within each, see their relative distance to wildlands, see their number of historic wildfires, and more. By incorporating a Maui-specific WUI map with other wildfire-related factors in a shareable, public, and interactive platform, the Dashboard has a broad audience and can be used by local government and wildfire managers, as well as the private sector and the general public on Maui.

Both broad assessment of the WUI summaries, including the number of buildings and people that fall in Maui's WUI, and localized census block WUI assessment are useful for Maui County's wildfire management, urban planners, and fire departments. The WUI maps and Dashboard created from this thesis can support future updates to the existing community and wildfire protection plans on Maui, as well as building and landscape codes. The Dashboard can support updating wildfire mitigation strategies, transportation and evacuation plans, utility networks, firefighting resource allocations, and risk assessments across the island. Furthermore, the Dashboard can help in choosing priority areas for existing strategies on Maui to enforce defensible space guidelines, develop firebreaks, reduce fuels, and replace invasive grasses with native plants. The Dashboard can inform decisions on targeting educational initiatives in high-risk communities, as well as decisions regarding the placement of new development.

Beyond the government sector, the audience of the Dashboard extends to the private sector and general public on Maui. Homebuyers, homeowners, real estate developers, and insurance agencies are invested in the safety of homes and buildings in relation to wildfires, and the well-rounded Dashboard presents valuable information for them when assessing where to buy, build, or insure on Maui. The general public can explore the Dashboard as an educational resource and learn about WUI.

6.6 Limitations

While the thesis project makes great strides in researching WUI in Maui, studying WUI is a complex process, and not all angles of WUI analysis can be addressed in one research project. Furthermore, multiple methodological approaches exist for WUI mapping, and the census block approach used in this thesis is limited due to the varying sizes of census blocks. Limits on accuracy are also placed by the datasets used in this project.

6.6.1 Multiple WUI-Calculation Factors

WUI analysis contains many aspects; not all could be explored during this project. This thesis reveals the impacts that vegetation cover datasets and agricultural datasets have on WUI classification in Maui. However, other WUI research frequently tests the sensitivity of the structural density threshold set nationally by the Federal Register (6.18 structures per square kilometer) and vegetation cover threshold (50% vegetation cover) in WUI definitions for a study area. These threshold sensitivities are not tested in this thesis. The national Federal Register threshold definitions are maintained, which are not custom for Maui's unique landscape. Using these thresholds assumes that Maui's building density distribution and vegetation cover generally aligns with trends across the fire-prone areas of the US, while the island's characteristics are unique.

6.6.2 Zonal-Based Census Block Approach

Another limitation of the WUI results is inherent from using the census block analysis approach; by design, census blocks vary greatly in shape and size. While they are the smallest census division available for research, census block shapes are determined by natural and manmade features, such as roads or streams (US Census Bureau 1994). Across Maui, census blocks vary in size greatly, ranging from less than one square kilometer in highly developed communities to 250 square kilometers in the rainforests of East Maui. Building density and vegetation cover are often not evenly distributed throughout large census blocks, so metrics used for WUI calculation can be skewed. For illustration, comparing the map of building locations to the map of building density in Chapter 3.3.1 reveals that high-density metrics are often assigned to low density areas, when high density buildings may only be in part of a census block. Most noticeably, Upcountry Maui and East Maui have large swaths of mostly uninhabited land that exceed the building density threshold.

Therefore, the WUI results in this thesis are an overestimate of WUI area, especially in the larger census blocks deemed WUI. Likely, portions of the census blocks would not qualify as WUI if the census blocks were assessed in smaller pieces, and not skewed by building densities and vegetation cover relatively far away. While a fine-scale zonal-based approach based on zones of relatively equal size or population is ideal, these kinds of zones are not available for Maui or nationally, and census-block based WUI analysis is still a trusted and popular method.

6.6.3 Dataset Limitations

The two datasets with the most accuracy concerns in this project are the ESA landcover dataset and the census block dataset. The 2021 ESA landcover dataset has 76.7% accuracy, which is an improvement from the 74.4% accuracy in the 2020 ESA landcover dataset (Tsendbazar et al., 2022) used in the SILVIS Lab worldwide WUI map. However, potential misclassification in the 2021 dataset remains a concern. As mentioned in Chapter 3.2.2, the ESA dataset appears to underestimate the coverage of developed land, especially in communities in Upcountry Maui. These landcover classifications, although not extreme, skew the vegetation coverage percentage metrics of WUI calculation higher, and can alter WUI classification. The alignment of the ESA landcover dataset with census block outlines is also an accuracy limitation. The outline of the island does not line up perfectly between the two datasets, although the difference is not extreme. When census blocks around the coast extend into what the ESA dataset classifies as ocean, vegetation cover percentages are lowered. The vegetation cover metrics around the coast are not as accurate as the vegetation cover metrics in the inland census blocks.

Data update frequency is another concern. The datasets used in the final WUI analysis are from either 2020 or 2021, so the WUI map created in this thesis is a few years outdated, even though this is beneficial for seeing the conditions of Maui before the 2023 wildfires. The agricultural data from 2020 is an update of 2015 baseline data, so updates may be several years apart. The building footprint dataset is from 2020; there is a prior building footprint dataset from 2018, but future updates are uncertain. The 2021 ESA WorldCover dataset followed a 2020 ESA WorldCover dataset, but no others have been released since, so the timeline of the next update is uncertain. Census data updates are every 10 years, so WUI updates should occur no more than 10 years apart. The uncertain update frequencies are a limitation of the datasets, which is important when considering updating the WUI map in the future.

6.7 Future Research

While this thesis project thoroughly explores WUI in Maui and produces a highly accurate WUI map for Maui, many opportunities exist to expand WUI research in Maui and enhance the Dashboard product. The Dashboard needs to be updated with new and improved data over time. Also, input from Maui residents can improve the Dashboard, making the product more useful for local viewers. This thesis project intentionally uses national WUI-calculation thresholds so that the final map product can be compared to other standard WUI maps across the US. However, WUI research literature reveals that WUI maps provide further insight into specific regions when they are viewed in isolation with locally adjusted density and vegetation cover thresholds. These adjustments can enhance Maui WUI map products in the future.

6.7.1 Future WUI Research

While this thesis has WUI sub-classifications that are Maui-specific, exploring Maui-specific building density and vegetation cover metric thresholds can increase the WUI calculations' appropriateness for Maui. Altering them may cause significant changes to WUI classification results. The building density on Maui is much greater than the building density threshold of 6.18 buildings per square kilometer, so increasing the building density threshold may improve the limitation in this thesis project that large census blocks are skewed to classify as WUI by their building densities. Furthermore, resolving the census block size issue on a broader level by researching a zonal-based WUI classification approach that is not limited by the various sizes of census blocks would not only improve WUI classification results on Maui, but for the rest of the country as well.

Nevertheless, having used census block data for this thesis project opens a variety of research opportunities regarding the incorporation of other census data. The plethora of demographic data associated with each WUI classified census block can be explored, along with discovered correlations between demographics and WUI classifications. Housing occupancy can also be studied with WUI and wildfire patterns. Furthermore, the WUI map can be compared with nationwide (48 conterminous states) census block-based WUI datasets.

Finding an alternative to either zonal-based or pixel-based WUI classification methodologies that neither overestimates nor underestimates WUI is an endeavor worthy of further research. The next step of interest for this thesis project is to assign WUI classification attributes to building footprints themselves, to calculate specifically the human-impacted area of WUI. The area of Maui covered by WUI buildings would be substantially less than the area of Maui covered by WUI census blocks. Assessing WUI directly on a human-affected scale can provide a more precise measurement of the true reach of WUI.

Automating WUI mapping analysis would make WUI mapping more accessible for other government entities to replicate, rather than replicating and conducting the extensive analysis manually. The methodology steps in this thesis can be made into an ArcGIS ModelBuilder or written in a script that automates the WUI mapping workflow in ArcGIS Pro. Automating the process would save considerable time, especially when repeating WUI mapping multiple times to experiment with different datasets. Mapping vegetation cover multiple times, to gather all vegetation cover, all vegetation cover without agricultural land, forest cover, and grassland cover, demonstrates the suitability for streamlining the WUI mapping process with automation. An automated WUI mapping process can be exported to various entities that could benefit from creating WUI maps.

Going forward, another endeavor to improve WUI research is to create predictive WUI maps to forecast future WUI growth. Predictive WUI maps are not currently created in WUI literature, and adding the time dimension to WUI can increase the uses of WUI. While the WUI analysis in this thesis project is useful for retroactively assessing the WUI conditions in Maui before the August 2023 wildfires, predictive WUI maps should be created to support land use planning and controlling the growth of WUI into the future. Predictive landcover data is becoming more popular, and while this data must be improved before proving useful for the Maui study area, a proactive approach to WUI mapping can greatly benefit WUI research, wildfire management, and land use planning.

6.7.2 Enhancing Existing Dashboard

This thesis has proved that slight data changes alter WUI classifications significantly, and therefore the overall representation of community danger, development's relation with wildlands, and wildfire risk distribution on Maui. Any future WUI experimentations with adjustments to building density and vegetation cover thresholds would yield additional WUI maps, which could each be added as additional layers in the Dashboard. Along with the other existing layers in the

Dashboard, the added WUI maps would provide more transparency to viewers; additional WUI maps would highlight and increase viewers' awareness of the scientific subjectivity of WUI classification.

To maintain accuracy and relevancy, the WUI map and Dashboard will need to be updated with new data as it becomes available. Landcover, buildings, population, and agricultural datasets should be monitored for new releases to create updated WUI maps in the future. For the Dashboard, the supplemental data layers will need to be replaced over time as they are updated, so the product is relevant. With strong GIS backing from census data, the ESA, and the Hawaii Statewide and Maui County GIS Depts., the WUI map and Dashboard products should be updated every few years.

Furthermore, past datasets and future dataset updates create the opportunity to make the Dashboard time-enabled. While the WUI layer, Web Map, and Dashboard are currently not time-enabled, creating WUI maps from past datasets and future datasets would enable comparisons over time, and a time-enabled product. A time-enabled WUI layer would provide insight for Maui wildfire managers and stakeholders into the growth of WUI in Maui over time. Viewing past datasets would allow users to see the progression of development, landcover, and other WUI-related factors over time, deepening their understanding of the changes in WUI.

From a cartographic standpoint, adding features promoting accessibility is important for future research. This thesis project uses red and green tones for symbology because these colors are standard in WUI literature to represent fire and wildlands, but these colors are difficult to see for red-green colorblind viewers. Experimenting with different color schemes that are colorblind-friendly and adding additional data layers that communicate the same information in a colorblind-friendly manner would improve the accessibility of the WUI map and Dashboard.

As Dashboards gain more features in the future, adding a widget with geoprocessing ability can improve the functionality and impact of the Dashboard. Although dependent on WUI mapping becoming automated, a widget with a WUI analysis geoprocessing service would allow users to run WUI analysis with their own datasets and add the map product to the Dashboard. Allowing Dashboard users to run WUI analysis and create their own map products would increase the learning potential of the platform, as well as extend its usefulness.

6.7.3 Maui County Feedback

The robust GIS department in Maui County was one of the inspirations for this thesis project. The final WUI map and Dashboard products will be shared with Maui County GIS Specialists as an information-sharing act and to receive feedback. Ideally, the Dashboard will obtain recommendations from Maui County GIS on additional wildfire-related datasets that are relevant and important to stakeholders. Incorporating feedback on matters of interest that Maui residents or the Maui fire departments would like to see on the Dashboard will greatly benefit this project. In the future, perhaps many local governments will create Dashboards informing their stakeholders about the WUI and other wildfire-related data in their areas, customized for the needs in their own communities with their own local data.

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