Development of Decision Support Systems for Ecosystem Management
A case study on Hawai`i Island

Heather Kimball
Master’s Thesis
Tropical Conservation Biology and Environmental Sciences
University of Hawai‘i at Hilo
200 West Kawili Street
Hilo, HI 96720

Thesis Advisor: Dr. Jonathan Price
Research Committee: Drs. Christian Giardina and Ryan Perroy
Acknowledgements

I would like to thank my family for putting up with me through the course of my thesis work. My husband, Scott Fleming, has always been generous with his support of all my dreams and ambitions. My daughters: Leigh, Anastasia, Lillian and Katherine have endured less than my full attention. I want them to know that I love them all and could not have done this without their help. I hope I have shown by example the value of always seeking out new knowledge and working hard to accomplish your goals.

I would also like to thank the stakeholders for this project. Mike Robinson, Natural Resource Manager for the Department of Hawaiian Home Lands provided a wealth of information and I wish him well in retirement (we never thought he would actually go through with it). I am also grateful to Cheyenne Perry, Coordinator for the Mauna Kea Watershed Alliance for his expertise and time. Thank you Cheyenne for introducing me to Humu’ula. I would also like to thank the other collaborators on this project outside of my committee: Paul Selmants, Alvaro Moreno, Steve Running, Tony Kimmit and Benjamin Sleeter.

Working on this project for three years and viewing the landscape from the ground and the sky, I have developed a personal connection with Humu’ula. If my work on this project facilitates the restoration of this landscape in any small way, that will be the greatest reward I could receive from this experience. I am grateful to have had the opportunity to work in this area of Hawai`i. It truly is Wao Akua – The realm of the gods.

Kanakaleonui Bird Corridor out planting crew at the Wailuku River gulch in Humu’ula in March 2016: Jake Caldwell, Stephanie Gayle, the author (Heather Kimball), Mike Doherty and James Akau. Photo taken by Cheyenne Perry.
Abstract

Ecosystem management decisions are inherently complex, requiring the integration of ecological science, economics, policy, cultural values, and stakeholder needs. Decision support systems (DSS) are tools intended to facilitate communication between researchers, land managers and policy makers, with the goal of more informed and holistic decision making at the ecosystem scale. The objective of this thesis was to assess the process of DSS development and generate components of a DSS for an individual land owner to assist in planning ecosystem management. The study area selected to demonstrate this process is 23,000 hectares in the Humu‘ula tract on Hawai‘i Island administered by the Department of Hawaiian Home Lands. This site was selected because it has an existing land management plan, the ‘Āina Mauna Legacy Plan, and it represents two main threats to ecosystems in Hawai‘i, habitat degradation and non-native plant and animal species invasions. Based on nearly three years of discussions with the stakeholders, the following management goals were identified for the study area: restoration and protection of native plant and bird habitat, gorse (Ulex europaeus) removal, watershed restoration, fire reduction, and most importantly, increased and more consistent funding to support the aforementioned goals. This study is divided into three sections. The first section describes establishing Gross Primary Productivity and Net Primary Productivity parameter estimates for the different land cover classes in the study area in order to project the capacity of the ecosystem to capture carbon under the alternative scenarios. The second section evaluates the use of high resolution imagery to model the current land cover of the study area, particularly the spatial distribution of the invasive shrub gorse. The final section covers a summary, conclusion and the next steps for this project including the parameterization of a state and transition model, used in the Carbon Assessment of Hawai‘i, to generate projections and data layers to develop a decision support system for the study area as an appendix.
Table of Contents

Acknowledgements ......................................................................................... ii
Abstract .......................................................................................................... iii
List of Tables ..................................................................................................... v
List of Figures .................................................................................................. vi
Chapter 1: Project Background and Objectives ............................................. 1
  Section 1.1 Introduction .............................................................................. 1
  Section 1.2 Overview of Ecosystem Management and Decision Support Systems..1
  Section 1.3 Thesis objective .................................................................5
  Section 1.4 Study Area ............................................................................. 6
  Section 1.5 The ʻĀina Mauna Legacy Plan ...........................................9
  Section 1.6 The Carbon Assessment of Hawaiʻi and Carbon Credits ..........12
  Section 1.7 Thesis Content Overview ..................................................13
Chapter 2: Generating land cover specific parameter estimates of Gross Primary
Productivity and Net Primary Productivity using MOD17 ............................14
  Section 2.1 Introduction ..........................................................................14
  Section 2.2 MOD17 GPP and NPP Model Overview ...........................15
  Section 2.3 Methods ............................................................................17
  Section 2.4 Results .............................................................................22
    2.4.1 MOD12Q1 and CAH-LC Comparison ......................................22
    2.4.2 GPP Model Comparisons .........................................................23
    2.4.3 GPP and NPP parameter estimates ...........................................28
  Section 2.5 Discussion ...........................................................................29
Chapter 3: Using high resolution satellite imagery and phenology to determine the
distribution of Ulex europaeus on Hawaiʻi Island .........................................35
  Section 3.1 Introduction .........................................................................35
  Section 3.2 Methods .............................................................................38
    3.2.1 Evaluation of the CAH Land Cover Model for the study area .......38
    3.2.2 2015 WorldView-2 imagery acquisition ....................................39
    3.2.3 Spatial Analysis .........................................................................42
    3.2.4 Final Land Cover Model Production ..........................................43
  Section 3.3 Results ................................................................................43
  Section 3.4 Discussion ...........................................................................49
Chapter 4: Thesis Summary, Conclusions and Future Projects .....................51
Appendix 1. State and Transition Modeling ................................................54
  Section A1.1 State and Transition Modeling Overview ..........................54
  Section A1.2 Parameterization of the AMLP state and transition model ....57
  Section A1.3 Key Assumptions in the AMLP Model .............................61
  Section A1.4 Expected Outputs and Further Analysis ............................62
  Section A1.5 Transitions defined for the AMLP state and transition models ..65
  Section A1.5 Pathways for the state and transition models ...................72
References .................................................................................................79
List of Tables

Table 2.1. The five biome properties from the BPLUT ........................................ 17
Table 2.2. The CAH-LC model vegetation ............................................................ 18
Table 2.3. MOD12Q1 and CAH-LC alignment matrix ........................................... 23
Table 2.4. GPP parameter estimates by land cover class ...................................... 28
Table 2.5. Parameter estimates for CUE based on land cover class ....................... 29
Table 3.1. The eight spectral bands from DigitalGlobe’s WorldView-2 imagery .......... 41
Table 3.2. Training and Accuracy Assessment Regions of Interest ......................... 42
Table 3.3. Producer and user accuracies by land cover class ................................. 47
Table 3.4. Confusion matrix for the 2013 WorldView-2 imagery ............................ 48
Table A1.1. Transition groups and types for the `Āina Mauna Legacy Plan ............. 56
List of Figures

Figure 1.1. The location of the `Āina Mauna Legacy Plan study area ......................6
Figure 1.2 Environmental models for the `Āina Mauna Legacy Plan study ......................8
Figure 1.3. The `Āina Mauna Legacy Plan land management ......................................11
Figure 2.1. A simplified flowchart adapted from the MOD17 User Guide ......................16
Figure 2.2. Mean GPP model for Hawai`i .................................................................17
Figure 2.3. The MOD12Q1 and CAH-LC land cover models for Hawai`i ......................19
Figure 2.4. Density plots for each land cover class .......................................................21
Figure 2.5. Relative coverage area state wide by land cover .....................................23
Figure 2.6. Statewide annual carbon by GPP model ....................................................24
Figure 2.7. GPP Distribution by model ....................................................................24
Figure 2.8. Distribution of differences between GPP ......................................................25
Figure 2.9. The differences in total annual carbon usage by land cover .....................26
Figure 2.10. The distributions of annual GPP by land cover class ............................27
Figure 2.11. Difference in GPP estimates between the GBC+GBL and HIC+GBL ......30
Figure 2.12. Difference in GPP estimates between the GBC+GBL and HIC+HIL ......30
Figure 2.13. Solar radiation model for Hawai`i ..........................................................31
Figure 2.14. Difference in GPP estimates between the HIC+GBL and HIC+HIL ......32
Figure 2.15. Hawai`i GPP Model based on HIC+HIL ...............................................33
Figure 2.16. Hawai`i NPP Model based on HIC+HIL ...............................................34
Figure 3.1. The location of the core gorse population within the study area ...............36
Figure 3.2. Images from gorse flowering in Humu`ula, February 2016 .......................37
Figure 3.3. Point grid across the study area ...............................................................39
Figure 3.4. WorldView-2 imagery from the study area .................................................40
Figure 3.5. WorldView-2 imagery from a portion of the core gorse population ..........41
Figure 3.6. Flow chart showing the process for creating a final land cover model .......43
Figure 3.7. Interpolated CAH-LC error map of the study area ....................................44
Figure 3.8. Mean spectral values by vegetation type by wavelength ...........................45
Figure 3.9. Data value histograms for the spectral bands .........................................46
Figure 3.10. Classified images from the Humu`ula and Pi`ihonua ahupua`a ..........49
Figure 3.11. The land cover classification maps for the study area ...........................50
Figure A1.1 The `Āina Mauna Legacy Plan land management designations ............55
Figure A1.2. Initial gorse rage limit for time step zero .............................................58
Figure A1.3. Prioritization for timber planting .........................................................59
Figure A1.4. An example of the accumulation curves produced from ST-SIM ..........64
Chapter 1: Project Background and Objectives

Section 1.1 Introduction

Ecosystem management decisions are inherently complex, requiring the integration of ecological science, economics, policy, cultural values, and stakeholder needs (Grumbine 1994; Quigley et al. 2001). The complexity is both a matter of scale and the variety of perspectives on the priorities of ecosystem management (Nute et al. 2004). The Hawaiian archipelago boasts diverse ecosystems, unique flora and fauna, and a vibrant cultural community, and faces a number of multifaceted resource management challenges. Natural resource concerns in Hawai`i include: invasive species, groundwater recharge, resource sustainability, land conversion, habitat degradation, and urban-wild land interfaces (Turner 1996; Rodriguez-Iturbe 2000; Vorsino et al. 2014). These natural resource concerns are linked to broader policy issues such as: economic viability, food security, human health and access to affordable housing. Decision support systems (DSS) are tools designed to simplify and improve the quality of the decision making process. The use of DSS for ecosystem management is intended to facilitate communication between researchers, land managers and policy makers, with the goal of more informed and holistic decision making at the ecosystem scale (Mower et al. 1997; Rauscher 1999; Reynolds et al. 2014). The objective of this thesis project was to initiate development of an ecosystem management DSS to assess the process of DSS development and evaluate the use of existing data sets and tools to develop components of a DSS for an individual landholder in Hawai`i.

Section 1.2 Overview of Ecosystem Management and Decision Support Systems

In the early 1990’s, US Federal natural resource management agencies began to focus increasingly on ecosystem level strategies for land management. Evidence of natural resource loss and degradation highlighted the need to manage our natural environment proactively and adaptively (FEMAT 1993). This resulted in a shift from management based solely on perpetuating resource usage to a continuous process of...
ecosystem restoration and/or preservation with the goal of sustaining both resource 
products and usage as well as biodiversity, provisioning ecosystem services, and aesthetic 
and cultural value (Overbay 1992; FEMAT 1993; Thomas 1995). To effectively manage 
resources at the ecosystem scale, decision makers must combine: 1) ecological 
knowledge of current ecosystem form and function, 2) scientifically-based predictions of 
future conditions resulting from alternative management strategies and/or climatic 
scenarios and 3) an understanding of the limitations on time, funding and scientific 
knowledge in the current social, political and economic context (Grumbine 1994; 
Christensen et al. 1996; Smith 1997).

DSS have been implemented to assist in complex, multifaceted decision scenarios 
in several fields including finance, manufacturing, medicine and agriculture (Aynes & 
Aplan 2001; Bates et al. 2001; Jones et al. 2003). In response to the Federal commitment 
towards a more holistic approach to resource management, efforts arose to develop DSS 
specifically for ecosystem management. The concept of DSS first emerged in the mid-
1960s from the combination of theoretical research at the Carnegie Institute of 
Technology on organizational decision making and technical research in artificial 
intelligence conducted at MIT (Keen 1978). DSS are broadly defined as computer based 
tools that incorporate a knowledge-base containing information relevant to the decision 
being made, models representing the relationships and dependencies of the information 
within the knowledge-base in the context of the decision, and a user interface that allows 
decision makers to manipulate criteria and/or desired outcomes, thereby assisting them in 
making informed judgments. The primary functions of DSS are to reduce the challenges 
inherent in processing large quantities of complex data with the goals of improving the 
quality of decision making, increasing transparency and creating a reproducible decision 
process while allowing flexibility from direct human interaction (Larsen et al. 1997; 
Reynolds et al. 1998).

Developing DSS for ecosystem management is challenging for several reasons. 
The precise definition of the problem to be solved through ecosystem management is still 
evolving, and there are conflicting views between long-term ecosystem protection based 
on intrinsic value versus preserving an ecosystem based on its ability to continue to meet 
the needs of an increasing global population (Rauscher 1999; Nute et al. 2004; Reynolds
et al. 2014). For conservation biologists, ecosystem management represents a paradigm shift from simply conserving resources on the basis of continuous product yields to preserving ecosystem integrity over the long-term to conserve biodiversity and sustain the ecosystem as a whole (Grumbine 1994; Quigley et al. 2001). While resource management agencies often view ecosystem management, for the sake of the ecosystem, not as the end goal but as a continuous process by which ecological conditions are restored or preserved in order to sustain desired ecosystem services (Overbay 1992; FEMAT 1993; Thomas 1995). As a result, the problems to be addressed through ecosystem management decisions are dependent on the perspective from which the problems are viewed (Rittel & Webber 1973; Allen & Gould 1986).

Another challenge in developing ecosystem management DSS is the need to identify, quantify, and value ecosystem content and function. Developing the initial database describing the current condition of the ecosystem to be managed can require a large quantity of data collection, which increases exponentially with scope and diversity of management goals (Nute et al. 2004). Limitations in personnel, financial resources, time and political will to monitor over the long term can inhibit DSS development and implementation (Rauscher 1999; Reynolds et al. 2014). Many ecosystem attributes and functions are also difficult to quantify (de Groot et al. 2010; Berger 2011). Products have been developed to assess the economic value of ecosystem services (InVEST, Sharp et al. 2014; ARIES, Villa et al. 2009). However, most identified ecosystem services still lack models for market value, particularly those that are provisioning and cultural services (Costanza et al. 1998; de Groot et al. 2010). Furthermore, while the ecosystem service model may be the most concise approach for performing cost-benefit analysis for an ecosystem management DSS, this concept is limited in that the values attributed to ecosystem services are restricted temporally and spatially and are generally anthropocentric (McCauley 2006).

The importance of the human dimension cannot be overstated when considering challenges to developing DSS for ecosystem management. DSS are intended to assist humans in making informed judgments. However, human decision making is most often based on gut instinct, or trial and error (Miller 1965; Wilensky 1967; Walters & Holling 1990; Larsen et al. 1997; Reynolds et al. 1998). Decision makers tend to simplify
problems and avoid seeking additional information and expertise, despite the need for quantitative, transparent and defensible decisions. It is not always obvious to stakeholders that a DSS will actually provide a benefit to their decision making process, particularly if there is a significant cost in either time or money to the DSS development (Keen 1981; Allen & Gould 1986).

Several ecosystem management DSS have been effective in modeling baselines of ecosystem conditions and providing planning alternatives (Mowrer et al. 1997; Rauscher 1999; Reynolds et al. 2014). For example, DSS have been used to; evaluate landscape restoration priorities in the Rocky Mountain based on historical land cover and the anticipated effects of climate change (Bollenbacher et al. 2014), assess coastal watershed quality for fish habitat in terms of sediment in northern California (Dai et al. 2004), identify potential translocation sites for threatened turtles in the Mojave desert (Heaton et al. 2008), evaluate land use options in Guizhou China with respect to carbon sequestration, and inform the allocation of funds for forest fire prevention in Colorado and Utah (Hessburg et al. 2007). Because of the challenges mentioned above, very few have been successfully implemented as part of the organizational decision making process. Reviews of several DSS concur on the key factors in effective DSS and subsequent application development (Keen 1981; Rauscher 1999; Reynolds 2001; Arnott & Pervan 2008). DSS development must be driven by stakeholders who define the scope of the problem and the decision priorities they want the DSS to address. This increases the likelihood that the stakeholders will consider the DSS valuable to their decision making process. The DSS development process must be iterative and facilitated, requiring constant communication between the developer and the stakeholders. The DSS developer must form a relationship with the stakeholders so that the stakeholders’ decision support needs can be accurately assessed. Finally, because of the initial investment of resources in the knowledgebase development, existing data sources should be leveraged as much as possible.
Section 1.3 Thesis objective

The objective of this thesis project was to initiate development of an ecosystem management DSS to assess the process of DSS development and evaluate the use of existing data sets and tools to develop components of a DSS for an individual landholder in Hawai‘i. To evaluate this process, I focused on 23,000 hectares in the Humu‘ula tract on Hawai‘i Island administered by the Department of Hawaiian Home Lands (DHHL, Figure 1.1). This area was selected for several reasons. First, in 2009 DHHL unanimously approved a 100-year management plan, called the `Āina Mauna Legacy Plan (AMLP), which can be used to inform state and transition modeling in order to project long term management outcomes. This site is also representative of the two main threats to ecosystems in Hawai‘i, habitat degradation due to land-use and non-native plant and animal species invasions. Should portions of Humu‘ula be restored as prescribed in the AMLP, the areas have enormous potential to provide a variety of ecosystem goods and services including: native bird and plant habitat, watershed improvement, sustainable wood products, and cultural and educational opportunities. Another important factor in choosing this site are the existing relationships I had with the key stakeholders, Cheyenne Perry of the Mauna Kea Watershed Alliance and Mike Robinson, Natural Resource Manager for DHHL. Building a successful DSS requires the ability to accurately assess the needs of the stakeholders. Based on nearly three years of discussions with these stakeholders and review of the AMLP, the primary management goals for the study area were identified as: restoration and protection of native habitat, gorse (*Ulex europaeus*) removal, watershed restoration, and fire reduction. More importantly, it became clear that in order for these goals to be met, increased and more consistent funding is required.
Figure 1.1. The location of the ʻĀina Mauna Legacy Plan study area in the Humuʻula ahupuaʻa on east side of Hawaiʻi Island viewed from the direction of Hilo, Hawaiʻi (study area center 19°46′32″ N, 155°22′44″ W). Inset shows location of the ʻĀina Mauna Legacy Plan study area on the Island of Hawaiʻi.

With these stakeholder goals in mind I sought to develop models using existing data products and tools that would reflect the probabilities for different outcomes with respect to native forest, gorse and fire with and without the implementation of the AMLP and including the influence of anticipated climate change. These models can be used to create visualization products to help the stakeholders to supplement funding efforts necessary to implement the AMLP and evaluate management strategies. These models will produce data layers that can be used as DSS components to help stakeholders prioritize their work areas based on costs and their specific objectives.

Section 1.4 Study Area

The study area in the Humuʻula and Piʻihonua ahupuaʻa, is part of roughly 80,000 hectares set aside by the US government in 1920 under the Hawaiian Homes Commission Act. The goal of this Act was to return native Hawaiians to the land in order to preserve
cultural ties with the natural landscape. The study area represents 27% of all DHHL trust lands in Hawai`i and is the department’s largest continuous land holding.

Located on the windward slopes of Mauna Kea, the elevation range of the study area is from 1400-2800 m ASL with the majority of the area being in 1,800-2,100 m range (Gesch et al. 2002; Figure 1.2 a). The average air temperature throughout the year across the study area ranges from 7.9°-13.6° C, with an overall mean of 10.2°C +/- 1.1°C (Giambelluca et al. 2014; Figure 1.2 b). Both rainfall and substrate age vary greatly. The moisture zones range from wet (>2500 mm/yr.) to dry (<1200 mm/yr. dry (Giambelluca et al. 2013; Figure 1.2 c). Substrate age ranges from young lava flow less than 200 years old to substrates ~15,000 years old, with a few areas that are 100-300 thousand years old (Trusdell et al. 2006; Figure 1.2 d). Based on dynamically downscaled climate models, this area is projected to experience an increase in mean annual air temperature of 3.4°C, and the entire study area is projected to shift to a mesic moisture zone (Fortini et al. CAH 2016).

From 1902-2002 the study area was leased to Parker Ranch and subsequently converted to pasture-based rangeland. This now heavily degraded, mesic to dry subalpine habitat is primarily covered by non-native pasture grasses and the non-native invasive shrub gorse. Gorse, introduced to Hawai`i in the late 1800s from Western Europe, was identified as an invasive species in the early 1900s. In 2011 it was estimated to cover an area of ~2,000 hectares of dense growth and another ~10,000 hectares of scattered growth in Humu`ula (Markin & Conant 2011). One point, repeated frequently throughout the AMLP, is that gorse removal is critical to the success of the program. The study area includes open koa (Acacia koa)/ohia (Metrosideros polymorpha) forest on the eastern side of the project area where the DHHL land borders the Hakalau Forest National Wildlife Refuge and a degraded mamane (Sophora chrysophylla) forest on the western side bordering the Mauna Kea Forest Reserve. To the south of Saddle Road there is a 4,500 hectare section that contains a young lava flow and sparse native shrubs and ohia. Feral ungulates and cattle are distributed across the area and negatively impact the ecosystem (Juvik & Juvik. 1984).
Figure 1.2 Environmental models for the `Āina Mauna Legacy Plan study area in the Humu‘ula ahupua‘a on east side of the Island of Hawai‘i. Study area center 19°46’32" N, 155°22’44" W. Models include a) elevation in meters, b) mean annual temperature in °C, c) mean annual rainfall in mm and d) substrate age.
Section 1.5 The ‘Āina Mauna Legacy Plan

The mission of the DHHL is “To manage the Hawaiian Home Lands trust effectively and to develop and deliver land to native Hawaiians.” To this end, in 2009, DHHL finalized the AMLP, a development and natural resources management plan for Humu‘ula and Pi‘ihonua. The AMLP program was designed to create a sustainable community for native Hawaiians, pursuant to the DHHL mission, as well as to restore and protect the native forests and habitats. The DHHL defines a sustainable community as one that provides homesteading opportunities and access to the area for hunting, gathering and cultural activities, and also protects and maintains natural resources in a manner that is economically viable over the long term. The AMLP was unanimously approved by the Hawaiian Homes Commission on December 15, 2009. The AMLP final draft includes 27 letters of support from stakeholders and partner agencies including the Nature Conservancy, the Hawai‘i Audubon Society, the Conservation Council for Hawai‘i and Big Island Invasive Species Council (DHHL 2009 p.234).

Under the AMLP the study area has been divided into 9 management categories, each with a planned future land use designation (Figure 1.3). Under the AMLP, areas designated for restoration and sustainable koa forestry are either currently or will be fully fenced and all feral ungulates will be removed. These areas will then be replanted with koa and native understory plants. Sustainable harvesting will take place in the koa forestry areas after approximately 50 years, and the plan allows for some of this area to be converted to homesteading after harvesting, if necessary. The mamane forests will also be fenced, and ungulates will be removed. The AMLP does not specify active out planting of mamane in these areas but anticipates recruitment will occur from the existing seed bank. The pasture areas will be used for raising sheep and cattle or used for other types of agriculture. The pasture lease area is currently leased to a private individual and the future of this area is not specified in the plan. The area that contains an historic sheep station will be developed for light commercial activities. Homesteading will occur in designated locations with the first phase including 100 homes on approximately 1 & 2-acre plots with a 15-acre park area and 800 acres for community pasture/ agriculture. The
timber/homestead areas, which cover the area of the current core gorse population, will be leased and planted with non-native timber, most likely sugi pine (Cryptomeria japonica). The selection of sugi as the timber crop is based on the fact that gorse is shade intolerant at less than 10% sunlight availability (Perry 2010). The AMLP asserts that once gorse is removed, sugi will grow quickly enough to prevent recruitment of gorse from the existing seed bank. The AMLP specifies that gorse will first be contained to the core area with a 250 m timber buffer. Subsequently, gorse will be removed from the containment area and additional timber will be planted. The AMLP does not specify a particular method for gorse removal. The AMLP states that the timber will be harvested between 25 and 45 years after planting. After the first timber harvest, there are three possible options in the plan: a second timber planting and harvest cycle, replanting with native forest, or conversion to an additional 150-300 homesteads. It is important to note that the timber lease is the main source of funding in the AMLP for the restoration efforts, fencing and infrastructure development for the homestead areas. Finally, the AMLP does not delineate any specific management actions for the open young lava flow and shubland portion on the southern end of the study area. Both this description and the associated map include some modifications that have been made to the original plan by DHHL. These modifications include the addition of one mamane protection area and the removal of a gorse control area that had been leased for experimentation on the use of gorse as biofuel. This lease expired in 2014 and this area has been integrated into the area designated for timber. An environmental assessment for the plan was finalized in 2012 with the finding that the AMLP would have no significant (negative) impact on the environment (DHHL 2012).
Figure 1.3. The `Āina Mauna Legacy Plan land management designations (DHHL 2009). The study area is located in Humu`ula ahupua`a on east side of the Island of Hawai`i. Study area center 19°46'32 N, 155°22'44 W. Total area 22,732 ha; Open 4,515 ha, Timber/Homestead 4,410 ha, Koa Forestry 4,224 ha, Mamane 4,033 ha, Restoration 2,659 ha, Pasture 1,544 ha, Homestead 801 ha, Pasture Lease 330 ha and Light Commercial 215 ha.
In consideration of the stakeholder needs for the study area, and in the interest of leveraging existing data sets and tools, the Carbon Assessment of Hawai`i was selected as a source for data products and tools for DSS development. With climate change and the implication of carbon emissions as its primary driver, understanding our landscapes’ carbon storage potential and carbon fluxes is key to making management decisions at the ecosystem level (USDA 2008). In 2007, the Congressional Energy Independence and Security Act, Section 712, established objectives for a nationwide assessment of carbon storage capacity and flux rates. Regional assessments include baseline estimates for carbon stocks including: above ground carbon density, below ground carbon density, soil organic carbon, and forest floor carbon. The assessments also estimate annual carbon fluxes including: fire emission rates, aquatic flux rates, and net ecosystem production based on GPP and ecosystem respiration rates (Zhu et al. 2010). The carbon assessments also include end of the century (year 2100) projections for these stocks and fluxes based on land cover transitions, with and without management action, and including the impacts of biome shifts anticipated with climate change. The US Geological Survey has completed assessment reports for the Continental US and Alaska. The CAH was prepared by the US Geological Survey in collaboration with the US Forest Service, the University of Hawai`i and the Carnegie Institution for Science. The CAH is currently under review and will be publicly released in 2016. The CAH data products were made available for the purpose of this thesis prior to public release of the final report.

In concert with the data products and tools from the CAH, I incorporated carbon credits as a way to valuate and compare management decisions for the study area. The Nature Conservancy and the USDA Forest Service have been working with the California-based Climate Action Reserve to allow Hawai`i to participate in California’s Carbon Credit program. Participation in this program requires that projects: 1) be additional, meaning that new trees will be planted in areas that are not currently forested; 2) be long-term, with trees remaining for at least 100 years, though some sustainable forestry is allowed; 3) do not result in compensatory conversion of other forested areas to non-forest land-uses, termed leakage; and 4) use native trees. Participation also requires
baseline estimates of carbon (C) stocks and projections for C accumulation resulting from project implementation. Baseline C stocks are available from the CAH data products. Projected carbon accumulation has to be modeled based on estimates of Gross Primary Production (GPP) and its derivative Net Primary Production (NPP). Participation in a carbon credit program can be a source of funding for the stakeholders and can be used for cost benefit analysis of management options for the study area.

Section 1.7 Thesis Content Overview

This thesis contains three chapters in addition to this introductory chapter, which defines the background and scope of the project. Chapter 2 and 3 of this study assess how data products from the CAH, in combination with other data sets, can be adapted to develop components of a DSS to support the stakeholder needs for the study area. The results of these analyses provide input for models to project future CAH and carbon credit related outcomes. Chapter 2 specifically covers the establishment of GPP parameter estimates for the primary land cover classes in the study area using the CAH land cover model and the global model GPP/NPP MOD17. Establishing these parameters was complicated by the fact that the global land cover map product used by MOD17 was not well aligned with the land cover model provided in the CAH. Chapter 2 describes how this was resolved and the impact the resolution had on statewide GPP estimates. Chapter 3 describes how the CAH land cover map was not adequate to address stakeholder needs, particularly the spatial distribution of the invasive shrub gorse. This was solved using high resolution imagery to model the current land cover of the study area. Having a high resolution gorse footprint will allow managers to prioritize treatment areas. Chapter 4 provides a summary of this initial phase of DSS development and describes how the results produced in Chapters 2 and 3 provide essential information to support state and transition models that will lead to a more comprehensive DSS for the study area.
Chapter 2: Generating land cover specific parameter estimates of Gross Primary Productivity and Net Primary Productivity using MOD17

Section 2.1 Introduction

Tropical ecosystems have enormous potential to remove CO$_2$ from the atmosphere but this capacity is dependent on land management and usage (Houghton et al. 2015). To compare land management strategies in terms of carbon accumulation potential, or reduction in the case of deforestation, it is necessary to quantify the rates of accumulation for different land cover classes taking into account climatic influences (Waring & Running, 2007). Gross Primary Productivity (GPP) is the total amount of CO$_2$ fixed in an ecosystem during photosynthesis, typically expressed as Mg C ha$^{-1}$ yr$^{-1}$. On an annual time step, usually around 50% of GPP is lost to respiration, leaving Net Primary Production (NPP). NPP is the total amount of C fixed through photosynthesis that is not converted back to CO$_2$ during growth and maintenance respiration.

As part of DSS development for the stakeholders for the study area of this thesis, I sought to generate parameter estimates of GPP by land cover class and by environmental conditions as a method for quantifying and comparing land management options. With parameter estimates by land cover class, state and transition models can be developed to estimate the accumulation of carbon over time given different land management actions. These parameter estimates, and the modeled accumulation of carbon over time, can be used to evaluate the costs and benefits of different management actions in the study area if Hawai`i were to become part of the carbon credits program as described in Chapter 1. The process of generating these parameter estimates revealed that the MOD12Q1 land cover map was misaligned with the heterogeneous land cover of Hawai`i. Working with NTSG, a GPP models for Hawai`i was produced using Carbon Assessment of Hawai`i Land cover model (CAH-LC; Jacobi et al. CAH 2016) and local climate models. Comparisons of these local models with the publicly available MOD17 GPP model provides additional insight into the challenges of applying global models at the scale of an individual land owner (Turner et al. 2009; Shim et al. 2014; Gilabert et al. 2015).
Section 2.2 MOD17 GPP and NPP Model Overview

One of the most widely used spatially explicit models of global GPP is MOD17 maintained by **Numerical Terradynamic Simulation Group** (NTSG) at the University of Montana in Missoula (Running et al. 2004). The MOD17 algorithm uses the remotely sensed fraction of photosynthetically active radiation (fPAR) from the U.S. National Aeronautics and Space Administration (NASA) Earth Observing System (EOS). This fPAR data product (MOD15) is collected globally at a 1-km spatial resolution, and is multiplied by a model of photosynthetically active radiation (PAR) from NASA’s Global Modeling and Assimilation Office (GMAO) to calculate absorbed photosynthetically active radiation (APAR). APAR is then multiplied by a land cover specific radiation conversion efficiency factor that has been adjusted based on climatic factors, also from GMAO, to calculate GPP (Running & Zhao 2015). Data derived from GMAO PAR and climate models are collected at a spatial resolution of 0.5 Latitude degree by 0.67 Longitude degree.

NPP is derived by subtracting land cover specific growth and maintenance respiration terms using allometric equations relating remotely sensed leaf area index to annual growth (Running and Hunt 1993; White et al. 2000). For both GPP and NPP the spatial distribution of land cover classes is defined by MOD12Q1 using the University of Maryland land cover classification system (Friedl et al. 2010). Figure 2.1, adapted from the MOD17 user guide, diagrams the logic behind the MOD17 GPP/NPP algorithm (Running & Zhao 2015).
The MOD17 user guide states of MOD12Q1, “The importance of this product cannot be overstated as the MOD17 algorithm relies heavily on land cover type through use of the BPLUT”. BPLUT is the Biome Properties Look-Up Table. The first five variables from BPLUT shown in Table 2.1 are used to calculate GPP. These include; $\varepsilon_{\text{max}}$, the maximum radiation conversion efficiency for a given land cover class, $T_{\text{min}}$ and $T_{\text{min}}^{\text{max}}$ (C), the daily minimum air temperature at which $\varepsilon = \varepsilon_{\text{max}}$ or $\varepsilon = 0.0$ respectively, and $\text{VPD}_{\text{min}}$ (Pa) and $\text{VPD}_{\text{max}}$ (Pa) the daytime average vapor pressure deficit at which at which $\varepsilon = \varepsilon_{\text{max}}$ or $\varepsilon = 0.0$ respectively. These values have been established based on literature review and flux tower data (Running et al. 1994, Belward et al. 1999, Zhao et al. 2006; Friedl et al. 2010). MOD12Q1 is estimated to be 65-80% accurate with homogeneous landscapes represented more accurately than heterogeneous landscapes (Friedl et al. 2010).
Table 2.1. The five biome properties from the BPLUT used in the calculation of GPP shown for the main land cover classes found in Hawai`i; Evergreen Broad Leaf Forest (EBL), Closed Shrubland (CS), Open Shrubland (OS), Woody Savannah (WS) and Grassland (GL).

<table>
<thead>
<tr>
<th>MOD12Q1 Land Cover</th>
<th>EBL</th>
<th>CS</th>
<th>OS</th>
<th>WS</th>
<th>GL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{max}}$ (KgC/m²/day/MJ)</td>
<td>0.00127</td>
<td>0.00128</td>
<td>0.00084</td>
<td>0.00124</td>
<td>0.00086</td>
</tr>
<tr>
<td>$T_{\text{min},\text{min}}$ (°C)</td>
<td>-8</td>
<td>-8</td>
<td>-8</td>
<td>-8</td>
<td>-8</td>
</tr>
<tr>
<td>$T_{\text{min},\text{max}}$ (°C)</td>
<td>9.09</td>
<td>8.61</td>
<td>8.8</td>
<td>11.39</td>
<td>12.02</td>
</tr>
<tr>
<td>VPD_{min} (Pa)</td>
<td>800</td>
<td>650</td>
<td>650</td>
<td>650</td>
<td>650</td>
</tr>
<tr>
<td>VPD_{max} (Pa)</td>
<td>3100</td>
<td>4700</td>
<td>4800</td>
<td>3200</td>
<td>5300</td>
</tr>
</tbody>
</table>

Section 2.3 Methods

To generate parameter estimates of GPP by land cover class and moisture zone, a raster containing MOD17 modeled GPP estimates averaged from 2001-2010 was overlaid in ArcMap 10.2.2 (ESRI, Redlands, CA) with a the CAH-LC model and a rainfall model for the state of Hawai`i (Figure 2.2; Giambelluca et al. 2013; Jacobi et al. CAH 2016; Selmants, unpublished work). A 1-km fishnet was created over the main Hawaiian Islands and points were placed at the center of each grid, resulting in one point per MOD17 pixel. GPP values, land cover class and rainfall were extracted by point and the resulting distributions were evaluated in R 3.1.2 (2014).

Figure 2.2. Mean GPP model for Hawai`i Island based on the publically available MOD17 products averaged from 2002-2010 (left) and the CAH land cover map (right).
The distributions of GPP values by land cover class and moisture zone, and the spatial distribution of GPP estimates across the state, indicated that there was misalignment between the CAH-LC Model and MOD12Q1 used to estimate GPP in MOD17 (Figure 2.3). To determine the degree of misalignment between MOD12Q1 and CAH-LC, the Hawai`i specific land cover classes in CAH-LC were converted to one of the broader classes used in the MOD12Q1 classification scheme (J. Price, Pers. Comm.; Table 1.1). This revised CAH-LC was then resampled from 30-m to 500-m resolution in ArcMap 10.2.2. I created polygons for each of the five key land cover classes present in Hawai`i: evergreen broad leaf forest, grassland, closed shrubland, open shrubland and woody savannah. These polygons were then used to mask a MOD12Q1 raster that had been transformed from a custom sinusoidal projection to WGS_1984. I calculated the number of pixels per class that were identified as the same land cover class in both land cover products.

Table 2.2. The CAH-LC model vegetation types and the associated MOD12Q1 class designation: Closed Shrubland (CS), Evergreen Broad Leaf Forest (EBL), Grassland (GL), Open Shrubland (OS) and Woody Savannah (WS). Cropland and developed land cover classes were not included.

<table>
<thead>
<tr>
<th>CAH-LC Vegetation Type</th>
<th>General Community</th>
<th>MOD12Q1 Class</th>
<th>CAH-LC Vegetation Type</th>
<th>General Community</th>
<th>MOD12Q1 Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alien mesic shrubland</td>
<td>Alien Mesic Shrub</td>
<td>CS</td>
<td>Closed koa-ohia mesic forest</td>
<td>Native Mesic Forest</td>
<td>EBL</td>
</tr>
<tr>
<td>Alien wet shrubland</td>
<td>Alien Wet Shrub</td>
<td>CS</td>
<td>Open ohia mesic forest</td>
<td>Native Mesic Forest</td>
<td>EBL</td>
</tr>
<tr>
<td>Mixed native-alien mesic shrubs and grass</td>
<td>Mixed Mesic Shrub</td>
<td>CS</td>
<td>Native mesic to dry forest and shrubland</td>
<td>Native Mesic Forest</td>
<td>EBL</td>
</tr>
<tr>
<td>Mixed native-alien wet shrubs and grass/sedges</td>
<td>Mixed Wet Shrub</td>
<td>CS</td>
<td>Open koa-ohia mesic forest</td>
<td>Native Mesic Forest</td>
<td>EBL</td>
</tr>
<tr>
<td>Native mesic shrubland</td>
<td>Native Mesic Shrub</td>
<td>CS</td>
<td>Closed koa-ohia wet forest</td>
<td>Native Wet Forest</td>
<td>EBL</td>
</tr>
<tr>
<td>Open koa-ohia wet forest</td>
<td>Native Wet Forest</td>
<td>CS</td>
<td>Low stature ohia wet forest</td>
<td>Native Wet Forest</td>
<td>EBL</td>
</tr>
<tr>
<td>Native wet cliff community</td>
<td>Native Wet Shrub</td>
<td>CS</td>
<td>Open ohia wet forest</td>
<td>Native Wet Forest</td>
<td>EBL</td>
</tr>
<tr>
<td>Native wet shrubland</td>
<td>Native Wet Shrub</td>
<td>CS</td>
<td>Closed ohia wet forest</td>
<td>Native Wet Forest</td>
<td>EBL</td>
</tr>
<tr>
<td>Uluhe ferns and native shrubs</td>
<td>Native Wet Shrub</td>
<td>CS</td>
<td>Alien dry grassland</td>
<td>Alien Dry Grassland</td>
<td>GL</td>
</tr>
<tr>
<td>Alien dry forest</td>
<td>Alien Dry Forest</td>
<td>EBL</td>
<td>Alien mesic grassland</td>
<td>Alien Mesic Grassland</td>
<td>GL</td>
</tr>
<tr>
<td>Alien mesic forest</td>
<td>Alien Mesic Forest</td>
<td>EBL</td>
<td>Alien wet grassland</td>
<td>Alien Wet Grassland</td>
<td>GL</td>
</tr>
<tr>
<td>Plantation forest</td>
<td>Alien Tree Plantation</td>
<td>EBL</td>
<td>Native Deschampsia grassland</td>
<td>Native Mesic Grassland</td>
<td>GL</td>
</tr>
<tr>
<td>Alien wet forest</td>
<td>Alien Wet Forest</td>
<td>EBL</td>
<td>Alien dry shrubland</td>
<td>Alien Dry Shrub</td>
<td>OS</td>
</tr>
<tr>
<td>Mixed native-alien dry forest</td>
<td>Mixed Dry Forest</td>
<td>EBL</td>
<td>Mixed native-alien dry cliff community</td>
<td>Native Dry Shrub</td>
<td>OS</td>
</tr>
<tr>
<td>Mixed native-alien mesic forest</td>
<td>Mixed Mesic Forest</td>
<td>EBL</td>
<td>Native dry shrubland</td>
<td>Native Dry Shrub</td>
<td>OS</td>
</tr>
<tr>
<td>Mixed native-alien wet forest</td>
<td>Mixed Wet Forest</td>
<td>EBL</td>
<td>Coastal strand vegetation</td>
<td>Native Mesic Shrub</td>
<td>OS</td>
</tr>
<tr>
<td>Closed ohia dry forest</td>
<td>Native Dry Forest</td>
<td>EBL</td>
<td>Very sparse vegetation to unvegetated</td>
<td>Bare</td>
<td>UV</td>
</tr>
<tr>
<td>Open ohia dry forest</td>
<td>Native Dry Forest</td>
<td>EBL</td>
<td>Kawe dry forest and shrubland</td>
<td>Alien Dry Forest</td>
<td>WS</td>
</tr>
<tr>
<td>Closed ohia mesic forest</td>
<td>Native Mesic Forest</td>
<td>EBL</td>
<td>Mixed mamane-naio native trees dry woodland</td>
<td>Native Dry Forest</td>
<td>WS</td>
</tr>
<tr>
<td>Closed hala forest</td>
<td>Native Mesic Forest</td>
<td>EBL</td>
<td>Open koa-mamane dry forest</td>
<td>Native Dry Forest</td>
<td>WS</td>
</tr>
</tbody>
</table>
Figure 2.3. The MOD12Q1 (left) and CAH-LC (right) land cover models for Hawai`i showing the differences in the spatial distribution of land cover classes.

Based on the results of the land cover comparison, two new GPP models for Hawai`i were requested from NTSG, one including local climate models and another with local climate models and the CAH-LC model. The publicly available MOD17 GPP product was then compared with these two models, and each other, to determine the influence of local climate models and local land cover models on statewide estimates of annual GPP. The GBC+GBL model is the publicly available annual MOD17 product averaged from 2002-2010. GBC+GBL uses MOD12Q1 and global PAR and climate models from GMAO. A second model (HIC+GBL) resulted from a special MOD17 run that used MOD12Q1 and local models for annual vapor pressure deficit, average air temperature, minimum air temperature, maximum temperature, rainfall, and solar radiation in place of climate inputs and PAR from the GMAO models (Giambelluca et al. 2013, Giambelluca et al. 2014). HIC+GBL also includes a Version 6 fAPAR product specifically adapted with quality filtering and gap-filling techniques, using 12 years of MOD15 data (Moreno et al. 2014). The adapted fAPAR product, at 500-meter resolution, enables the model to account for the high occurrence of clouds in some areas of Hawai`i. A third model (HIC+HIL), also produced by with a special MOD17 run uses the local climate data, the gap-filled fAPAR as described above, and the revised CAH-LC as the land cover model.
Total state-wide annual GPP per model was compared in ArcMap 10.2.2 using the point sampling method previously described except that a 1-km fishnet was used for GBC+GBL and 500-m fishnets were used for HIC+GBL and HIC+HIL. GPP values were extracted by point, summed and multiplied by the appropriate area to calculate total annual GPP. Land cover class from the revised CAH-LC was also extracted to each point and was used to calculate total annual GPP by land cover class and by model. I excluded points without an assigned land cover class in CAH-LC. To compare the spatial differences between the three models, I used 500-m fishnets and points. The differences in GPP by point were calculated between GBC+GBL and HIC+GBL, between GBC+GBL and HIC+HIL and between HIC+GBL and HIC+HIL. The differences were plotted in R 3.1.2 (2014), compared to no difference using a 1-sample t-test, and mapped in ArcMap 10.2.2.

Using the HIC+HIL model point sampling data set, I plotted density distributions of GPP values by mean annual temperature, mean annual rainfall and solar radiation for each land cover class in R 3.1.2 (Giambelluca et al. 2013, Giambelluca et al. 2014; Figure 2.4). Based on these density plots, none of these factors alone showed a linear relationship to GPP. I also found no relationship between elevation and soil age with GPP by land cover class (Gesch et al. 2002, Trusdell et al. 2006). This indicated that both the factors and interactions between factors contribute to GPP values. Therefore, to establish parameter estimates for GPP by land cover class, I first partitioned the point sampling data into the current mean annual temperature range for my study area (7.8-13.5 C) and the projected future annual temperature range (11.2-16.9 C; Fortini et al. CAH 2016). These data sets were further partitioned by rainfall in 500 mm increments from 500 mm (dry) to 3000 mm (wet). In some cases, these subsets still did not show a normal distribution of GPP values. I partitioned them further based on soil age class and elevation and found that this did not improve the distributions. The distribution of GPP by solar radiation was evaluated to determine if it was the driving factor for GPP by land cover class. Solar radiation was not used as a partitioning factor because predictions of future solar radiation are not possible. Parameter estimates were generated for GPP by land cover class based on temperature and rainfall alone, with the understanding that some estimates are based on non-normal distributions and may require further analysis.
Figure 2.4. Density plots for each land cover class by rainfall, temperature and solar radiation. Plot densities are relative to each class; Closed Shrubland (CS) n=3885, Evergreen Broad Leaf Forest (EBL) n=11087, Grassland (GL) n=7867, Open Shrubland (OS) n=2398 and Woody Savannah (WS) n=716.
To establish NPP estimates from HIC+HIL modeled GPP, a Carbon Use Efficiency (CUE) multiplier had to be derived for each land cover class. NTSG produced a NPP model for Hawai`i based on HIC+HIL modeled GPP values using MOD12Q1 for estimates of LAI and land cover class specific respiration. NTSG does not maintain this portion of the MOD17 NPP modeling process; therefore, it was not possible to substitute the revised CAH-LC for MOD12Q1 to model NPP. We determined that it would be best to use a land cover specific CUE multiplier with the HIC+HIL GPP model to produce statewide estimates of NPP. To determine CUE by land cover class, NPP was sampled from the model produced by NTSG using the same 500-m point method previously described. In addition to NPP, HIC+HIL GPP, MOD12Q1 and CAH-LC values were also extracted. All points where MOD12Q1 and CAH-LC did not match were removed and CUE was calculated with the remaining points by dividing NPP by GPP. These CUE values for each land cover class were then multiplied by the HIC+HIL GPP model values to produce a new spatial NPP model.

Section 2.4 Results

2.4.1 MOD12Q1 and CAH-LC Comparison

Analysis of the alignment between MOD12Q1 and CAH-LC showed an overall agreement of 46% with evergreen broad leaf forest having the greatest agreement at 80%, and closed shrubland and woody savannah having the least agreement, each at 10% (Table 2.3). In terms of total coverage area, closed shrubland area is more than double in CAH-LC than in MOD12Q1. Woody savannah is greater by ~50% and grassland by ~25% between MOD12Q1 and CAH-LC, while coverage areas for evergreen broad leaf forest and open shrubland are lower by 30% and 50% respectively (Figure 2.5).
Table 2.3. MOD12Q1 and CAH-LC alignment matrix. The CAH-LC classes are shown in rows. For each row the percentage of pixels from the MOD12Q1 classification is shown in columns. Percentages on the diagonal in grey represent the percent of pixels aligned between the two models. Closed Shrubland (CS), Evergreen Broad Leaf Forest (EBL), Grassland (GL), Open Shrubland (OS) and Woody Savannah (WS). Other includes classes not included in this study: cropland, developed and un-vegetated.

<table>
<thead>
<tr>
<th>CAH-LC</th>
<th>MOD12Q1 Land Cover Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>10 46 12 12 6 14</td>
</tr>
<tr>
<td>EBL</td>
<td>5  80  4  3  2  6</td>
</tr>
<tr>
<td>GL</td>
<td>7  19 40 15 4 15</td>
</tr>
<tr>
<td>OS</td>
<td>21 15 15 43 1 5</td>
</tr>
<tr>
<td>WS</td>
<td>11 21 21 15 10 16</td>
</tr>
</tbody>
</table>

Figure 2.5. Relative coverage area state wide by land cover class between MOD12Q1 and CAH-LC. Closed Shrubland (CS), Evergreen Broad Leaf Forest (EBL), Grassland (GL), Open Shrubland (OS) and Woody Savannah(WS).

2.4.2 GPP Model Comparisons

Statewide, both HIC+GBL and HIC+HIL both were roughly 10% lower in total carbon utilized through GPP per year as compared to GBC+GBL (Figures 2.6 & 2.7). The mean difference in GPP between GBC+GBL and HIC+GBL, taking spatial distribution into account, was -0.191 (95% CI +/- 0.006) kg C m⁻² y⁻¹, while the mean difference between GBC+GBL and HIC+HIL was -0.183 (95% CI +/- 0.007) kg C m⁻² y⁻¹ (Figure 2.8). The difference between HIC+GBL and HIC+HIL was irregular with an
overwhelming spike at zero, the mean difference was -0.007 (95% CI +/- 0.003) kg C m\(^{-2}\) y\(^{-1}\). All mean differences were shown to be significantly different from zero.

Figure 2.6. Statewide annual carbon assimilation estimated from each GPP model in Tg C y\(^{-1}\).

Figure 2.7. GPP Distribution by model.
Figure 2.8. Distribution of differences between GPP models on a point by point basis. All differences were shown to be significantly different from zero:  

\[(GBC+GBL)-(HIC+GBL) t = 34.623, df = 6541, p-value < 2.2e-16,\]  

\[(GBC+GBL)-(HIC+HIL) t = 33.9744, df = 6541, p-value < 2.2e-16\]  

and  

\[(HIC+HIL)-(HIC+GBL) t = 2.9238, df = 6541, p-value = 0.00347.\]

The mean differences between models were all significantly different from zero. The impact of the land cover model on total carbon utilized through GPP per year between HIC+GBL and HIC+HIL was not substantial at the state level, however, there are distinct differences between the two models when considering carbon utilized per year by land cover class. Evergreen broad leaf forest, which had an 80% agreement between the two land cover models, showed only a 3% higher Tg C y\(^{-1}\) contribution in HIC+HIL and very similar distributions between HIC+GBL and HIC+HIL (Figures 2.9 & 2.10). Closed shrubland and woody savannah each showed approximately 10% higher Tg C y\(^{-1}\) contribution in HIC+HIL compared to HIC+GBL, while grassland and open shrubland each showed about 20% lower contribution of Tg C y\(^{-1}\) in HIC+HIL compared to HIC+GBL. The distributions of GPP for grassland, open shrubland and woody savannah also showed distinct differences between models (Figure 2.10; c, d, e).
Figure 2.9. The differences in total annual carbon usage by land cover class based on the three GPP model estimates.
Figure 2.10. The distributions of annual GPP by land cover class.
2.4.3 GPP and NPP parameter estimates

Parameter estimates for GPP by land cover class are shown in Table 2.4. For closed shrubland, evergreen broad leaf forest and grassland there is a trend toward increased productivity in the higher temperature range. There is also a trend of increased productivity with increased rainfall, as well as an increase in variability. open shrubland and woody savannah did not have enough values in many of the rainfall subsets to establish parameter estimates and evaluate trends. CUE values to convert these GPP estimates to NPP are shown in Table 2.5. Based on the distribution of CUE values the medians were used to calculate NPP from HIC+HIL GPP.

Table 2.4. GPP parameter estimates by land cover class in kg C m$^{-2}$ y$^{-1}$ (* indicated estimates that were taken from distributions that had more than one peak, ~ indicates data subsets with fewer than n=10 samples).

<table>
<thead>
<tr>
<th>Land Cover</th>
<th>Current Temp</th>
<th>Projected Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>stdev</td>
</tr>
<tr>
<td>CS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500-1000 mm</td>
<td>0.93</td>
<td>0.30</td>
</tr>
<tr>
<td>1000-1500 mm</td>
<td>~</td>
<td></td>
</tr>
<tr>
<td>1500-2000 mm</td>
<td>0.82</td>
<td>0.35</td>
</tr>
<tr>
<td>2000-2500 mm</td>
<td>1.01</td>
<td>0.47</td>
</tr>
<tr>
<td>2500-3000 mm</td>
<td>1.40*</td>
<td>0.82</td>
</tr>
<tr>
<td>EBL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500-1000 mm</td>
<td>1.13</td>
<td>0.43</td>
</tr>
<tr>
<td>1000-1500 mm</td>
<td>~</td>
<td></td>
</tr>
<tr>
<td>1500-2000 mm</td>
<td>0.70</td>
<td>0.23</td>
</tr>
<tr>
<td>2000-2500 mm</td>
<td>1.31</td>
<td>0.50</td>
</tr>
<tr>
<td>2500-3000 mm</td>
<td>2.47</td>
<td>0.60</td>
</tr>
<tr>
<td>GL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500-1000 mm</td>
<td>0.82</td>
<td>0.18</td>
</tr>
<tr>
<td>1000-1500 mm</td>
<td>0.70</td>
<td>0.21</td>
</tr>
<tr>
<td>1500-2000 mm</td>
<td>0.90*</td>
<td>0.21</td>
</tr>
<tr>
<td>2000-2500 mm</td>
<td>1.09</td>
<td>0.24</td>
</tr>
<tr>
<td>2500-3000 mm</td>
<td>1.31*</td>
<td>0.20</td>
</tr>
<tr>
<td>OS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500-1000 mm</td>
<td>0.48</td>
<td>0.18</td>
</tr>
<tr>
<td>1000-1500 mm</td>
<td>0.42</td>
<td>0.18</td>
</tr>
<tr>
<td>WS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1500-2000 mm</td>
<td>1.50</td>
<td>0.18</td>
</tr>
</tbody>
</table>
Based on the finding that there was only a 46% alignment between MOD12Q1 and CAH-LC, I had expected that changing the land cover model in MOD17 would result in a substantial difference in the distribution of GPP values. However, the results of this study clearly indicate that local climate models have a greater impact on GPP estimates than the land cover model at the statewide level. While the difference in GPP values are slightly greater between GBC+GBL and HIC+GBL than between GBC+GBL and HIC+HIL (Figures 2.11 and 2.12), the spatial distribution of these differences is similar across comparisons. In both cases, there is a reduction in GPP estimates statewide of ~10%. The spatial distribution of these reductions in GPP are aligned with areas with lower solar radiation (Giambelluca et al. 2014; Figure 2.13). This indicates that the calculation of APAR using local climate data may be the primary driver of the differences in GPP estimates between models even though the density plots of GPP by solar radiation show that this factor alone cannot be used to predict GPP values (Figure 2.4).

### Table 2.5. Parameter estimates for CUE based on land cover class.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>+/-</th>
<th>Median</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>0.544</td>
<td>0.073</td>
<td>0.545</td>
<td>80</td>
</tr>
<tr>
<td>EBL</td>
<td>0.486</td>
<td>0.056</td>
<td>0.495</td>
<td>8188</td>
</tr>
<tr>
<td>GL</td>
<td>0.484</td>
<td>0.068</td>
<td>0.485</td>
<td>2411</td>
</tr>
<tr>
<td>OS</td>
<td>0.501</td>
<td>0.055</td>
<td>0.484</td>
<td>1123</td>
</tr>
<tr>
<td>WS</td>
<td>0.464</td>
<td>0.076</td>
<td>0.476</td>
<td>85</td>
</tr>
</tbody>
</table>
Figure 2.11. Difference in GPP estimates between the GBC+GBL and HIC+GBL statewide.

Figure 2.12. Difference in GPP estimates between the GBC+GBL and HIC+HIL models statewide.
The contribution to total estimated carbon assimilation through GPP by land cover class did show differences using the local land cover model. In this case, there was no apparent pattern to the spatial distribution of these differences other than areas on Hawaii Island where grassland had been classified as evergreen broadleaf forest in MOD12Q1 (Figure 2.14). The largest difference in carbon assimilated through GPP between HIC+GBL and HIC+HIL was for grassland, which had a ∼23% reduction in Tg C yr⁻¹ (Figure 2.9). One third of grassland was classified as closed shrubland, evergreen broad leaf forest or woody savannah in MOD12Q1. These three vegetation classes have a maximum radiation conversion efficiency roughly 1.5 times that of grassland (Table 2.1). This difference in land cover distribution and the associated radiation conversion efficiency terms used in MOD17 explain the irregular distributions of GPP in my original analysis which lead to the evaluation of the MOD12Q1 land cover model.
The production of the HIC+HIL GPP model enabled the generation of parameter estimates for GPP by vegetation class, when estimates were also partitioned by rainfall and temperature. In general, these estimates showed a trend of increased GPP with both increased rainfall or increased temperature, which is consistent with previous studies (Zhang et al. 2009). Not surprising, variability in these estimates also increased. These estimates will be used in the state and transition model and having the estimates subset by rainfall and temperature will allow for the model to account for the effects of climate change on GPP within the study area.

This study highlights the resolution issues associated with using global data products at a local scale particularly in highly heterogeneous landscapes. GPP can be measured at the plot level with flux tower data. There are three flux towers in Hawai`i but data from these towers have not been published nor would three plots be representative of the diversity of climate and land cover in the state. Previous studies have shown that the specificity of the local climate and land cover models result in improved estimates of GPP (Turner et al. 2009; Shim et al. 2014; Gilabert et al. 2015). As a result of this study
statewide estimates of GPP and NPP from the HIC+HIL model will be made available to the public as part of the Carbon Assessment of Hawai`i (Selmants et al. CAH 2016; Figures 2.15 & 2.16). The NPP values will be used in state and transition modeling, described in Chapter 4, to project carbon accumulation over time. These projections can then be used to valuate different management scenarios for the study area with respect to carbon credits.

Figure 2.15. Hawai`i GPP Model based on HIC+HIL.
Figure 2.16. Hawai‘i NPP Model based on HIC+HIL and the CUE multipliers from this study.
Chapter 3: Using high resolution satellite imagery and phenology to determine the distribution of *Ulex europaeus* on Hawai`i Island

Section 3.1 Introduction

Hawaii’s dry and mesic subalpine forests are vital to watershed health and as a habitat for rare native flora and fauna (Banko et al. 2014; DLNR 2015). The primary threats to this habitat are land conversion for human use, fire, non-native browsing fauna and invasive plant species (Cabin et al. 2000; Motooka et al. 2003; Elmore et al. 2005; Hess & Banko 2011). In particular, the subalpine dry and mesic forest habitat on the eastern side of Hawai`i Island has been decimated by a century of grazing by feral ungulates and the invasive shrub *Ulex europaeus* (gorse; Motooka et al. 2003; Nogueira-Filho et al. 2009). Gorse is a branched, spiny shrub of the Fabaceae family that was introduced to Hawai`i in the late 1800s from Western Europe where it is considered useful as a hedge plant and animal fodder. Gorse was identified as a noxious weed in Hawai`i in the early 1900s and is considered one of the world’s 100 worst invasive species (Invasive Species Specialist Group, Species Survival Commission, International Union for Conservation of Nature 2013). On Hawai`i Island, the gorse infestation was estimated in 2011 to cover a core area of ~2,000 hectares and an additional 10,000 hectares of scattered growth in the Humu`ula ahupua`a on the border with Pi`ihonua (Markin & Conant 2011; Figure 3.1).
Figure 3.1. The location of the core gorse population within the study area with respect to the Humu`ula and Pi`ihonua ahupua`a on the east side of Hawai`i Island (19°46’32 N, 155°22’44 W). The hatched area indicates area covered by 2012/2013 imagery (the `Āina Mauna Legacy Plan study area) and crosshatched area indicates the overlapping coverage of the 2015 imagery used in this study.

Gorse thrives in degraded and disturbed landscapes such as the former pasture land in Humu`ula. Gorse grows in extremely dense thickets, measured in Hawai`i at a density of ~60,000 stems/hectares (Cuddihy & Stone 1990). It has an extensive mat root system usually found within the first 10 cm of soil with a tap root growing to depths of 30 cm or more. This root system has nitrogen-fixing nodules, and additional roots grow from the lower branches (Coombs et al. 2004). Pea-like flowers, which develop within the second or third year of growth, are insect pollinated. In Humu`ula the main flowering event occurs in late January through early February, and there is often a second, less abundant flowering in early fall (Figure 3.2). Some gorse seeds are distributed by feral ungulates, insects, streams and gusting winds. However, most seeds fall to the ground below the parent plant and become part of the seed bank. Annual seed production of dense gorse thickets is estimated at ~2,000 seeds/m²/year (Hill et al. 1996). These seeds can lie dormant in the soil for 30-70 years, resulting in tens of thousands of seeds/m² in
the seed bank (Hill et al. 1996; Hill et al. 2001). Gorse seeds require scarification or heat to geminate and generally do not sprout under dense gorse thickets. After removal of the adult gorse, seedlings have also been shown to be inhibited in the presence of more competitive pasture grasses and sedges (Richardson & Hill 1998). Gorse seedlings are shade intolerant at light levels of less than 10% (DiTomaso 1998; Perry 2010). Gorse is "pyrophytic" and has a high concentration of oils in its leaves and stems. Gorse thickets are highly flammable and will burn quickly and intensely. In addition to preventing recruitment of native species, the gorse in the Humuʻula area presents a serious fire risk.

![Figure 3.2. Images from gorse flowering in Humuʻula, February 2016.](image)

A decision support system for the Department of Hawaiian Home Lands (DHHL) study area would be incomplete without an accurate model of the current spatial distribution of gorse. The `Āina Mauna Legacy Program (AMLP; DHHL 2009) proposes initial containment of gorse to the core population area. The main concern of the stakeholders with respect to gorse is containing the core population and preventing further expansion. This includes preventing expansion downslope (east) of the core population. Therefore, the study area for this particular portion of my thesis extends beyond the eastern boundary of the AMLP study area.

The land cover model created as part of the Carbon Assessment of Hawaii (CAH-LC), introduced in the previous chapter, is a substantial improvement in land cover modeling for the state. However, it does not have the spatial resolution to address the stakeholder requirements. Identifying small, accessible, incipient populations of gorse outside of the core area would allow managers to prioritize treatment locations. The
AMLP proposes eventual eradication of the entire core gorse population. With a better estimate of the current size of this core population, cost estimates could be calculated for various treatment options. A highly resolved and current land cover model for the AMLP study area is also required as the starting point for additional DSS layer development and state and transition modeling described in Chapter 4. Michez et al. 2016 found that a combination of phenology and remotely sensed imagery could be used to detect individual plant species with a high degree of accuracy. Given the seasonal and prolific flowering of gorse, I sought to determine if using gorse phenology would improve the ability to create an accurate footprint for this area using the highest resolution imagery available.

Section 3.2 Methods

3.2.1 Evaluation of the CAH Land Cover Model for the study area

To evaluate the accuracy of the CAH-LC for the study area, I compared it to a mosaic DigitalGlobe (Westminster, CO) WorldView-2 satellite image from 2013-2013 provided by the USDA NRCS – National Geospatial Center of Excellence. I created a 500 m grid over the study area and placed a point in the center of each grid cell, resulting in 912 points (Figure 3.3). Using the WorldView-2 two image and field knowledge of the study area, I determined at each point location if the CAH-LC map had correctly identified the land cover class. Values of zero or one for correct and incorrect were assigned to each point and then interpolated across the study area using inverse distance weighting (Tobler 1970).
3.2.2 2015 WorldView-2 imagery acquisition

2015 WorldView-2 satellite imagery from DigitalGlobe was provided by the USDA NRCS – National Geospatial Center of Excellence from February, May, and November. I requested imagery from NRCS for an area that included the core population and the surrounding area where gorse was suspected to be expanding. This included the area downslope and outside of the AMLP study area on the eastern side (Figure 3.1). I excluded portions of the AMLP study area where gorse had not been observed. The excluded areas were the higher elevation portion the AMLP study area and southern portion south of Saddle Road. The previously mentioned mosaic WorldView-2 image from 2012-2013 was then used to cover the portion of the AMLP study area not included in the 2015 imagery for the final land cover model. Using this older imagery along with the 2015 imagery also allowed to me quantify the change in the extent of the core population over this short time period (Figure 3.4).
Figure 3.4. WorldView-2 imagery from the study area in the Humu‘ula and Pi‘ihonua ahupua‘a on the east side of Hawai‘i Island (19°46’32 N, 155°22’44 W). The image on the left is a mosaic from 2012-2013. The image on the right is from November 2015. Note the expansion of gorse that has occurred in the orange circles and areas where treatment has taken place in the yellow boxes.

WorldView-2 imagery is comprised of eight multispectral bands with 2 m spatial resolution (Table 3.1). The images for the study area were converted from 11-bit color to 8-bit color, radiometrically and atmospherically calibrated, and rescaled through a Dynamic Range Adjustment (DRA) by DigitalGlobe. WorldView-2 imagery is collected with a panchromatic p band at 0.4 m resolution. The images from 2015 were processed in ERDAS Imagine 2014 and both georectified and pan sharpened to 0.4m resolution using the Pan Sharpen HPF Resolution Merge program by NRCS. The 2013-2013 image was not pan sharpened. The February 2015 image was taken during flowering, and the yellow flowers are clearly visible in the imagery to the unaided eye (Figure 3.5). In the May and November 2015 images, the gorse is a more typical dark green. Since these later images were fairly similar and the image from November 2015 had less cloud cover, only the November image was used for comparison to the image from February 2015.
Table 3.1. The eight spectral bands and wavelengths (nm) available from DigitalGlobe’s WorldView-2 imagery.

<table>
<thead>
<tr>
<th>Band #</th>
<th>Band Name</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1</td>
<td>costal blue</td>
<td>400-450</td>
</tr>
<tr>
<td>Band 2</td>
<td>blue</td>
<td>450-510</td>
</tr>
<tr>
<td>Band 3</td>
<td>green</td>
<td>510-581</td>
</tr>
<tr>
<td>Band 4</td>
<td>yellow</td>
<td>585-625</td>
</tr>
<tr>
<td>Band 5</td>
<td>red</td>
<td>630-690</td>
</tr>
<tr>
<td>Band 6</td>
<td>red-edge</td>
<td>705-745</td>
</tr>
<tr>
<td>Band 7</td>
<td>NIR-1</td>
<td>770-895</td>
</tr>
<tr>
<td>Band 8</td>
<td>NIR-2</td>
<td>860-1040</td>
</tr>
</tbody>
</table>

Figure 3.5. WorldView-2 imagery from a portion of the core gorse population in the Humu`ula and Pi`ihonua ahupua`a on the east side of Hawai`i Island (19°46’32 N, 155°22’44 W) from February, 2015 (left) and November, 2015 (right).
3.2.3 Spatial Analysis

The images from February and November 2015 and from 2012-2013 were used to generate supervised land cover classifications of the core gorse population and the surrounding areas. Supervised classifications require the selection of training data from the imagery to establish the spectral signatures of each land cover class. I identified four key land cover classes for the study area: mixed forest/shrubland (labeled forest), gorse, grass and barren. I created regions of interest (ROIs) in ENVI 5.3.1 (Exelis, Boulder, CO) of roughly 20 hectares for each land cover class. I created additional accuracy assessment ROIs totaling about 10 hectares per land cover class (Table 3.2). ROIs were rectangular and sized between 0.15-0.10 hectares. The suggested minimum area for training ROIs to produce a high quality classification is 16 acres (640,000 pixels at 0.4 m resolution) with an equal number of pixels representing each land cover class and with several small ROIs rather than a few large ROIs (Joyce 1978: Campbell 1981). I generated the spectral distributions for each land cover types to determine if there was enough variation between land cover types to perform a supervised classification.

Table 3.2. Training and Accuracy Assessment Regions of Interest (ROIs) area and pixel counts.

<table>
<thead>
<tr>
<th>Class</th>
<th>Hectares</th>
<th>Pixels (0.4 m)</th>
<th>Pixels (2 m)</th>
<th>Class</th>
<th>Hectares</th>
<th>Pixels (0.4 m)</th>
<th>Pixels (2 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barren</td>
<td>20.79</td>
<td>1,263,233</td>
<td>51,979</td>
<td>Barren</td>
<td>10.34</td>
<td>616,450</td>
<td>25,838</td>
</tr>
<tr>
<td>Forest</td>
<td>20.27</td>
<td>1,153,574</td>
<td>50,686</td>
<td>Forest</td>
<td>10.23</td>
<td>592,300</td>
<td>25,573</td>
</tr>
<tr>
<td>Gorse</td>
<td>20.19</td>
<td>1,185,841</td>
<td>50,463</td>
<td>Gorse</td>
<td>10.03</td>
<td>582,531</td>
<td>25,069</td>
</tr>
<tr>
<td>Grass</td>
<td>20.34</td>
<td>1,190,318</td>
<td>50,862</td>
<td>Grass</td>
<td>10.18</td>
<td>580,599</td>
<td>25,442</td>
</tr>
</tbody>
</table>

Classifications were performed in ENVI using the maximum likelihood algorithm (Richards 1999). The maximum likelihood algorithm assumes a normal distribution for each band, and classifications are based on the probability that a given pixel belongs in a given class. Pixels are assigned to the class with the highest probability. The maximum likelihood classifications were performed with a minimum 0.25 probability threshold. Classifications were performed once using all bands and again using a subset of bands 3,
I performed an accuracy assessment of the classification using the accuracy assessment ROIs and a confusion matrix to generate overall accuracy, kappa coefficient, and user and producer accuracies.

### 3.2.4 Final Land Cover Model Production

To produce the final classification data layer for future DSS development, I created a mosaic of the 2015 classification with portions of the 2012-2013 classification to cover the entire study area (Figure 3.6). The 2015 imagery was first resampled to 2 m resolution in ENVI 5.3.1 using majority analysis. In majority analysis, the classification of the larger pixel is determined by the most frequent class of 0.4 m pixels encompassed in the 2 m pixel. The mosaic, or joining process, was performed in ArcMap 10.2.2 with precedence given to the more current 2015 classification where the two images overlapped. I used reclassification to convert forest pixels to shrubland where shrubland is visible on the imagery and based on site visits to the area. I also resampled the final image to 30 m resolution in ArcMap 10.2.2 using the majority method to match the resolution of other data layers that will be used for the development of additional models for a study area DSS.

![Flow chart showing the process for creating a final land cover model for the study area using multiple data sources.](image)

**Figure 3.6.** Flow chart showing the process for creating a final land cover model for the study area using multiple data sources.

### Section 3.3 Results

I found that the CAH-LC was 86.2% correct as compared to the 2012-2013 WorldView-2 image (Figure 3.7). This is more accurate than previous studies have found
for the US Geological Survey’s Gap Analysis Program Land Cover Model (70-75%; Zhu et al. 2000; Nusser & Klaas 2003). The error occurs in specific locations in the CAH-LC and can be explained either by the rate of gorse expansion or by the resolution of topographical features. 64.3% of the error can be attributed to expansion of the core gorse population. The error in the upper east portion can be explained by a fire that occurred in 2007 that converted forest to grassland. The remaining areas of error are due to vegetated areas interspersed with either barren cinder cones or lava flows.

Figure 3.7. Interpolated CAH-LC error map of the study area based on the point sampling comparison of the WorldView-2 imagery and the CAH Land Cover Model.

Comparing the mean values by spectral band for each land cover class between February and November 2015 shows that the grass and barren classes have distinctly different signatures across all bands compared to gorse and forest (Figure 3.8). It also shows that, in the visible spectrum (bands 1-5), gorse and forest have very similar mean values in November while they diverge in bands 6-8. In contrast, the mean values from February show a greater separation between gorse and forest in bands 3, 4 and 5 and
show the same level of divergence in bands 6-8. It is important to note that because the images from February and November went through DRA independently, a comparison of the relative mean values between data sets in not meaningful. The distributions of data values for each spectral band and land cover classes are shown in Figures 3.9.

![Figure 3.8. Mean spectral values by vegetation type by wavelength. Note the increased differences in means between 500 nm and 625 nm in February (F) as compared to November (N).](image-url)
Figure 3.9. Data value histograms for Band 1-8 (top to bottom) from the February (left) and November (right) imagery for vegetation classes forest, grass and gorse.
The distinction between the distributions of data values for bands 3, 4 and 5 in February 2015 resulted in this data set generating the best classified image, with an overall accuracy of 98% (Table 3.3; Figure 3.10). The November and 2012-2013 imagery had overall accuracies of 96% and 95% respectively. The two most similar land cover classes based on the spectral signatures are gorse and forest. The User accuracy was 95.1% for gorse and 95.7% for forest in the February 2015 image and in the confusion matrix we see that gorse is most often misclassified as forest and vice versa (Table 3.4). The user accuracies for gorse and forest were ~2-3% lower in the November 2015, 92.3% and 94.0%. The 2012-2013 user accuracies for gorse and forest were ~4-6% lower than the February 2015 image. The classified final images are shown in Figure 3.10.

Reviewing these classified images with the stakeholders and based on my field observations at the site, the misclassified pixels are most likely in the western, upslope portion of the study area. This area falls just outside the climate envelope in which gorse thrives based on a combination of moisture zone (mesic) and minimum temperature (2 degrees C) requirements (Richardson 1998; Giambelluca et al. 2013; Fortini et al. CAH 2016). The dominant shrub in this area is mamane (Sophora chrysophylla). Mamane is also a nitrogen fixing plant that produces yellow flowers, which may explain the gorse designation in the classification.

Table 3.3. Producer and user accuracies by land cover class, overall accuracy and Kappa coefficient for each classified image.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gorse</td>
<td>95.6</td>
<td>95.1</td>
<td>94.4</td>
<td>92.3</td>
<td>93.4</td>
<td>89.2</td>
</tr>
<tr>
<td>Grass</td>
<td>99.8</td>
<td>99.9</td>
<td>98.8</td>
<td>99.3</td>
<td>96.9</td>
<td>99.1</td>
</tr>
<tr>
<td>Forest</td>
<td>95.3</td>
<td>95.7</td>
<td>92.6</td>
<td>94.0</td>
<td>88.9</td>
<td>90.8</td>
</tr>
<tr>
<td>Barren</td>
<td>99.7</td>
<td>100.0</td>
<td>99.9</td>
<td>100.0</td>
<td>99.2</td>
<td>99.7</td>
</tr>
<tr>
<td>Overall</td>
<td>98%</td>
<td></td>
<td>96%</td>
<td></td>
<td>94%</td>
<td></td>
</tr>
<tr>
<td>Kappa Coefficient</td>
<td>0.9683</td>
<td></td>
<td>0.9525</td>
<td></td>
<td>0.9281</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.4. Confusion matrix (in percent) for the February 2016, November 2016 and 2012-2013 WorldView-2 imagery using all bands and the maximum likelihood algorithm with 25% probability threshold.

<table>
<thead>
<tr>
<th>Class</th>
<th>Ground Truth (percent)</th>
<th>Gorse</th>
<th>Grass</th>
<th>Forest</th>
<th>Barren</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unclassified</td>
<td></td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Gorse</td>
<td></td>
<td>95.6</td>
<td>0.2</td>
<td>4.7</td>
<td>0.0</td>
<td>24.7</td>
</tr>
<tr>
<td>Grass</td>
<td></td>
<td>0.1</td>
<td>99.8</td>
<td>0.0</td>
<td>0.0</td>
<td>24.5</td>
</tr>
<tr>
<td>Forest</td>
<td></td>
<td>4.3</td>
<td>0.0</td>
<td>95.3</td>
<td>0.1</td>
<td>24.9</td>
</tr>
<tr>
<td>Barren</td>
<td></td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>99.7</td>
<td>25.9</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class</th>
<th>Ground Truth (percent)</th>
<th>Gorse</th>
<th>Grass</th>
<th>Forest</th>
<th>Barren</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unclassified</td>
<td></td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Gorse</td>
<td></td>
<td>94.4</td>
<td>0.8</td>
<td>6.9</td>
<td>0.0</td>
<td>25.1</td>
</tr>
<tr>
<td>Grass</td>
<td></td>
<td>0.1</td>
<td>98.8</td>
<td>0.6</td>
<td>0.0</td>
<td>24.4</td>
</tr>
<tr>
<td>Forest</td>
<td></td>
<td>5.5</td>
<td>0.4</td>
<td>92.6</td>
<td>0.1</td>
<td>24.6</td>
</tr>
<tr>
<td>Barren</td>
<td></td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>99.9</td>
<td>26.0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class</th>
<th>Ground Truth (percent)</th>
<th>Gorse</th>
<th>Grass</th>
<th>Forest</th>
<th>Barren</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unclassified</td>
<td></td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Gorse</td>
<td></td>
<td>93.4</td>
<td>0.6</td>
<td>10.5</td>
<td>0.0</td>
<td>25.8</td>
</tr>
<tr>
<td>Grass</td>
<td></td>
<td>0.5</td>
<td>96.9</td>
<td>0.4</td>
<td>0.0</td>
<td>24.4</td>
</tr>
<tr>
<td>Forest</td>
<td></td>
<td>5.9</td>
<td>2.5</td>
<td>88.9</td>
<td>0.8</td>
<td>24.6</td>
</tr>
<tr>
<td>Barren</td>
<td></td>
<td>0.3</td>
<td>0.0</td>
<td>0.0</td>
<td>99.2</td>
<td>25.2</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Figure 3.10. Classified images from the Humu`ula and Pi`ihonua ahupua`a on the east side of Hawai`i Island (19°46’32 N, 155°22’44 W) from February, 2015 (left) and November, 2015 (right).

Section 3.4 Discussion

The ability to quantify the current gorse footprint and pinpoint incipient populations was identified by stakeholders as a key concern with respect to DSS development for the study area. With this information, the stakeholders will be able to evaluate gorse management and removal options, and prioritize their efforts in the interest of limiting gorse expansion outside the core population. Evaluation of the accuracy of the CAH-LC model for the study area showed that it was an insufficient model to address these stakeholder needs because it did not capture the full extent of the current gorse population. Using high resolution imagery and phenology, this study produced high quality land cover models that not only provide a better estimate of the gorse population but also give an indication of the rate at which gorse is expanding (Figure 3.10). Previous work using ASTER data from 2002-2015 suggested that this rate has been increasing from ~25 to ~200 ha per year (Kimball 2015, unpublished work). Based directly on pixel counts from the February 2015 images and correcting for a 5% error, there is a total of ~ 4100 hectares of gorse in the Humu`ula area. Using polygons to delineate densely and sparsely covered areas, the estimated current core population is ~2460 hectares with another 14,000 hectares of sparse growth. From the 2012-2013
image, the densely populated area was ~2080 hectares and the sparsely covered area was ~12,500. The vegetation model produced in this study is vital to the development of other DSS layers for the study area. This land cover model will be used in state and transition modeling to project future land cover scenarios based on management options, evaluate costs of treatment and to estimate carbon accumulation potential discussed in Chapter 4.

Figure 3.11. The land cover classification map for the study area from the Carbon Assessment of Hawai‘i (Jacobi et al. CAH 2016) on the left and the new land cover classification map resulting from this project on the right. Both images are at 30 m resolution.
Chapter 4: Thesis Summary, Conclusions and Future Projects

The objective of this thesis project was to initiate development of an ecosystem management DSS to assess the process of DSS development and evaluate the use of existing data sets and tools to develop components of a DSS for an individual landholder in Hawai`i. After three years of discussions with the stakeholders for the study area, the primary management goals were: restoration and protection of native habitat, gorse (Ulex europaeus) removal, watershed restoration, and fire reduction. In addition to these goals, it was clear that in order for these goals to be met, increased and more consistent funding is required. Based on the management goals established by the stakeholders and the need for funding, I developed three objectives for this study: 1) Establish parameter estimates for GPP by vegetation type that could be used in state and transition modeling to evaluate the differences in biomass accumulation that would occur under different land use scenarios, 2) Develop an accurate vegetation map of the study area, particularly the current footprint of gorse, and 3) Use the products from the first two components for state and transition modeling of the study area to evaluate the effects of different land use scenarios on ecosystem services.

Comparison of the statewide land cover model developed as part of the Carbon Assessment of Hawai`i (CAH) and the land cover model currently used for global modeling of Gross Primary Productivity and Net Primary Productivity (GPP and NPP) led to discovery that there was less than 50% agreement between the two land cover models. In collaboration with the researchers at Numerical Terradynamic Simulation Group (NTSG), new GPP and NPP models were developed for the state of Hawai`i that included both the CAH land cover model and local climate models. Analysis of these new models showed that, at the state scale, the local climate models had a greater influence on GPP estimates than the CAH land cover model. However, in evaluating GPP for individual land cover classes, I found that the use of the CAH land cover model did influence both the total contribution to statewide GPP by each land cover class statewide and the distributions of GPP values by land cover class. I was able to use the new GPP product to generate parameter estimates for GPP and NPP by land cover class within specific rainfall and temperature ranges. These new GPP/NPP models will also be
included as part of the CAH analysis of current carbon stocks, the CAH state and transition models, and as supplemental data provided with the final report. This study highlighted the challenges of using global data sets in a heterogeneous landscape such as Hawai`i.

The land cover model from CAH, while useful at the state level, did not have the resolution to meet the needs of the stakeholders in my study area. I was able to use high resolution imagery from WorldView-2 to produce a current, highly accurate, classified land cover model for the study area. From this model I was able to estimate the current size of the core gorse area and the area covered by scattered growth. By looking at imagery from 2012-2013 and 2015 I was able to get an estimate of the expansion of gorse during this time period. Having an accurate map of gorse will help the stakeholders to target areas for gorse containment and eradication.

This land cover model and the NPP estimates by land cover class are crucial inputs for state and transition models developed for the study area. During the course of this study it was not possible to complete the state and transition modeling, however, the model has been designed and is described in Appendix 1. The state and transition modeling application used in the CAH for projecting future carbon stocks and fluxes, and land cover distributions will be used to develop projections for the study area. CAH fire probabilities, recruitment and growth rates, and future climate projections will all be used to parameterize these local models. State and transition simulations for the study area will project biomass accumulation under different ecosystem management scenarios. These estimates can be used to calculate carbon credits available, which can be compared with other funding options. Additional data layers based on the projected land cover models for the study can be developed to be included in the knowledge base for a DSS for the study area. This DSS can then be used by the stakeholders to make decisions with respect to ecosystem management of the study area based on their priorities.

The next steps for this project are to finalize the state and transition models, run the simulations and analyze the results. As mentioned in the introduction, implementation of DSS is most effective when iterative and facilitated. I have interacted with some of the decision makers throughout this project. At this stage, the data products from this study should be reviewed with the stakeholders to evaluate how well these products meet their
needs and assess additional requirements. It is also necessary to expand the stakeholder input to include the leadership of the DHHL and the Hawaiian Homes Commission. I hope to have the opportunity to present the results of this project to this broader group of stakeholders for their feedback.

Decision Support Systems represent a form of organizational management. Changes to an organization’s management are often met with resistance unless the process is facilitated and gradual. However, I do not think this will be a barrier to implementation of a DSS in this case, given that there was substantial buy in and input from the current stakeholders. What could prevent implementation is the fact that the stakeholders are changing and, given the current state of the study area and funding, the stakeholders are always operating in crisis mode and cannot devote time and resources to organizational change. The future of Humu’ula is in question. How the AMLP will be implemented or if it will be implemented at all remains to be seen. Hopefully, the informational resources produced in this study will prove useful to the decision makers as they determine how to proceed.
Appendix 1. State and Transition Modeling

Section A1.1 State and Transition Modeling Overview

The state and transition modeling application, ST-SIM (version 3.0.17), is available online through Apex Resources Management Solutions (Daniel & Frid 2012). Modeling with ST-SIM requires the identification of three components: strata, state classes and transitions. Strata are defined areas in which the state classes will undergo particular set of transitions. For this project, the strata are determined by the management designation areas defined by the `Āina Mauna Legacy Plan (AMLP; DHHL 2009; Figure A1.1). State classes refer to the land cover class assigned to each pixel. For the AMLP model these include: adult mix native forest, barren, developed, gorse, homestead, mixed native shrubland, nonnative grass, sugi plantation, young mixed native forest and young native shrubland. Mixed native forest categories are assumed to be koa dominated and native shrubland mamane dominated. The spatial distribution of these state classes at the initial time step is defined by the 30 m resolution classified land cover map produced in Chapter 3. During the simulations with ST-SIM, for each pixel, the state class, age and time since transition are tracked using annual time steps. Transitions are defined as the processes that change the state class of a pixel from one state to another. Each transition is linked to a probability that can be either static or dynamic over time. For example, the probability that a nonnative grass pixel will be converted to young native forest through planting is based on the restoration rate established in the AMLP of 500 hectares per year. Each transition can occur through multiple pathways. For this model I identified 20 transition groups, 39 transition types and 72 transition pathways (Table A1.1). Based on these transition types and their associated rates and probabilities, 100+ Monte Carlo simulations will be run within the ST-SIM. These simulations will produce projections for biomass accumulation with a 95% confidence interval, using the NPP estimates from chapter 2, and projected future land cover models.
Figure A1.1 The ‘Āina Mauna Legacy Plan land management designations (DHHL 2009). The study area is located in Humu‘ula ahupua‘a on the east side of the Island of Hawai‘i. Study area center 19°46’32 N, 155°22’44 W.
Table A1.1. Transition groups and types established for the `Āina Mauna Legacy Plan state and transition models.

<table>
<thead>
<tr>
<th>Transitions</th>
<th>State Classes Affected</th>
<th>Becomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gorse Expansion Fire</td>
<td>Adult Mixed Native Forest</td>
<td>Gorse</td>
</tr>
<tr>
<td>Gorse Expansion Fire</td>
<td>Young Mixed Native Forest</td>
<td>Gorse</td>
</tr>
<tr>
<td>Gorse Expansion Fire</td>
<td>Non Native Grass</td>
<td>Gorse</td>
</tr>
<tr>
<td>Gorse Expansion Fire</td>
<td>Young Native Shrubland</td>
<td>Gorse</td>
</tr>
<tr>
<td>Gorse Expansion Fire</td>
<td>Mixed Native Shrubland</td>
<td>Gorse</td>
</tr>
<tr>
<td>Gorse Expansion Grazing</td>
<td>Young Mixed Native Forest</td>
<td>Gorse</td>
</tr>
<tr>
<td>Gorse Expansion Grazing</td>
<td>Non Native Grass</td>
<td>Gorse</td>
</tr>
<tr>
<td>Gorse Expansion Grazing</td>
<td>Young Native Shrubland</td>
<td>Gorse</td>
</tr>
<tr>
<td>Gorse Expansion Grazing</td>
<td>Mixed Native Shrubland</td>
<td>Gorse</td>
</tr>
<tr>
<td>Gorse Expansion Grazing</td>
<td>Barren</td>
<td>Gorse</td>
</tr>
<tr>
<td>Gorse Expansion Recruitment</td>
<td>Non Native Grass</td>
<td>Gorse</td>
</tr>
<tr>
<td>Gorse Removal</td>
<td></td>
<td>Gorse</td>
</tr>
<tr>
<td>Grass Expansion Fire</td>
<td>Adult Mixed Native Forest</td>
<td>Non Native Grass</td>
</tr>
<tr>
<td>Grass Expansion Fire</td>
<td>Young Mixed Native Forest</td>
<td>Non Native Grass</td>
</tr>
<tr>
<td>Grass Expansion Fire</td>
<td>Young Native Shrubland</td>
<td>Non Native Grass</td>
</tr>
<tr>
<td>Grass Expansion Fire</td>
<td>Mixed Native Shrubland</td>
<td>Non Native Grass</td>
</tr>
<tr>
<td>Grass Expansion Fire</td>
<td>Sugi Plantation</td>
<td>Non Native Grass</td>
</tr>
<tr>
<td>Grass Expansion Grazing</td>
<td>Young Mixed Native Forest</td>
<td>Non Native Grass</td>
</tr>
<tr>
<td>Grass Expansion Grazing</td>
<td>Young Native Shrubland</td>
<td>Non Native Grass</td>
</tr>
<tr>
<td>Grass Expansion Grazing</td>
<td>Mixed Native Shrubland</td>
<td>Non Native Grass</td>
</tr>
<tr>
<td>Grass Expansion Primary Succession</td>
<td>Barren</td>
<td>Non Native Grass</td>
</tr>
<tr>
<td>Native Forest Growth</td>
<td>Young Mixed Native Forest</td>
<td>Adult Mixed Native Forest</td>
</tr>
<tr>
<td>Native Forest Primary Succession</td>
<td>Barren</td>
<td>Young Mixed Native Forest</td>
</tr>
<tr>
<td>Native Forest Recruitment</td>
<td>Gorse</td>
<td>Young Mixed Native Forest</td>
</tr>
<tr>
<td>Native Forest Recruitment</td>
<td>Non Native Grass</td>
<td>Young Mixed Native Forest</td>
</tr>
<tr>
<td>Young Mixed Native Planting</td>
<td>Gorse</td>
<td>Young Mixed Native Forest</td>
</tr>
<tr>
<td>Young Mixed Native Planting</td>
<td>Non Native Grass</td>
<td>Young Mixed Native Forest</td>
</tr>
<tr>
<td>Young Mixed Native Planting</td>
<td>Barren</td>
<td>Young Mixed Native Forest</td>
</tr>
<tr>
<td>Adult Mixed Native Harvest</td>
<td>Adult Mixed Native</td>
<td>Young Mixed Native Forest</td>
</tr>
<tr>
<td>Native Shrub Growth</td>
<td>Young Native Shrubland</td>
<td>Mixed Native Shrubland</td>
</tr>
<tr>
<td>Native Shrub Planting</td>
<td>Non Native Grass</td>
<td>Young Native Shrubland</td>
</tr>
<tr>
<td>Native Shrub Planting</td>
<td>Barren</td>
<td>Young Native Shrubland</td>
</tr>
<tr>
<td>Native Shrub Primary Succession</td>
<td>Barren</td>
<td>Young Native Shrubland</td>
</tr>
<tr>
<td>Native Shrub Recruitment</td>
<td>Non Native Grass</td>
<td>Young Native Shrubland</td>
</tr>
<tr>
<td>Sugi Planting</td>
<td>Gorse</td>
<td>Sugi Plantation</td>
</tr>
<tr>
<td>Sugi Planting</td>
<td>Non Native Grass</td>
<td>Sugi Plantation</td>
</tr>
<tr>
<td>Sugi Planting</td>
<td>Barren</td>
<td>Sugi Plantation</td>
</tr>
<tr>
<td>Sugi Harvest and Native Planting</td>
<td>Sugi Plantation</td>
<td>Young Native Shrubland</td>
</tr>
<tr>
<td>Sugi Harvest and Replanting</td>
<td>Sugi Plantation</td>
<td>Sugi Plantation</td>
</tr>
</tbody>
</table>
Section A1.2 Parameterization of the AMLP study area state and transition model

Pathways for the AMLP study area state and transition model were identified based on three scenarios. The first scenario assumes no management of any kind within the study area. In this scenario all strata are treated the same in terms of possible transition pathways. Conversion of a pixel to gorse or nonnative grass from other state classes will occur through grazing, fire, recruitment and primary succession. Initiation of wildfires will occur at random locations in the model based on the frequency of fire starts per land cover class calculated from historical data in the CAH (Hawbaker et al. CAH 2016). Burn severity and extent will also be assigned randomly to each fire, again based on CAH estimates. Burned pixels will be converted to nonnative grass unless next to an existing gorse pixel or if that pixel had been gorse within the previous 70 years of the simulation. In this scenario, gorse and grass expansion due to grazing will increase over time based on the assumption that without any ungulate control, ungulate populations and, therefore, grazing rates would increase. Furthermore, without maintenance of existing fence lines, areas currently protected from grazing would become vulnerable. Initial recruitment of gorse will occur at a rate of 25 hectares per year. This is based on preliminary estimates of the gorse expansion rate from satellite imagery over the last 12 years (H. Kimball, unpublished work). This rate will increase as the size of the core population increases. Conversion to gorse will initially be limited to the current gorse range (Figure A1.2). This range will gradually expand, until the year 2060 when the entire study area would be suitable for gorse based on the dynamically downscaled climate projections in the CAH (Fortini et al. CAH 2016). In this scenario, transitions to native forest and shrubland will occur through recruitment and primary succession. These transition rates and growth rates for these state classes will be based on the rates used in the CAH models (Sleeter et al. CAH 2016).
The second scenario is based the land management actions defined in the AMLP. There are two overriding assumptions in this scenario. First, gorse eradication will be successful and second, the fire prevention and suppression measures outlined in the AMLP will reduce the frequency and extent of fires in the study area. These assumptions introduce a substantial degree of uncertainty to the model that warrant further consideration. These assumptions are discussed in more detail in section A1.3.

In the AMLP defined scenario, the commercial, homestead, pasture and pasture lease strata will undergo gorse removal at the initial time step but will not go under any further transitions as part of the state and transition model. State class modifications to the commercial and homesteading areas will be made after the ST-SIM process based on the development plan outlined in the AMLP. The restoration and sustainable koa forestry strata will undergo transition to young native forest, each at a rate of 500 hectares per year (AMLP 2009). Planting is assumed to occur in the most accessible areas first, those
closest to Mauna Road, the main access road in the study area (Figure A1.3). In the koa sustainable forestry strata, harvesting will occur after 50 years at a rate of 20 hectares per year. Forest growth rates will be based on those used in the CAH (Sleeter et al. CAH 2016).

Of the mamane strata, two of the five areas are currently fenced (M1 and M2; Figure A1.1). The remaining three mamane areas are assumed to become fenced at 5, 10 and 15 years after the initial time step, in the order of smallest to largest. These time intervals are based only on the assumption that available funding and labor resources would not allow for all fencing to occur immediately at the initial time step. This is an uncertainty in the model that may require refinement. In the mamane strata, transitions due to grazing will no longer occur once fencing is in place. Mamane dominated shrubland expansion and growth is based on Scowcroft & Conrad 1988 & Reddy et al. 2012. An additional assumption in this strata is that the majority of this areas is currently
too dry for native forest recruitment; however, this will change by 2060 based on the projected changes in moisture zone from the dynamically downscaled climate models in the CAH (Fortini et al. CAH 2016). Therefore, native forest recruitment will initially be limited to the same area as gorse mentioned in the previous scenario, and this range will expand over time. Native forest recruitment and growth will be based on the rates from the CAH.

In the timber strata, planting of sugi pine will take place at a rate of 1000 hectares per year. Timber planting will occur first in a 250 m buffer around the core gorse population, then in the area of the core population and finally, in the remaining area designated for timber (Figure A1.3). The AMLP has several estimates of the time from timber planting to harvest (25-45 years). For this model a harvest age of 35 years was used. The AMLP also states that there may be one or two timber cycles followed by native forest restoration. I chose to simulate two harvest cycles in the model. The decision to grow sugi pine as timber in core gorse area in the AMLP is based on: 1) the timber lease funding other aspects of the plan, and 2) sugi is fast growing and it is expected to shade out gorse recruitment after initial treatment. Given the longevity of the gorse seed bank, it would take two harvest cycles (70 years) to deplete this seed bank. In this scenario, after the two harvest cycles, the timber areas will be planted with mixed native forest. The AMLP allows for the option that some of this area could be converted to additional homesteading after the timber harvests, but this was not included as part of this state and transition model.

Finally, for the open strata, no management actions are specified in the AMLP. Therefore, this area will be subject to the same transitions in this scenario as it was in the first scenario. Fire will continue to occur across the study area as described in the first scenario. However, rates will be reduced because of fire suppression measures in the AMLP. This is another key assumption in the models discussed more in section 4.4.

The third scenario is based on optimizing the AMLP for maximum carbon credits. Two of the requirements for participation in a carbon credits program are that projects are additive and use native tree species. An additive project can include both active planting or improved forest management. For the third scenario I modeled the AMLP with three changes: the timber areas will be planted with mixed native forest, active reforestation
will occur in the mamane areas and the open area will be fenced. This assumes not only that gorse removal will be successful, but also that it will be done in a method that prevents recruitment from the gorse seed bank even with the slower growth rates of a koa dominated forest.

Section A1.3 Key Assumptions in the AMLP Model

One of the key assumptions in scenarios two and three is that gorse removal will be successful and that recruitment from the seed bank will be suppressed. The AMLP does not specify a particular method for removal of the current gorse population. There are three possible methods for the removal of gorse: grating, herbicide, and burning. Each of these methods has important drawbacks. Grating would be costly and it presents the problem of disposing of the uprooted biomass and potentially the upper level soil. If the upper level of soil is not removed, grating will only serve to scarify dormant seeds and create the type of disturbance that promotes gorse regrowth. Grating is also a limited option in Humu’ula because of that area’s topography. Use of herbicide is also costly and potentially labor intensive. Herbicide treatments would have to be repeated several times to be effective. The use of fire presents the danger of spread to adjacent areas and may only serve to scarify seeds within the seed bank and create ideal growing conditions for gorse seedlings. In 2001-2002 Parker Ranch did attempt a removal program in Humu’ula that included aerial spraying and burning and 95% of the existing gorse was removed. However, without subsequent controls in place for regrowth, the population returned to its previous density within three years (Markin & Conant 2011).

Any successful removal plan for gorse must be accompanied by a management plan for regrowth. Options for controlling seedling regrowth include: continued mechanical removal, herbicides, mulching, grazing by goats and sheep and shading. Both herbicide and mulch were shown to effectively suppress gorse in Canada (Prasad 2003). Introducing grazing by both goats and sheep after a cutting, herbicide and burning treatments were found to be an effective strategy in New Zealand with full eradication within 4-5 years (Radcliffe 1995 & Radcliffe 1990). Shading has also been proposed as a regrowth control strategy given the evidence of reduced seedling recruitment at lower (5-
10% light levels (Perry 2010). The shade intolerance of gorse is the justification for the use of sugi pine for timber planting in the AMLP.

For the state and transition models I did not specify a particular method for gorse removal. To do so would have added another layer of significant uncertainty to the models. Instead I chose to set gorse pixels to grass at time step one. This is highly unlikely in reality, and it will have to be made clear to stakeholders that this is a substantial limitation of the models. Additional data layers that could be added to a DSS for the study area relating to gorse removal are discussed further in the next section.

The second key assumption in the state and transition models is that incidents of fire will be reduced under implementation of the AMLP. Fire is an important concern for the stakeholders. A detailed fire management plan is included in the AMLP that specifies the creation of fire breaks and addition water reserves to suppress fire. However, it is important to note that most fires in Hawai`i are human ignited. It could be argued that increasing the number of people accessing this area might result in an increase in fires. Without being able to predict which outcome of the AMLP was more likely, I chose to reduce the rate of fire in scenarios two and three for the state and transition models because projecting the effect of reducing fire would provide more useful information to the decision makers for the study area.

Section A1.4 Expected Outputs and Further Analysis

ST-SIM modeling will produce two types of projection outputs. It will provide estimates of biomass accumulation over time based on the NPP estimates from Chapter 2 and projected future land cover models for comparison with the current land cover model produced in Chapter 3. The transition pathways for the state and transition models for the study area are still being built into the model. At this point, I am only able to discuss at the expectations for the simulation outputs and how they can be used for future DSS development.

Biomass accumulation curves represent the projected cumulative increase in Tg C over time. Examples of Tg C accumulation curves produced using ST-SIM are shown in Figure A1.4. Because the mean values are projected based on Monte Carlo simulations,
confidence intervals can also be established. In the first scenario, with no management action, I expect to see that gorse will expand to cover the entire study area by the final time step at year 2100, if not before. In terms of biomass accumulation, I expect that this will result in a biomass accumulation projection curve that is initially fairly steep, as much of what is now grassland is converted to gorse, but then levels out as gorse becomes established. In scenario two, I expect to see a more gradual accumulation curve in the koa sustainable forestry and restoration areas that eventually level off but at a higher level of Tg C than gorse in scenario one. For the timber areas, I expect to see a more rapid increase in biomass accumulation than in the koa forestry and restoration areas with a leveling off prior to the first harvest. I expect this will be followed by another rapid increase as the second timber cycle is planted. In the mamane and open areas I expect a gradual increase in biomass accumulated over time with the open area reaching a slightly higher level of Tg C because the open area is 500 hectare larger than the mamane, and I expect a higher ratio of forest/shrub in the open area. In scenario three, the differences between this model and the model in scenario two are in the timber, mamane and open areas. In the timber area, which will undergo the same transitions as the koa sustainable forestry areas, I expect a similar pattern in biomass accumulation. I also expect the timber areas in this scenario may level out at a slightly lower level of Tg C than the curve produced from the sugi pine in scenario two. In the mamane and open areas I would expect the biomass accumulation curves to be slightly steeper than the curves for these areas in scenario two but I expect that they may will level off at roughly the same level Tg C. The biomass accumulation curves produced from the three scenarios can be used to compare the differences in total C accumulation and differences in accumulation between land cover classes across the study area. I expect to find that projected total accumulation of C in the AMLP scenario will be slightly higher than scenario three, optimized for carbon credits, I expect the no management scenario will have the lowest overall biomass accumulation. Scenario three was based on maximizing the amount of biomass accumulated from native forest. The differences in biomass accumulation from native plants between scenarios two and three can then be used to calculate the differences in the amount of carbon credits available between the two scenarios. The difference in available carbon credits can be converted to a dollar value.
based on the current market value of carbon credits, which can be compared to the estimated revenue generated from the timber leases.

![Graph showing accumulation curves produced from the ST-SIM state and transition models. Mean and 95% confidence interval are shown over time. This example shows a comparison of total ecosystem carbon storage between two simulations with and without projected statewide moisture zone change. – Sleeter et al. CAH 2016.]

The second set of data products produced from the ST-SIM models will be the projected future land cover models. These models can be used for comparison with the current land cover model for the study area developed in Chapter 2. In addition to showing the changes in the spatial distribution of land cover classes, these models can be used in other applications to evaluate the difference in additional ecosystems services between land cover models. For example, the effects the different land cover models on the hydrology of the study area can be compared using the University of Washington’s Distributed Hydrology Soil Vegetation Model (DHSVM). The DHSVM models the effects of vegetation on water fluxes within the ecosystem, taking into account climate and topography (Wigmosta et al., 1994). Habitat quality for rare flora and fauna can be compared using the Natural Capital Project’s InVEST habitat analysis tool (Tallis H. T. et al. 2010). Finally, if further research is done to analyze the effectiveness of the different gorse removal and regrowth prevention treatments, cost of treatment could be assessed for the study area. It may be of particular interest, for example, to produce land
cover projections from scenario one at one year intervals to see how delays in management would influence the overall cost of the AMLP. The information produced in this thesis along with these additional data layers can form the knowledge base of a DSS for the study area. With state and transition models for the “worst case” (no management) and “best case” (AMLP optimized for carbon credits), logic models can be developed that reflect the relationships and dependencies of the information in the knowledgebase. Development of a DSS user application, supported with the knowledgebase and logic models, would allow decision makers to evaluate the management options for the study area based on their individual management priorities.

Section A1.5 Transitions defined for the AMLP state and transition models

**Strata**
Light Commercial (C)
Homestead (H)
Koa Sustainable Forestry (K 1-5)
Mamane (M 1-5)
Open (O)
Pasture (P)
Pasture Lease (PL)
Restoration (R)
Timber (T)

**State Classes**
adult mix native forest
barren
developed
gorse
homestead
mixed native shrubland
nonnative grass
sugi plantation
young mixed native forest
young native shrubland

**Transitions Scenario #1 – No Management**

**Strata: ALL STRATA**
Transition 1: **Gorse Expansion Grazing** - Grass goes to gorse if next to existing gorse due to grazing. Only in area where gorse_range = 1
Transition 2: **Gorse Expansion Fire** - Grass goes to gorse if next to existing gorse or if pixel was gorse in the previous 70 yrs because of fire. No limit on expansion area. Only
in area where gorse_range = 1. Probability of fire from CAH Fire chapter. No fire prevention
Transition 3: Native Forest Recruitment - A very small fraction of grass converted to Young Mixed Native. Must be next to Adult Mixed Native also limited to gorse_range = 1
Transition 4: Native Shrub Recruitment - A very small fraction of grass converted to Mixed Native Shrubland. Must be next to Young Native shrubland
Transition 5: No Change
Transition 6: Native Forest Recruitment - A very small fraction of gorse could be converted to Young Mixed Native. Must be next to Adult Mixed Native also limited to gorse_range = 1
Transition 7: No Change - gorse – stays gorse under all disturbances
Transition 8: Grass Expansion Fire - Young Mixed Native Forest goes to grass because of fire if not next to gorse. Probability of fire from CAH Fire chapter. No fire prevention
Transition 9: Gorse Expansion Fire - Young Mixed Native Forest goes to gorse if next to existing gorse or if pixel was gorse in the previous 70 yrs because of fire. No limit on expansion area. Only in area where gorse_range = 1
Transition 10: Grass Expansion Grazing - Young Mixed Native Forest goes to grass because of grazing if not next to gorse.
Transition 11: Gorse Expansion Grazing - Young Mixed Native Forest goes to gorse if within 2 m of existing gorse because of grazing. No limit on expansion area. Only in area where gorse_range = 1
Transition 12: Native Forest Growth - Young Mixed Native Forest develops into Adult Mixed Native Forest based on growth curves (Ohia and Koa)
Transition 13: Grass Expansion Fire – Adult Mixed Native Forest goes to grass because of fire if not next to gorse. Probability of fire from CAH Fire chapter. No fire prevention
Transition 14: Gorse Expansion Fire - Adult Mixed Native Forest goes to gorse if next to existing gorse or if pixel was gorse in the previous 70 yrs because of fire. No limit on expansion area. Only in area where gorse_range = 1
Transition 15: No Change - Mixed Native Forest remains Mixed Native Forest
Transition 16: Grass Expansion Fire - Young Native Shrubland goes to grass because of fire if not next to gorse. Probability of fire from CAH Fire chapter. No fire prevention
Transition 17: Gorse Expansion Fire - Young Native Shrubland goes to gorse if next to existing gorse or if pixel was gorse in the previous 70 yrs because of fire. No limit on expansion area. Only in area where gorse_range = 1. Probability of fire from CAH Fire chapter. No fire prevention
Transition 18: Gorse Expansion Grazing - Young Native Shrubland goes to gorse if within 2 m of existing gorse because of grazing. No limit on expansion area. Only in area where gorse_range = 1
Transition 19: Grass Expansion Grazing - Young Native Shrubland goes to grass because of grazing if not next to gorse.
Transition 20: Native Shrub Growth - Young Native Shrubland grows to Mixed Native Shrubland
Transition 21: **Grass Expansion Fire** - Mixed Native Shrubland goes to grass because of fire if not next to gorse. Probability of fire from CAH Fire chapter. No fire prevention.
Transition 22: **Gorse Expansion Fire** - Mixed Native Shrubland goes to gorse if next to existing gorse or if pixel was gorse in the previous 70 yrs because of fire. No limit on expansion area. Only in area where gorse_range= 1. Probability of fire from CAH Fire chapter. No fire prevention.
Transition 23: **Gorse Expansion Grazing** - Mixed Native Shrubland goes to gorse if within 2 m of existing gorse because of grazing. No limit on expansion area. Only in area where gorse_range= 1.
Transition 24: **Grass Expansion Grazing** - Mixed Native Shrubland goes to grass because of grazing if not next to gorse.
Transition 25: **No Change** - Mixed Native Shrubland remains Mixed Native Shrubland.
Transition 26: **Gorse Expansion Primary Succession** - Barren goes to gorse if next to existing gorse. Max expansion 25 hectares/year across study area. Only in area where gorse_range= 1.
Transition 27: **Grass Expansion Primary Succession** - Barren goes to grass if next to grass.
Transition 28: **Native Forest Primary Succession** - Barren goes to Young Mixed Native. Must be next to Adult Mixed Native also limited to gorse_range = 1.
Transition 29: **Native Shrub Primary Succession** - Barren goes converted to Mixed Native Shrubland. Must be next to Mixed Native Shrubland.
Transition 30: **No Change** - Barren remains Barren.
Transition 31: **Gorse Expansion Recruitment** - Grass goes to gorse if within 2 m of existing gorse due to recruitment. Only in area where gorse_range = 1. Max initial expansion 25 hectares/year across study area.

**Transitions Scenario #2 – AMLP**

**Assumptions**
1. Gorse removal is successful
2. Restoration happens in R at a rate of 500 ha/year
3. Sustainable Koa Forestry happens in K at a rate of 500 ha/year
4. Timber is planted in T at a rate of 1000 ha/year
5. Timber harvest cycle is 35 years
6. There will be two timber harvests followed by native planting
7. Unfenced mamane areas (M 3-5) will be fenced sequentially from smallest to largest. One every 5 years
8. Recruitment is slightly higher in fenced mamane areas.
9. There will be fire prevention and suppression efforts

**Strata: C, H, P & PL – CONVERT GORSE TO GRASS – NO OTHER CHANGES**

**Strata: K**
Transition 1K: **Young Mixed Native Planting** – Gorse, Grass and Barren planted to Young Mixed Native. 500 ac blocks per year starting at the southernmost end working north.
Transition 2K: **Native Forest Growth** - Young Mixed Native Forest develops into Adult Mixed Native Forest based on growth curves.
Transition 3K: **No Change** - Mixed Native Forest remains Mixed Native Forest
Transition 4K: **Grass Expansion Fire** - Young Mixed Native Forest goes to grass because of fire. Probability of fire from CAH Fire chapter reduced due to increased fire prevention and suppression.
Transition 5K: **Grass Expansion Grazing** – Young Mixed Native Forest goes to grass due to grazing
Transition 6K: **Grass Expansion Fire** - Adult Mixed Native goes to grass because of fire. Probability of fire from CAH Fire chapter reduced due to increased fire prevention and suppression.
Transition 7K: **Adult Mixed Native Harvest**- Harvest after 50 years – no more than 20 ha per year – replanted after harvesting
Transition 8K: **No Change** – Grass remains Grass
Transition 9K: **No Change** – Barren Remains Barren

**Strata: M**
Transition 1M: **Native Shrub Recruitment** – Non Native Grass and Barren to Mixed Native Shrub.
Transition 2M: **No Change** – Grass remains Grass
Transition 3M: **Grass Expansion Fire** - Young Native Shrubland goes to grass because of fire. Probability of fire from CAH Fire chapter reduced due to increased fire prevention and suppression.
Transition 4M: **Grass Expansion Grazing** – Young Native Shrubland goes to grass – Only in M3, M4 and M5 first 5 Years – Only in M4 and M5 between 5 and 10 years – Only in M5 after 10 years. All M areas fenced after 15 years – no more grazing.
Transition 5M: **Native Shrub Growth** - Young Native Shrubland grows to Mixed Native Shrubland
Transition 6M: **Grass Expansion Fire** - Mixed Native Shrubland goes to grass because of fire. Probability of fire from CAH Fire chapter reduced due to increased fire prevention and suppression.
Transition 7M: **Grass Expansion Grazing** - Mixed Native Shrubland goes to grass – Only in M3, M4 and M5 first 5 Years – Only in M4 and M5 between 5 and 10 years – Only in M5 after 10 years. All M areas fenced after 15 years – no more grazing.
Transition 8M: **No Change** - Mixed Native Shrubland remains Mixed Native Shrubland
Transition 9M: **Grass Expansion Primary Succession** - Barren goes to grass if next to grass.
Transition 10M: **Native Shrub Primary Succession** - Barren goes converted to Mixed Native Shrubland. Must be next to Mixed Native Shrubland
Transition 11M: **No Change**- Barren remains Barren
Transition 12M: **Native Forest Recruitment** - A very small fraction of grass converted to Young Mixed Native. Must be next to Adult Mixed Native also limited to gorse_range = 1
Transition 13M: **Native Forest Primary Succession** - Barren goes to Young Mixed Native. Must be next to Adult Mixed Native also limited to gorse_range = 1
Transition 14M: **Gorse Removal** – At time zero set any gorse pixels in M to grass

**Strata: O**
Transition 1-O: **Grass Expansion Primary Succession** - Barren goes to grass if next to grass.
Transition 2-O: **Native Forest Primary Succession** - Barren goes to Young Mixed Native. Must be next to Adult Mixed Native also limited to gorse_range = 1
Transition 3-O: **Native Shrub Primary Succession** - Barren goes converted to Mixed Native Shrubland. Must be next to Mixed Native Shrubland
Transition 4-O: **No Change** - Barren remains Barren
Transition 5-O: **Native Forest Growth** - Young Mixed Native Forest develops into Adult Mixed Native Forest based on growth curves
Transition 6-O: **Grass Expansion Fire** - Young Mixed Native Forest goes to grass because of fire. Probability of fire from CAH Fire chapter reduced due to increased fire prevention and suppression.
Transition 7-O: **Grass Expansion Grazing** – Young Mixed Native Forest goes to grass due to grazing
Transition 8-O: **Grass Expansion Fire** - Adult Mixed Native Forest goes to grass because of fire. Probability of fire from CAH Fire chapter reduced due to increased fire prevention and suppression.
Transition 9-O: **No Change** - Adult Mixed Native Forest remains Adult Mixed Native Forest
Transition 10-O: **Grass Expansion Fire** - Young Native Shrubland goes to grass because of fire. Probability of fire from CAH Fire chapter reduced due to increased fire prevention and suppression.
Transition 11-O: **Grass Expansion Grazing** – Young Native Shrubland goes to grass due to grazing
Transition 12-O: **Native Shrub Growth** - Young Native Shrubland grows to Mixed Native Shrubland
Transition 13-O: **Grass Expansion Fire** - Mixed Native Shrubland goes to grass because of fire. Probability of fire from CAH Fire chapter reduced due to increased fire prevention and suppression.
Transition 14-O: **Grass Expansion Grazing** - Mixed Native Shrubland goes to grass due to grazing
Transition 15-O: **No Change** - Mixed Native Shrubland remains Mixed Native Shrubland
Transition 15-O: **Native Forest Recruitment** - A very small fraction of grass converted to Young Mixed Native. Must be next to Adult Mixed Native also limited to gorse_range = 1
Transition 16-O: **Native Shrub Recruitment** – Non Native Grass to Mixed Native Shrub.
Transition 18-O: **No Change** – Grass remains Grass
Transition 19-O: **Gorse Removal** – At time zero set any gorse pixels in O to grass

**Strata:** R
Transition 1R: **Young Mixed Native Planting** – Gorse, Grass and Barren planted to Young Mixed Native. 500 ac blocks per year starting at the southernmost end working north
Transition 2R: **Native Forest Growth** - Young Mixed Native Forest develops into Adult Mixed Native Forest based on growth curves
Transition 3R: **No Change** - Mixed Native Forest remains Mixed Native Forest
Transition 4R: **Grass Expansion Fire** - Young Mixed Native Forest goes to grass because of fire. Probability of fire from CAH Fire chapter reduced due to increased fire prevention and suppression.

Transition 5R: **Grass Expansion Fire** - Adult Mixed Native goes to grass because of fire. Probability of fire from CAH Fire chapter reduced due to increased fire prevention and suppression.

Transition 6R: **No Change** – Grass remains Grass

Transition 7R: **No Change** – Barren Remains Barren

**Strata:** T

Transition 1T: **Sugi Planting** – Gorse, Grass and Barren planted to Sugi timber. 1000 ac blocks per year starting in timber_pri = 2 then timber_pri = 1 and finally timber_pri = 0. In all cases starting at the southernmost end working north. If pixel has been planted twice with sugi cannot be replanted with sugi.

Transition 2T: **Grass Expansion Fire** - Adult Mixed Native Forest goes to grass because of fire. Probability of fire from CAH Fire chapter reduced due to increased fire prevention and suppression.

Transition 3T: **No Change** - Adult Mixed Native Forest remains Adult Mixed Native Forest

Transition 4T: **Grass Expansion Fire** - Sugi goes to grass because of fire. Probability of fire from CAH Fire chapter reduced due to increased fire prevention and suppression.

Transition 5T: **Sugi Harvest and Replanting** – Sugi harvested after 35 years and replanted with sugi. If pixel has been planted twice with sugi cannot be replanted with sugi.

Transition 6T: **Sugi Harvest and Native Planting** – Second Sugi planting harvested after 35 years and replanted with Young Mixed Native Forest.

Transition 7T: **Native Forest Growth** - Young Mixed Native Forest develops into Adult Mixed Native Forest based on growth curves

Transition 8T: **Grass Expansion Fire** - Young Mixed Native Forest goes to grass because of fire. Probability of fire from CAH Fire chapter reduced due to increased fire prevention and suppression.

Transition 9T: **Grass Expansion Grazing** – Young Mixed Native Forest goes to grass due to grazing

Transition 10T: **Young Mixed Native Planting** – Grass is planted with Young Mixed Native Forest if pixel has already been planted twice with sugi.

**Transitions – Scenario #3 AMLP for Carbon Credits**

**Assumptions**

1. Gorse removal is successful
2. Restoration in R happens at a rate of 500 ha/year
3. Sustainable Koa Forestry happens in K at a rate of 500 ha/year
4. Timber area (T) from AMLP is planted at a rate of 1000 ha/year with Natives (Basically same as K)
5. Unfenced mamane areas (M 3-5) will be fenced sequentially from smallest to largest. One every 5 years
6. Recruitment is slightly higher in fenced mamane areas.
7. Native shrub and forest will actively be planted in M areas rate of 500 ha/year.
8. Open area (O) will be fenced. Grazing removed. No active planting
9. There will be fire prevention and suppression efforts

**Strata: C, H, P & PL – CONVERT GORSE TO GRASS – NO OTHER CHANGES**
**Strata:K** – Same as AMLP Strata K
**Strata:T** – Same as AMLP Strata K except 1000 ac/year
**Strata:M** – Same as AMLP except add transition
Transition 15M: Young Mixed Native Planting – Barren or Grass is planted with Young Mixed Native Forest at a rate of 500 ac/year

**Strata:O** – Same as AMLP Strata O except after year 20
No More - Grass Expansion Grazing – O-7, O-11 and O-14 will no longer occur
**Strata:R** – Same as AMLP Strata R
Section A1.6 Pathways for the state and transition models
Pathways for DHHL
Scenario 2 - AMLP
Strata: C, H, P & PL – CONVERT GORSE TO GRASS – NO OTHER CHANGES

**Strata: K**

- **Gorse** → Transition 1K → Young Mixed Native Forest
- **Non Native Grass** → Transition 1K → Young Mixed Native Forest
- **Barren** → Transition 2K → Young Mixed Native Forest
- **Young Mixed Native Forest** → Transition 2K → Adult Mixed Native Forest
- **Adult Mixed Native Forest** → Transition 3K
- **Young Mixed Native Forest** → Transition 4K → Non Native Grass
- **Young Mixed Native Forest** → Transition 5K → Non Native Grass
- **Adult Mixed Native Forest** → Transition 6K → Non Native Grass
- **Adult Mixed Native Forest** → Transition 7K → Young Mixed Native Forest
- **Non Native Grass** → Transition 8K
- **Barren** → Transition 9K

**Strata: M1-S**

- **Non Native Grass** → Transition 1M → Young Native Shrubland
- **Non Native Grass** → Transition 2M
- **Young Native Shrubland** → Transition 3M → Non Native Grass
- **Young Native Shrubland** → Transition 4M → Non Native Grass
- **Young Native Shrubland** → Transition 5M → Mixed Native Shrubland
- **Mixed Native Shrubland** → Transition 6M → Non Native Grass
- **Mixed Native Shrubland** → Transition 7M → Non Native Grass
- **Mixed Native Shrubland** → Transition 8M
- **Barren** → Transition 9M → Non Native Grass
- **Barren** → Transition 10M → Young Native Shrubland
- **Barren** → Transition 11M
- **Non Native Grass** → Transition 12M → Young Mixed Native Forest
- **Barren** → Transition 13M → Young Mixed Native Forest
- **Gorse** → Transition 14M → Non Native Grass
Pathways for DHHL
Scenario 2 - AMLP

Strata: O

Barren → Transition 1-O → Non Native Grass
Barren → Transition 2-O → Young Mixed Native Forest
Barren → Transition 3-O → Young Native Shrubland
Barren → Transition 4-O
Young Mixed Native Forest → Transition 5-O → Adult Mixed Native Forest
Young Mixed Native Forest → Transition 6-O → Non Native Grass
Young Mixed Native Forest → Transition 7-O → Non Native Grass
Adult Mixed Native Forest → Transition 8-O → Non Native Grass
Adult Mixed Native Forest → Transition 9-O
Young Native Shrubland → Transition 10-O → Non Native Grass
Young Native Shrubland → Transition 11-O → Non Native Grass
Young Native Shrubland → Transition 12-O → Mixed Native Shrubland

Mixed Native Shrubland → Transition 13-O → Non Native Grass
Mixed Native Shrubland → Transition 14-O → Non Native Grass
Mixed Native Shrubland → Transition 15-O
Non Native Grass → Transition 16-O → Young Mixed Native Forest
Non Native Grass → Transition 17-O → Young Native Shrubland
Non Native Grass → Transition 18-O
Gorse → Transition 19-O → Non Native Grass
Pathways for DHHL
Scenario 2 - AMLP

Strata: R – Same as K w/o harvest or grazing

```
Gorse  Transition 1R  Young Mixed Native Forest
Non Native Grass  Transition 1R  Young Mixed Native Forest
Barren  Transition 1R  Young Mixed Native Forest
Young Mixed Native Forest  Transition 2R  Adult Mixed Native Forest
Adult Mixed Native Forest  Transition 3R
Young Mixed Native Forest  Transition 4R  Non Native Grass
Adult Mixed Native Forest  Transition 5R  Non Native Grass
Non Native Grass  Transition 6R
Barren  Transition 7R
```

Strata: T

```
Gorse  Transition 1T  Sugi Plantation
Non Native Grass  Transition 1T  Sugi Plantation
Barren  Transition 1T  Sugi Plantation
Adult Mixed Native Forest  Transition 2T  Non Native Grass
Adult Mixed Native Forest  Transition 3T
Sugi Plantation  Transition 4T  Non Native Grass
Sugi Plantation  Transition 5T  Sugi Plantation
Sugi Plantation  Transition 6T  Young Mixed Native Forest
Young Mixed Native Forest  Transition 7T  Adult Mixed Native Forest
Young Mixed Native Forest  Transition 8T  Non Native Grass
Young Mixed Native Forest  Transition 9T  Non Native Grass
Non Native Grass  Transition 10T  Young Mixed Native Forest
```
Pathways for DHHL

Scenario 3 - AMLP for Carbon Credits

Strata: O

Barren → Transition 1-O → Non Native Grass
Barren → Transition 2-O → Young Mixed Native Forest
Barren → Transition 3-O → Young Native Shrubland
Barren → Transition 4-O →
Young Mixed Native Forest → Transition 5-O → Adult Mixed Native Forest
Young Mixed Native Forest → Transition 6-O → Non Native Grass
Young Mixed Native Forest → Transition 7-O → Non Native Grass
Adult Mixed Native Forest → Transition 8-O → Non Native Grass
Adult Mixed Native Forest → Transition 9-O →
Young Native Shrubland → Transition 10-O → Non Native Grass
Young Native Shrubland → Transition 11-O → Non Native Grass
Young Native Shrubland → Transition 12-O → Mixed Native Shrubland

Mixed Native Shrubland → Transition 13-O → Non Native Grass
Mixed Native Shrubland → Transition 14-O → Non Native Grass
Mixed Native Shrubland → Transition 15-O →
Non Native Grass → Transition 16-O → Young Mixed Native Forest
Non Native Grass → Transition 17-O → Young Native Shrubland
Non Native Grass → Transition 18-O →
Gorse → Transition 19-O → Non Native Grass
Pathways for DHHL
Scenario 3 - AMLP for Carbon Credits

Strata: R – Same as K w/o harvest or grazing

- Goise ➔ Transition 1R ➔ Young Mixed Native Forest
- Non Native Grass ➔ Transition 1R ➔ Young Mixed Native Forest
- Barren ➔ Transition 1R ➔ Young Mixed Native Forest
- Young Mixed Native Forest ➔ Transition 2R ➔ Adult Mixed Native Forest
- Adult Mixed Native Forest ➔ Transition 3R ➔ Young Mixed Native Forest
- Young Mixed Native Forest ➔ Transition 4R ➔ Non Native Grass
- Adult Mixed Native Forest ➔ Transition 5R ➔ Non Native Grass
- Non Native Grass ➔ Transition 6R
- Barren ➔ Transition 7R
This thesis would not have been possible without advanced access to the following chapters of the Carbon Assessment of Hawai‘i currently in review:

Chapter 1. An Assessment of Baseline and Projected Carbon Storage and Flux in the Hawaiian Archipelago - Scope and Methodology
Christian P. Giardina, Paul C. Selmants, James D. Jacobi

Chapter 2. Baseline Land Cover

Chapter 5. Wildland fires and greenhouse gas emissions in Hawaii
Todd J. Hawbaker Clay Trauernicht, Stephen Howard, Creighton M., Christian P. Giardina, James Jacobi, Lucas Fortini, R. Flint Hughes, Paul C. Selmants, and Zhiliang Zhu


Chapter 8. Projected Future Carbon Storage and Carbon Fluxes in Terrestrial Ecosystems of Hawaii from Changes in Climate, Land use and Disturbance


Department of Hawaiian Home Lands, 2009. `Āina Mauna Legacy Program. Hookuleana LLC, Kailua, HI.


Hess, S. C., and Banko, P. C., 2011: Sheep vs. palila on Mauna Kea: after 200 years of damage, can these native birds recover? Wildlife Professional **5**: 60 –63


Keen, P. G. W. 1978. Decision support systems: an organizational perspective. Addison-Wesley, Reading, MA.


Thomas, J. W. 1995. The forest service program for forest and rangeland resources: a long-term strategic plan, draft, RPA Program. Washington, DC.


USDA Forest Service. 2008. Forest Service Strategic Framework for Responding to Climate Change available online at www.fs.fed.us/climatechange/documents стратегический план изменения климата федеральное управление лесов


