CHARACTERIZING HUMAN-ENVIRONMENT INTERACTIONS IN THE GALÁPAGOS ISLANDS: A CASE STUDY OF LAND USE/LAND COVER DYNAMICS IN ISABELA ISLAND

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Abstract

AMY L. MCCLEARY: Characterizing Human-Environment Interactions in the Galápagos
Islands: A Case Study of Land Use/Land Cover Dynamics in Isabela Island
(Under the direction of Stephen J. Walsh)

This dissertation examines contemporary land use and land cover (LULC) change in the communities and protected areas of Isabela Island to provide insights into human-environment interactions in the Galápagos Islands of Ecuador. The growing human presence in Galápagos over the last four decades has been accompanied by significant changes in LULC on inhabited islands in the archipelago. Local stakeholders and decision-makers have recently called for a more integrative approach to understanding interactions between people and the environment in the archipelago.

This study is guided by two complementary bodies of work situated within the human-environment tradition of Geography – land change science and landscape ecology. First, support Vector Machine (SVM) and Object Based Image Analysis (OBIA) classifiers are evaluated for mapping LULC from high spatial resolution satellite images. The results show that thematic LULC classifications produced by OBIA are more accurate overall than those generated by SVM. However, important tradeoffs exist between improvements in classification accuracy and processing requirements.

The composition and spatial configuration of LULC change are then mapped and quantified from a time series of QuickBird and WorldView-2 satellite images from 2003 to 2010. The pattern metric and change detection analyses reveal that land use change is extensive within the communities due to the expansion and consolidation of built-up areas, and fragmentation of and declines in agriculture. The Galápagos National Park is primarily transformed by exotic plant invasion, forests expansion, and shrinking coastal lagoons.

Patterns of agricultural land abandonment, plant invasion, and forest expansion over the same period are described from pattern metric and overlay analyses. Potential drivers of these LULC transitions are identified from logistic regression models, descriptive statistics of agricultural surveys and population censuses, and interviews with landowners. The results reveal that agricultural abandonment is widespread throughout Isabela, and many abandoned fields are invaded by introduced plants, such as guava. Biophysical and geographic factors, such as topography and distance to roads, do not significantly explain patterns of agricultural land abandonment or associated land cover transitions at the pixel level. However, rural-urban migration, declines in the profitability of agriculture, and small labor pools appear to influence agricultural abandonment.

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List of Abbreviations

AMSL – Above Mean Sea Level

ASTER – Advanced Spaceborne Thermal Emission Reflection Radiometer

CA – Class Area

CDF – Charles Darwin Foundation

CGREG – Consejo de Gobierno de Régimen Especial de Galápagos

CLIRSEN – Centro de Levantamientos Integrados de Recursos Naturales por Sensores Remotos

DEM – Digital Elevation Model

ED – Edge Density

ENN – Euclidean Nearest Neighbor Distance

GCP – Ground Control Point

GEOBIA – Geographic Object Based Image Analysis

GIS – Geographic Information Systems

GLCM – Gray-level Co-occurrence Matrix

GNP – Galápagos National Park

GNPS – Galápagos National Park Service

GPS – Global Positioning System

IGM – Instituto Geográfico Militar

IJI – Interspersion-Juxtaposition Index

INEC – Instituto Nacional de Estadistica y Censo

ISA – Intensive Study Area

IUCN – International Union for Conservation of Nature

JM – Jeffries-Matusita

LPI – Largest Patch Index

LULC – Land Use and Land Cover

MAGAP – Ministerio de Agricultura, Ganadería, Acuacultura y Pesca

MPS – Mean Patch Size

NNCV – Nearest Neighbor Coefficient of Variation

NP – Number of Patches

NWS CPC – National Weather Service Climate Prediction Center

OBIA – Object Based Image Analysis

PLAND – Percentage of Landscape

PSCV – Patch Size Coefficient of Variation

RBF – Radial Basis Function

ROI – Region of Interest

RPC – Rational Polynomial Coefficients

RMSE – Root Mean Square Error

SR – Simple Ratio

SVM – Support Vector Machine

SWIR – Short Wave Infrared

TIR – Thermal Infrared

TNC – The Nature Conservancy

VNIR – Visible and Near Infrared

CHAPTER 1: Introduction

1.1 Background

The Galápagos Islands, renowned for their wildlife, are perhaps best known for inspiring Charles Darwin's theory of evolution by natural selection. This volcanic island chain located in the Pacific Ocean is home to plant and animal species found nowhere else on Earth, such as giant tortoises. While the archipelago retains an estimated 95% of its original (i.e., pre-discovery) biodiversity (CDF and WWF, 2002), the social and ecological setting of the Galápagos has been drastically transformed over the past four decades. The archipelago was sparsely populated from its discovery by Europeans in the 1530s through the early 1970s. Since then, tens of thousands of Ecuadorians, driven by poor economic conditions on the mainland and attracted by the possibility of job opportunities in tourism and commercial fisheries, have immigrated to Galápagos (Bremner and Perez, 2002; Boersma et al., 2005; Watkins and Cruz, 2007). As a result, the population of Galápagos has more than quadrupled, growing from 4,000 residents in 1974 to more than 25,000 by 2010 (Epler, 2007; INEC, 2011). Over the same period, the tourism industry expanded considerably, cementing Galápagos' reputation as one of the premier ecotourism destinations in the world. In 2011, more than 185,000 Ecuadorian and foreign visitors traveled to Galápagos (GNPS, 2012).

The growing human population in Galápagos has been accompanied by significant changes in land cover and land use, particularly on the four inhabited islands in the archipelago – Santa Cruz, San Cristóbal, Isabela, and Floreana. The prevalence of introduced plants and animals has increased in-step with population growth (Mauchamp, 1997; Kerr et al., 2004; Watkins and Cruz, 2007). Some of the worst invaders, such as guava (*Psidium guajava* L.) and red quinine (*Cinchona pubescens*), transform plant communities composed of native and endemic species within the protected area (Jäger et al., 2009) and reduce agricultural productivity on farms (Chiriboga et al., 2007). Coastal towns have become more urbanized with the expansion and densification of buildings and the development of transportation infrastructure to support the influx of residents and tourists (Cléder and Grenier, 2010; Walsh et al., 2010; Gardener and Grenier, 2011; Hennessy and McCleary, 2011). As a result, bays and coastal lagoons have become polluted and freshwater sources have been depleted (Kerr et al., 2004; d'Ozouville et al., 2008), threatening aquatic ecosystems and negatively impacting human health (Gelin and Gravez, 2002; Walsh et al., 2010). Further, the shift toward a more market-oriented economy based on tourism has led to agricultural land abandonment, which facilitates the expansion of invasive plants across communities and protected areas in the highlands (Rodriguez, 1993; Chiriboga and Maignan, 2006).

In 1998, the Ecuadorian government passed the Special Law for Conservation and Sustainable Development of the Province of Galápagos[1] in an effort to address environmental degradation and increasing social conflicts in the archipelago. The law provided local institutions more autonomy in governing Galápagos through a legal framework designed to ensure sustainable development of the inhabited islands and continued protection of biodiversity throughout the archipelago (Ospina, 2008). By granting the province special status within Ecuador, lawmakers were able to institute strict immigration and residency

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[1] Ley de Régimen Especial para la Conservación y Desarrollo Sustentable de la Provincia de Galápagos (LOREG), Registro Oficial No. 278, 18 March 1998, Ecuador.

restrictions to limit population growth; create an inspection and quarantine system to prevent the introduction of non-native flora and fauna; and establish a quota system for hotel beds and cruise ship berths to regulate tourism (Epler, 2007; González et al., 2008).

The Special Law, however, was not entirely effective in curbing immigration, limiting tourism, or slowing the introduction of exotic species. In the mid-2000s, national and international concern grew over continued environmental and social changes in the Galápagos. In April, 2007 the President of Ecuador issued an Emergency Decree declaring Galápagos "at risk", and the UNESCO World Heritage Committee took similar steps months later by inscribing the archipelago on their list of World Heritage In Danger.

In June 2010 the archipelago was formally removed from the In Danger list. At the time, a number of organizations voiced their apprehension over the de-listing, noting that many of problems cited in the World Heritage Committee's decision to place Galápagos on the list had yet to be fully addressed and warranted continued action (Galapagos Conservancy, 2010; IUCN, 2010a). Several authors have argued that this "social-ecological crisis"[2] (González et al., 2008: 7) not only brings attention to recent social and ecological changes, but that it also highlights the need for more comprehensive and integrative approaches to understanding and addressing interactions between people and the environment in Galápagos (Watkins and Cruz, 2007; González et al., 2008; Tapia et al., 2009).

1.2 Study Aims

The aim of this research is to contribute to an improved understanding of human-

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[2] González et al. (2008) use this term to refer to the period following passage of the Galápagos Special Law (1998) through UNESCO's removal of Galápagos from its "In Danger" list (2010).

environment interactions in the Galápagos Islands during the latter half of this “crisis” period by mapping and modeling the patterns and determinants of land use and land cover (LULC) change on Isabela Island, and by considering the consequences of these changes for people and the environment. Land change is recognized as an issue of global importance that has considerable implications for defining human-environment interactions (Gutman et al., 2004; Rindfuss et al., 2004b). The following research questions are addressed in this study:

1) Which classification approach – Support Vector Machine (SVM) or Object Based Image Analysis (OBIA) – is more effective in mapping LULC and discriminating among LULC types from remotely sensed data?

2) How has the composition and spatial configuration of LULC in Isabela Island changed between 2003/2004 and 2010? How do the patterns of LULC change differ between the island’s two communities and the Galápagos National Park?

3) What are the patterns of agricultural land abandonment, plant invasion, and forest expansion, at the farm and community levels, between 2004 and 2010 in Isabela Island? How do biophysical, geographic, socio-economic, and demographic factors contribute to these LULC transitions?

This study combines remote sensing, Geographic Information Systems (GIS), and statistical analyses of satellite images, spatial data layers representing the physical environment, secondary socio-economic and demographic data sets, and a small landowner survey to address these questions.

Isabela Island was selected for this study for several reasons. First, many of the changes in land cover and land use identified elsewhere in Galápagos, such as agricultural land abandonment, the development of coastal areas, and the widespread expansion of invasive species, have only recently occurred on Isabela (since the early 1990s). Therefore, Isabela offers an opportunity to examine the early stages of these land cover transitions, which may shed light on how these processes unfolded on other islands in the archipelago. Second, Isabela is important from the perspective of conservation because it has the highest concentration of endemic species in Galápagos (Epler, 2007; Proaño, 2007) and it contains the largest marine-coastal wetlands complex in the archipelago (Chávez and Cruz, 2002). The natural features that give the island its ecological value are also attractive to tourists, fueling speculation that Isabela could soon become a hub for land-based tourism (Epler, 2007; Walsh et al., 2010).

The objective of this introductory chapter is to provide an overview of the dissertation. In the sections that follow, the characteristics of the study area are described; summaries of the specific research questions, hypotheses, data, and methods employed in each chapter are presented; the theories and bodies of literature that inform this work are briefly described; and the contributions of this research are highlighted.

1.3 Study Area

The Galápagos Archipelago is a chain of volcanic islands in the Pacific Ocean, located approximately 1,000 km off the coast of Ecuador. The archipelago is comprised of 14 large islands, four of which are inhabited, and more than one hundred small islands and rocks totaling 8,010 km^2 dispersed throughout an area of 70,000 km^2. Among the most active volcanic islands in the world, the Galápagos Islands have formed as the Nazca Plate moved over a mixed mantle plume, or “hot spot” (Simkin, 1984; Stewart, 2006). The oldest islands in the archipelago lie to the southeast (e.g., Española Island), as the Nazca Plate moves in that direction, while the westernmost islands (Fernandina and Isabela) are currently situated over the Galapágos hot spot (Neall and Trewick, 2008; Christie et al., 1992).

The archipelago has never been connected to the mainland (Simkin, 1984), and as a result, the plants and animals that colonized the islands evolved in isolation. This isolation, which persisted until the islands were discovered by Europeans in 1535, led to unique life forms highly adapted to their surroundings. The differences that emerged among species on different islands, and in comparison to mainland South America, are what Charles Darwin found so interesting about Galápagos (Durham, 2008). However, this isolation has declined over the last several decades due to the influx of people, goods, and non-native species (Watkins and Cruz, 2007; Durham, 2008).

1.3.1 Biophysical Setting

This research takes place in southern Isabela Island, between Latitude 0°47' and 0°58' S and Longitude 91°06' to 90°59' W (Figure 1.1). Located in the western portion of the Galápagos, Isabela is the largest (4,588 km^2) and one of the youngest islands in the archipelago. The island is comprised of six shield volcanoes geographically divided from north to south by Perry Isthmus; northern Isabela includes Alcedo, Ecuador, Darwin, and Wolf volcanoes, while southern Isabela consists of Sierra Negra and Cerro Azul. Two intensive study areas (ISAs) are located along the southeastern flank of Sierra Negra Volcano. The Coastal ISA, totaling 8 km^2, encompasses the growing community of Puerto Villamil (1.5 km^2), and a surrounding area protected under the Galápagos National Park (6.5 km^2). The Highlands ISA includes the rural community of Santo Tomás (52 km^2) and a buffer that extends into the National Park (8 km^2).

The climate of southern Isabela is semi-arid and sub-tropical, with two distinct seasons. During the warm season from January to May, air temperatures average between

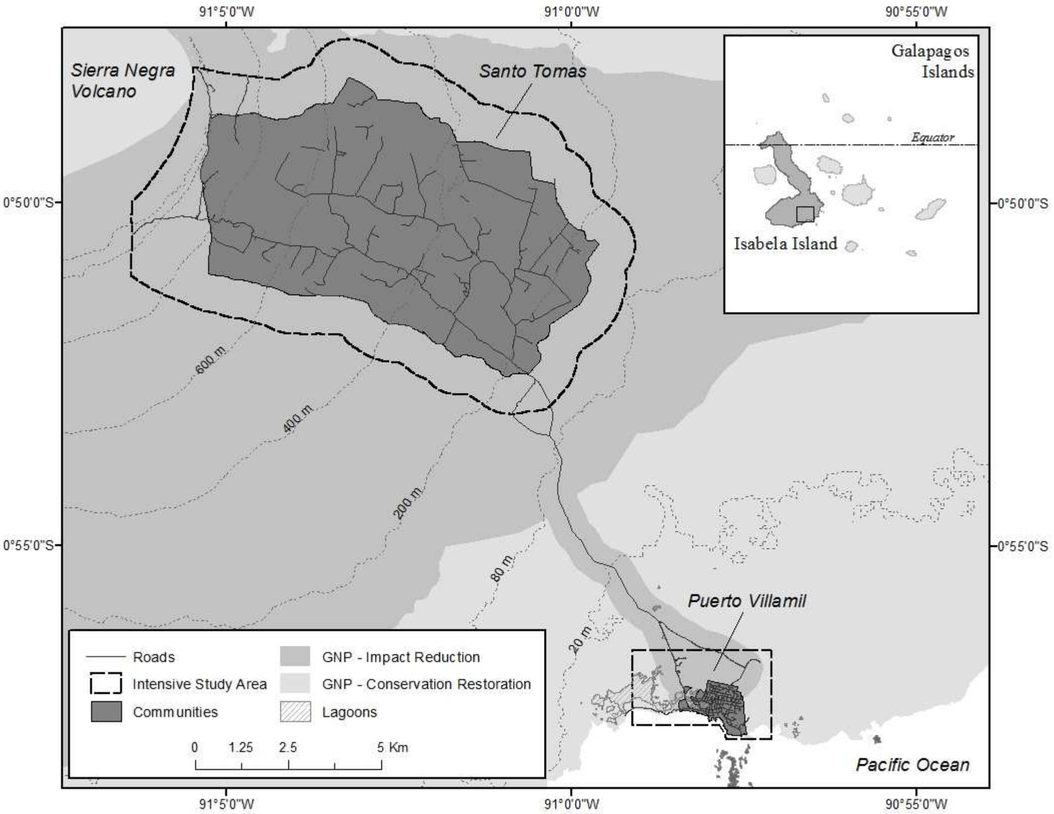

Figure 1.1 The study area located in southern Isabela Island includes two intensive study areas (ISA). The Highlands ISA includes the community of Santo Tomás and part of the Galápagos National Park (GNP). The Coastal ISA encompasses the community of Puerto Villamil and the surrounding GNP

22°C to 30°C (monthly), and sporadic rain showers are common (Guézou et al., 2007; Trueman and d'Ozouville, 2010). The cool season, from June to December, is marked by a reduction in precipitation and air temperatures (19°C to 26°C) (ibid.). Although it is drier along the coast, a near permanent fog, called *garúa*, occurs in the highlands during this period due to an inversion layer that forms over the archipelago (Collins and Bush, 2011; Pryet et al., 2012). Weather patterns shift markedly, however, during El Niño (warmer, wetter) and La Nina (cooler, drier) events.

Elevation in the study area varies from sea level to 1040 m above mean sea level (AMSL). Along the coast the topography is relatively flat, with slope angles less than 0.5° and only a small rise in elevation from south to north. In contrast, the highlands are characterized by high topographic relief. Elevation rises gradually from 80 m to 1040 m AMSL from southeast to northwest, while slope angles vary from 0° to 42°. The parent geological material is primarily basaltic lava flows and pyroclastic materials, with extremely shallow sandy soils dominating the lowlands, and clayey loams up to several meters in depth in the highlands (Laruelle, 1966; Franz, 1980; Valarezo, 2008).

Vegetation patterns on Isabela Island are determined by geomorphology (which affects soils and landforms), elevation (which generates temperature and moisture gradients), and aspect (which controls moisture availability) (Shimizu, 1997). Six vegetation zones are commonly recognized in southern Isabela, progressing upward in elevation from the coast (Figure 1.2): littoral, arid, transition, scalesia, miconia, and fern-sedge (Wiggins and Porter, 1971; McMullen, 1999). Vegetation along the coastal fringe and within several meters of coastal lagoons, the littoral zone, is comprised of woody shrubs and small trees, as well as a few salt-tolerant herbs and perennial grasses (Wiggins and Porter, 1971; Colinvaux, 1984). Mangrove forests here are composed of three species – *Laguncularia racemosa* (white),

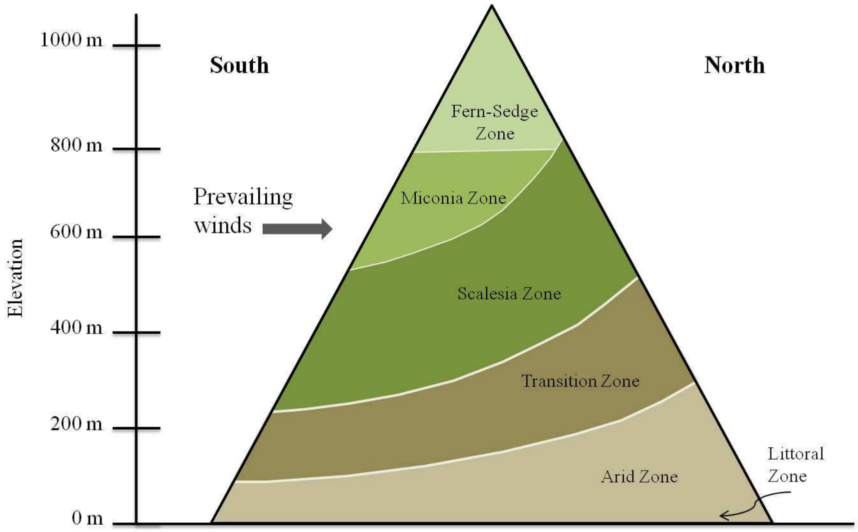

Figure 1.2 Vegetation zones organized by elevation on Isabela Island, according to Wiggins and Porter (1971). Adapted from Trueman et al. (2011)

Avicennia germinans (black), and *Rhizophora mangle* (red) – and associated species such as *Hippomane mancinella* (manzanillo) (Wiggins and Porter, 1971; Heumann, 2011). Vegetation in the arid zone, encompassing dry lowland communities immediately inland and up to 80 m in elevation AMSL, includes several endemic cacti (*Opuntia* spp.), a mix of spiny shrubs and small trees such as cat's claw (*Zanthoxylum fagara* (L.) Sarg.) and palo santo (*Bursera graveolens*), and herbs that emerge during the wet season (Wiggins and Porter, 1971; Colinvaux, 1984). The Coastal ISA lies within the littoral and arid zones on Isabela.

The Highlands ISA coincides with the other four vegetation zones – the transition zone composed of evergreen and semi-deciduous plants, and the scalesia, miconia, and fern-sedge zones, sometimes collectively referred to as the humid zone, where introduced vegetation occupies areas once dominated by endemic *Scalesia cordata* forests and open grasslands. The transition zone begins at an elevation of 80 m AMSL and continues upward to the lower edge of the humid zone at approximately 200 m AMSL. As its name implies, the transition zone is an intermediate region that includes xerophytic plants that extend upward from the arid zone (e.g., *B. graveolens*) and mesophytic plants (e.g., *Psidium galapageium*) that are characteristic of the humid zone at higher elevations (Wiggins and Porter, 1971; Itow, 2003).

The humid zone has traditionally been sub-divided on the basis of three native vegetation types - forests of endemic *S. cordata* (200 m to 500 m AMSL), shrubs above treeline (sometimes referred to as the "miconia zone"; 500 to 800 m AMSL), and fern-sedge communities at the highest elevations (above 800 m AMSL) (Wiggins and Porter, 1971; Froyd et al., 2010). The humid zone was favored for agriculture because there is sufficient precipitation and soil material to grow crops and raise livestock. However, plants introduced for cultivation have significantly transformed these communities, and invasive plants are replacing native vegetation within the humid zone (Tye, 2001). For example, *S. Cordata*, a small, endemic tree that was once ubiquitous in the humid zone of southern Isabela has been almost wholly replaced by introduced vegetation such as guava (*Psidium guajava* L.) and rose apple (*Syzygium jambos* (L.) Alston), and is now considered extremely threatened by the International Union for Conservation of Nature (IUCN) (IUCN, 2010b; Philipp and Nielsen, 2010; Mauchamp and Atkinson, 2010). Guava and rose apple, woody species once cultivated for their fruit, now form dense, monospecific stands that shade out native vegetation (Soria et al., 2002) and significantly transform the ecosystems they invade in the archipelago (Tye et al., 2002).

1.3.2 Social Setting

Isabela Island (Isabela Canton) consists of two parishes: the urban parish of Puerto Villamil and the rural parish of Tomás de Berlanga (locally referred to as Santo Tomás). Cantons, administrative divisions in Ecuador equivalent to the county-level in the United States, are sub-divided into parishes that are classified as urban if they include the provincial capital or the cantonal head, and rural otherwise. These parishes make up only 1.1% of Isabela’s terrestrial area, with the remaining 98.9% of land on the island protected under the Galápagos National Park.

The administration of Puerto Villamil and Santo Tomás, which are comprised of privately owned and municipal held lands, is the responsibility of the Municipality of Isabela. The municipality generally adopts rules and regulations that apply to Puerto Villamil, while a parish board is the decision making body for Santo Tomás; these communities are further subject to regulations adopted by the Province of Galápagos, and by the Ecuadorian state. The Galápagos National Park Service manages the protected areas on Isabela Island, which make up all land outside the island's two communities. Human settlements are not permitted in the National Park, but a limited number of special uses are permitted in select sites including tourism, transportation infrastructure, and water extraction.

The history of human settlements in Isabela, as in the rest of Galápagos, is relatively short. In the late 1890s, a small number of families and individuals settled Isabela Island. Although a few people resided in the port town of Puerto Villamil, located on the island's southeastern coast, the majority of households lived and worked on a large hacienda established in the humid highlands near what is now Santo Tomás (Perry, 1984; Ospina-Peralta, 2006; Chiriboga and Maignan, 2006). Settlement of Isabela coincided with Ecuadorian policies meant to populate Galápagos to reinforce the state's territorial claims to the remote archipelago (Constantino, 2007).

Within thirty years of its establishment, the hacienda was dissolved and its land was redistributed among former laborers, each of whom received between 10 and 20 ha of land (Chiriboga and Maignan, 2006). These small, family farms were characterized by subsistence-based agricultural production that included annuals like yucca, potatoes, and vegetables, small numbers of domesticated animals grazing on natural pastures, and shade-grown coffee (a legacy of the hacienda) (Perry, 1984; Chiriboga and Maignan, 2006; Ospina-Peralta, 2006). Extensification of agriculture and ranching continued throughout the 1970s, primarily driven by the slow influx of immigrants from mainland Ecuador; artisanal fishing along the coast became a secondary economic activity (MacFarland and Cifuentes, 1996). Large areas of native vegetation were cleared in the highlands and replaced by cultivars and other plants introduced from the mainland. In 1974, fifteen years after the Galápagos National Park was established, the boundaries of the protected area were formalized (Maignan, 2007; Villa and Segarra, 2010). Existing settlements, including Santo Tomás and Puerto Villamil, were excluded from the National Park and human activities were restricted to areas that had already been cleared, developed, or otherwise modified.

In the two decades that followed, Isabela's economy diversified and jobs outside of traditional industries (i.e., agriculture and artisanal fishing) increased (Ospina-Peralta, 2006; MacFarland and Cifuentes, 1996). A substantial number of administrative jobs in local government agencies and institutions were created after Galápagos was incorporated as the 22nd province of Ecuador (Epler, 2007). Expansion of land-based tourism on the island led to increased employment opportunities in construction and in businesses catering to tourists (e.g., hotels, restaurants, tour companies) (González et al., 2008). The majority of these new jobs were located in Puerto Villamil, where the central government funded development projects to enhance infrastructure and public services, such as electricity, water, and schools (Epler, 2007). Lucrative off-farm job opportunities combined with declining agricultural profits attracted many people to move to Puerto Villamil (Chiriboga et al., 2007). Landowners increasingly invested less time and money in agricultural production, and as a result, marginal agricultural lands were abandoned (PNG, 2005; Chiriboga and Maignan, 2006; González et al., 2008).

A fishing boom in Galápagos during the 1990s, coupled with poor economic conditions in mainland Ecuador, resulted in new waves of immigration to Isabela as people sought to profit from commercial fisheries (Bremner and Perez, 2002; Boersma et al., 2005; Watkins and Cruz, 2007). Isabela's population grew steadily in the years that followed from

870 residents in 1990, and 1,600 in 2001, to more than 2,200 by 2010; this equates to growth rates between 5.9% and 3.3% per year (authors calculations based on INEC, 2002; INEC, 2011). Between 1992 and 2009, the extent of Puerto Villamil nearly tripled, and the density of buildings and roads within the community increased significantly (Walsh et al., 2010). Continued development of the community is visible in the construction of new homes, hotels and restaurants, and new dock and airport facilities meant to improve accessibility for tourists (ibid.). *Isabela Crece por Ti* (Isabela Grows for You), the unofficial motto of the island, can be seen on signs, park benches, and vehicles across town and seems indicative of the Island's future. Figure 1.3 shows several photos of the communities and protected areas on Isabela Island.

Figure 1.3 Clockwise from top left: Lowland vegetation; farmers market in Puerto Villamil; farm in Santo Tomás; Puerto Villamil beach; invasive Guava in the National Park; sign proclaiming "Isabela Grows for You". Photos by author (2008, 2009)

In contrast, the number of Santo Tomás residents has declined since 1990; in 2010, fewer than 170 individuals (7.6% of Isabela's population) remained in the community (INEC, 2011). Land within the community is still used primarily for crop cultivation and livestock grazing, and is characterized by residential buildings set on small- to medium-sized parcels. However, an increasing amount of agricultural land is no longer actively managed and has been abandoned as farm households continue to emigrate to Puerto Villamil (Chiriboga and Maignan, 2006).

1.4 Chapter Summaries

The research presented in this dissertation is organized into three chapters that take the form of journal articles. The research questions, hypotheses, data sets, and methods pertaining to each chapter are summarized below. The last chapter of the dissertation synthesizes the research questions, analyses, and results; discusses the contributions and implications of the major findings; and identifies potential avenues for future research.

1.4.1 Chapter 2: Comparison of Support Vector Machine and Object Based Image Analysis Approaches for Mapping Land Use/Land Cover

Remote sensing and image interpretation have become standard approaches for mapping LULC. Of the many automated classification approaches that exist, two have emerged in recent years for LULC characterization based on high spatial resolution imagery: Support Vector Machine (SVM) and Object Based Image Analysis (OBIA). SVM is a non-parametric machine learning algorithm that uses training data samples to determine the optimal linear boundary between pairs of classes (Vapnik, 2000). Image pixels are then assigned to discrete classes based on their position with respect to the decision boundary in feature space. OBIA is a rule-based classification approach that integrates image processing and GIS functionalities in the classification of non-overlapping image segments, or objects, which represent landscape features. In addition to the spectral data contained in the image bands, contextual information, such as the spatial, topological, and textural characteristics of the image objects, can be used to define the inclusion or exclusion parameters for OBIA classification (Lang, 2008).

In Chapter 2, SVM and OBIA classifiers are evaluated for mapping LULC from a high spatial resolution satellite image of southern Isabela Island. Two research questions are specifically addressed in this chapter:

1) How do the LULC classification results from SVM and OBIA differ?
2) Which classification approach is more effective in distinguishing and mapping LULC as measured by the accuracy of the resulting thematic maps?

To this end, pixel-based (SVM) and object-based (OBIA) classifiers are applied to a contemporary image of the southeastern slope of Sierra Negra Volcano on Isabela Island acquired October 23, 2010 from the newly launched WorldView-2 sensor. General LULC categories that represent the most common land uses and cover types in the study area are mapped, including built-up, dry grassland, agriculture/grassland, lava rock, bare soil, and forest/shrub. Two introduced invasive plant species, guava (*Psidium guajava* L.) and rose apple (*Syzygium jambos* (L.) Alston), are also mapped. *In situ* LULC data collected in 2008 and 2009 are used to train the classifiers and to assess the accuracy of the classified maps. The results are discussed in light of the tradeoffs between improvements in classification accuracy and the processing time, training data requirements, and the amount of analyst control over classification parameters associated with each approach.

1.4.2 *Chapter 3: Land Use and Land Cover Change in Southern Isabela Island, 2003-2010*

Inhabited islands in the Galápagos Archipelago have undergone major changes in LULC over the last three decades. Land change has been recognized as an issue of global importance as land use activities and resultant changes in land cover can change the structure and function of ecosystems (Foley et al., 2005) and can reduce biodiversity through habitat modification (Pimm and Raven, 2000; Sala et al., 2000). In many countries, protected areas have been established as a mechanism to limit the direct impacts of human activities on biodiversity and to maintain ecosystem functioning. Unfortunately, data on LULC and change in the Galápagos Islands are limited (González et al., 2008). The lack of spatially-explicit data and the coarse nature of existing maps have hampered previous efforts to quantify changes in land use for the purpose of resource management in communities (Villa and Segarra, 2010), and to assess human-caused land degradation (Watson et al., 2009).

The aim of Chapter 3 is to provide an improved understanding of contemporary LULC change in the Galápagos Islands by quantifying recent changes in the communities and surrounding protected areas of southern Isabela Island. Two research questions are specifically addressed:

1) How has the composition and spatial configuration of LULC changed in southern Isabela Island between 2003/2004 and 2010?

   It is hypothesized that during this period, the amount of land devoted to agriculture declined and built-up land use increased in southern Isabela. Declines in vegetation cover have likely occurred where built-up cover increased, and an expansion of invasive species cover is anticipated at the expense of agriculture. It is expected that built-up land and invasive plant patches each coalesced as they expanded to occupy new areas, while natural land covers – forest/shrubs, grasslands, coastal vegetation, and coastal lagoons – became more fragmented as they were converted to other cover types.

2) How do the patterns of LULC change differ between the communities and the protected areas?

   LULC in the protected areas is hypothesized to be less likely to change due to the large size of the protected area in comparison to land set aside for the communities, and because of restrictions on land use within the National Park. It is expected, however, that some changes in land cover have occurred in the protected area as the result of land use change within the adjacent communities (e.g., invasion of National Park grasslands by introduced plants found in agricultural fields), particularly along park-community borders.

To answer these questions, an object-based classifier is applied to a time series of high spatial resolution QuickBird and WorldView-2 satellite images from 2003/2004, 2008, and 2010 to generate LULC maps of the study area. Landscape composition is quantified in each period from the classified maps, and spatial configuration is described using pattern metric analysis. Changes in landscape composition and configuration between 2003/2004 and 2010 are quantified with from-to change matrices. The LULC changes observed in southern Isabela are then discussed relative to other inhabited islands in the archipelago using the most complete map of LULC for the Galápagos Islands to date (completed in 2006), and from changes reported in the literature.

1.4.3 Chapter 4: Patterns and Drivers of Agricultural Abandonment, Plant Invasion, and Forest Expansion in Southern Isabela Island

Agricultural extensification and deforestation remain prominent land change processes in many parts of Latin America, but an increasing number of countries are witnessing the abandonment of marginal agricultural lands and the subsequent recovery of forest ecosystems (Ramankutty and Foley, 1999a; Aide and Grau, 2004; Grau and Aide, 2008). Agricultural land abandonment was first reported in the Galápagos Islands in the 1980s (Rodriguez, 1989; Rodriguez, 1993; González et al., 2008), but the rate of abandonment and the prevalence of abandoned farms appears to have increased in the last two decades (Chiriboga and Maignan, 2006; Maignan, 2007). Several reasons for this process have been proposed, including a shift toward a more market-oriented economy based on tourism rather than traditional livelihoods (e.g., fishing and agriculture); migration of farm households to the coastal communities to take advantage of these new opportunities; and declines in available labor to maintain productive farms.

The goal of Chapter 4 is to identify patterns and potential determinants of agricultural land abandonment and resultant land cover changes (exotic plant invasion and forest expansion) in Isabela Island between 2004 and 2010. Three research questions are addressed:

1) What are the patterns of agricultural land abandonment, plant invasion, and forest expansion in Isabela Island, at the farm and community level, between 2004 and 2010?

   Previous work has shown that the amount of land devoted to agricultural land use declined in southern Isabela between 2004 and 2010 (this work, Chapter 3). It is expected that small fields, rather than entire farms, were abandoned in the period, with losses primarily concentrated on the largest farms. Guava (*Psidium guajava* L.) invasion and forest expansion likely occurred where agricultural land was abandoned (i.e., in old fields), leading to similar patterns of abandonment, invasion and forest expansion.

2) How are agricultural land abandonment, plant invasion, and forest expansion related to variables representing the biophysical and geographic characteristics of southern Isabela?

   Agricultural abandonment is hypothesized to be associated with marginal sites located at lower elevations and on steeper slopes, where the geomorphic substrate is rocky, and in remote areas (i.e., farther from roads) where the cost of production is greater. Guava can adapt to a range of environments and climatic conditions, so it is expected that guava invasion will be associated with all but the lowest elevations, regardless of slope or aspect, and in the least accessible sites. Forest expansion is expected to be associated with higher elevation sites, in areas where the substrate is less rocky, and in remote sites far from roads and Puerto Villamil.

3) In what ways have socio-economic and demographic characteristics of the island's communities changed between 2000 and 2010, and how might these factors be associated with agricultural abandonment?

   As a result of agricultural land abandonment, crop harvests and livestock production are expected to decline. It is hypothesized that increased off-farm employment opportunities will result in a larger proportion of the island's population residing in Puerto Villamil. The proportion of farms employing agricultural laborers is not expected to rise, however, due to declines in the profitability of agriculture.

The composition and configuration of agricultural abandonment, guava invasion, and forest expansion between 2004 and 2010 are described from pattern metrics calculated for the LULC transitions generated in Chapter 3. Land parcel boundaries are superimposed on the transition maps in a GIS database to summarize the extent and magnitude of changes at the farm and community level. Logistic regression models are then developed to assess how agricultural abandonment, guava invasion, and forest expansion (dependent variables) are related to a set of biophysical and geographic factors (e.g., topography, geomorphology, distance to roads; independent variables); one model is generated for each LULC transition.

Descriptive statistics and cross-tabulations of secondary data – including national population censuses (INEC, 2002; 2011), a national agricultural census (INEC and MAG, 2001), and a living standards survey of Galápagos (INEC and CGREG, 2010) – are generated to assess changes in the socio-economic and demographic characteristics of Santo Tomás and Puerto Villamil between 2000 and 2010. These data are supplemented by information from interviews of 45 Santo Tomás landowners conducted by the author in 2008, which are used to contextualize the quantitative analyses and to provide a deeper understanding of LULC transitions and population change in southern Isabela. The lack of fine-level spatial information for the secondary data sets prevents quantitative modeling of the socio-economic and demographic drivers of the transitions. The goal, therefore, is to generate hypotheses about the social factors responsible for land change in Isabela.

1.5 Theoretical Framework

This research is guided by two complementary bodies of work situated within the human-environment tradition of Geography: land change science and landscape ecology. Land change science has emerged as an interdisciplinary approach for understanding LULC patterns and processes as they affect the structure and function of the Earth system. This approach incorporates theories and methodologies for assessing the causes and consequences of LULC change. Landscape ecology considers the linkages between landscape pattern, process, and function and provides a set of metrics with which to characterize landscape pattern.

1.5.1 Land Change Science

Concern over global environmental change has led to a resurgence of research addressing human impacts on, and interactions with, the Earth’s surface (Rindfuss et al., 2004b). The renewed focus on human-environment interactions has been accompanied by greater interest in understanding land use change (de Sherbinin, 2002). Research on human-environment interactions examined through the lens of land use change has been prolific over the last decade, with contributions from a number of different research communities, such as remote sensing, landscape ecology, political ecology, and resource economics among others (Turner et al., 2007). These efforts have generated an interdisciplinary effort to better understand the patterns and processes of LULC change referred to as *land change science*, or *integrated land change science* (Gutman et al., 2004; Rindfuss et al., 2004b; Turner et al., 2007). Studies under the umbrella of land change science have integrated remotely sensed, biophysical, and social science data and approaches to (1) observe and monitor LULC and its change; (2) explain the biophysical, social, and environmental processes that generate changes in land use, and often as a result, land cover; and (3) use information about the patterns and determinants of land use change to improve spatially-explicit models of coupled human-natural systems (Rindfuss et al., 2004b; Turner et al., 2007).

In its simplest definition, land cover is the set of biophysical attributes that cover the Earth’s surface, and land use encompasses the purposes for which humans exploit land cover

(Lambin et al., 2003). Land change has been recognized as an issue of global importance because land use activities and resultant changes in land cover can impact the physical environment and societies alike. For example, land use practices can reduce biodiversity through habitat modification and the direct exploitation of native species (Pimm and Raven, 2000; Sala et al., 2000). Changes in LULC can also alter the structure and function of ecosystems (Foley et al., 2005). Such alterations may diminish the capacity of ecosystems to provide services that support human needs, such as the provisioning of freshwater or the capacity for food production (Vitousek et al., 1997).

Remote sensing and image interpretation have become standard approaches for mapping LULC. Remotely sensed imagery can not only cover large spatial extents but can also capture information for features of small grains and extents, particularly with the increased availability of moderate resolution data, such as Landsat, combined with high spatial resolution products, such as Ikonos or QuickBird (Walsh et al., 2004). Image interpretation and GIScience methodologies include automated approaches for mapping and assessing change that are efficient and easily repeatable, which can reduce the costs associated with *in situ* data collection and field visits.

A fundamental goal of land change science, in addition to efforts to observe and monitor patterns of land use change, is to better understand the causes and consequences of landscape dynamics by considering pattern-process relationships that represent the social, ecological, and geographic domains (Turner, 2002; Rindfuss et al., 2004b). For example, demographic factors such as population density, fertility, mortality, and the age and sex composition of households can influence LULC change, often in the context of other factors such as land settlement policies and market forces (Entwisle and Stern, 2005). Variability in biophysical and geographic factors, such as climate, soils, topography, and distance to roads or market centers can define the predisposing environmental conditions for land use change (Geist et al., 2006).

Determining the factors that generate land use change requires integrative approaches that link human and natural systems (Rindfuss et al., 2004b). This can be accomplished by directly linking people to the lands that they own, manage, or otherwise influence. For example, the socio-economic characteristics of agricultural households, and the biophysical characteristics of the land they manage, can be spatially associated with farm-level land use change (Walsh et al., 2004). However, linking presents both theoretical and methodological challenges (c.f., Fox et al., 2003), such as deciding whether to link units of land to the people that manage them, or to start with people and link them to the land they own; and how to deal with possible scale mismatches between social, biophysical, and land use datasets (Rindfuss et al., 2004a; Rindfuss et al., 2004b).

Studies of the expansion of agriculture, deforestation, and urbanization have dominated the land change science literature (Lambin et al., 2001; Ramankutty et al., 2006). As a result, processes of land use intensification, particularly agricultural extensification and deforestation in the tropics, are fairly well understood (Geist and Lambin, 2002; Hansen et al., 2008). Some regions across the globe, however, have seen the amount of land devoted to crops stabilize, and a few areas have witnessed declines in agriculture (Ramankutty and Foley, 1999a; Ramankutty et al., 2006). Agricultural land abandonment is not a new process as evidenced by studies documenting abandonment and forest transitions in the United States and Western Europe in the 19th and 20th centuries (Foster, 1992; Ramankutty and Foley, 1999b; Mather, 2001; Gellrich et al., 2007). Abandoned land is becoming more widespread, however, and rates of abandonment appear to be on the rise (Baudry, 1991; Gellrich and Zimmermann, 2007; Hobbs and Cramer, 2007). As previously noted, agricultural land abandonment has even been documented in the Galápagos Islands in the last three decades (MacFarland and Cifuentes, 1996; Chiriboga and Maignan, 2006; Maignan, 2007). Despite the increasing prevalence of agricultural abandonment, the patterns, drivers, and impacts of land abandonment and forest transition remain poorly understood and are an active area of research within land change science (Gellrich and Zimmerman, 2007; Sluiter and de Jong, 2007; Baumann et al., 2011; Diaz et al., 2011).

1.5.2 Landscape Ecology

Landscape ecology provides a theoretical framework and methodology to analyze spatial pattern in order to understand the underlying processes associated with LULC change (Crews-Meyer, 2004). Of particular interest within the field is the detection and characterization of pattern, understanding how and why it develops and changes over time, and its implications for landscape function. Landscape, as the term is used here, refers to an area characterized by spatial heterogeneity (in relation to some factor of interest), on the order of a few hectares to hundreds of square kilometers in size (Turner et al., 1989; Turner et al., 2001). Landscapes are composed of patches, defined as homogenous areas of particular LULC types that differ from their surroundings (Turner et al., 2001).

Land cover patterns are generated by the complex interaction of social and biophysical processes that operate across spatial and temporal scales (Gardner et al., 1987; Urban et al., 1987; Gustafson, 1998). This relationship is reciprocal, as changes in pattern can alter landscape function by interfering with ecological processes (e.g., those that maintain biodiversity) (Turner et al., 1989; Forman, 1995). Quantifying the spatial and temporal patterns of LULC can facilitate the inference of landscape processes that drive LULC change (Brown et al., 2000; Crews-Meyer, 2004). In fact, the description and quantification of landscape composition and configuration, the two components of pattern, is a prerequisite for studies of pattern-process relations (McGarigal and Marks, 1994; Schröder and Seppelt, 2006).

The scale of observation is an important consideration in landscape studies. The patterns that can be observed are determined by the scale of observation, which, in turn, is used to infer process (Crews-Meyer, 2006). Scale encompasses both grain (resolution of the data) and extent (scope or boundary of the data). Scale dependence, or how patterns and processes vary with scale, has been an area of extensive research within geography and landscape ecology. Landscapes exhibit scale dependency in two ways. First, patterns may be exhibited only at particular scales or ranges of scale, such that they are seen as operating at particular levels of organization (Lam and Quattrochi, 1992). Second, the ability to discern pattern depends on the scale of observation and analysis. The spatial and temporal grain and extent of data employed to measure landscape pattern (and changes in pattern) can affect the types of pattern that can be observed, and will therefore impact the inference of process.

Landscape pattern can be measured and represented in a variety of ways, from field based studies to the interpretation of remotely sensed data, and from spatial point to linear network representations (Gustafson, 1998; McGarigal, 2002). Landscape patches can be delimited and thematically attributed through ground-based measurements or, as is the case in this study, from analyses of remotely sensed imagery (Crews-Meyer, 2006). Landscape pattern metrics are then calculated from the resulting thematic maps at the level of individual patches, classes (integrated over all the patches of a particular type), or the landscape (integrated over all patch types or classes across the full extent of the landscape) (McGarigal, 2002). The description of landscape pattern falls into two categories based on the components of pattern: composition and configuration. Composition refers to the variety of LULC types and their relative abundances. Configuration, or structure, is the spatial arrangement of patches on the landscape.

1.6 Contributions

This research will contribute to an improved understanding of human-environment interactions in the Galápagos Islands, examined through the lens of LULC change. First, the results of the comparison of two relatively new methods for characterizing LULC, SVM and OBIA, may assist researchers in selecting an appropriate approach for mapping LULC from high spatial resolution imagery. Second, this study will add to what little is known about landscape change in southern Isabela by characterizing LULC change over the last decade, considering transitions in the rural and urban communities, and contrasting changes within and outside of protected areas on the island. The differences between and similarities among changes in these sites have implications for how human use zones and protected areas are managed in the Galápagos and beyond. Third, the findings from this research will provide a better understanding of the patterns and determinants of agricultural land abandonment, guava invasion, and forest expansion in Isabela. These results will be of interest to various stakeholders in Galápagos who are working to improve agricultural productivity and promote food sovereignty in the region. Additionally, they will contribute to the ongoing debate on the patterns, causes, and consequences of agricultural land abandonment, an important addition to the broader study of land use change.

1.7 Conclusions

The goal of this study is to contribute to an improved understanding of human-environment interactions in the Galápagos Islands during the latter half of the "social-ecological crisis" period (González et al., 2008: 7) by mapping and modeling the patterns and determinants of LULC change on Isabela Island, and by considering the consequences of these changes for people and the environment. Remote sensing, GIS, and statistical analyses of satellite images, spatial data layers representing the physical environment, secondary socio-economic and demographic data sets, and a small landowner survey are integrated to address the main research questions. This research is guided by two complementary bodies of work situated within the human-environment tradition of Geography: land change science and landscape ecology. The findings from this research will not only contributed a more nuanced understanding of interactions between people and the environment in the Galápagos Islands, but will also contribute to human environment research more generally.

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CHAPTER 2: Comparison of Support Vector Machine and Object Based Image Analysis Approaches for Mapping Land Use/Land Cover

2.1 Introduction

Remote sensing and image interpretation have become standard approaches for mapping land use and land cover (LULC). Remotely sensed imagery can not only cover large spatial extents but can also capture information on features of small grains and extents, particularly because of the increased availability of high spatial resolution data products. Image interpretation and GIScience methodologies include automated approaches for mapping that are efficient and easily repeatable, which can reduce the costs associated with *in situ* data collection and field visits. Further, remote sensing can provide information on areas that are difficult to access because of isolation, difficult terrain, or other constraints (e.g., private property or protected sites).

There are many methodological approaches for characterizing LULC with remotely sensed data, each with their own advantages and disadvantages. Generally, the automated approaches can be subdivided into two general categories based on whether the clustering of pixels into classes is based on training information provided by the user (supervised) or is derived from the data itself (unsupervised). Of the many supervised classification approaches that exist, two have emerged in recent years for characterizing LULC from high spatial resolution imagery: Support Vector Machine (SVM) and Object Based Image Analysis (OBIA). In this chapter, SVM and OBIA classifiers are evaluated for mapping LULC in southern Isabela Island, Galápagos with a WorldView-2 satellite image.

SVM is a non-parametric machine learning algorithm. SVM classifications use training data samples to determine the optimal linear boundary between pairs of classes (Vapnik, 2000). Image data, often pixels, are then assigned to discrete classes based on their position in feature space with respect to the decision boundary. Studies employing SVMs for remote sensing applications have significantly increased in recent years, although the method has not yet been widely adopted (as reviewed by Mountrakis et al., 2011). SVM applications range from vegetation mapping (Boyd et al., 2006; Huang et al., 2008; Lardeux et al., 2009; Dalponte et al., 2008) and crop identification (Wilson et al., 2004; Karimi et al., 2006; Mathur and Foody, 2008), to urban feature extraction (Zhu and Blumberg, 2002; Inglada, 2007; Huang and Zhang, 2009), and LULC mapping (Huang et al., 2002; Keuchel et al., 2003; Pal and Mather, 2005; Dixon and Candade, 2008; Watanachaturaporn et al., 2008; Warner and Nerry, 2009; Li et al., 2010). One advantage of SVM classifiers is that they tend to produce higher classification accuracies than statistical classification approaches because they are less sensitive to the size of training data sets or to the manner of sample collection (Mantero et al., 2005).

OBIA is a rule-based classification approach that integrates image processing and GIS functionalities in the classification of non-overlapping image segments that represent features of interest. Image data are first partitioned into homogenous groups of pixels, image objects, that comprise real world objects (e.g., buildings, trees, or fields). Knowledge-based membership functions that explicitly define the rules for classification are then applied at the object level rather than on a per-pixel basis. In addition to the spectral data contained in the image bands, contextual information, such as the spatial, topological, and textural characteristics of the image objects, can be used to define the inclusion or exclusion parameters for OBIA classification (Lang, 2008); the inclusion of contextual information often improves classification accuracy (Benz et al., 2004). Object-based classifications of LULC have become increasingly popular (Hay et al., 2005) in step with the availability of high spatial resolution imagery and commercial OBIA software (Blaschke et al., 2000; Blaschke and Hay, 2001). As recently reviewed by Blaschke (2010), OBIA has been applied to a wide variety of applications including the delineation of forest cover types (Dorren et al., 2003; Heyman et al., 2003), habitat mapping (Weiers et al., 2004; Bock et al., 2005, Lathrop et al., 2006, Diaz Varela et al., 2008; Jobin et al., 2008), general LULC assessments (Rahman and Saha, 2008; Platt and Rapoza, 2008), and in numerous studies of urban land use/cover (Kong et al., 2006; Chen et al., 2007; Stow et al., 2007). An advantage of OBIA is that objects are the basic unit of analysis and thus avoid the 'salt-and-pepper' effect in pixel-based classifications derived from high resolution data (Blaschke et al., 2000).

2.1.1 Study Aims

In this chapter SVM and OBIA classification approaches are evaluated for mapping LULC with high spatial resolution imagery. Two research questions are specifically addressed:

1) How do the LULC classification results from SVM and OBIA differ?
2) Which classification approach is more effective in distinguishing and mapping LULC as measured by the accuracy of the resulting thematic maps?

To this end, pixel-based (SVM) and object-based (OBIA) classifiers are applied to a recent image (acquired 23 October 2010) of the southeastern slope of Sierra Negra Volcano on Isabela Island in the Galápagos Archipelago of Ecuador from the newly launched

WorldView-2 sensor. This region was chosen because it includes a mix of land use and cover types situated within an agricultural community comprised of privately held lands, as well as the surrounding protected area managed by the Galápagos National Park Service.

In addition to general categories of LULC that represent the most common land uses and cover types in the study area (built-up, dry grassland, agriculture/grassland, lava rock, bare soil, and forest/shrub), the distributions of two introduced, invasive plants are also mapped: *Psidium guajava* L. (*guayaba* or common guava) and *Syzygium jambos* L. (*pomarrosa* or rose apple). *In situ* LULC data collected in 2008 and 2009 are used to train the classifiers and to assess the accuracy of the classified maps. Tradeoffs between classification accuracy and processing time, training data requirements, and analyst control over classification parameters with SVM and OBIA are then discussed.

2.2 Study Area

The study area is located along the southeastern slope of Sierra Negra volcano on Isabela Island, in the Galápagos Archipelago of Ecuador, between Latitude 0°47' and 0°53' South and Longitude 91°06' and 90°59' West (Figure 2.1). This site, totaling 89 km^2, encompasses the agricultural community of Santo Tomás (52 km^2) and includes a buffer that extends into the adjacent Galápagos National Park (37 km^2). Santo Tomás, a rural community of approximately 165 persons (INEC, 2011) is characterized by smallholder agriculture, agroforestry (coffee and lumber), and small-scale livestock production (cattle, horses, and chickens). The National Park, in contrast, maintains strict control over access and use aimed at protecting native and endemic plant communities and natural land cover.

The climate of southern Isabela is semi-arid and sub-tropical with two distinct

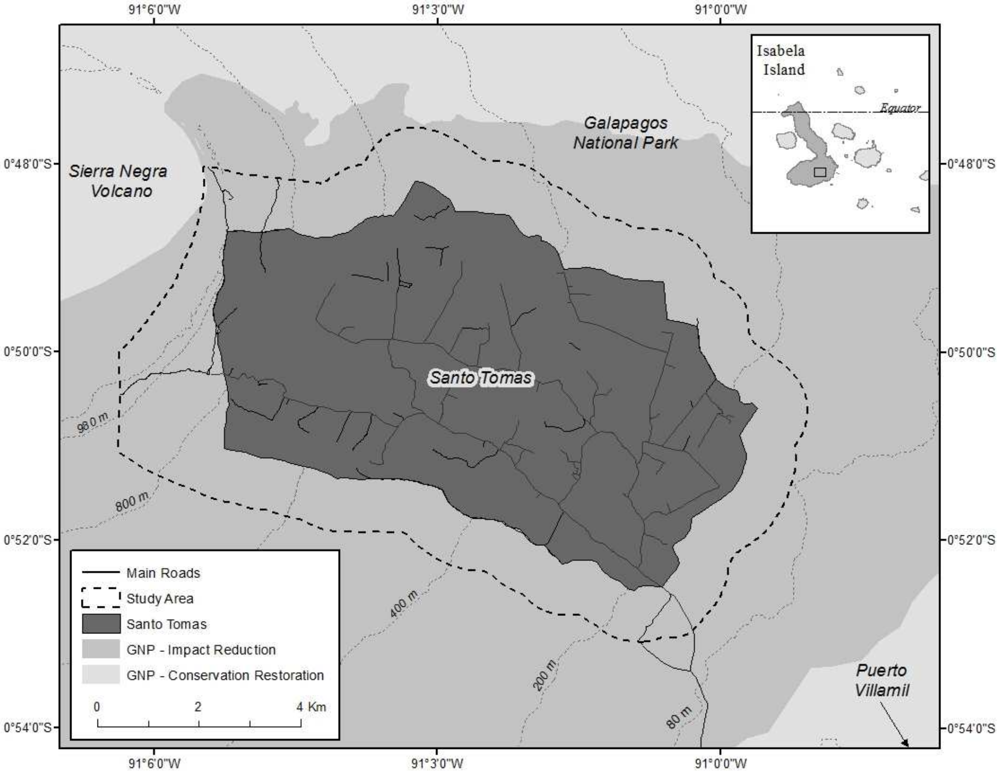

Figure 2.1 Study area on southern Isabela Island. The community of Santo Tomás is shown in dark grey, while Galápagos National Park (GNP) management zones are shown in medium and light grey

seasons – a rainy, warm period from January to May and a dry, cool episode June to December (Trueman and d'Ozouville, 2010). At lower elevations, the mean monthly temperature ranges from 22°C to 30°C in the warm season, and from 19°C to 26°C during the cooler *garúa* season (Guézou et al., 2007). Annual rainfall is highly variable, with a mean of 11 mm in the cool season compared to 48 mm in the warm season (ibid.). The upper slopes of Isabela are sufficiently high and large enough to force moisture-laden air masses upward, bringing significant precipitation to the highlands zone (Perry, 1984); the present study is situated within this humid zone.

The relief of the study area is gently sloping, with isolated hills formed by parasitic cones. Elevation ranges from 80 to 1040 m and slope angles vary from 0 to 42°. Vegetation in the site is divided into two, commonly recognized zones, progressing upward in elevation:

(1) the transition zone composed primarily evergreen and semi-deciduous plants, and (2) the humid zone where introduced vegetation dominates areas once occupied by endemic scalesia forests and fern-sedge communities (Wiggins and Porter, 1971; McMullen, 1999; Froyd et al., 2010). The humid zone is favored for agriculture because there is sufficient moisture and soil for cultivation and livestock rearing, making it a site of significant plant introduction.

Introduced species are considered the principal threat to terrestrial ecosystems in the Galápagos Islands (Loope et al., 1988). As an important component of the landscape, two such exotic invasive plants are included in the LULC categories of interest in this study: guava and rose apple. These plants were intentionally introduced to the Galápagos Islands in the late 1890s and were originally cultivated for their fruits (Lawesson and Ortiz, 1990). They are now considered among the most aggressive invaders in Galápagos because they significantly alter terrestrial ecosystems and have led to economic losses for the agricultural sector (Tye, 2001; Tye et al., 2002; Soria et al., 2002).

2.3 Data & Pre-Processing

The data sources used in this study included a relatively cloud-free WorldView-2 image of the study area acquired 23 October 2010; a digital elevation model derived from topographic maps; band ratios and vegetation indices calculated from the WorldView-2 data; an ASTER image of the study site from 27 March 2005 used to aid in field data collection; and geo-referenced field observations of LULC feature types collected in 2008 and 2009. Each of the data types and associated pre-processing steps are described below.

2.3.1 Field Observations

In situ LULC data were collected in the study area during July and August 2008 to aid in designing a land cover classification scheme, provide training data for the classifications, and supply reference data for thematic accuracy assessments. Sampling areas were selected from a map of general land cover classified from an ASTER (Advanced Spaceborne Thermal Emission Reflection Radiometer) satellite image of the study area. The ASTER VIR (Level 1B) data acquired 27 March 2005 was the most contemporary remotely sensed imagery available at the time field work was undertaken. The ASTER sensor, onboard the Terra satellite platform, contains three imaging subsystems that collect multispectral data: visible and near infrared (VNIR), shortwave infrared (SWIR), and thermal infrared (TIR). The VNIR subsystem utilizes a pushbroom sensor to collect data in three visible and near infrared channels (15 m pixel spatial resolution): green (520-600 nm), red (630-690 nm), and near infrared (760-860 nm).

A hybrid unsupervised-supervised classification approach was used to classify the ASTER image into eight land cover classes at the pixel level. Spectral clusters (n=256) were generated from an unsupervised ISODATA classifier applied to the ASTER data at the pixel level in ERDAS Image 8.5 (Leica Geosystems GIS & Mapping, Atlanta, Georgia). Distinct clusters, those with transformed divergence values greater than 1950 (on a scale of 0 to 2000), were used as inputs for a supervised, maximum-likelihood classification of the ASTER image data. The resulting spectral clusters were attributed based on descriptions of the study area from prior field visits in 2006 and 2007, and from a small number of differentially-corrected GPS points. The resulting land cover map (Figure 2.2) included clouds and shadows (not sampled in the field), lava rock, bare soil, dry vegetation

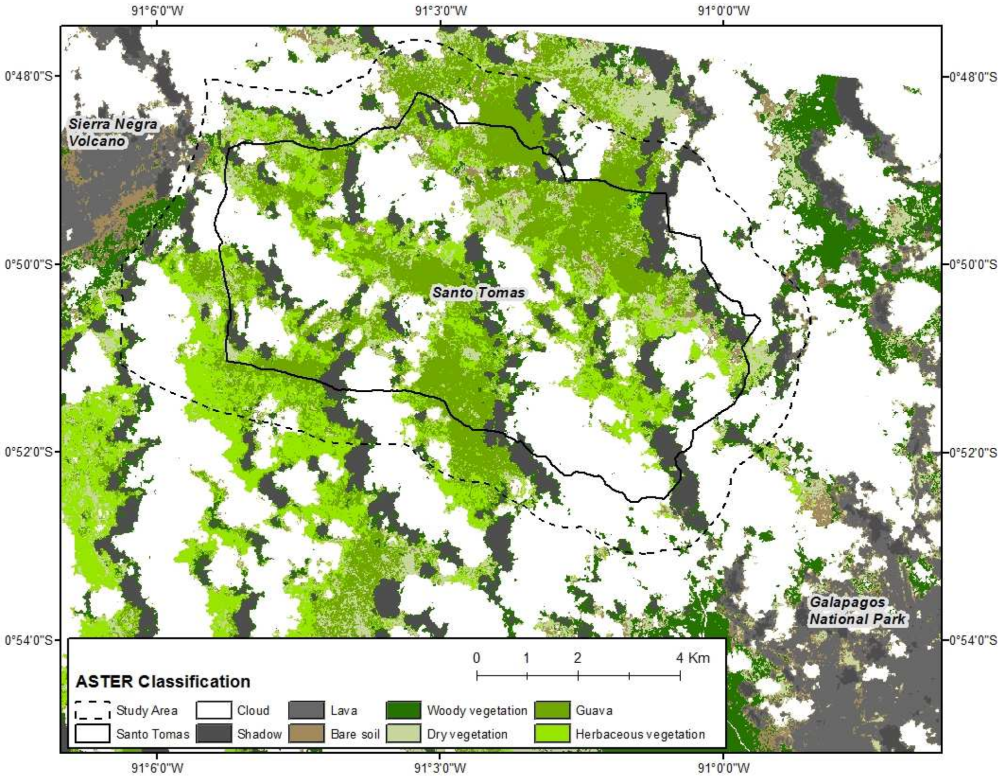

Figure 2.2 ASTER-based LULC classification (2005) of the study area generated for *in situ* data collection

(agriculture and grassland), woody vegetation (forest and shrub), guava, and herbaceous vegetation (agriculture and grassland).

Sampling areas, stratified by general land cover type, were randomly selected[1] to capture features of interest at a finer level of detail than the 2005 map (e.g., agricultural fields). Between July and August 2008, 162 locations were sampled, and an additional 101 locations were sampled during July and August 2009. LULC type, LULC within 10 m (in each cardinal direction), descriptive information, and digital photographs were recorded for each sampling site. A GPS coordinate was collected at each sampling location to geo-locate the observations. A post-processing differential correction was applied to the coordinates

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[1] Some of the selected sites could not be visited due to constraints such as rugged terrain and private property boundaries. In these cases, points close to the originals and in accessible areas were included to approximate planned sampling levels.

with receiver data from permanent base stations on Sierra Negra maintained by UNAVCO (2010).

Persistent cloud cover over Sierra Negra combined with the remote location of the Galápagos archipelago limit the availability of remotely sensed data products in the region. However, the relative stability of land cover types and general spatial patterns within the study area allowed for good correspondence between remotely sensed and *in situ* data collection despite temporal lags between the date of image acquisition (2010) and the dates of field assessment (2008, 2009).

2.3.2 WorldView-2 Data

The WorldView-2 data (Figure 2.3) were acquired over the study area on 23 October 2010; the image, acquired during the *garúa* season, corresponds to the period of peak agricultural production. WorldView-2 is a relatively new satellite imaging system that was launched October 8, 2009 and became fully operational January 4, 2010. The WorldView-2 sensor collects multispectral data in eight visible and near-infrared channels ranging from 450 to 1040 nm (2.0 m pixel spatial resolution[2]), and one panchromatic channel (450-800 nm; 0.5 m spatial resolution), using bi-directional push broom sensors. In addition to the blue (450-501 nm), green (510-580 nm), red (630-690 nm), and near-infrared (770-895 nm) bands found in other Digital Globe products (e.g., QuickBird), four new bands – coastal blue (400-450 nm), yellow (585-625 nm), red-edge (705-745 nm) and a second near-infrared (860-1040 nm) channel – were added to aid in vegetation, soil, and water discrimination.

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[2] WorldView-2 multispectral and panchromatic bands have a ground sample distance (at nadir) of 0.46 meters and 1.84, respectively. The data are re-sampled by DigitalGlobe to coarser spatial resolutions (0.5 m panchromatic; 2.0 m multispectral) prior to distribution to comply with U.S. regulations.

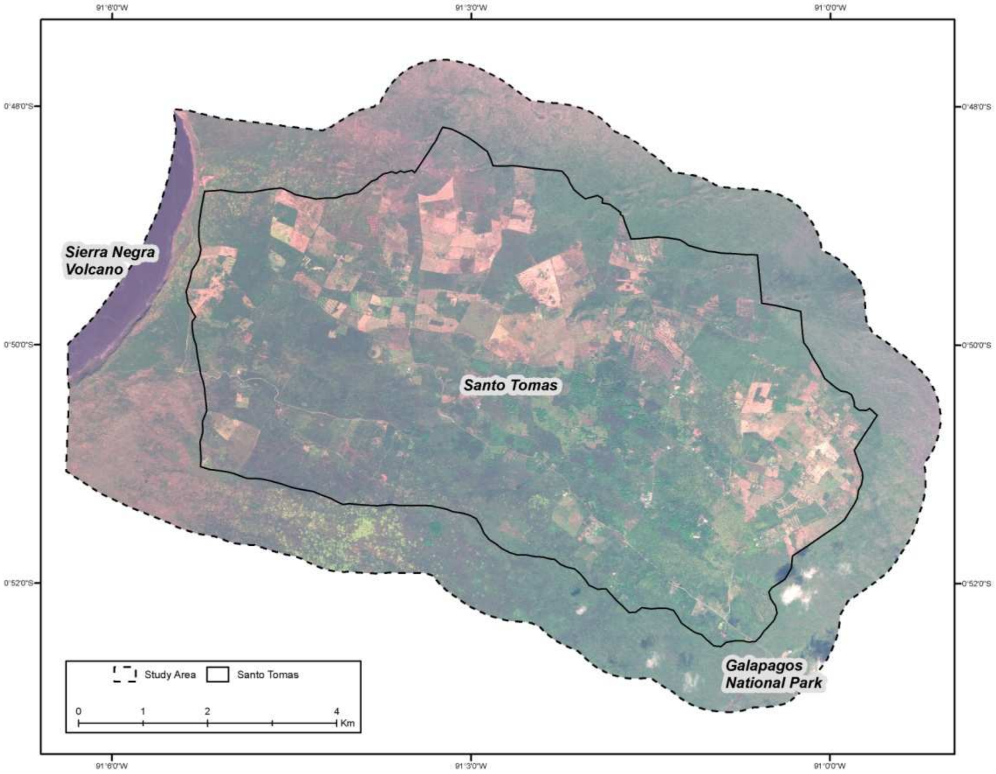

Figure 2.3 WorldView-2 true color composite of the study area. The community of Santo Tomás is surrounded by the Galápagos National Park

The multispectral data (Ortho Ready Standard Product) were co-registered to an orthorectified QuickBird image (22 October 2004) of the study area in PCI Geomatica V10.2 (PCI Geomatics, Ontario, Canada) using forty-eight ground control points (GCPs). The GCPs were located evenly across the scene at obvious features in both images, such as road intersections and building corners. A rational function transformation was applied to the image (4^{th} order polynomial) and a root mean square error (RMSE) of less than one-half pixel (0.94 m) was achieved. A rational function is a simple mathematical model that builds a correlation between image pixels and ground locations with user-defined GCPs and a digital elevation model (DEM). The DEM used for image registration was derived in ArcGIS Desktop 9.3 (ESRI Inc., Redlands, California) from elevation points and contours on a digital topographic map produced by Ecuador's Instituto Geográfico Militar (IGM, 2009).

The WorldView-2 panchromatic band was co-registered to the rectified multispectral bands using 27 evenly-distributed GCPs. A rational function transformation (4th order polynomial) was applied to the data and an RMSE of 0.51 m was achieved. The image data were not corrected for atmospheric or radiometric errors[3] due to the lack of available atmospheric parameters at the time of image acquisition; atmospheric corrections often have minimal effects on the accuracy of single-date classifications (Song et al., 2001). Clouds and cloud shadows were masked prior to image classification to minimize spectral confusion.

2.3.3 Index Ratios and Texture Measures

Previous studies have found that the addition of band ratios, indices, and texture measures can improve pixel- and object-based classifications (Huang et al., 2002; Puissant et al., 2005; Wijaya and Gloaguen, 2007). The simple ratio vegetation index (SR), calculated from the multispectral data according to Equation (1), can be used to detect differences in photsynthetically active vegetation:

$$\mathrm{SR} = \mathrm{NIR}_2 / \mathrm{red} \qquad (1)$$

where NIR_2 = WorldView-2 band 8 and red = band 5. Mean image texture was derived from the panchromatic band using a gray-level co-occurrence matrix (GLCM) (after Haralick et al., 1973; Haralick, 1979). GLCM is a spatial dependence matrix of the relative frequency of pixel values, gray levels, within a neighborhood defined by a specified distance and direction (Haralick et al., 1973). Previous studies have used texture extracted from panchromatic bands of high spatial resolution imagery (e.g., QuickBird and Ikonos) to map mangrove species (Wang et al., 2004b), distinguish among forest stands of varying age (Franklin et al., 2001),

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[3] Radiometric corrections (dark offset subtraction and a non-uniformity correction) are applied to raw QuickBird data by DigitalGlobe. The final product is delivered to customers as radiometrically corrected image pixels (counts).

and classify coniferous and broad-leaved forests (Kosaka et al., 2005). Here, mean GLCM texture values were calculated for the panchromatic band using a 9 x 9 moving window.

To determine which combination of image data and indices would yield the best classification result for further testing, four image stacks were created:

Stack 1: WorldView-2 Multispectral bands

Stack 2: WorldView-2 Multispectral bands + SR

Stack 3: WorldView-2 Multispectral bands + GLCM texture

Stack 4: WorldView-2 Multispectral bands + SR + GLCM texture

The separability of all classes in feature space was calculated with the Jeffries-Matusita (JM) distance measure for each stack using the training data set (Richards and Jia, 2006). The JM distance between class pairs ranges from 2.0 for perfectly separable classes (implying a classification of the two classes with 100% accuracy), to 0.0 for classes that are inseparable (ibid.). The separability analysis revealed that when relying only on the WorldView-2 image data (Stack 1), agriculture/grassland and forest vegetation were the least separable classes (JM 1.43). There was also confusion among other class pairs, including dry grassland and agriculture/grassland (JM 1.82), dry grassland and soil (JM 1.85), and guava and forest (JM 1.88). The best separability for all classes was obtained with Stack 4 (multispectral bands + ratio + texture). Most class pairs were highly separable (JM > 1.93) and the separability of agriculture/grassland and forest improved over the multispectral only stack (JM 1.74). Image layer stack 4 is used as the input for the SVM and OBIA classifiers.

2.3.4 Classification Scheme and Training Data

The classification scheme in this study included eight LULC categories: built-up, dry

Table 2.1 LULC classification scheme with class description and training sizes

Land Use/Cover	Description	SVM Training (pixels)	OBIA Training (objects)
Built-up	Individual buildings including residences, storage buildings, and structures for animals	158	10
Dry grassland	Dry or senescent vegetation including fields for pasture and fallow lands	94	7
Guava	Areas dominated by the woody shrub guava (*Psidium guajava*)	156	13
Agriculture/ Grassland	Crops, pastures, and other herbaceous vegetation	158	16
Lava	Exposed lava outcrops and rocky areas	108	10
Rose apple	Sites with closed canopy of rose apple trees (*Syzygium jambos*)	88	6
Soil	Areas of exposed soil with little to no vegetative cover	119	12
Forest/Shrub	Mostly evergreen trees or taller shrubs, including native/endemic and introduced species	137	12

grassland, guava, agriculture/grassland, lava, rose apple, soil and forest/shrub (Table 2.1). These classes represent the most common land uses and covers in the study area and those that are relevant to the broader goals of this research. One-third (n=86) of the geo-located field samples were used to train the SVM and OBIA classifications; the same set of samples was used with each classifier. For the SVM classification, a region of interest (ROI) was digitized around the feature associated with a field point to increase the number of training pixels for each class. For the OBIA classification, each image object coincident with a field point was selected to train the classifier.

2.4 Methods

2.4.1 Support Vector Machines

Support Vector Machines (SVMs) are supervised, non-parametric machine learning algorithms based on statistical learning theory (Huang et al., 2002). The objective of SVM classifications is to separate image data into discrete classes using support vectors to determine an optimal hyperplane (linear boundary) that maximizes the difference between classes (Vapnik, 2000). The optimal separating hyperplane refers to a decision boundary in a multi-dimensional feature space that separates the training data samples of two classes and maximizes the distance between the closest data points and the plane (Huang et al., 2002; Mountrakis et al., 2011). The training data points closest to the optimal separating hyperplane in feature space are called support vectors. Only data points that lie at the margin of the class distributions (i.e., support vectors) contribute to the classification, while those at the center are considered redundant (Foody and Mathur, 2006).

The simplest SVM classification, sometimes referred to as the two-class problem, involves two linearly separable classes. In the training step, a linear optimal separating hyperplane is fit to the data samples within a two-dimensional feature space. Unknown data points are then assigned to one of the classes during the classification step based on where they fall with respect to the hyperplane (i.e., above or below the boundary) (Fletcher et al., 2011). The probability of membership to each class is then calculated, ranging from 0 to 1, and pixels are labeled according to the class with the highest membership (ENVI, 2010). The binary SVM classifier can also be extended to multiclass problems using methods such as one-against-one, one-against many, and directed acylic graph (Hsu and Lin, 2002). The SVM in this study was implemented in ENVI Version 4.8 using the one-against-one classification strategy in which a binary classifier is created for each possible pair of classes (ENVI, 2010).

An assumption of linear SVMs is that data points from different classes do not overlap in feature space. However, LULC classes are often not linearly separable (Foody and Mathur, 2004) and in these cases a kernel function can be employed to transform the data to a higher dimension space where the classes can be separated using a linear hyperplane (Huang et al., 2002; Foody and Mathur, 2004). The four basic types of kernels are linear, polynomial, radial basis function (RBF) and sigmoid. A penalty parameter (C) is included in the kernel to control the tradeoff between allowing errors due to misclassification of the training data and enforcing strict boundaries (ENVI, 2010).

For this research, a RBF kernel was used to map the input data to a higher dimension feature space, and suitable gamma and penalty parameters were selected for the SVM classifier following the approach described by Yang (2011). The gamma and penalty parameters were systematically varied over several classification runs while keeping the kernel function constant. Gamma values of 0.083 (1/# of image bands), 0.1 (default in ENVI), and 0.125 were tested alongside penalty parameters ranging from 0 to 200 (Table 2.2). Overall accuracies were then calculated for each of the 18 machines to determine the optimal parameter set.

Table 2.2 Accuracy of SVMs with various parameter settings

SVM	Gamma	Penalty	Overall Accuracy (%)	Kappa
1	0.083	0	47.5	0.39
2	0.083	25	71.8	0.68
3	0.083	50	75.7	0.72
4	0.083	100	74.0	0.70
5	0.083	150	75.1	0.71
6	0.083	200	75.1	0.71
7	0.1	0	47.4	0.39
8	0.1	25	71.8	0.68
9	0.1	50	75.7	0.72
10	0.1	100	74.0	0.70
11	0.1	150	75.1	0.71
12	0.1	200	75.1	0.71
13	0.125	0	47.4	0.39
14	0.125	25	71.8	0.68
15	0.125	50	75.7	0.72
16	0.125	100	74.0	0.70
17	0.125	150	75.1	0.71
18	0.125	200	75.1	0.71

Varying gamma had no noticeable effect on classification accuracy, although visual inspection of the classified maps revealed small differences (< 50 pixels). Varying the penalty parameter did, however, impact the overall classification accuracy; Figure 2.4 shows the differences in classification outputs for low, moderate, and high penalty values. This error term controls the tradeoff between enforcing strict class boundaries (low penalty values) and allowing for errors due to the misclassification of training data (higher penalty values). When the misclassification of training data was prohibited (penalty = 0), the SVM failed to generalize well and the overall accuracy of the classification was extremely low (47.5%, kappa = 0.39). When the penalty parameter was large (e.g., 200), the resulting classification had reasonable accuracies (75.1%, kappa = 0.71), but visual inspection of the classified map

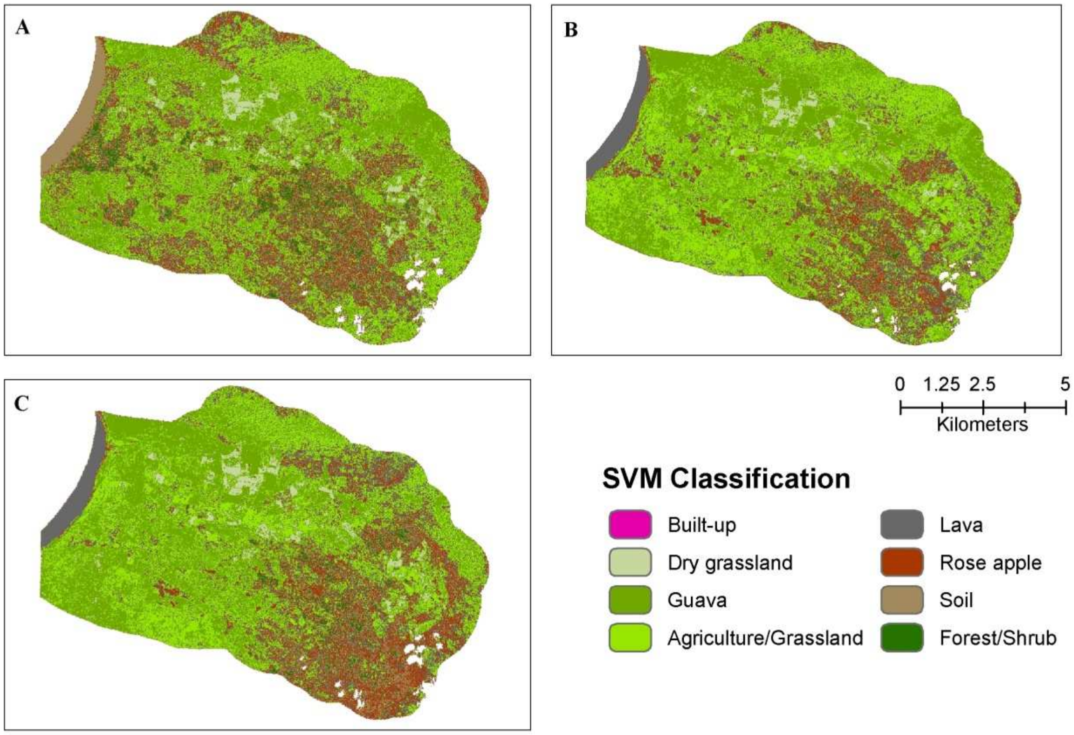

Figure 2.4 Results of SVM parameter testing. With a penalty value of 0 (A), the SVM failed to generalize well. SVMs with moderate penalty values, such as 50 (B), had the highest overall accuracy. SVMs with large penalty values, such as 200 (C), suffered from over-fitting

in comparison to field-based knowledge of the study area showed the data suffered from over-fitting. Machines that included a moderate level of error (e.g., penalty = 50) had the highest accuracies (75.7%, kappa = 0.72). The SVM configured with gamma and penalty parameters of 0.1 and 50, respectively, was chosen as the final classification for comparison to the OBIA analysis.

2.4.2 Object Based Image Analysis

OBIA, also sometimes referred to as Geographic OBIA (GEOBIA), is a knowledge-based classification approach that attempts to mimic the way humans interpret remote sensing images (Hay and Castilla, 2008). Traditional per-pixel analyses of high spatial resolution imagery (pixels < 5m) can result in speckled classifications caused by variations in the spectral reflectance of individual features and LULC classes (Mathieu et al., 2007). An advantage of the OBIA approach is that homogenous groups of pixels, or objects, are the basic unit of analysis and thus avoid the ‘salt-and-pepper’ effect in classifications derived from high spatial resolution data (Blaschke et al., 2000). Further, OBIA can exploit the textural, spatial, and topological characteristics of image objects (Definiens, 2006; Lang, 2008) to improve the value and accuracy of classifications (Benz et al., 2004).

The OBIA workflow typically involves three main steps: (1) segmentation of image data to create objects, (2) definition of classification scheme and rule set development, and (3) classification (Benz et al., 2004; Blaschke and Hay, 2001). These steps are frequently repeated in an iterative process to distinguish or capture a variety of features. In this study, each of these steps was carried out in Definiens Professional 5 (Definiens AG, München, Germany). The processing details associated with each workflow step are described below.

2.4.2.1 Image Segmentation

The first step in OBIA is the segmentation of image data into objects. Using the multispectral segmentation algorithm in Definiens Professional, the image data were segmented into two levels with various scale and homogeneity criterion (Table 2.3); all input layers were equally weighted. Multiresolution segmentation is a bottom up region-merging procedure (Benz et al., 2004) that has the benefit of creating objects of similar size and shape as features of interest in the image without requiring extensive processing time (Definiens, 2006). The technique begins with one-pixel objects that are merged into larger objects over several steps. The goal is to minimize the heterogeneity of extracted image objects while maximizing the contrast to neighboring objects.

In the analysis of high resolution image data it is often not possible to extract objects that represent all features or classes of interest simultaneously with a single set of segmentation parameters (ibid.). In Definiens Professional, image data can be partitioned into homogenous objects at different spatial scales so that specific features can be represented within a particular level. When multiple object levels are created they are linked such that small objects are nested within larger ones (Burnett and Blaschke, 2003). In this study, the image object hierarchy was created through a bottom-up approach in which small objects were first generated to represent buildings, roads, and individual trees (level 1); a set of

Table 2.3 OBIA segmentation parameters

	Input Layers	Scale	Color/ Shape	Compactness/ Smoothness
Level 1	WorldView-2 bands Simple ratio GLCM texture	18	0.6 / 0.4	0.2 / 0.8
Level 2	WorldView-2 bands GLCM texture	40	0.7 / 0.3	0.2 / 0.8

larger objects were then generated to represent vegetation patches including forests and agricultural fields (level 2).

The user-defined criteria that describe the threshold for allowable object heterogeneity – scale, color/shape, and smoothness/compactness – constrain the multiresolution segmentation region growing process. Segmentation parameters at each level of analysis are selected through an iterative process that relies on visual assessments of object fit for features of interest (Meinel and Neubert, 2004). Scale is a somewhat abstract parameter that determines the level of allowable heterogeneity in resulting image objects (Definiens, 2006). Altering the scale parameter varies the size of image objects; as the scale parameter increases, so too does the size of extracted image objects. In level 1, the image data were segmented with a scale parameter of 18, while a scale parameter of 40 was used in level 2.

Color refers to the pixel values (digital numbers across all input data layers) of the resulting image objects. Shape on the other hand defines the textural homogeneity of extracted image objects and is indirectly related to color, such that by increasing the weight of color, the contribution of shape to the overall homogeneity of image objects is reduced. Although the best segmentation results for multispectral LULC classifications are often obtained by heavily weighting the color criteria, some use of the shape value can improve the quality of object extraction (ibid.). In both segmentation levels the color criterion was weighted more heavily than the shape parameter (0.6 and 0.7 for levels 1 and 2, respectively) to base the segmentation primarily on the multispectral information contained in the image stack.

The shape criterion is further composed of two factors, smoothness and compactness (shape = smoothness + compactness). When smoothness is prioritized the extracted image objects have smooth borders that mimic the shape of the feature. In contrast, compactness optimizes image object borders so that the resulting features are compact and do not have frayed edges when the contrast between different features is relatively weak. Smoothness (0.8) was given preference over compactness (0.2) in levels 1 and 2 to mimic feature boundaries.

2.4.2.2 Classification Scheme & Rule Sets

The next step in the OBIA workflow is to define the rules that describe each category in the classification scheme. In Definiens Professional, LULC types are arranged in a class hierarchy that represents the relationships among the different categories. Classes can be related by *inheritance* when they have similar spectral or contextual characteristics or by *semantic group* when they have a similar meaning irrespective of their spectral characteristics. For example, patches of guava and walnut trees share similar spectral traits (high values in the simple ratio vegetation index) and therefore both belong to the same inheritance group (‘High SR’). However, they each belong in different semantic groups with guava in its own category and walnut trees in the ‘forest/shrub’ group. Here, the target LULC categories were used to construct a semantic class hierarchy, which consisted of various sub-classes from the inherited class hierarchy (Figure 2.5).

Each LULC category in the hierarchy contains a set of expressions, or rules, that describe the class. These knowledge-based rules can draw on spectral data contained in the image bands and/or contextual information such as the spatial, texture, and topological

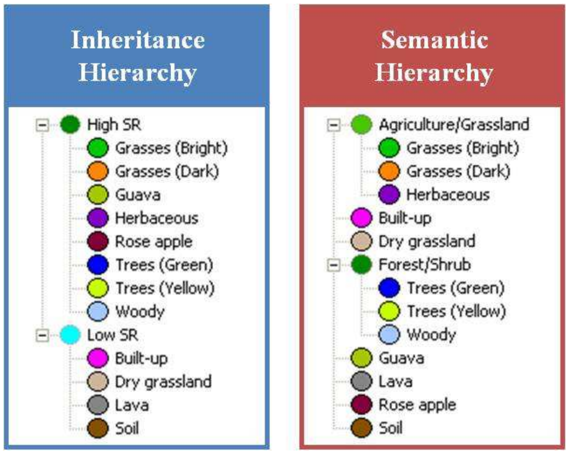

Figure 2.5 Inheritance and semantic classification hierarchies (OBIA)

characteristics of image objects; the information used to construct a rule, such as mean spectral value or object shape, are referred to as features. In constructing rules for each class, users convert the range of feature values into fuzzy membership values between 0 and 1 (Definiens, 2006). These expressions can include sharp thresholds or mathematical functions to describe some aspect of the class, and multiple membership functions can be combined to create the rule set for a class. Here, objects corresponding to points in the training data set were isolated and their spectral, textural, and contextual attributes were used to establish the rules – features and data ranges – for each class using the Feature View tool within Definiens.

2.4.2.3 Classification

The application of the classification scheme to image objects is the final step in the OBIA workflow. The classification flowchart and the features that describe each class are shown in Figure 2.6. The classification algorithm evaluates the membership value of an image object to the list of classes and the class with the highest membership value is assigned to the image object. Here the image data were first separated into ‘High SR’ and ‘Low SR’

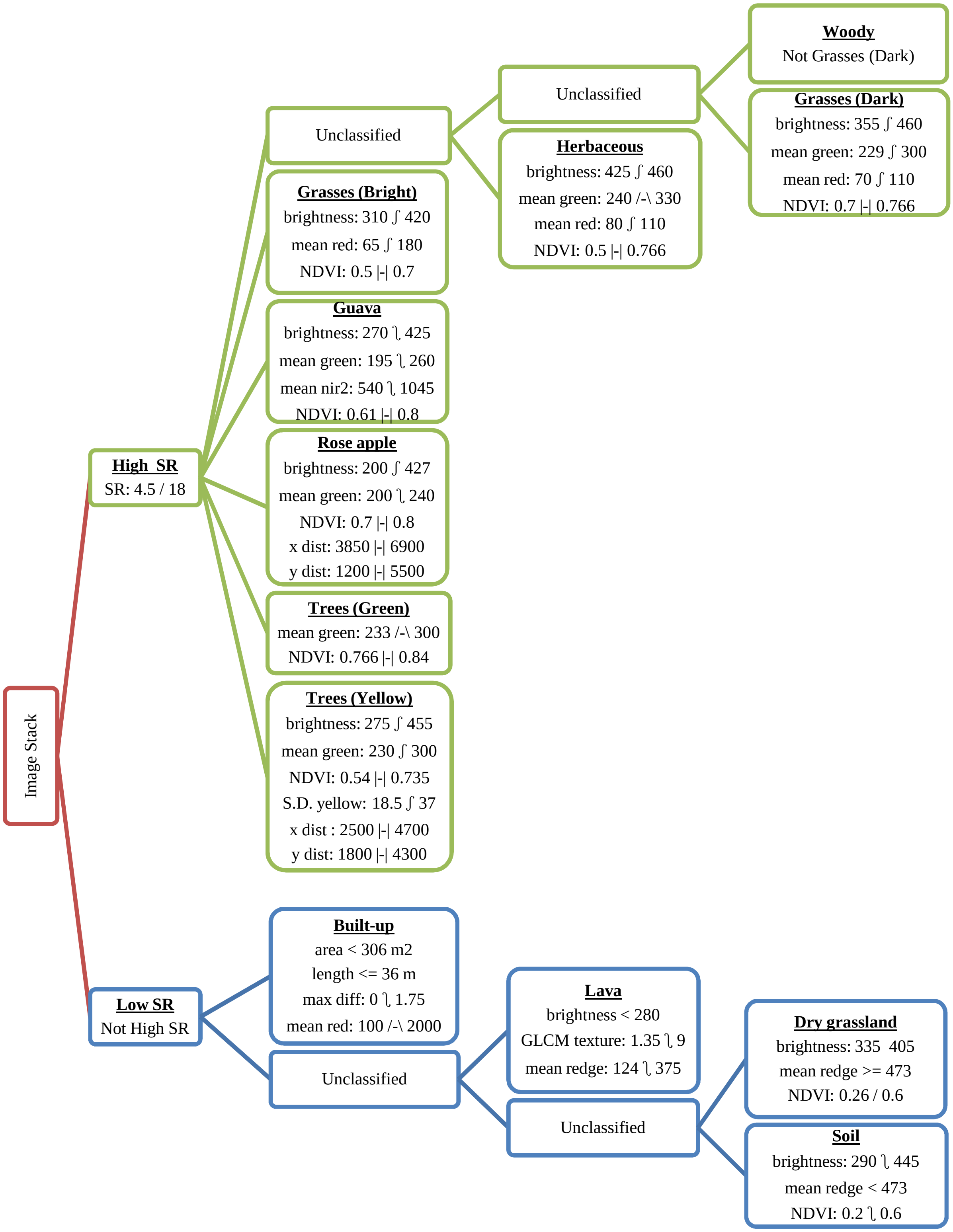

Figure 2.6 OBIA classification flow chart. Blue boxes indicate classes applied at level 1, green at level 2. Bold headings represent classes in the inheritance hierarcy; feature values for classification are listed below. Symbols represent mathematical functions used to assign feature values to membership values: □ = greater than, □ = less than, /-\ = approximately, and |-| = exactly

classes based on a linear membership to mean Simple Ratio (SR) vegetation values. Objects with SR values between 4.5 and 18 were assigned membership to ‘High SR’, ranging from 0 for SR values near 4.5 and 1.0 for SR values approaching 18. Objects with low membership to ‘High SR’ were assigned to the ‘Low SR’ class. In subsequent steps, ‘Low SR’ objects were further refined into several sub-classes (i.e., buildings, lava, dry grassland, and soil) at level 1, while ‘High SR’ sub-classes were defined at level 2 (coarser objects) according to the inheritance hierarchy. The classifications at levels 1 and 2 were then merged to create a single output classification according to the semantic hierarchy in Figure 2.5.

2.4.3 Accuracy Assessment

The thematic accuracy of each classification was assessed using two-thirds of the field samples for each LULC type (n=177 pixels) set aside for accuracy assessment. Standard error matrices were calculated to determine the overall accuracy, producer’s and user’s accuracies, and overall kappa statistic for the SVM and OBIA thematic classifications on a per pixel basis. For consistency, identical reference data were used to evaluate each approach. McNemar’s test (Foody, 2004) was used to determine whether the accuracy of the classified maps were measurably different.

2.6 Results and Discussion

2.6.1 Classification Accuracy

The pixel-based SVM classification had the lower accuracy of the two classifiers with an overall accuracy of 75.7% and a kappa statistic of 0.72 (Table 2.4). Of this overall accuracy, the forest/shrub class was the least reliable with a producer’s accuracy of 56% and

Table 2.4 Error matrices for SVM and OBIA classifications

	Reference Class								
Mapped Class	Built	Dry grassland	Guava	Agriculture/ Grassland	Lava	Rose apple	Soil	Forest/ Shrub	Total
SVM (pixel-based)									
Built-up	20	0	0	0	0	0	2	0	22
Dry grassland	0	10	0	3	0	0	3	0	16
Guava	0	0	24	2	0	2	0	10	28
Agriculture/grassland	0	0	0	19	0	0	2	1	28
Lava	0	0	0	0	20	0	1	0	21
Rose apple	0	0	0	2	0	10	0	0	11
Soil	1	4	0	0	1	0	17	0	23
Forest/Shrub	0	0	2	7	0	0	0	14	28
Total	21	14	26	33	21	12	25	25	177
Overall = 75.7%									
Kappa = 0.72									
OBIA (object-based)									
Built-up	21	0	0	0	0	0	1	0	22
Dry grassland	0	12	2	1	0	0	1	0	16
Guava	0	0	23	3	0	0	0	2	28
Agriculture/grassland	0	0	0	26	0	0	0	2	22
Lava	0	0	0	0	21	0	0	0	21
Rose apple	0	0	0	0	0	11	0	0	12
Soil	0	1	0	0	0	0	22	0	23
Forest/Shrub	0	1	1	3	0	1	1	21	23
Total	21	14	26	33	21	12	25	25	177
Overall = 88.7%									
Kappa = 0.87									

Table 2.5 Producer's and User's accuracies for SVM and OBIA classifications

	SVM		OBIA	
LULC Class	Producer’s (%)	User’s (%)	Producer’s (%)	User’s (%)
Built-up	95.2	90.9	100.0	95.5
Dry grassland	71.4	62.5	85.7	75.0
Guava	92.3	63.2	88.5	82.1
Agriculture/grassland	57.6	86.4	78.8	92.9
Lava	95.2	95.2	100.0	100.0
Rose apple	83.3	83.3	91.7	100.0
Soil	68.0	73.9	88.0	95.7
Forest/Shrub	56.0	60.9	84.0	75.0

a user’s accuracy of 60.9% (Table 2.5). Producer’s accuracy (1 – omission error) is the percentage of pixels of a given LULC type that are correctly identified in the classification. User’s accuracy (1-commission error), is the percentage of pixels assigned to a particular LULC class that represent the class on the ground. Forest patches and shrubs were frequently confused with guava in areas where tall trees cast shadows on neighboring vegetation. The shadowed forest pixels were misclassified as guava due to their similar spectral responses, resulting in errors of omission.

The forest class also suffered from errors of commission due to the misclassification of agriculture/grassland areas as forest/shrub. This error is not surprising given that the spectral separability analysis revealed these classes were not completely separable (JM distance 1.93). Spectral confusion between these classes may be the result of large variation in the values of pixels included as training data for agriculture/grassland. This mixed class of herbaceous crops, pasture for grazing animals, and natural grasses was constructed to indicate areas of active agricultural activity in the LULC classification scheme. However, the SVM might have performed better in such areas if more training data were available for the components of this class.

The soil class had fairly low producer’s (68%) and user’s (73.9%) accuracies, primarily because of confusion with dry grassland. Areas of bare soil are often a component of fields containing senescent grasses. This fact combined with the similar spectral responses of bare soil and dry grassland may explain some of the classification error. Although great care was taken to select training and testing data that reflected LULC classes as depicted in the imagery, it is possible that permanent land cover change took place in the time between field data collection in 2008 and image data acquisition in 2010. Such change could be manifested as errors in the training and/or test data sets. It should be noted that the built-up, guava, and lava classes had individual class accuracies greater than 92%.

The OBIA classification approach yielded a higher accuracy than the SVM classifier, with an overall accuracy of 88.7% and a kappa statistic of 0.87 (Table 2.4). Producer's and user's accuracies for individual classes increased across the board, with guava the sole exception. The forest class had the greatest increase from 56% (producer's accuracy) using the pixel-based approach to 84% with the object-based method. Errors of omission due to the misclassification of dark or shadowed forest/shrub pixels as guava were reduced in the OBIA map. The classification of image objects, rather than individual pixels, allowed for more intra-class spectral heterogeneity since a single object could include illuminated and shadowed components of forest patches. Confusion between forests and agriculture/grassland was also reduced with the OBIA approach by including contextual and spectral features that separated crops and grasses from trees with a strong response in the yellow band. These improvements contributed to an overall increase in forest/shrub class accuracy.

The soil class had the second greatest increase in accuracy (+20% producer's, +21.7% user's) using the object-based approach. This class benefitted from improvements in the classification of built-up areas by including image object geometry, such as object area and length, in the classification rules since both features had similar spectral responses. Areas of bare soil were also easier to separate from dry grassland using a rule-based classification approach that focused on differences in overall brightness, and average pixel values in the red-edge band and vegetation index.

In the case of guava, the user's accuracy increased by nearly 19% over the SVM classifier. The classification of image objects rather than individual pixels improved the classification of forest patches and shadowed vegetation that had been misclassified as guava in the SVM approach. The producer's accuracy, however, declined from 92.3% with the SVM classifier to 82.1% for the OBIA approach. The decline in this case was the result of one additional reference pixel being misclassified (24 of 26 correct for SVM; 23 of 26 for OBIA), which translates to a significant difference in the estimates of guava cover (discussed in section 2.6.2). The misclassification of guava in the OBIA map occurred in an area of the National Park adjacent to the Sierra Negra caldera where guava is mixed with native shrubs, ferns, and sedges. Larger image objects generated in this area resulted in mixed patches being wholly classified as forest/shrub, agriculture/grassland, or guava. The reference points indicate that the misclassifications occurred at the boundaries of mixed patches, each with slight differences in LULC composition.

McNemar's test, a non-parametric calculation that follows a chi-squared distribution (Foody, 2004) was used to compare the accuracy assessments of the SVM and OBIA thematic maps. Differences in thematic map accuracy are frequently assessed with a z-statistic that compares the individual kappa coefficient from each classification (ibid.). However, the reference data set used to calculate each classification's kappa was identical, violating the assumption of data independence. McNemar's test (Equation 2) is expressed as:

$$\chi^2 = \frac{(|f_{12} - f_{21}| - 1)^2}{f_{12} + f_{21}} \tag{2}$$

where f_{12} denotes the number of cases incorrectly classified by the SVM, but correctly classified by OBIA; and f_{21} is the number of cases correctly classified by the SVM, but incorrectly classified by OBIA. The significance of the difference in accuracies is based on the magnitude of the computed χ^2 value. McNemar's test confirmed that the SVM and OBIA error matrices were significantly different ($\chi^2 = 28.2$, $p < 0.001$).

2.6.2 Thematic Maps and Cover Statistics

The final SVM and OBIA classifications are presented in Figure 2.7. The visual difference between the classification approaches is readily apparent in these maps, and in a comparison of two subset areas (Figure 2.8). Whereas the SVM classification suffers from a speckled appearance that is the result of spurious pixels, the OBIA classification appears spatially cohesive. Agricultural fields, buildings, and vegetation patches are better defined and general patterns of LULC are easier to see in the OBIA map. The maps not only differ in their appearance, but more importantly in LULC composition.

The breakdown of landscape composition points to interesting differences in the two classifications (Table 2.6). The largest difference between the SVM and OBIA maps was in the estimation of forest/shrub cover (+/- 17.12 km^2). The OBIA approach provided a much higher estimate of forest/shrub cover (26.57 km^2) compared to the SVM classification (9.45 km^2). This was largely due to the better differentiation between dark forest areas and guava with OBIA. Transition areas composed of woody species within the National Park were also captured in the forest/shrub category in the OBIA map, which boosted the cover estimate for that category.

The second largest difference in cover estimates involves guava. Guava covered just over 48 km^2 in the SVM map, compared to 35 km^2 in the OBIA map (a decline of approximately 9 km^2). This result is not surprising given the accuracy assessment results that indicated guava was over-classified in the SVM classification, and under-classified in the OBIA classification within the National Park. The true extent of guava is likely closer to the areal estimate provided by the object-based approach given its higher overall accuracy in the OBIA map.

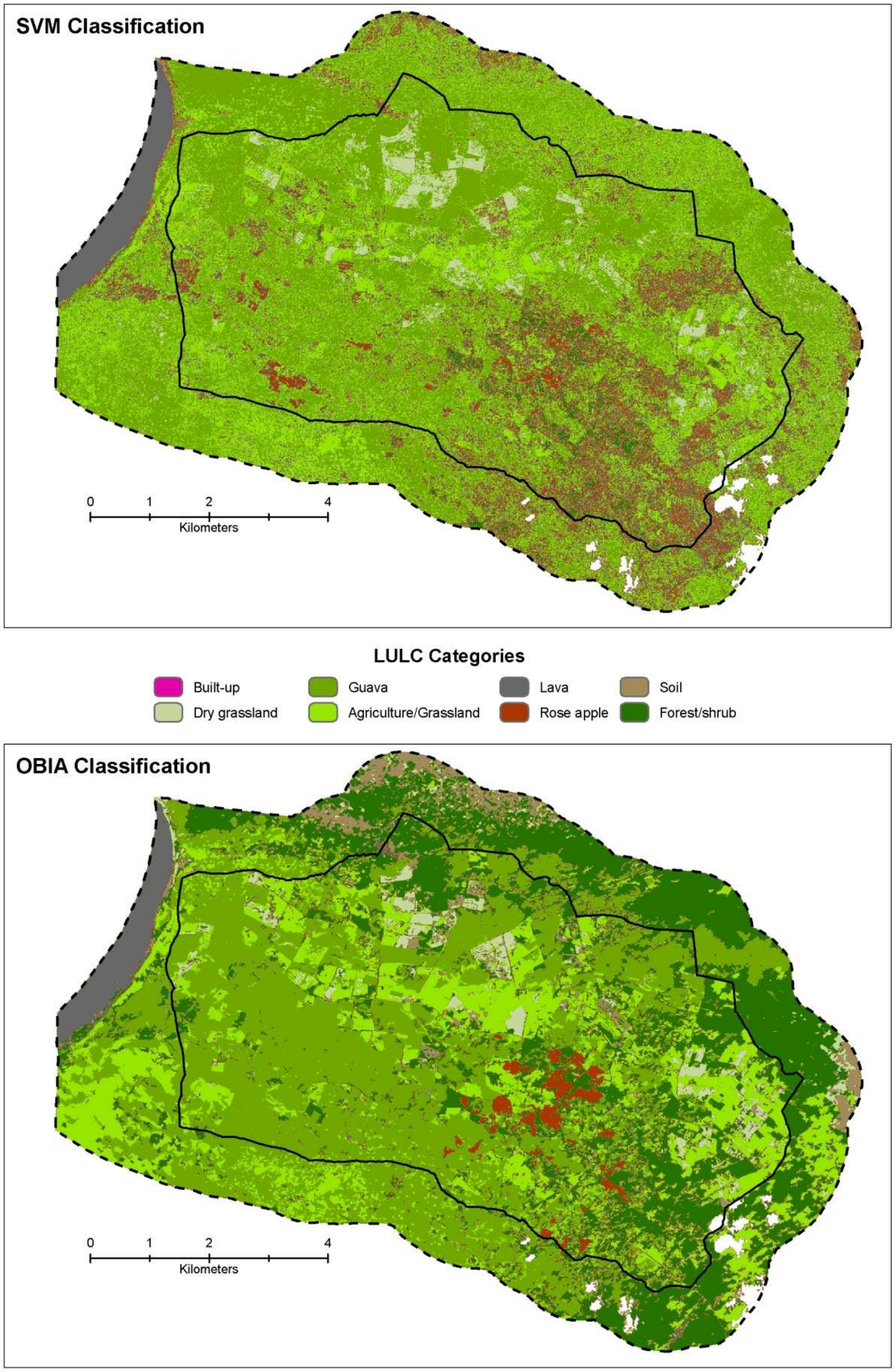

Figure 2.7 SVM (top) and OBIA (bottom) classification maps. White areas indicate clouds. The community of Santo Tomás (central; solid line) is surrounded by the Galápagos National Park

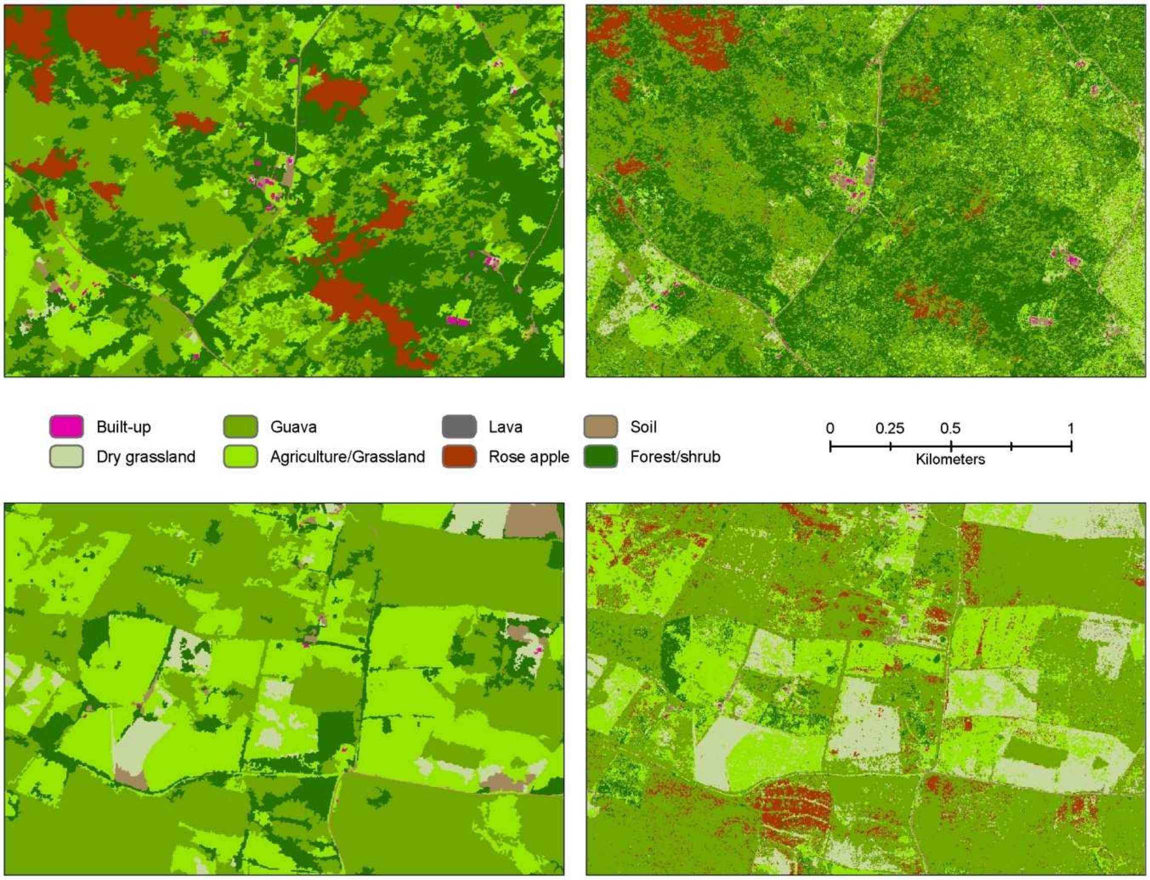

Figure 2.8 Comparison of OBIA (left) and SVM (right) classified maps for two sites within the study area

Table 2.6 Extent of LULC type, by area and percent of landscape, for each classifier

	SVM		OBIA	
LULC Class	Area (km^2)	Percent of landscape (%)	Area (km^2)	Percent of landscape (%)
Built-up	0.04	0.1	0.05	0.0
Dry grassland	10.66	11.9	2.92	3.3
Guava	48.45	54.2	35.01	39.1
Agriculture/Grassland	11.24	12.6	17.96	20.1
Lava	2.12	2.4	2.04	2.3
Rose apple	4.33	4.8	1.15	1.3
Soil	2.34	2.6	3.10	3.5
Forest/shrub	9.45	10.6	26.57	29.7
Unclassified*	0.85	1.0	0.69	0.8
Total	89.49	100.0	89.49	100.0

* Unclassified category includes clouds, shadows, and scene edges.

There was also a moderate difference in the estimate of dry grassland in the two classifications (10.66 km^2 SVM; 2.92 km^2 OBIA). The biggest reason for the lower estimate of dry grassland in the OBIA map is that many areas were instead classified as agriculture/ grassland, and forest/shrub in a few cases. In the SVM classification, individual and small groups of pixels made up the majority of the dry grassland cover class. In the OBIA classification these individual pixels were contained within larger image objects in which dry grassland was not the dominant cover type and were thus classified differently.

Despite the aforementioned differences, there were some similarities among the two classifications. For example, there was little difference in the estimates of the extent of built-up (SVM: 0.04 km^2; OBIA: 0.05 km^2) and lava (SVM: 2.12 km^2; OBIA: 2.04 km^2) cover, and the class accuracies were fairly consistent between the methods. The soil category also had a similar extent estimated with each approach, covering 2.34 km^2 in the SVM map and 3.11 km^2 in the OBIA map. Recall however that the accuracy of the soil class improved significantly with the OBIA classifier (+20% producer's, +21.74% user's), signaling differences in landscape structure.

2.7 Conclusions

The goal of this research was to evaluate two classification approaches for mapping LULC with remotely sensed data, using southern Isabela Island, Galápagos as a case study. The OBIA classification approach yielded an overall accuracy that was 13% higher than the classification derived from the SVM approach. OBIA also had the highest individual class accuracies. The results of this research are consistent with the conclusions of previous studies that object-based classifications generally outperform pixel-based assessments of LULC using remotely sensed data (e.g., Wang et al., 2004a; Chonchedda et al., 2008; Cleve et al., 2008). This study extends the comparison to a non-parametric classifier, SVM, which has shown potential for its ability to accurately map LULC. Further, performance of the classifiers was evaluated with a classification scheme that included a range of vegetation types and man-made features, rather than a single target. This study also provides one of the first applications of Worldview-2 imagery for LULC research, demonstrating its potential for vegetation discrimination.

As with the selection of any classification approach, it is important to consider the tradeoffs between classification accuracy and processing time, training data requirements, and analyst control over classification parameters. The OBIA approach offers the greatest degree of control in selecting and adjusting classification parameters. An analyst can not only select the spectral or contextual information to include in classification rules, but multiple rules can be combined for feature classification. The parameters can also be changed post-classification if the output is unsatisfactory. SVM classifiers offer less flexibility in adjusting the classification parameters that determine how image data are assigned to classes, and changing the classification output requires the user modify the training data based on the intermediate fuzzy classification product.

With respect to analysis, object-based analyses require a significant amount of front-end processing time, particularly for determining appropriate segmentation parameters and developing rule sets. These steps can take weeks to months depending on the complexity of the landscape and classification scheme. As a result, its use may be impractical beyond a certain threshold. However, the OBIA processing steps can be applied to multiple images using an established set of segmentation parameters and rule sets, which speeds up the processing of image time series. SVMs have the benefit of requiring little front-end time, limited mainly to the selection of appropriate kernel and error parameters. If there are only a few images to be classified and processing time needs to be minimized, the SVM approach may be more appropriate.

SVM is a complex classification algorithm and requires a fair amount of training data, particularly when the number of input variables (image bands) is high. While an SVM classification can be trained using small data sets, in such cases it is ideal to have data points that lie along the edges of class distributions to improve class separation (Mathur and Foody, 2008). OBIA can be trained with or without specific training data points, but the classifier works best when expert knowledge based on training data and experience with the study area can be pooled to define the classification rules.

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CHAPTER 3: Land Use and Land Cover Change in Southern Isabela Island, 2003-2010

3.1 Introduction

Inhabited islands in the Galápagos Archipelago have undergone major changes in land use and land cover (LULC) over the last three decades. Humid upland areas have been significantly altered by introduced and invasive plants and animals (Walsh et al., 2008; Henderson and Dawson, 2009; Watson et al., 2009; Guézou et al., 2010). A number of plants introduced for cultivation have become invasive, not only transforming the habitats of native and endemic fauna, but also acting as a nuisance for farmers. Coastal towns have become more urbanized with the expansion and densification of buildings and the development of transportation infrastructure to support growing local and tourist populations (Cléder and Grenier, 2010; Walsh et al., 2010; Gardener and Grenier, 2011). As a result, bays and coastal lagoons have become polluted and freshwater sources have been depleted (Kerr et al., 2004; d'Ozouville et al., 2008), threatening aquatic ecosystems and negatively impacting human health (Gelin and Gravez, 2002; Walsh et al., 2010). Such changes have not only taken place within the port towns and highland communities that comprise under 3% of land in the archipelago, but also in the remaining 97% of land that is protected and managed under the Galápagos National Park. In response to concerns about the increasingly negative impact of human activities on Galápagos, the Present of Ecuador issued an Emergency Degree in 2007 declaring the islands at risk, and the UNESCO World Heritage Committee inscribed the archipelago on their list of World Heritage In Danger from 2007 to 2010.

Land change has been recognized as an issue of global importance. Land use activities (human use of land surface) and resultant changes in land cover (biophysical attributes of land) can impact the environment and societies alike. For example, land use practices can reduce biodiversity through habitat modification and the direct exploitation of native species (Pimm and Raven, 2000; Sala et al., 2000). Changes in LULC can also change the structure and function of ecosystems (Foley et al., 2005). Such alterations may diminish the capacity of ecosystems to provide services that support human needs, such as the provisioning of freshwater or the capacity for food production (Vitousek et al., 1997).

Protected areas have been established in many countries as a mechanism to limit the direct impacts of human activities on biodiversity and to maintain ecosystem functions. However, protected areas are often situated within larger ecosystems and changes outside their boundaries (i.e., in the unprotected part of the ecosystem), such as land use intensification, may negatively impact natural resources within its borders and affect its conservation capacity (DeFries, 2007; Hansen and DeFries, 2007). For example, LULC change may degrade or isolate natural habitats that extend beyond a park, alter the flow of materials (e.g., water, air, or energy) in and out of a protected area, or modify disturbance regimes in the region (Hansen and DeFries, 2007). Timely and accurate information on LULC change in and around protected areas can be useful when developing and evaluating the effectiveness of different conservation strategies (Nagendra et al., 2004; Alo and Pontius Jr., 2008; Gibbes et al., 2009), in the design of site-specific land management plans (Brandt and Townsend, 2006), or when identifying conservation priorities (Buchanan et al., 2008). Therefore, understanding not only changes that occur within protected areas, but also in places along their borders, are worthy of attention (Jones et al., 2009).

Unfortunately, data on LULC and LULC change in the Galápagos Islands are limited (González et al., 2008). The Galápagos are not unique in this respect as LULC change assessments are often lacking in remote areas of developing countries because of limited existing data, a lack of financial resources for data collection and analysis, and study sites that are difficult to access (Brandt and Townsend, 2006). The LULC information that does exist for Galápagos is often incomplete and outdated. The first archipelago-wide maps of land use were produced by the National Institute of Galápagos in 1987 as part of an effort to inventory features of the natural environment (PRONAREG et al., 1987). However, maps were not produced for Isabela or Floreana, two of the four inhabited islands in the archipelago. More recently, The Nature Conservancy (TNC), with the Centro de Levantamientos Integrados de Recursos Naturales por Sensores Remotos (CLIRSEN), produced a series of LULC maps of Galápagos using satellite imagery collected in 2000 (TNC and CLIRSEN, 2006). LULC maps were produced for all major islands in Galápagos, but the classification scheme lacked detail; for example, areas set aside for communities were wholly classified as “cultural features” without regard to actual land use or cover (i.e., whether those areas had been developed in any way). The coarse nature of existing maps and the lack of spatially-explicit data for some of the inhabited islands have hampered previous efforts to assess changes in land use and vegetation cover for resource management purposes within local communities (Villa and Segarra, 2010), and to quantify areas transformed by human activities throughout the archipelago (Watson et al., 2009).

To begin to fill the gap in our understanding of LULC change patterns in the Galápagos Islands, this chapter employs remote sensing data and methods to map LULC and quantify recent changes in the communities and surrounding protected areas of Isabela

Island. Remote sensing provides an efficient and robust technique for observing and monitoring land change over large areas and across multiple dates (Lu et al., 2004). Further, remote sensing can be employed to characterize LULC in areas that are isolated, difficult to access, or where field data collection is constrained for any number of reasons. Numerous studies to date have successfully used high spatial resolution satellite imagery (e.g., Ikonos, QuickBird, and WorldView-2) to observe and monitor LULC for various applications, such as examining changes in coastal and wetland ecosystems (Zhou et al., 2010; White and Lewis, 2011); observing the spread of invasive plants (Laba et al., 2008; Kimothi and Dasari, 2010); assessing changes in agriculture and pasture vegetation in semi-arid environments (Castillejo-González et al., 2009; Muñoz-Robles et al., 2012); and mapping human settlements in rural-urban landscapes (Dessí and Niang, 2009; Moran, 2010).

3.1.1 Study Aims

The goal of this chapter is to gain a better understanding of contemporary LULC change in the Galápagos Islands through a case study of southern Isabela Island. The study area encompasses two contrasting management zones: private lands located within two communities and adjacent areas protected by the Galápagos National Park. Two research questions are specifically addressed in this study:

1) How has the composition and spatial configuration of LULC changed in southern Isabela Island between 2003/2004 and 2010?

   It is hypothesized that during this period, the amount of land devoted to agriculture declined and built-up land use increased in southern Isabela. Declines in vegetation cover have likely occurred where built-up cover increased, and an expansion of invasive species cover is anticipated at the expense of agriculture. It is expected that built-up land

and invasive plant patches each coalesced as they expanded to occupy new areas, while natural land covers – forest/shrubs, grasslands, coastal vegetation, and coastal lagoons – became more fragmented as they were converted to other cover types.

2) How do the patterns of LULC change differ between the two management zones (i.e., the communities and protected areas)?

   LULC in the protected areas is hypothesized to be less likely to change due to the large size of the protected area in comparison to land set aside for the communities, and because of restrictions on land use within the National Park. It is expected, however, that some land cover changes in the protected area have occurred as the result of changes in land use within the adjacent communities (e.g., invasion of National Park grasslands by introduced plants found in agricultural fields), particularly along park-community borders.

To answer these questions, LULC change is explored using a combination of remote sensing data and methods, field observation, and GIS (Geographic Information Systems) data and methods. An object-based classifier is applied to high spatial resolution QuickBird and WorldView-2 satellite images from 2003/2004, 2008, and 2010 to generate LULC maps of the study area. Landscape composition is quantified in each period from the classified maps, and configuration is described using pattern metric analysis. Changes in landscape composition and configuration between 2003/2004 and 2010 are quantified with from-to change matrices and a panel approach.

Isabela Island was selected for this study for several reasons. The island is important from the perspective of conservation because it has the highest concentration of endemic species in Galápagos (Epler, 2007; Proaño, 2007) and it contains the largest marine-coastal wetlands complex in the archipelago (Chávez and Cruz, 2002). Historically, Isabela was somewhat isolated from the kinds of development taking place on other islands, in spite of its early colonization (relative to other islands in the archipelago) and its history of resource extraction. However, the natural features that give the island its ecological value are also attractive to visitors, fueling speculation that Isabela could soon become a hub for land-based tourism (Epler, 2007; Walsh et al., 2010). Further, large areas in the highlands invaded by introduced species may signal important changes in land use on farms in the highlands (Walsh et al., 2008).

Understanding recent LULC changes in the private lands and protected areas of Isabela will not only add to what little is known about the nature of LULC change on this particular island, but it may provide a realization of the changes that have taken place or that are possible on other islands in the archipelago. This research also contributes to the ongoing discussions of LULC change in and around protected areas, expanding previous work on the topic to a site that includes a large protected area with fairly strict land use restrictions surrounding small-footprint communities.

3.2 Study Area

This research takes place in southern Isabela Island, in the Galápagos Archipelago of Ecuador, between Latitude 0°47' and 0°58' S and Longitude 91°06' to 90°59' W (Figure 3.1). Located in the western portion of the Galápagos, Isabela is the largest (458,800 ha) and one of the youngest islands in the archipelago. Formed by oceanic hotspot volcanism, the island is comprised of six shield volcanoes geographically divided from north to south by Perry Isthmus. The climate is semi-arid and sub-tropical, with two distinct seasons. During the

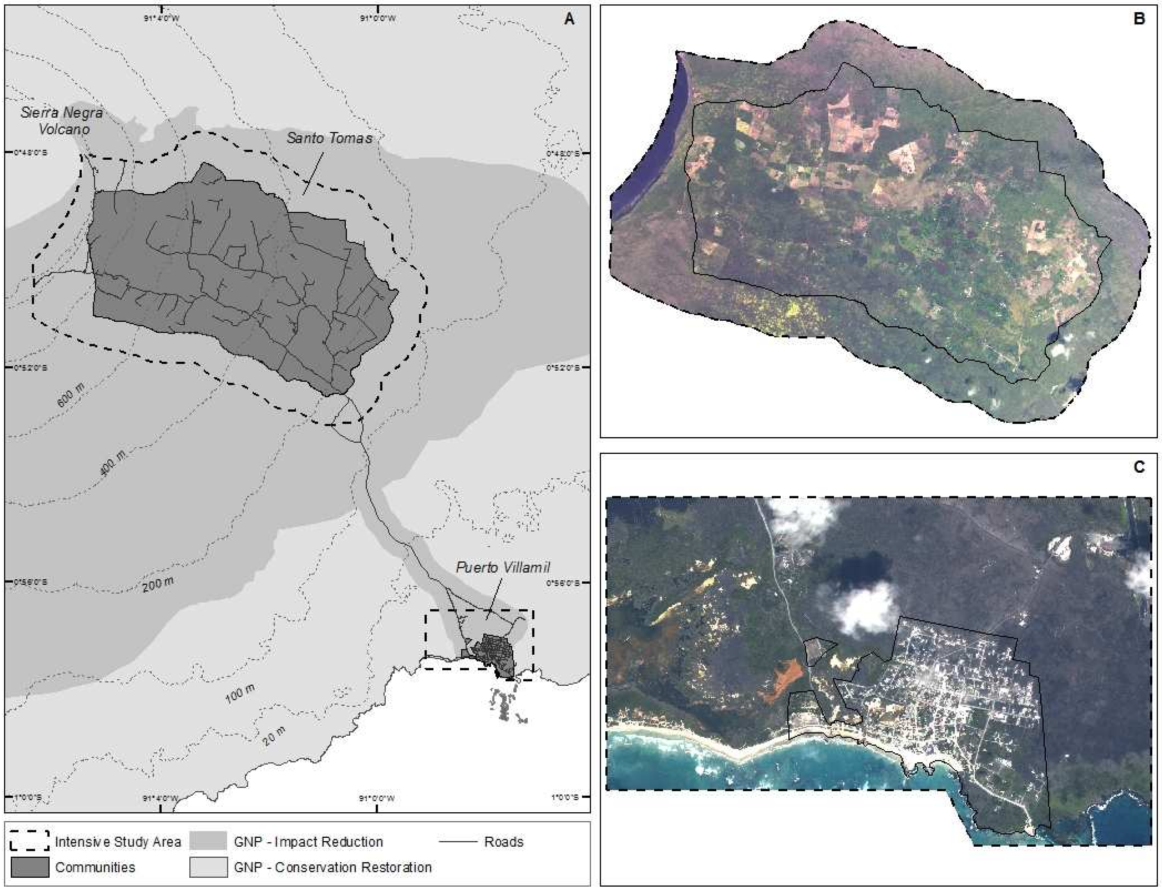

Figure 3.1 The study site on (A) Isabela Island includes (B) the Highlands Intensive Study Area (ISA), centered on Santo Tomás and a portion of the Galápagos National Park (GNP); and (C) the Coastal ISA centered on Puerto Villamil and adjacent areas of the GNP

warm season from January to May, air temperatures average between 22°C to 30°C (monthly), and sporadic rain showers are common (Guézou et al., 2007; Trueman and d'Ozouville, 2010). The cool season, from June to December, is marked by a reduction in precipitation and air temperatures (19°C to 26°C) (ibid.). Although it is drier along the coast, a near permanent fog called *garúa* occurs in the highlands during this period due to an inversion layer that forms over the archipelago (Collins and Bush, 2011; Pryet et al., 2012).

The analysis in this study focuses on two intensive study areas (ISAs) located along the southeastern flank of Sierra Negra Volcano – the Coastal ISA and the Highlands ISA – each of which is centered on a community, Puerto Villamil and Santo Tomás, respectively, and includes a portion of the surrounding protected area within the Galápagos National Park. The administration of Puerto Villamil and Santo Tomás, which are comprised of privately held and municipal land, is the responsibility of the Municipality of Isabela. The municipality generally adopts rules and regulations that apply to Puerto Villamil, while a *Junta Parroquial* (parish board) is the decision making body for Santo Tomás; these communities are further subject to regulations adopted by the Province of Galápagos and by the Ecuadorian state. On the other hand, the Galápagos National Park Service manages the protected areas on Isabela, which make up all land not within the island's two communities. Human settlements are not permitted in the National Park, but a limited number of special uses, including tourism, transportation infrastructure, and water extraction, are allowed in select sites.

The Coastal ISA is located in the southern portion of the larger study site and lies along the coastal lowlands (Figure 3.1). Totaling 800 ha, the site encompasses the growing community of Puerto Villamil (150 ha), the cantonal seat and locus of tourism activity on the island, and a surrounding area protected under the Galápagos National Park and Galápagos Marine Reserve (650 ha). The topography is relatively flat (slope angles less than 0.5°) with only a small rise in elevation (less than 10 m) from south to north. A sandy beach of organic origin serves as a barrier between Puerto Villamil Bay and coastal lagoons. The Sur de Isabela wetlands, which include brackish water lagoons and mangrove forests recognized under the Ramsar Convention, form the largest marine-coastal wetlands complex in the Galápagos (Chávez and Cruz, 2002). In the littoral zone, vegetation along the coastal fringe and within several meters of lagoons is comprised of woody shrubs and small trees, as well as a few salt-tolerant herbs and perennial grasses (Wiggins and Porter, 1971; Colinvaux, 1984). Mangrove forests in this site are comprised of three species –*Laguncularia racemosa* (white), *Avicennia germinans* (black), *Rhizophora mangle* (red) – and associated species such *Hippomane mancinella* (manzanillo) (Wiggins and Porter, 1971; Heumann, 2011). The Sur de Isabela wetlands not only provide habitat for aquatic fauna and a host of migrant and resident birds, but they also stabilize the coast, recharge shallow aquifers, and provide flood control (Chávez and Cruz, 2002; Gelin and Gravez, 2002).

The municipality of Puerto Villamil extends northward from the coast toward basaltic lava fields. The community includes a network of sandy residential streets and a mix of residences, hotels, restaurants, and small commercial buildings. In the adjacent terrestrial area of the Galápagos National Park, a paved road connecting Puerto Villamil to Santo Tomás, a small airport, and a few non-residential buildings (i.e.., electric generation plant, tortoise breeding center, gas station, and community center) are present; several unpaved roads and trails provide access to visitor sites west of the community.

Lava fields with sparse vegetation dominate the inland coast. Native vegetation in the arid zone, encompassing dry lowland communities immediately inland and up to 80 m in elevation above mean sea level (AMSL), includes several endemic cacti (*Opuntia* spp.), a mix of spiny shrubs and small trees such as cat's claw (*Zanthoxylum fagara* (L.) Sarg.) and palo santo (*Bursera graveolens*), and herbs that emerge during the wet season (Wiggins and Porter, 1971; Colinvaux, 1984). Soils are superficial (rarely greater than 10 cm in depth), brownish in color, sandy, and primarily develop within the cavities between un-weathered blocks of basaltic lava (Franz, 1980). Around the lagoons, soils are slightly deeper due to their connection to the Bay (Chávez and Cruz, 2002).

In contrast, the Highlands ISA is characterized by high topographic relief, extensive vegetation cover, and remains largely undeveloped. Located in the uplands of Sierra Negra, the site includes the rural community of Santo Tomás (5200 ha) and a buffer that extends into the National Park (3700 ha) (Figure 3.1). Elevation rises gradually from 80 to 1040 m AMSL moving southeast to northwest, while slope angles vary from 0° to 42° across the site. Land within the community is used primarily for crop cultivation and livestock grazing, and is characterized by residential buildings set on small- to medium-sized parcels. A network of unimproved roads links many of the farms within Santo Tomás, while an all-weather main road connects the communities of Santo Tomás and Puerto Villamil and provides access to the Sierra Negra visitor site in the National Park. Within the National Park there are a few small buildings that belong to the Park Service, unimproved trails that provide access to visitor sites, and an open-air dump.

The Highlands ISA coincides with two vegetation zones – the transition zone composed of evergreen and semi-deciduous plants, and the humid zone where introduced vegetation occupies areas once dominated by endemic scalesia forests and open grasslands. The transition zone begins at an elevation of 80 m AMSL and continues upward to the lower edge of the humid zone at approximately 200 m AMSL. As its name implies, the transition zone is an intermediate region that includes xerophytic plants that extend upward from the arid zone (e.g., *B. graveolens*) and mesophytic plants (e.g., *Psidium galapageium*) that are characteristic of the humid zone at higher elevations (Wiggins and Porter, 1971; Itow, 2003). Outcrops of basaltic rock are frequently observed in the transition zone, while soils several meters in depth are present near the caldera in the humid zone (Valarezo, 2008). These soils are reddish brown to brown clayey-loams and are derived from pyroclastic materials (Laruelle, 1966; Valarezo, 2008). The humid zone has traditionally been sub-divided on the basis of three native vegetation types - forests of endemic *Scalesia cordata* (200 to 500 m

AMSL), shrubs above treeline (sometimes referred to as the miconia zone; 500 to 800 m AMSL), and fern-sedge communities at the highest elevations (above 800 m AMSL) (Wiggins and Porter, 1971; Froyd et al., 2010). However, plants introduced for cultivation have significantly transformed these communities and invasive plants are replacing native vegetation within the humid zone (Tye, 2001). For example, *S. Cordata*, a small, endemic tree that was once ubiquitous in the humid zone of southern Isabela has been almost wholly replaced by introduced vegetation such as guava (*Psidium guajava* L.) and rose apple (*Syzygium jambos* (L.) Alston), and is now considered extremely threatened by the International Union for Conservation of Nature (IUCN) (IUCN, 2010; Philipp and Nielsen, 2010; Mauchamp and Atkinson, 2010). Guava and rose apple, woody species once cultivated for their fruit, now form dense, monospecific stands that shade out native vegetation (Soria et al., 2002) and significantly transform the ecosystems they invade in the archipelago (Tye et al., 2002).

3.3 Data & Pre-processing

3.3.1 Field Data

In situ LULC data were collected throughout the study area from July to August 2008 and July to August 2009 to provide training and validation data for the classifications and ground control points (GCPs) for geometric correction of the satellite images. Sampling areas (Coastal ISA: n=356; Highlands ISA: n=263) were randomly selected[1] from a map of general land cover derived from a 2005 ASTER image of the larger study area (see Chapter 2). The Coastal ISA map (Figure 3.2) included clouds (not sampled), lava / lagoon, ocean, bare soil,

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[1] Some pre-selected sites could not be visited due to constraints such as difficult terrain and private property. Points in more accessible areas near the originals were included to approximate planned sampling levels.

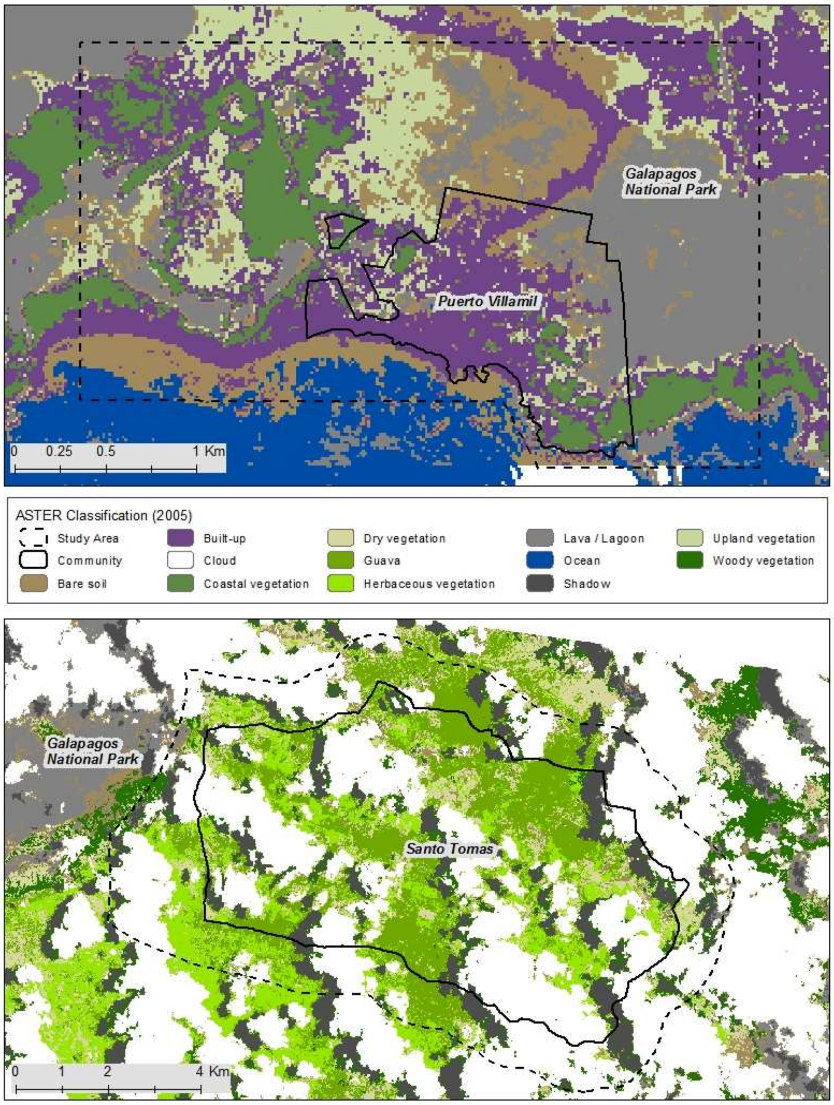

Figure 3.2 ASTER LULC classifiations of the Coastal ISA (top) and Highlands ISA (bottom) generated for field observation and *in situ* data collection

coastal vegetation, upland vegetation, and built-up areas. The Highlands ISA map (Figure 3.2) included clouds and shadows (not sampled), lava, bare soil, dry vegetation (agriculture and grassland), woody vegetation (forest and shrub), guava, and herbaceous vegetation (agriculture and grassland). At each sampling location the LULC type was noted, as was LULC within 10 meters (in each cardinal direction), a site description was recorded, and digital photographs were taken. GPS coordinates were collected to geo-locate the observations, and post-processing differential corrections were applied using data from permanent base stations on Isabela Island (UNAVCO, 2010).

3.3.2 Satellite data

A time series of QuickBird and WorldView-2 satellite images were used to characterize LULC in southern Isabela in the period from 2003/2004 to 2010. Image data for the Coastal ISA were acquired on June 06, 2003 and August 27, 2008 by QuickBird, and on October 1, 2010 by WorldView-2 (Table 3.1). Imagery for the Highlands ISA was collected by QuickBird on October 22, 2004 and by WorldView-2 on October 23, 2010. The image dates were chosen to obtain temporal coverage of the period just prior to- and during the Galápagos Islands' placement on UNESCO's In Danger list; images were also selected to minimize cloud cover in each scene, which is nearly persistent over Sierra Negra. The images were acquired during the same season (cool, *garúa* season) to minimize differences in vegetation phenology.

Each QuickBird data set (Ortho Ready Standard Product) consists of a panchromatic image with a spatial resolution of 0.6 m (450-900 nm), and a multispectral image at 2.4m spatial resolution that includes the following four bands: blue (450-520 nm), green

Table 3.1 Satellite imagery and geometric correction parameters

Acquisition Date	Sensor	Geometric correction	Number of GCPs	RMSE (m)
Coastal ISA				
06/06/2003	QuickBird	Orthorectification	16 (MS), 19 (P)	1.08 (MS), 0.68 (P)
08/27/2008	QuickBird	Registration (2003 scene)	17 (MS), 20 (P)	1.08 (MS), 0.96 (P)
10/01/2010	WorldView-2	Registration (2003 scene)	32 (MS), 20 (P)	0.82 (MS), 0.71 (P)
Highlands ISA				
10/22/2004	QuickBird	Orthorectification	13 (MS), 26 (P)	0.32 (MS), 0.28 (P)
10/23/2010	WorldView-2	Registration (2004 scene)	48 (MS), 27 (P)	0.94 (MS), 0.51 (P)

MS = multispectral bands; P = panchromatic band

(520-600 nm), red (630-690 nm), and near-infrared (760-900 nm). The WorldView-2 data (OrthoReady Standard Product) are also comprised of a single-band panchromatic image (0.5 m; 450-800 nm) and an eight-band multispectral image (2.0 m spatial resolution) that includes the blue, green, red and near-infrared QuickBird bands, as well as four additional channels: coastal blue (400-450 nm), yellow (585-625 nm), red-edge (705-745 nm) and a second near-infrared (860-1040 nm) channel.

The 2003 (Coastal ISA) and 2004 (Highlands ISA) QuickBird scenes were first orthorectified, and all other image data were co-registered to them to reduce potential change detection errors due to mis-registration; Table 3.1 provides details on the geometric correction applied to each image. In the Coastal ISA, the 2003 multispectral data were orthorectified using Toutin's Model in PCI Geomatica V10.2 (PCI Geomatics, Ontario, Canada), with 16 GCPs obtained in the field, rational polynomial coefficients (RPC) provided with the image data, and a digital elevation model (DEM). The corresponding panchromatic band and the other QuickBird and WorldView-2 images were co-registered to the orthorectified 2003 scene using the rational function transformation (4th order polynomial). Following the same methodology, the 2004 multispectral data from the Highlands ISA were orthorectified by applying Toutin's Model (with 13 GCPs). The panchromatic band and WorldView-2 data were co-registered to the 2004 scene. Root mean square errors (RMSEs) were less than 0.5 pixels for the multispectral data, and less than 1.6 pixels for the panchromatic images.

The WorldView-2 multispectral data for the Coastal and Highlands ISAs were re-sampled to 2.4 m x 2.4 m pixel size using the cubic convolution re-sampling technique to make the images compatible for change detection. The QuickBird and WorldView-2 image data were not corrected for atmospheric or radiometric errors[2] due to the lack of available atmospheric parameters at the time of image acquisition over the study area. Clouds and cloud shadows were masked from the images prior to classification to minimize spectral confusion.

The addition of band ratios, indices, and textures measures have been shown to improve classification results (Huang et al., 2002; Puissant et al., 2005; Wijaya and Gloaguen, 2007). The simple ratio vegetation index (SR) was calculated from the multispectral data (NIR band / Red band), and mean texture was derived from the panchromatic band using a gray-level co-occurrence matrix (GLCM) for each image (after after Haralick et al., 1973; Haralick, 1979). An image layer stack consisting of the multispectral bands, vegetation index, and texture measure was created for each image date and used as the classification input.

3.3.3 Classification Scheme and Training Data

The LULC classes representing the most common LULC types in the ISAs were identified during field visits and selected for image classification (Table 3.2). In the Coastal ISA the classification scheme consisted of barren, beach, built-up, coastal vegetation, lagoon, ocean, and upland vegetation. In the Highlands ISA, agriculture/grassland, barren, built-up, dry grassland, forest/shrub, guava, and rose apple were included. One-third of the geo-located field samples in each study site (Coastal ISA n=86; Highlands ISA n=118) were used to train the classifications. Image objects derived from the object-based image segmentation that coincided with field samples were selected to train the classifier. The remaining

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[2] Radiometric corrections (dark offset subtraction and a non-uniformity correction) are applied to raw QuickBird and WorldView-2 data by DigitalGlobe. The final data products are delivered to customers as radiometrically corrected image pixels (counts).

Table 3.2 LULC classification scheme with class description, and training and reference sizes

Class	Description	Training (objects)	Reference (pixels)
Coastal ISA			
Barren	Lava rock outcrops and bare soil with little to no vegetation	21	43
Beach	Exposed sand along the shoreline.	7	14
Built-up	Man-made features including buildings, transportation, and utilities	33	67
Coastal vegetation	Mangroves and salt-tolerant species found along coast and lagoons	24	48
Lagoon	Brackish water coastal lagoons	9	18
Ocean	Water within the Puerto Villamil Bay	7	13
Upland vegetation	Arid zone vegetation composed of cacti, shrubs, and few herbs	17	35
Highlands ISA			
Agriculture/ grassland	Area dedicated to crop cultivation, managed pastures, and natural grassland	16	33
Barren	Lava rock outcrops and bare soil with little to no vegetation	16	32
Built-up	Man-made features including buildings, roads, and structures for livestock	14	34
Dry grassland	Dry or senescent vegetation including managed pastures and natural grassland	8	15
Forest/Shrub	Dense growth of mostly evergreen trees or taller shrubs, including native and introduced species	12	25
Guava	Sites dominated by guava (*Psidium guajava*), an invasive woody tree	14	26
Rose apple	Closed canopies of rose apple (*Syzygium jambos*), an invasive tree	6	12

two-thirds of field data (Coastal ISA n=238; Highlands ISA n=177) were reserved for thematic accuracy assessment of the 2008 Coastal and 2010 Highlands ISA classifications.

3.3.4 GIS Data

LULC in the private and protected areas was compared to investigate whether the pattern of LULC change differed by management zone in southern Isabela Island. GIS coverages of the community and National Park boundaries obtained from the Galápagos National Park Service were used to partition each ISA into community and protected zones. Additionally, a digital elevation model (DEM) generated from a topographic map of Isabela Island (see Chapter 2) was used in the object-based classifications described below.

3.4 Methods

An object-based supervised classifier was applied to high spatial resolution QuickBird and WorldView-2 satellite images from 2003/2004, 2008, and 2010 to generate LULC maps of the ISAs; the processing workflows for the Coastal and Highlands ISAs are presented in Figures 3.3 and 3.4, respectively. *In situ* LULC data collected in 2008 and 2009 were used to establish the classification rule set and membership functions, and to assess the thematic accuracy of the 2010 classifications. The rule set and membership values from the 2010 classification were applied to the 2003/2004 and 2008 classifications; the Feature View tool in Definiens was used to determine appropriate membership values based on visual

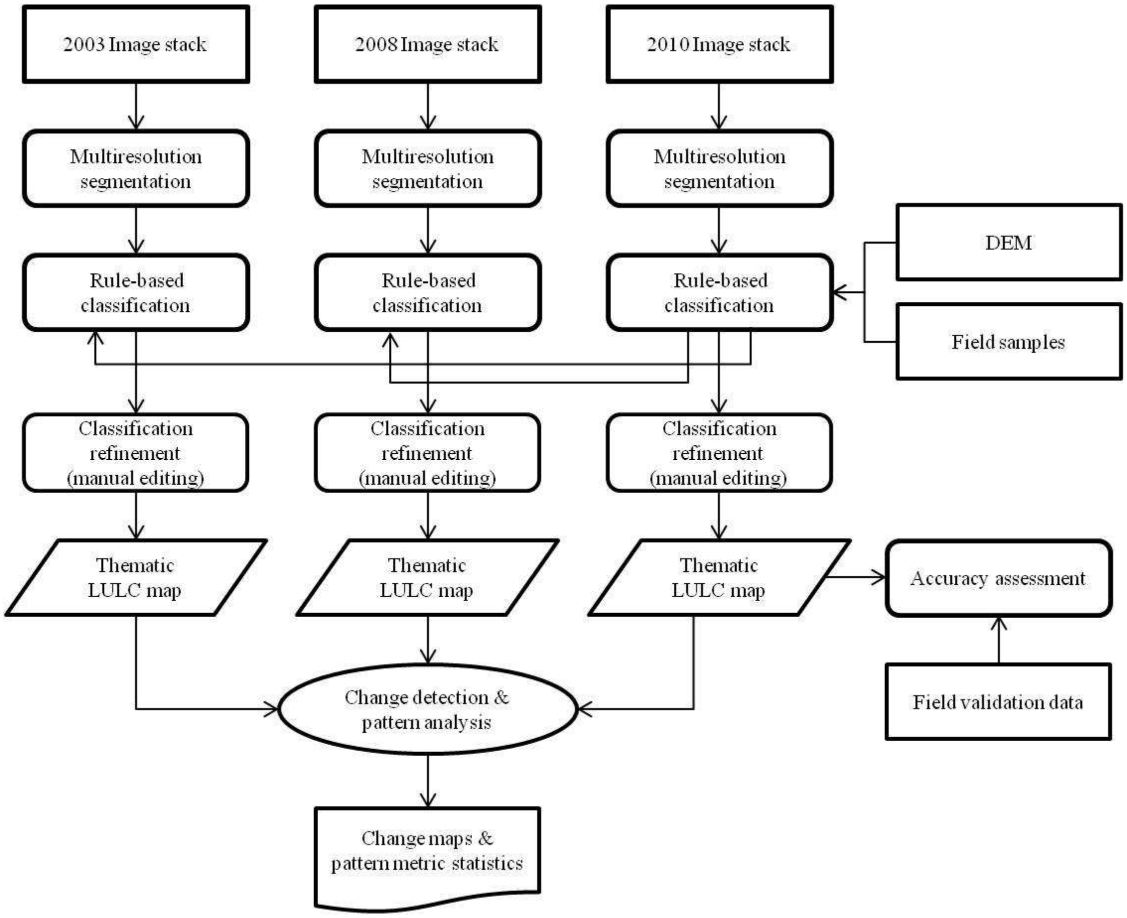

Figure 3.3 Coastal ISA workflow of LULC assessment and change detection

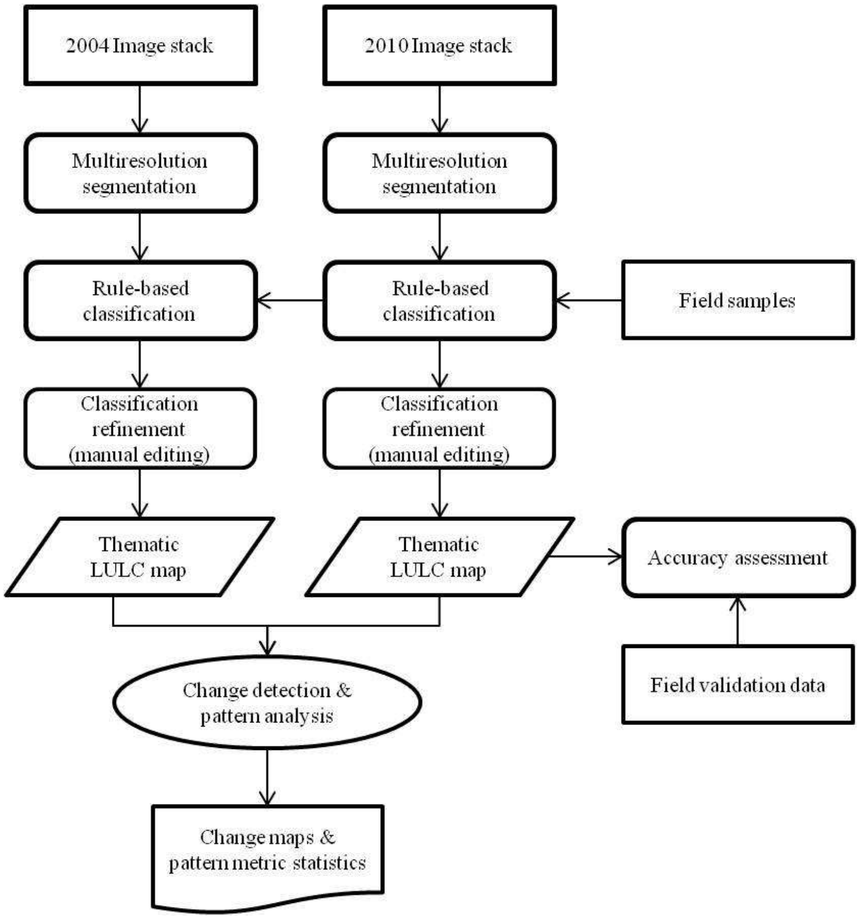

Figure 3.4 Highlands ISA workflow of LULC assessment and change detection

inspection of training sample values and their impact on the output classification. The resulting classified images from 2003-2010 were analyzed using post-classification change detection (from-to) to produce maps of LULC change and statistics describing change and stability in landscape composition at the pixel level. Landscape configuration was assessed in each period through pattern metric analysis of the classified maps and compared across time.

3.4.1 Land Use/Cover Classification

Supervised classification of the QuickBird and WorldView-2 images was performed with the object-based image analysis (OBIA) approach. OBIA is a knowledge-based classification method that attempts to mimic the way humans interpret remote sensing images (Hay and Castilla, 2008). Homogenous groups of pixels, or objects, are the basic unit of analysis. Thus, this approach avoids the ‘salt-and-pepper’ effect that is often observed in classifications derived from high spatial resolution data (Blaschke et al., 2000). Further, OBIA can exploit the textural, spatial, and topological characteristics of image objects to improve the value and accuracy of classifications (Benz et al., 2004; Lang, 2008).

The image data were first segmented into objects with the multiresolution segmentation algorithm in Definiens Professional 5 (Definiens AG, München, Germany). Multiresolution segmentation is a bottom up region-merging procedure (Benz et al., 2004) that creates objects that generally correspond to features of interest in an image without extensive processing times. The goal is to minimize the heterogeneity of extracted image objects while maximizing the contrast to neighboring objects. In the Coastal ISA, the image data were segmented into objects in a single level (Table 3.3); the multispectral data and GLCM texture were included as inputs. In the Highlands ISA, two levels of objects were generated such that small objects were first created to represent buildings, roads, and other small features (level 1), using the multispectral data, simple ratio (SR) vegetation index, and

Table 3.3 OBIA segmentation parameters

	Input Layers	Scale	Color/shape	Compactness/ smoothness
Coastal ISA (2003, 2008, 2010)				
Level 1	Multispectral bands GLCM Texture	18	0.7 / 0.3	0.2 / 0.8
Highlands ISA (2004, 2010)				
Level 1	Multispectral bands Simple ratio GLCM Texture	18	0.6 / 0.4	0.2 / 0.8
Level 2	Multispectral bands GLCM Texture	40	0.7 / 0.3	0.2 / 0.8

GLCM texture as inputs. Larger objects (level 2) were generated to represent vegetation patches, including forests and open fields, using only the multispectral and GLCM texture layers. In both sites, input layers included in the segmentation process were weighted equally, and user-defined criteria describing the threshold for object heterogeneity – scale, color/shape, and smoothness/ compactness – were selected iteratively by visual assessment of object fit (Meinel and Neubert, 2004).

Image objects were then classified using a rule-based classification approach. In Definiens Professional, each LULC category in the classification scheme contains a set of expressions, or rules, that describe the class. Knowledge-based rules can draw on spectral data contained in the image bands and/or contextual information such as the textural, spatial and topological characteristics of image objects. Objects corresponding to points in the training data set were isolated and their spectral, textural, and contextual attributes were used to establish the rules for each class. Tables 3.4 – 3.8 describe the rules (features and membership functions) that define the classes in the classification scheme for each image.

The classification algorithm then evaluated the membership value of each image object to the list of classes and the class with the highest membership value (ranging from 0 to 1) was assigned to the object. The objects were first separated into 'High SR' (vegetation) and 'Low SR' (non-vegetation) classes based on linear membership to mean simple ratio (SR) vegetation index values. In subsequent steps, the 'vegetation' and 'non-vegetation' objects were further refined into several sub-classes (i.e., guava, crops, buildings, etc.). In the Coastal ISA, lagoons were manually edited using visual interpretation due to spectral confusion between barren cover (lava and soil) and shallow water. In the Highlands ISA, 'vegetation' sub-classes were defined at segmentation level 2, while 'non-vegetation'

Table 3.4 Coastal ISA (2003, QuickBird): OBIA classification rules with features and membership thresholds

Final Class	Sub-classes	Feature	Function[a] and threshold
Barren	Lava	Low SR[b]	
		Brightness	< 260
		NDVI	-0.19 /-\ 0.19
	Soil	Brightness	150 □ 550
		NDVI	0 □ 0.4
Beach		Low SR	
		Brightness	290 / 900
		Mean elevation	-0.15 /-\ 0.17 m
		Mean ratio red:green bands	0.59 /-\ 0.9
Built-up	Building	Low SR	
		Brightness	110 □ 900
		Mean elevation	> 0 m amsl
		Distance to left image border	> 1850 m
	Road	Classified as lava, soil, or building	
		Density	0.35 /-\ 1.15
		Length/Width	2.4 /-\ 15.8
Coastal Vegetation		High SR	
		Distance to lagoon or ocean	< 250 m
Lagoon		Low SR	
		Max difference	1.7 /-\ 1.9
		Mean elevation	> 0 m AMSL
		Mean red band	100 /-\ 240
		NDVI	-0.64 □ 0.4
		Distance to right image border	> 2000 m
		Distance to bottom image border	< 2750 m
Ocean		Low SR	
		Mean ratio NIR:blue band	0.14 □ 0.45
Upland Vegetation		High SR	
		Distance to lagoon or ocean	> 250 m

[a] Fuzzy membership functions: □ = lower than (non-linear), □ = greater than (non-linear), \ = lower than (linear), / = greater than (linear), /-\ = approximate range.

[b] High Simple Ratio (SR) = 0.6/7.5; Low SR = Not High SR; NDVI = Normalized Difference Vegetation Index

Table 3.5 Coastal ISA (2008, QuickBird): OBIA classification rules with features and membership thresholds

Final Class	Sub-classes	Feature	Function[a] and threshold
Barren	Lava	Low SR[b]	
		Brightness	< 290
		NDVI	-0.2 /-\ 0.2
	Soil	Brightness	225 □ 550
		NDVI	0 □ 0.6
Beach		Low SR	
		Brightness	175 / 900
		Mean elevation	-0.15 /-\ 0.17 m
		Mean ratio red:green bands	0.7 /-\ 1.0
Built-up	Building	Low SR	
		Brightness	120 □ 900
		Mean elevation	> 0 m amsl
		Distance to left image border	> 1850 m
	Road	Classified as lava, soil, or building	
		Density	0.5 /-\ 1.2
		Length/Width	2.4 /-\ 23
Coastal Vegetation		High SR	
		Distance to lagoon or ocean	< 250 m
Lagoon		Low SR	
		Max difference	1.5 /-\ 2.0
		Mean elevation	> 0 m amsl
		Mean red band	115 /-\ 220
		NDVI	-0.4 □ 0.5
		Distance to right image border	> 2000 m
		Distance to bottom image border	< 2750 m
Ocean		Low SR	
		Mean ratio NIR:blue band	0.14 □ 0.74
Upland Vegetation		High SR	
		Distance to lagoon or ocean	> 250 m

[a] Fuzzy membership functions: □ = lower than (non-linear), □ = greater than (non-linear), \ = lower than (linear), / = greater than (linear), /-\ = approximate range.

[b] High Simple Ratio (SR) = 0.6/7.5; Low SR = Not High SR; NDVI = Normalized Difference Vegetation Index

Table 3.6 Coastal ISA (2010, WorldView-2): OBIA classification rules with features and thresholds

Final Class	Sub-classes	Feature	Function[a] and threshold
Barren	Lava	Low SR[b]	
		Brightness	< 250
		NDVI	0 /-\ 0.4
	Soil	Brightness	150 □ 550
		NDVI	0 □ 0.5
Beach		Low SR	
		Brightness	350 / 800
		Mean elevation	-0.15 /-\ 0.17 m
		Mean ratio red:green bands	0.98 /-\ 1.15
Built-up	Building	Low SR	
		Brightness	100 □ 900
		Mean elevation	> 0 m amsl
		Distance to left image border	> 1850 m
	Road	Classified as lava, soil, or building	
		Density	0.35 /-\ 1.2
		Length/Width	2.5 /-\ 16
Coastal Vegetation		High SR	
		Distance to lagoon or ocean	< 250 m
Lagoon		Low SR	
		Max difference	1.6 /-\ 1.8
		Mean elevation	> 0 m amsl
		Mean red band	115 /-\ 225
		Distance to right image border	> 2000 m
		Distance to bottom image border	< 2750 m
Ocean		Low SR	
		Mean ratio NIR_2:blue band	0 □ 0.6
Upland Vegetation		High SR	
		Distance to lagoon or ocean	> 250 m

[a] Fuzzy membership functions: □ = lower than (non-linear), □ = greater than (non-linear), \ = lower than (linear), / = greater than (linear), /-\ = approximate range.

[b] High Simple Ratio (SR) = 0.75/15; Low SR = Not High SR; NDVI = Normalized Difference Vegetation Index

Table 3.7 Highlands ISA (2004 QuickBird): OBIA classification rules with features and membership threshold

Final Class	Sub-classes	Feature	Function[a] and threshold
Agriculture/Grassland	Grass – bright	High SR[b]	
		Brightness	275 □ 400
		Mean red band	89 □ 200
		NDVI	0.42 – 0.67
	Grass – dark	Brightness	345 □ 460
		Mean green band	229 □ 300
		Mean red band	70 □ 110
		NDVI	0.67 – 0.78
	Crops/pasture	Brightness	425 □ 460
		Mean green band	240 /-\ 330
		Mean red band	80 □ 110
		NDVI	0.5 – 0.766
Barren		Low SR	
	Lava	Brightness	< 260
		Mean GLCM texture	1.35 □ 9
		NDVI	< 0.3
	Soil	Brightness	240 □ 400
		NDVI	0.1 □ 0.5
Built-up	Building	Low SR	
		Area	< 306 m^2
		Length	< 36 m
		Max difference (to neighbors)	0 □ 1.25
		Mean red band	190 /-\ 2250
	Road	Classified as Lava or Soil	
		Length/width	3 – 21
Dry grassland		Low SR	
		Brightness	289 □ 370
		NDVI	0.1 □ 0.8
Forest/shrub	Trees – green	High SR	
		Mean green band	260 /-\ 360
		NDVI	0.7 – 0.78
	Trees – yellow	Brightness	270 □ 380
		Mean green band	255 □ 375
		NDVI	0.5 – 0.7
		Distance to right image border	2500 – 4700 m
		Distance to bottom image border	1750 – 3650 m
Guava		High SR	
		Brightness	250 □ 360
		Mean green band	19230□ 300
		Mean NIR band	480 □ 825
		NDVI	0.53 – 0.72
Rose apple		High SR	
		Brightness	250 □ 340
		Mean green band	225 □ 310
		NDVI	0.6 – 0.74
		Distance to right image border	3850 – 6900 m
		Distance to bottom image border	1500 – 5500 m

[a] Fuzzy membership functions: □ = lower than (non-linear), □ = greater than (non-linear), \ = lower than (linear), / = greater than (linear), /-\ = approximate range.

[b] High Simple Ratio (SR) = 1.5/8.1; Low SR = Not High SR; NDVI = Normalized Difference Vegetation Index

Table 3.8 Highlands ISA (2010 WorldView-2): OBIA classification rules with features and membership threshold

Final Class	Sub-classes	Feature	Function[a] and threshold
Agriculture/Grassland	Grass – bright	High SR[b]	
		Brightness	310 □ 420
		Mean red band	65 □ 180
		NDVI	0.5 – 0.7
	Grass – dark	Brightness	355 □ 460
		Mean green band	229 □ 300
		Mean red band	70 □ 110
		NDVI	0.7 – 0.76
	Crops/pasture	Brightness	425 □ 460
		Mean green band	240 /-\ 330
		Mean red band	80 □ 110
		NDVI	0.5 – 0.766
Barren		Low SR	
	Lava	Brightness	< 280
		Mean GLCM texture	1.35 □ 9
		Mean red edge band	124 □ 375
	Soil	Brightness	290 □ 445
		NDVI	0.2 □ 0.6
Built-up		Low SR	
	Building	Area	< 306 m^2
		Length	< 36 m
		Max difference (to neighbors)	0 □ 1.75
		Mean red band	100 /-\ 2000
	Road	Classified as Lava or Soil	
		Length/width	3 – 21
Dry grassland		Low SR	
		Brightness	335 □ 405
		Mean red-edge band	> 473
		NDVI	0.26 / 0.6
Forest/shrub	Trees – green	High SR	
		Mean green band	233 /-\ 300
		NDVI	0.766 – 0.84
	Trees – yellow	Brightness	275 □ 455
		Mean green band	230 □ 300
		NDVI	0.54 – 0.735
		Distance to right image border	2500 – 4700 m
		Distance to bottom image border	1750 – 3650 m
Guava		High SR	
		Brightness	270 □ 425
		Mean green band	195 □ 260
		Mean NIR-2 band	540 □ 1045
		NDVI	0.61 – 0.8

Table 3.8 continued

Final Class	Sub-classes	Feature	Function[a] and threshold
Rose apple		High SR	
		Brightness	200 □ 427
		Mean green band	200 □ 240
		NDVI	0.7 – 0.8
		Distance to right image border	3850 – 6900 m
		Distance to bottom image border	1200 – 5500 m

[a] Fuzzy membership functions: □ = lower than (non-linear), □ = greater than (non-linear), \ = lower than (linear), / = greater than (linear), /-\ = approximate range.

[b] High Simple Ratio (SR) = 4.5/18; Low SR = Not High SR; NDVI = Normalized Difference Vegetation Index

subclasses were defined at level 1. The classifications at levels 1 and 2 were then merged to create a single thematic LULC map for each image date. Roads were also manually edited due to confusion between barren cover (lava and soil) and roads which were constructed of the same materials.

3.4.2 Accuracy Assessment

Accuracy of the 2008 classification of the Coastal ISA was assessed with the field reference points (n=238) reserved for thematic classification validation (Table 3.2). Standard error matrices were calculated to determine the overall accuracy, producer’s and user’s accuracies, and overall kappa statistic on a per-pixel basis. The same procedure was followed to determine the accuracy of the 2010 Highlands ISA classification using field samples (n=177) reserved for validation. Field data to test the accuracy of the other three classifications were not available. However, similar segmentation parameters and membership functions were applied to the image data in each ISA in an effort to produce classifications with comparable accuracies.

3.4.3 Change Detection

The classified images were analyzed using post-classification change detection to produce categorical maps of LULC change and statistics describing change and stability at the pixel level. In the Coastal ISA, from-to change maps were generated by overlaying temporally adjacent classified images (i.e., 2003 and 2008; 2008 and 2010; 2003 and 2010) in ArcMap 10 (ESRI Inc, Redlands, California) so that each pixel included information on land cover for both dates. Cloud cover in each individual scene was masked out of all other images prior to change detection to facilitate comparison of LULC across time. Landscape composition was quantified from the change images by calculating the abundance of each LULC type (ha) and the proportion of the landscape occupied by each class (%) in 2003, 2008 and 2010, as well as absolute (ha) and relative (%) changes in abundance for each period. These measures of composition were calculated for the entire ISA, as well as for each management zone. A change matrix was produced to explore changes among different classes during each period (e.g., the amount of land in barren in 2003 that was converted to built-up by 2010). In addition to the pair-wise comparison, the trajectory of pixels in each time period was tracked using a panel approach. The panel (aka longitudinal) approach provides a representation of a pixel's history across more than two observations (Crews-Meyer, 2000; Mertens and Lambin, 2000; Crews-Meyer, 2001). The three classified images (2003, 2008, 2010) were overlaid in ArcMap, and 210 different change trajectories were generated (e.g., barren – barren – built-up). These trajectories were combined and reclassified to map stability, early vs. late losses, and early vs. late gains in each class; early refers to the 2003-2008 period, while late refers to the 2008-2010 period.

The from-to change detection approach was also applied to the 2004 and 2010 classified maps from the Highlands ISA to produce change maps and statistics describing landscape composition; areas under cloud in either of the two images were excluded from the analysis. Landscape composition was quantified from the change image by calculating the abundance of each LULC type (ha) and the proportion of the landscape occupied by each class (%) in 2004 and 2010, as well as absolute (ha) and relative (%) changes in abundance for the entire ISA and both management zones. A change matrix was constructed to explore changes among LULC categories during the 2004 to 2010 period.

3.4.4 Landscape Pattern Analysis

Land cover patterns are generated by the complex interaction of social and biophysical processes that operate across spatial and temporal scales (Gardner et al., 1987; Urban et al., 1987; Gustafson, 1998). This relationship is reciprocal, as changes in pattern can alter landscape function by interfering with ecological processes (e.g., those that maintain biodiversity) (Turner et al., 1989; Forman, 1995). Quantifying the spatial and temporal patterns of LULC can facilitate the inference of landscape processes that drive LULC change (Brown et al., 2000; Crews-Meyer, 2004). In fact, the description and quantification of landscape composition and configuration, the two components of pattern, is a prerequisite for studies of pattern-process relations (McGarigal and Marks, 1994; Schröder and Seppelt, 2006).

Landscape ecology provides a theoretical framework and methodology to analyze spatial pattern in order to understand the underlying processes associated with LULC change (Crews-Meyer, 2004). Of particular interest within the field is the detection and characterization of pattern, understanding how and why it develops and changes over time, and its implications for landscape function. Landscape, as the term is used here, refers to an area characterized by spatial heterogeneity (in relation to some factor of interest), on the order of a few hectares to hundreds of square kilometers in size (Turner et al., 1989; Turner et al., 2001). Landscapes are composed of patches, defined as homogenous areas of particular LULC types that differ from their surroundings (Turner et al., 2001).

The scale of observation is an important consideration in landscape studies. The patterns that can be observed are determined by the scale of observation, which, in turn, is used to infer process (Crews-Meyer, 2006). Scale encompasses both grain (resolution of the data) and extent (scope or boundary of the data). Scale dependence, or how patterns and processes vary with scale, has been an area of extensive area of research within geography and landscape ecology. Landscapes exhibit scale dependency in two ways. First, patterns may be exhibited only at particular scales or ranges of scale, such that they are seen as operating at particular levels of organization (Lam and Quattrochi, 1992). Second, the ability to discern pattern depends on the scale of observation and analysis. The spatial and temporal grain and extent of data employed to measure landscape pattern (and changes in pattern) can affect the types of pattern that can be observed, and therefore will impact the inference of process.

Landscape pattern can be measured and represented in a variety of ways, from field based studies to the interpretation of remotely sensed data, and from spatial point to linear network representations (Gustafson, 1998; McGarigal, 2002). Landscape patches can be delimited and thematically attributed through ground-based measurements or, as is the case in this study, from analyses of remotely sensed imagery (Crews-Meyer, 2006). Landscape pattern metrics are then calculated from the resulting thematic maps at the level of individual patches, classes (integrated over all the patches of a particular type), or the landscape (integrated over all patch types or classes across the full extent of the landscape) (McGarigal, 2002). The description of landscape pattern falls into two categories based on the components of pattern: composition and configuration. Composition refers to the variety of LULC types and their relative abundances. Configuration, or structure, is the spatial arrangement of patches on the landscape.

In this study, landscape pattern was assessed in both ISAs by conducting pattern metric analysis for each classified image. Landscape composition was quantified as described in the previous section (2.4.3 Change Detection). Landscape configuration was assessed by calculating landscape pattern metrics in the FragStats 4.0 software package (University of Massachusetts, Amherst, MA). More than one-hundred metrics are now available to quantify configuration, but many of them are redundant and not all are readily interpretable (Riitters et al., 1995; O'Neill et al., 1999; Cushman et al., 2008). For this reason, a small number of commonly used metrics that provide robust descriptions of pattern across a variety of environments (Cushman et al., 2008) were selected for this study; eight metrics were calculated at the class and landscape levels[3] (McGarigal et al., 2012):

(1) *Number of patches (NP)*: total number of patches; indicative of landscape patchiness.
(2) *Mean patch size (MPS)*: average patch size, in hectares; inversely related to number of patches.
(3) *Patch size coefficient of variation (PSCV)*: patch size standard deviation normalized by mean patch size; a measure of patch size distribution that is less impacted by outlier values than standard deviation.

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[3] Equations for the calculation of the metrics, along with fuller descriptions are provided by McGarigal et al., 2012.

(4) *Largest patch index (LPI)*: areal extent of the largest patch, as a percentage of total landscape area; also indicates degree of fragmentation.

(5) *Edge density (ED)*: sum of the lengths of all edge segments, divided by the total landscape area; indicative of boundary effects.

(6) *Mean Euclidean nearest neighbor distance (ENN)*: mean straight-line distance between patches of the same type, measured from patch edge to patch edge; quantifies patch isolation.

(7) *Nearest neighbor distance coefficient of variation (NNCV)*: nearest neighbor standard deviation normalized by mean nearest neighbor distance; a measure of nearest neighbor distance variation that is less impacted by outlier values than standard deviation

(8) *Interspersion-juxtaposition index (IJI)*: degree of interspersion of patches of a particular type with all other patch types, as a percentage (index ranges from 0 when a patch type is found adjacent to only one other type, to 100 when all patch types are equally adjacent to each other); measure of the intermixing of patch types.

3.5 Coastal ISA Results

3.5.1 Classification Accuracy

Overall accuracy of the 2008 classification was 95.4% with a kappa statistic of 0.94 (Table 3.9). Producer’s and user’s accuracies for individual classes exceeded the generally accepted standard of 85% (Foody, 2002). Upland vegetation, coastal vegetation, and barren classes had the lowest producer’s accuracies, resulting from errors of omission. In some cases, reference samples of upland vegetation were misclassified as barren, built-up, and coastal vegetation. The classification of mixed objects (i.e., objects containing pixels belonging to more than one class) as a single class may have contributed to the misclassification of upland vegetation. Ocean, barren, and built-up classes had the lowest user’s accuracies due to errors of commission. Although water classes tend to be fairly easy to distinguish from other LULC types in remotely sensed data, differences in tides and ocean

Table 3.9 Confusion matrix for 2008 QuickBird classification of the Coastal ISA

	Reference Class								
Mapped Class	Barren	Beach	Built-up	Coastal vegetation	Lagoon	Ocean	Upland vegetation	Total	User's accuracy
Barren	41	0	1	0	0	0	2	44	93.2%
Beach	0	14	0	0	0	0	0	14	100.0%
Built-up	1	0	65	2	0	0	1	69	94.2%
Coastal vegetation	0	0	1	45	0	0	1	47	95.7%
Lagoon	0	0	0	0	18	0	0	18	100.0%
Ocean	1	0	0	0	0	13	0	14	92.9%
Upland vegetation	0	0	0	1	0	0	31	32	96.9%
Total	43	14	67	48	18	13	35	238	-
Producer's accuracy	95.4%	100.0%	97.0%	93.8%	100.0%	100.0%	88.6%	-	-
Overall = 95.4%									
Kappa = 0.94									

level during reference data collection and image acquisition may explain the misclassification of barren samples as ocean. Built-up cover and bare soil have similar spectral responses, which likely resulted in spectral confusion between built-up and barren classes and misclassification among these cover types.

Accuracy of the 2003 and 2010 classifications could not be quantified due to the lack of field data or aerial photographs during this period. Although there was only a one to two year lag between the field reference data set and the 2010 image, substantial LULC changes in the Coastal ISA during that time, particularly in Puerto Villamil, would result in a biased error assessment. Therefore, the classifications for 2003, 2008, and 2010 were trained separately. However, the same classification rules with adjusted membership values were applied to all three images in an effort to produce classifications with comparable accuracies. Visual assessment of the 2003 and 2010 classifications showed that invariant features, such as the main roads to Santo Tomás, the airport runway, and dark lava flows were correctly classified.

3.5.2 Land Use/Cover Change: 2003-2010

The LULC maps of the Coastal ISA for 2003, 2008, and 2010 are presented in Figure 3.5; change maps for built-up, lagoons, and vegetation covers are shown in Figure 3.6. The area and proportion of each class during the three dates, and changes between 2003 and 2010 are presented in Tables 3.10 and 3.11. In 2003, the Coastal ISA was dominated by barren cover (33.9%), coastal vegetation (27.5%), and ocean (13.9%). One-quarter of the landscape was composed of upland vegetation (11.9%), lagoons (6.91%), built-up areas (4.34%), and beach (1.5%). The majority of LULC (84%) was stable between 2003 and 2010, but there were substantial changes in built-up areas, lagoons, and coastal and upland vegetation.

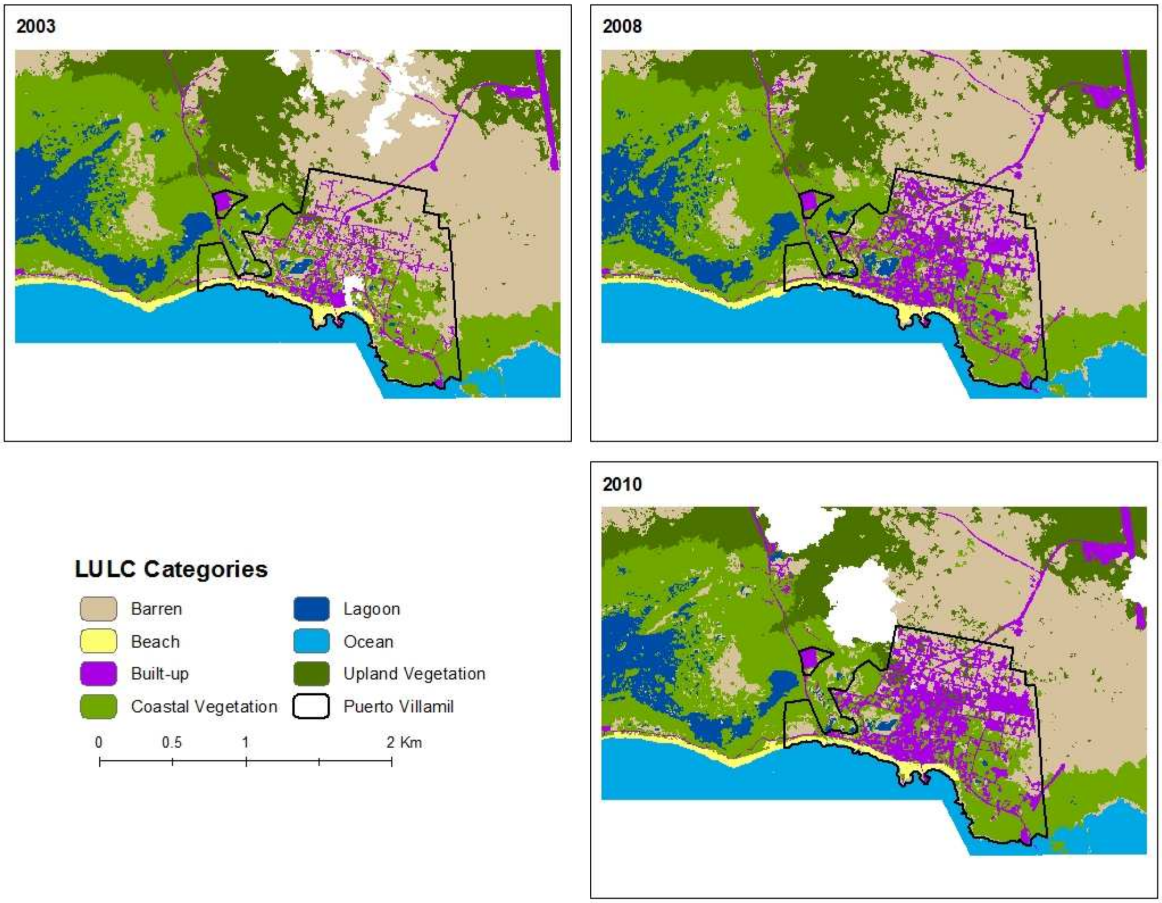

Figure 3.5 LULC classification maps of the Coastal ISA for 2003, 2008, and 2010. Clouds have been masked out (white)

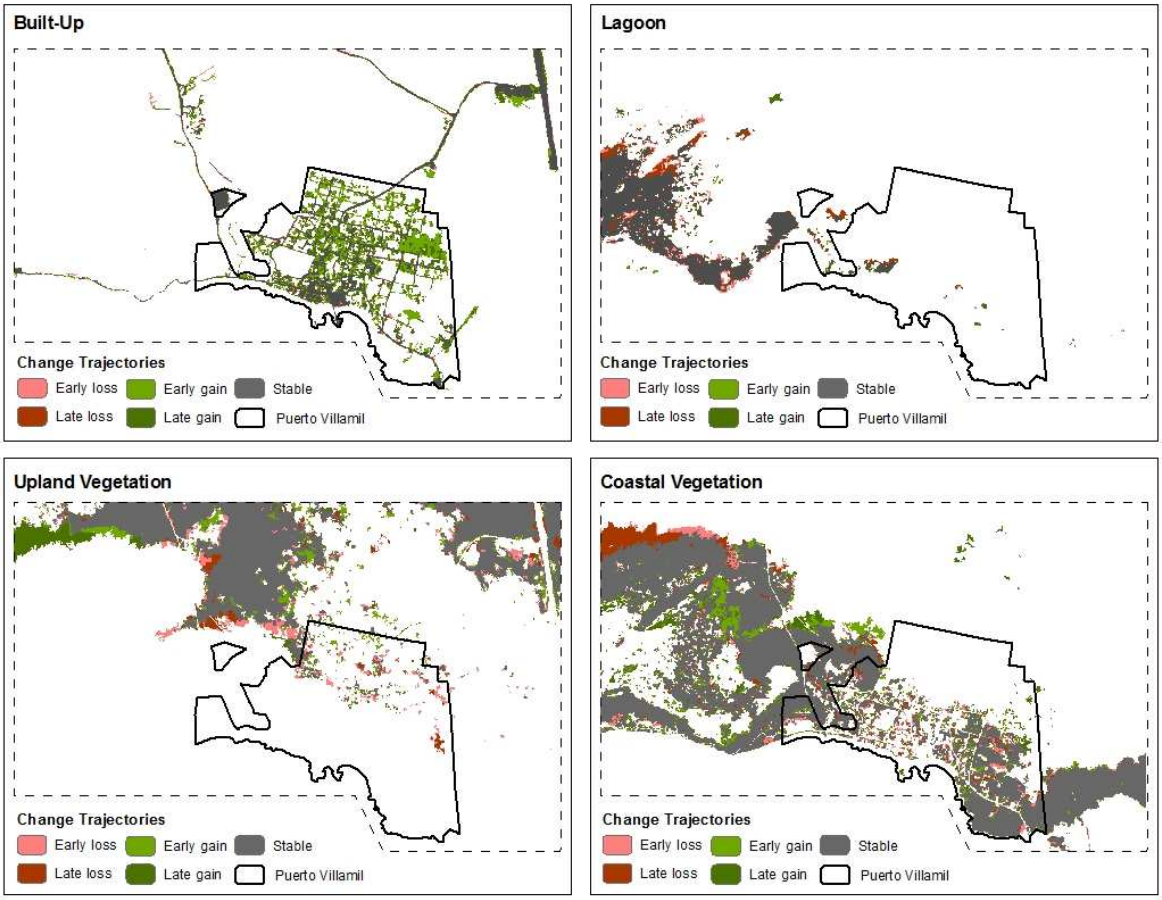

Figure 3.6 LULC change trajectories in the Coastal ISA. Early losses/gains refer to changes in the 2003-2008 period; late gains/losses refer to 2008-2010 period

Table 3.10 LULC statistics for the Coastal ISA, 2003-2010

	Total Area (ha)			Percent of landscape (%)			Change: 2003-2010	
Land Use Class	2003	2008	2010	2003	2008	2010	Absolute (ha)[a]	Relative (%)[b]
Barren	246.69	212.48	211.46	33.9	29.2	29.1	-35.23	-14.3
Beach	10.72	11.01	10.55	1.5	1.5	1.5	-0.17	-1.6
Built-up	31.55	55.18	64.54	4.3	7.6	8.9	32.98	104.5
Coastal vegetation	200.40	210.61	202.14	27.5	28.9	27.8	1.74	0.9
Lagoon	50.30	47.08	41.16	6.9	6.5	5.7	-9.14	-18.2
Ocean	101.00	101.02	101.74	13.9	13.9	14.0	0.75	0.7
Upland vegetation	86.86	90.14	95.93	11.9	12.4	13.2	9.07	10.4
Total	727.52	727.52	727.52	100.0	100.0	100.0	-	-

[a] Net change between periods was calculated as ($Area_{2010}$ – $Area_{2003}$)

[b] Percent change relative to 2003 was calculated as 100 x ($Area_{2010}$ – $Area_{2003}$)/$Area_{2003}$

Table 3.11 LULC statistics, by management zone, for the Coastal ISA

	Total Area (ha)			Percent of Landscape (%)			Change: 2003-2010		Change: 2003-2008		Change: 2008-2010	
	2003	2008	2010	2003	2008	2010	ha[a]	%[b]	ha[c]	%[d]	ha[e]	%[f]
Puerto Villamil												
Barren	58.34	36.03	33.15	41.0	25.3	23.3	-25.19	-43.2	-22.31	-38.2	-2.88	-11.4
Beach	5.37	5.64	5.22	3.8	4.0	3.7	-0.15	-2.8	0.27	5.0	-0.42	-10.6
Built-up	21.55	43.47	50.44	15.2	30.6	35.5	28.89	134.1	21.91	101.7	6.98	22.8
Coastal vegetation	47.39	47.68	45.75	33.3	33.5	32.2	-1.65	-3.5	0.28	0.6	-1.93	-5.8
Lagoon	1.48	2.37	1.18	1.0	1.7	0.8	-0.31	-20.8	0.89	60.0	-1.2	-71.8
Ocean	1.67	1.46	1.37	1.2	1.0	1.0	-0.29	-17.6	-0.21	-12.3	-0.09	-8.7
Upland vegetation	6.38	5.53	5.08	4.5	3.9	3.6	-1.3	-20.4	-0.84	-13.2	-0.46	-11.7
Total	142.18	142.18	142.18	100.0	100.0	100.0	-	-	-	-	-	-
Galápagos National Park												
Barren	188.35	176.45	178.31	32.2	30.1	30.5	-10.04	-5.3	-11.9	-6.3	1.86	1.1
Beach	5.35	5.37	5.33	0.9	0.9	0.9	-0.02	-0.3	0.02	0.4	-0.04	-0.7
Built-up	10.00	11.72	14.09	1.7	2.0	2.4	4.09	40.9	1.72	17.2	2.37	20.3
Coastal vegetation	153.00	162.93	156.39	26.1	27.8	26.7	3.39	2.2	9.93	6.5	-6.54	-4.0
Lagoon	48.82	44.7	39.99	8.3	7.6	6.8	-8.83	-18.1	-4.12	-8.4	-4.71	-10.5
Ocean	99.33	99.55	100.37	17.0	17.0	17.1	1.04	1.0	0.22	0.2	0.82	0.8
Upland vegetation	80.49	84.61	90.86	13.8	14.5	15.5	10.37	12.9	4.12	5.1	6.25	7.4
Total	585.34	585.34	585.34	100.0	100.0	100.0	-	-	-	-	-	-

[a] Net change between periods was calculated as ($Area_{2010}$ – $Area_{2003}$)
[b] Percent change relative to 2003 was calculated as 100 x ($Area_{2010}$ – $Area_{2003}$)/$Area_{2003}$
[c] Net change between periods was calculated as ($Area_{2008}$ – $Area_{2003}$)
[d] Percent change relative to 2003 was calculated as 100 x ($Area_{2008}$ – $Area_{2003}$)/$Area_{2003}$
[e] Net change between periods was calculated as ($Area_{2010}$ – $Area_{2008}$)
[f] Percent change relative to 2008 was calculated as 100 x ($Area_{2010}$ – $Area_{2008}$)/$Area_{2008}$

From 2003 to 2010, built-up cover more than doubled (104.5%) across the Coastal ISA as an additional 33 ha of land were converted to roads, buildings, and other types of development. However, the distribution of these changes was uneven. Puerto Villamil experienced an increase in built-up cover of 28.89 ha from 2003 to 2010. Built-up cover doubled in the period between 2003 and 2008, increasing at a rate of 14.0% per year[4]. Gains in this period were largely concentrated in previously undeveloped areas to the north and east of the established community. Increases in built-up cover slowed to 7.4% per year from 2008 to 2010, but by 2010 more than one-third (35.5%) of Puerto Villamil was built-up. In the Galápagos National Park, built-up cover increased by nearly half (40.5%) over the course of seven years. From 2003 to 2008, built-up cover expanded at a rate of 3.2% per year. Although the rate of increase was higher from 2008 to 2010 (9.2% per year), by 2010 built-up cover accounted for less than 3% of the management zone. In both periods this class expanded along existing transportation infrastructure in the protected area, specifically along the main roads leading to Santo Tomás, and near the airport. In both management zones, the increase in built-up cover occurred at the expense of barren, coastal vegetation, and upland vegetation classes (Table 3.12).

In contrast, lagoons shrank in extent by 18.2% between 2003 and 2010. In Puerto Villamil, lagoons occupied a small proportion of the landscape, with the largest complex located within the National Park. From 2003 to 2008, lagoons within the community increased in extent by more than one-half (60%) before declining by nearly three-quarters (71.8%) from 2008 to 2010. Lagoon cover consistently decreased in the National Park, falling by 8.4% early on, and 10.5% in the later period. Losses throughout the study area

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[4] Annual rate calculated as $r = [(1/(t_2-t_1)) \times \ln(A_2/A_1)] \times 100$, where A_1 and A_2 are the built-up cover at times t_1 and t_2, respectively according to Puyravaud (2003).

Table 3.12 Matrix of from-to LULC changes (hectares) in the Coastal ISA, by management zone

Puerto Villamil	2010							
2003	Barren	Beach	Built-up	Coastal vegetation	Lagoon	Ocean	Upland vegetation	2003 Total
Barren	28.01	0.06	22.38	4.99	0.13	0.24	2.53	58.34
Beach	0.10	4.53	0.20	0.37	0.00	0.17	0.00	5.37
Built-up	0.53	0.06	19.24	1.48	0.00	0.02	0.22	21.55
Coastal vegetation	2.69	0.12	6.54	37.82	0.12	0.03	0.07	47.39
Lagoon	0.36	0.00	0.00	0.20	0.92	0.00	0.00	1.48
Ocean	0.16	0.45	0.08	0.07	0.00	0.91	0.00	1.67
Upland vegetation	1.31	0.00	2.01	0.81	0.00	0.00	2.25	6.38
2010 Total	33.15	5.22	50.44	45.75	1.18	1.37	5.08	-

Galápagos National Park	2010							
2003	Barren	Beach	Built-up	Coastal vegetation	Lagoon	Ocean	Upland vegetation	2003 Total
Barren	165.17	0.26	3.02	8.41	0.74	0.46	10.30	188.35
Beach	0.01	4.44	0.01	0.14	0.00	0.76	0.00	5.35
Built-up	0.61	0.12	8.20	0.72	0.00	0.00	0.35	10.00
Coastal vegetation	5.23	0.35	1.15	134.79	1.63	0.36	9.49	153.00
Lagoon	2.53	0.00	0.00	8.67	37.62	0.00	0.00	48.82
Ocean	0.27	0.17	0.03	0.06	0.00	98.79	0.00	99.33
Upland vegetation	4.49	0.00	1.68	3.61	0.01	0.00	70.71	80.49
2010 Total	178.31	5.33	14.09	156.39	39.99	100.37	90.86	-

were concentrated along lagoon edges, which were largely converted to barren cover (2.89 ha) as they became drier or were colonized by coastal vegetation (8.87 ha) (Table 3.12).

From 2003 to 2010, total vegetation cover increased in area within the National Park, but declined slightly in Puerto Villamil. The National Park experienced gains in coastal vegetation (6.5%) and upland vegetation (5.1%) between 2003 and 2008. Upland vegetation expanded to the north, and coastal vegetation increased in areas to the west. Upland vegetation continued to increase in area (7.4%) between 2008 and 2010, while coastal vegetation contracted slightly (4.0%). The increase in vegetation cover within the National Park took place at the expense of barren and lagoon classes (Table 3.12). Some switching among coastal and upland vegetation classes also occurred (i.e., coastal vegetation converted to upland vegetation, and vice versa). These changes resulted not from actual conversion among vegetation types, but instead from the classification rule that distinguished among vegetation types based on their proximity to water; as lagoon and ocean levels changed between image dates, so too did the type of vegetation (i.e., upland or coastal) assigned to some vegetation objects. In Puerto Villamil, coastal vegetation cover increased in area by less than 1% between 2003 and 2008, but declined by roughly 6% in the following period. Upland vegetation cover declined by one-eighth in each period (13.2% from 2003-2008; 11.7% from 2008-2010). Vegetation losses occurred throughout Puerto Villamil, but were more prevalent in the southern portion of community, near areas of stable vegetation. These losses were primarily due to the conversion of both coastal and upland vegetation to built-up and barren classes (Table 3.12). The vegetation change map also shows that other areas throughout the community experienced gains in vegetation cover.

Beach cover in the Coastal ISA did not change appreciably during the study period, accounting for 1.5% of the landscape in 2003, 2008 and 2010. Not surprisingly, ocean cover was also extremely stable, and made up approximately 14% of landscape during the seven year study period.

3.5.3 Pattern Metrics

Landscape metrics for the Coastal ISA, broken down by management zone, are presented in Table 3.13. In the Coastal ISA, there was a general trend towards increased landscape fragmentation over time. This was evidenced by an increase in the number of patches, edge density, and nearest-neighbor distance, as well as a decrease in mean patch area and the largest patch index. However, the spatial pattern of patches differed by

Table 3.13 Landscape metrics for the Coastal ISA, by management zone, 2003-2010

	Coastal ISA			Puerto Villamil			Galápagos National Park		
Metric	2003	2008	2010	2003	2008	2010	2003	2008	2010
NP	1279	1338	1396	769	716	669	657	802	890
MPS	0.57	0.54	0.52	0.18	0.20	0.21	0.89	0.73	0.66
PSCV	1073.9	1073.5	1079.2	705.4	850.8	913.8	857.4	942.5	976.6
LPI	16.16	14.89	14.22	17.63	28.04	33.20	17.27	17.71	16.87
ED	269.68	279.64	290.99	681.55	663.56	666.68	177.41	193.27	206.56
ENN	15.81	16.53	16.41	11.07	13.53	12.75	25.86	19.85	20.10
NNCV	163.50	186.48	165.43	126.22	161.55	173.57	322.82	192.98	185.01
IJI	67.09	69.01	69.87	58.88	60.43	60.38	64.40	64.66	66.04

Metrics: NP = number of patches; MPS = mean patch size (ha); PSCV = patch size coefficient of variation; LPI = largest patch index (%); ED = edge density (m/ha); ENN = Euclidean nearest neighbor distance (m); NNCV = nearest neighbor coefficient of variation; IJI = interspersion and juxtaposition index.

management zone. In Puerto Villamil, patches decreased in number and increased in area between 2003 and 2010. At the same time, patches had fewer edges, as indicated by the decline in edge density, and the largest patch accounted for a larger proportion of the landscape, with an increase in the largest patch index; changes in these metrics are indicative of landscape homogenization. In the Galápagos National Park, declines in patch size and nearest neighbor distance were accompanied by increases in the number of patches and in edge density, symptomatic of LULC fragmentation within the protected area.

Patch dynamics varied by LULC class within each zone; class metrics, by management zone, are shown in Table 3.14. Barren cover, which acted as the background matrix in Puerto Villamil and the National Park (covering 41% and 32.2% of each zone, respectively) in 2003, declined. In the National Park, the decrease in barren cover was accompanied by an increase in its fragmentation, as evidenced by more numerous smaller patches and higher edge density. Barren areas in Puerto Villamil were also fragmented into smaller patches between 2003 and 2008. Between 2008 and 2010, the number of barren patches decreased by 19% and edge density declined, suggesting consolidation of barren

Table 3.14 Class metrics for the Coastal ISA, by management zone, 2003-2010

Puerto Villamil

	NP			MPS			PSCV			LPI		
Class	2003	2008	2010	2003	2008	2010	2003	2008	2010	2003	2008	2010
Barren	209	217	175	0.28	0.17	0.19	674.59	611.58	333.82	17.63	9.92	5.03
Beach	4	4	2	1.34	1.41	2.61	128.37	125.35	52.36	2.92	3.00	2.75
Built-up	210	98	84	0.10	0.44	0.60	1158.55	919.2	867.16	11.91	28.04	33.2
Coastal vegetation	191	234	239	0.25	0.20	0.19	457.15	406.97	403.88	8.54	5.96	5.88
Lagoon	7	14	11	0.21	0.17	0.11	138.29	303.14	183.84	0.61	1.40	0.49
Ocean	54	44	43	0.03	0.04	0.03	161.76	165.76	146.01	0.18	0.20	0.18
Upland vegetation	94	105	115	0.07	0.05	0.04	229.29	145.11	159.39	0.81	0.34	0.41

	ED			ENN			ENNCV			IJI		
Class	2003	2008	2010	2003	2008	2010	2003	2008	2010	2003	2008	2010
Barren	508.30	355.62	350.77	12.01	15.78	15.58	108.62	120.11	113.81	67.45	67.53	69.45
Beach	32.64	29.82	31.46	8.29	7.24	4.80	26.12	53.95	0.00	73.98	70.82	73.60
Built-up	356.15	439.62	447.35	9.59	10.28	10.62	125.99	170.66	201.69	50.22	56.19	58.67
Coastal vegetation	328.64	360.48	360.88	8.28	9.08	10.01	80.66	76.67	114.69	54.31	54.94	51.11
Lagoon	13.24	19.68	11.75	68.48	72.02	40.10	80.58	136.41	104.8	38.63	47.84	40.69
Ocean	28.74	22.55	28.24	6.00	11.66	7.49	27.86	153.67	57.54	63.79	76.03	66.79
Upland vegetation	95.38	99.35	102.90	16.74	15.10	15.17	96.14	87.47	252.31	31.51	44.25	43.12

Galápagos National Park

	NP			MPS			PSCV			LPI		
Class	2003	2008	2010	2003	2008	2010	2003	2008	2010	2003	2008	2010
Barren	242	269	314	0.78	0.66	0.57	925.25	1007.1	1064.3	15.84	15.41	15.20
Beach	2	13	2	2.67	0.41	2.67	99.98	329.40	99.89	0.82	0.78	0.82
Built-up	36	50	47	0.28	0.23	0.30	323.38	368.83	390.40	0.83	0.93	1.22
Coastal vegetation	167	171	209	0.92	0.95	0.75	967.83	943.82	1038.49	17.27	17.71	16.87
Lagoon	83	126	105	0.59	0.35	0.38	722.57	811.84	791.14	5.97	4.97	4.75

Table 3.14 continued

Galápagos National Park

	NP			MPS			PSCV			LPI		
Class	2003	2008	2010	2003	2008	2010	2003	2008	2010	2003	2008	2010
Ocean	1	5	4	99.14	19.88	25.05	0.00	199.99	173.16	15.25	15.29	15.41
Upland vegetation	126	168	209	0.64	0.50	0.43	518.54	584.4	641.08	4.54	4.54	4.26

	ED			ENN			ENNCV			IJI		
Class	2003	2008	2010	2003	2008	2010	2003	2008	2010	2003	2008	2010
Barren	97.45	98.93	119.39	21.03	19.52	20.58	199.49	140.21	173.45	67.32	66.59	64.38
Beach	5.43	7.33	6.40	1373.7	17.12	5.37	0.00	88.00	0.00	67.72	60.29	58.50
Built-up	28.85	32.75	34.73	41.03	23.10	37.60	171.93	144.14	220.03	64.72	71.08	69.70
Coastal vegetation	110.69	115.41	124.17	13.63	10.73	14.07	98.92	84.3	132.48	72.56	70.67	76.56
Lagoon	48.89	59.50	48.86	20.95	20.18	22.18	112.95	171.41	175.91	9.32	11.82	22.51
Ocean	7.58	8.85	8.11	N/A	5.03	90.82	N/A	5.52	160.89	61.91	62.42	69.42
Upland vegetation	55.93	63.77	71.44	28.88	29.10	19.21	143.38	225.27	138.39	44.15	42.59	44.80

Metrics: NP = number of patches; MPS = mean patch size (ha); PSCV = patch size coefficient of variation; LPI = largest patch index (%); ED = edge density (m/ha); ENN = Euclidean nearest neighbor distance (m); NNCV = nearest neighbor coefficient of variation; IJI = interspersion and juxtaposition index.

patches. However, the slight increase in mean patch size (which was less variable, as noted by the decline in the patch size coefficient of variation) and the distance between patches, along with the decline in largest patch index are indicative of ongoing fragmentation of barren cover as abundance continued to decline.

In Puerto Villamil, built-up patches became larger, less numerous, and more interspersed with other classes. The number of patches declined by over one-half (60%), and mean patch size more than quadrupled (485%) during the study period. The largest built-up patch also increased in extent from 11.9% of the zone in 2003, to 28.0% in 2008, and to 33.2% in 2010. These changes in patch configuration provide evidence for coalescence of built-up areas in Puerto Villamil. Built-up cover also increased within the National Park, although the changes in extent were fairly small compared to those in Puerto Villamil. Landscape structure trends shifted from diffuse expansion of built areas during the 2003 to 2008 period (more numerous, smaller patches that emerged fairly close to existing built-up areas) and coalescent growth between 2008 and 2010 (larger patches located farther from each other, that were less interspersed with other classes) (see Dietzel et al., 2005).

Vegetation fragmentation increased in the National Park and in Puerto Villamil between 2003 and 2010. While coastal vegetation and upland vegetation expanded within the National Park during this period, total vegetation cover declined within Puerto Villamil. Coastal vegetation and upland vegetation patches in both zones became smaller, more numerous, and had higher edge densities. However, mean patch size and the distribution of patch sizes (coefficient of variation) differed between the two zones. For example, the average size of coastal vegetation patches in Puerto Villamil was 0.25 ha in 2003 and declined to 0.19 ha in 2010. Mean patch size in the National Park, in contrast, was 0.92 ha and 0.75 ha in 2003 and 2010, respectively. In both management zones edge density increased and the largest patch index decreased.

3.6 Highlands ISA Results

3.6.1 Classification Accuracy

Overall accuracy of the 2010 classification was 88.7% with a kappa statistic of 0.87 (Table 3.15). Although overall accuracy exceeded the 85% standard (Foody, 2002), a few classes had producer's or user's accuracies below this threshold. Agriculture/grassland (78.8%) and forest/shrub (80.0%) had the lowest producer's accuracies, while forest/shrub (74.1%) and guava (82.1%) had the lowest user's accuracies. One possible reason for the classification errors is the time lag between reference data collection and image acquisition. Care was taken to ensure that training and validation data accurately reflected LULC in the image, but it is possible that permanent land cover change took place in the intervening period. Although classification of image objects, rather than individual pixels, is generally seen as an advantage of OBIA over pixel-based classifiers, it may have resulted in

Table 3.15 Confusion matrix for 2010 WorldView-2 classification of the Highlands ISA

	Reference Class								
Mapped Class	Agriculture/ grassland	Barren	Built-up	Dry grassland	Forest/ shrub	Guava	Rose apple	*Total*	User's accuracy
Agriculture/ grassland	26	0	0	0	3	0	0	29	89.7%
Barren	0	31	0	1	0	0	0	32	96.9%
Built-up	0	1	33	0	0	0	0	34	97.1%
Dry grassland	1	0	0	13	0	2	0	16	81.2%
Forest/shrub	3	0	1	1	20	1	1	27	74.1%
Guava	3	0	0	0	2	23	0	28	82.1%
Rose apple	0	0	0	0	0	0	11	11	100.0%
Total	33	32	34	15	25	26	12	177	-
Producer's accuracy	78.8%	96.9%	97.1%	86.7%	80.0%	88.5%	91.7%	-	-
Overall = 88.7%									
Kappa = 0.87									

classification errors in cases where similar proportions of multiple classes comprised an image object. Finally, the small number of samples for mixed classes, such as agriculture/grassland, could be responsible for classification errors.

Field data or additional high resolution images were not available to test the accuracy of the 2004 classification. The 2004 and 2010 classifications were trained separately, using the same classification rules with adjusted membership values to produce classifications with comparable accuracies. Visual assessment of the 2004 classification showed that invariant features, such as main roads, surface mines, and the Sierra Negra caldera were correctly classified.

3.6.2 Land Use/Cover Change: 2004-2010

The 2004 and 2010 Highlands ISA LULC maps are shown in Figure 3.7; change maps for agriculture/grassland, dry grassland, invasive plants, and forest/shrub classes are shown in Figure 3.8. The area and proportion of each class in both years, and changes between 2004 and 2010 are presented in Tables 3.16 and 3.17. Guava (35.5%), agriculture/grassland (28.8%), and forest/shrub (26.4%) were the dominant covers types within the Highlands ISA in 2004. Less than one-tenth of the study area was composed of dry grassland (5.6%), barren cover (2.8%), rose apple (0.7%), and built-up areas (0.3%). Guava, forest/shrub, and agriculture/grassland also dominated LULC in 2010, although the proportion of the landscape covered by each shifted in the intervening period. Slightly more than half (56%) of LULC was stable in 2010, suggesting a highly dynamic landscape that witnessed changes in agriculture and grasslands, invasive plants (guava and rose apple), and forest cover.

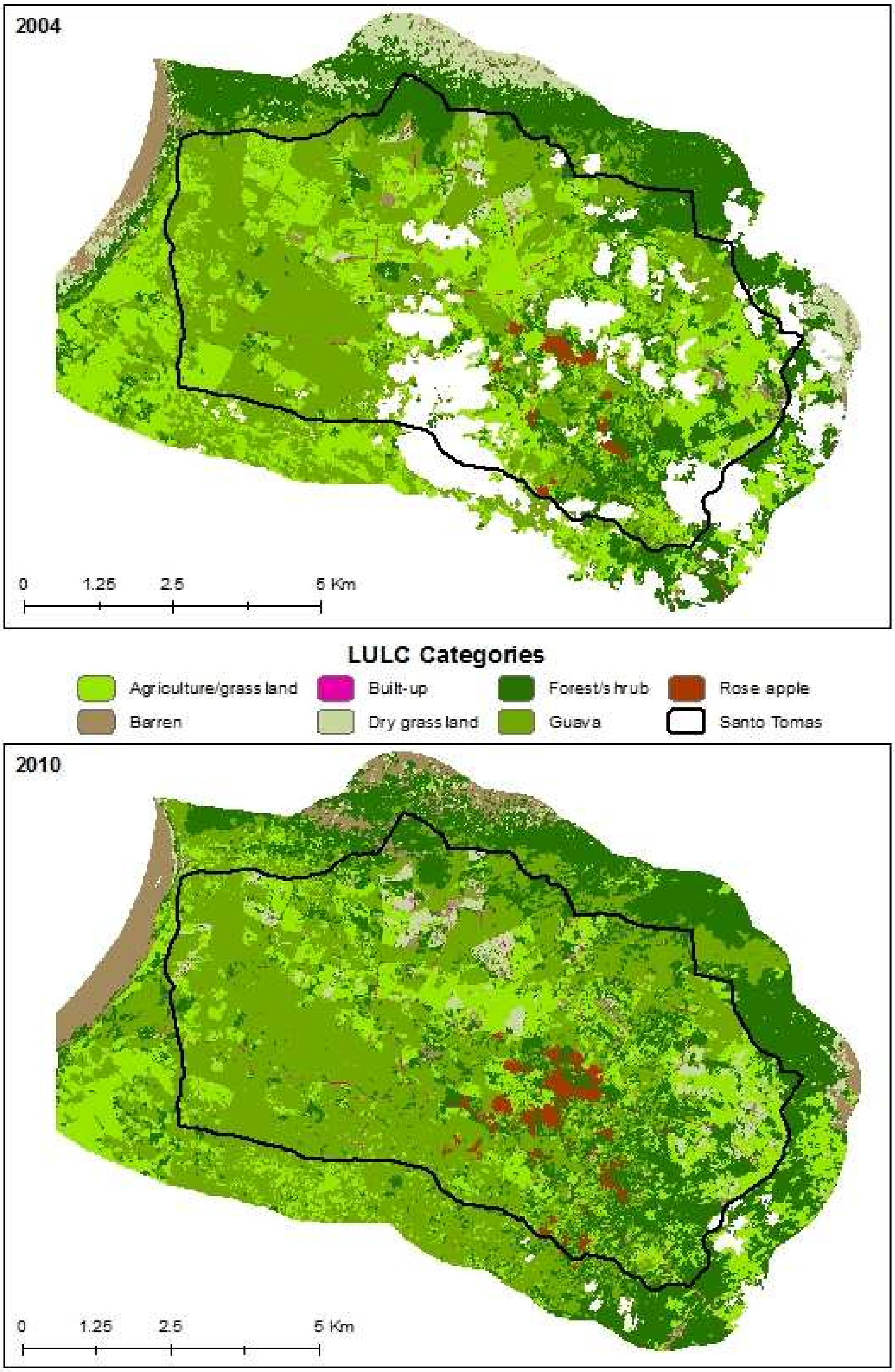

Figure 3.7 LULC classification maps of the Highlands ISA for 2004 and 2010. Clouds have been masked out (white)

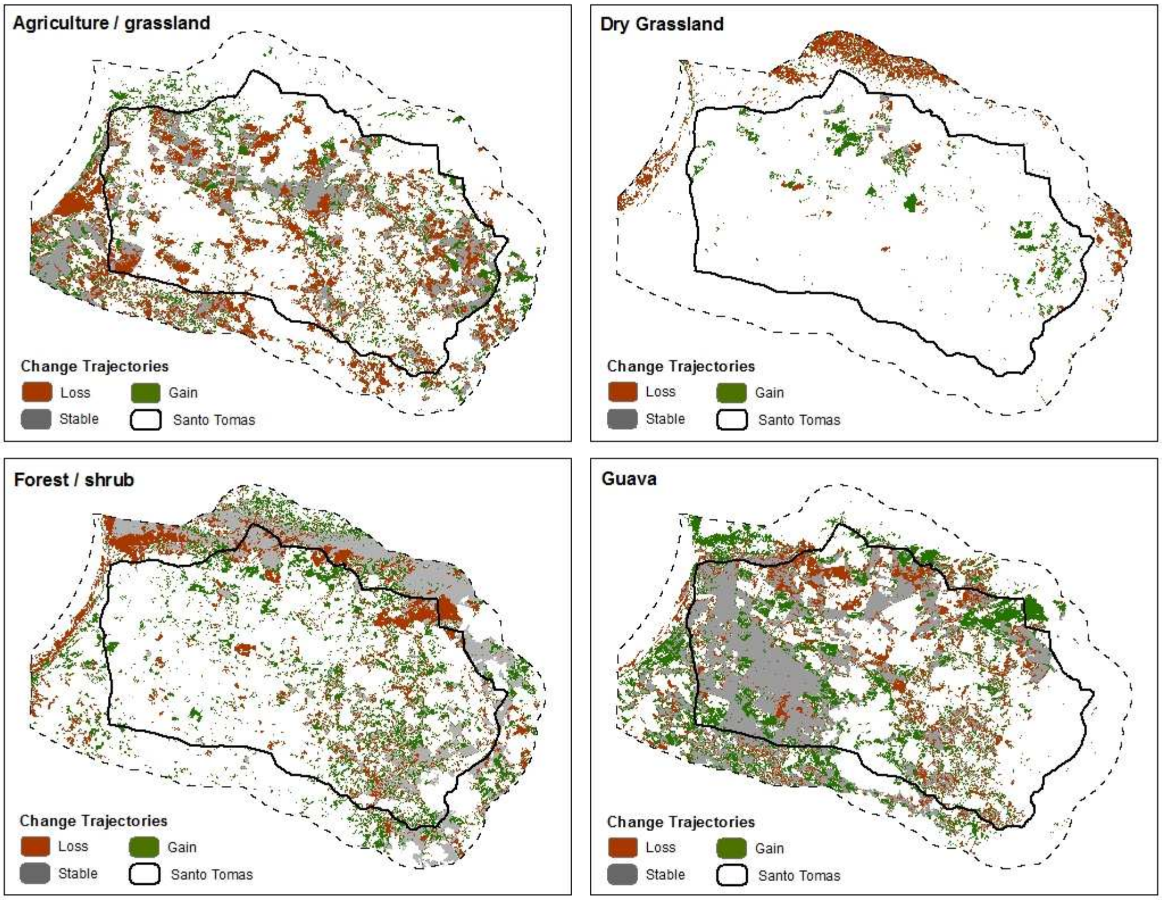

Figure 3.8 LULC change classes in the Highlands ISA, 2004-2010

Table 3.16 LULC statistics for the Highlands ISA, 2004-2010

	Total Area (ha)		Percent of landscape (%)		Change: 2004-2010	
Land Use Class	2004	2010	2004	2010	Absolute (ha)[a]	Relative (%)[b]
Agriculture/grassland	2167.76	1569.64	28.8	20.8	-598.12	-27.6
Barren	208.10	467.75	2.8	6.2	259.65	124.8
Built-up	23.65	26.11	0.3	0.3	2.45	10.4
Dry grassland	418.53	278.63	5.6	3.7	-139.91	-33.4
Forest/shrub	1992.51	2119.34	26.4	28.1	126.83	6.4
Guava	2673.34	2992.09	35.5	39.7	318.75	11.9
Rose apple	49.71	80.06	0.7	1.1	30.35	61.1
Total	7533.61	7533.61	100.0	100.0	-	-

[a] Net change between periods was calculated as ($Area_{2010}$ – $Area_{2004}$)

[b] Percent change relative to 2004 was calculated as 100 x ($Area_{2010}$ – $Area_{2004}$)/$Area_{2004}$

Table 3.17 LULC statistics, by management zone, in the Highlands ISA

	Total Area (ha)		Percent of landscape (%)		Change: 2004-2010	
	2004	2010	2004	2010	(ha)[a]	(%)[b]
Santo Tomás						
Agriculture/Grassland	1449.45	1032.70	32.2	22.9	-416.75	-28.8
Barren	48.49	87.75	1.1	1.9	39.26	81.0
Built-up	21.00	23.91	0.5	0.5	2.91	13.9
Dry grassland	82.35	216.43	1.8	4.8	134.08	162.8
Forest/shrub	798.01	963.62	17.7	21.4	165.61	20.8
Guava	2058.99	2104.27	45.7	46.7	45.28	2.2
Rose apple	49.70	79.29	1.1	1.8	29.59	59.5
Total	4507.97	4507.97	100.0	100.0	-	-
Galápagos National Park						
Agriculture/Grassland	718.31	536.94	23.7	17.7	-181.37	-25.2
Barren	159.62	380.00	5.3	12.6	220.38	138.1
Built-up	2.65	2.20	0.1	0.1	-0.45	-17.2
Dry grassland	336.19	62.19	11.1	2.1	-274.00	-81.5
Forest/shrub	1194.51	1155.72	39.5	38.2	-38.79	-3.2
Guava	614.35	887.82	20.3	29.3	273.47	44.5
Rose apple	0.01	0.78	0.0	0.0	0.77	9514.3
Total	3025.64	3025.64	100.0	100.0	-	-

[a] Net change between periods was calculated as ($Area_{2010}$ – $Area_{2004}$)

[b] Percent change relative to 2004 was calculated as 100 x ($Area_{2010}$ – $Area_{2004}$)/$Area_{2004}$

From 2004 to 2010, the Highlands ISA experienced a loss of land devoted to agriculture/grassland. In Santo Tomás, agricultural land decreased by 28.8% due to conversion to guava (380.79 ha), forest/shrub (223.04 ha), and dry grassland (147.79 ha) (Table 3.18). Over the same period, 211.34 ha of guava, 112.15 ha of forest/shrub, and 31.01 ha of dry grassland were cleared for agriculture. Areas of expansion and contraction were located throughout the community, with a net effect of agricultural decline owing to the encroachment of guava and forest/shrub. Agriculture/grasslands declined by a similar proportion (25.5%) in the Galápagos National Park. In this management zone the agriculture/ grassland class represents natural grasslands that consist of native and exotic grasses, sedges, and herbs as the cultivation of crops and the management of pastures are prohibited within the National Park. Grassland losses were concentrated in the south, east, and west of the

Table 3.18 Matrix of from-to LULC changes (hectares) in the Highlands ISA, by management zone

Santo Tomás	2010							
2004	Agriculture/ grassland	Barren	Built-up	Dry grassland	Forest/ shrub	Guava	Rose apple	2004 Total
Agriculture/Grassland	643.58	37.53	5.80	147.79	223.04	380.79	10.92	1449.45
Barren	28.99	3.52	0.79	9.63	3.78	1.78	0.00	48.49
Built-up	4.44	0.85	9.14	0.72	3.89	1.86	0.09	21.00
Dry grassland	31.01	4.33	0.49	28.54	10.33	7.65	0.00	82.35
Forest/shrub	112.15	19.63	3.65	11.31	393.39	245.35	12.52	798.01
Guava	211.34	21.89	4.01	18.43	320.42	1461.69	21.20	2058.99
Rose apple	1.20	0.01	0.03	0.00	8.77	5.14	34.56	49.70
2010 Total	1032.70	87.75	23.91	216.43	963.62	2104.27	79.29	-

Galápagos National Park	2010							
2004	Agriculture/ grassland	Barren	Built-up	Dry grassland	Forest/ shrub	Guava	Rose apple	2004 Total
Agriculture/Grassland	299.17	1.19	0.26	0.29	151.69	265.38	0.33	718.31
Barren	3.09	130.97	0.15	8.51	15.85	1.06	0.00	159.62
Built-up	0.51	0.06	1.44	0.02	0.45	0.16	0.00	2.65
Dry grassland	6.97	167.66	0.01	38.68	117.58	5.28	0.00	336.19
Forest/shrub	116.65	75.12	0.26	14.50	773.44	214.33	0.20	1194.51
Guava	110.54	5.00	0.08	0.19	96.70	401.60	0.24	614.35
Rose apple	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
2010 Total	536.94	380.00	2.20	62.19	1155.72	887.82	0.78	-

protected area, while gains were located throughout the National Park. While there was from-to change in this class associated with the forest/shrub class, an overall loss of grasslands due to the expansion of guava was observed.

Dry grassland cover significantly increased in area (162.8%) within Santo Tomás, but declined in the National Park (81.5%) over the same period. Only 34.7% and 11.5% of dry grassland area in Santo Tomás and the National Park, respectively, remained stable in 2010, suggesting from-to change in both directions. In Santo Tomás, 147.79 ha of agriculture were converted to dry grassland along the northern part of the community. In the National Park, 167.66 ha of dry grassland were converted to barren cover along the Sierra Negra caldera and areas to the north, and 116.65 ha were converted to forest/shrub in the eastern part of the management zone.

Guava expanded only slightly in Santo Tomás (2.2%). However, guava dominated the community (in terms of area), as nearly one-half (45.7%) of the study area was already invaded by 2004. The class was fairly stable, indicating limited from-to change (Table 3.18), although there was some evidence of guava cleared for agriculture. A larger area of expansion occurred in the National Park, where guava cover increased by 44.5% in six years to cover nearly one-third (29.3%) of the protected area. Total guava cover increased from 614.35 ha in 2004 to 887.82 ha in 2010, at the expense of grasslands, as previously mentioned, and forest/shrub. In both management zones, the expansion and contraction of guava cover occurred throughout the study area, except to the west and the far north. Over the same period, rose apple increased in area by 61% in the Highlands ISA. The vast majority of this increase occurred within Santo Tomás, where rose apple cover grew from 49.70 ha in 2004 to 79.29 ha in 2010. Rose apple was almost non-existent in the National Park in 2004, but by 2010 it had invaded 0.78 ha. Although the total area covered by rose apple is relatively small, the change detection shows that in a short period of time it has expanded from the privately managed land of the community into the protected area.

Forest/shrub cover increased in area by 6.4% across the study area, but changes in the class differed by management zone. In Santo Tomás, forest/shrub cover grew by 20.8% over the six year study period. Forest/shrub cover grew at the expense of agriculture (223.04 ha) and guava (320.42 ha), with a smaller amount of land converted from forest to agriculture (112.15 ha) and guava (245.35 ha). Changes in forest/shrub cover were primarily located in the eastern parts of the community where the majority of forests and shrub lands are located.

On the other hand, forest/shrub cover in the National Park shrank by 3.2%. Changes in the forest/shrub class occurred in the east and north where shrubs and small trees are present, and to the west, adjacent to the Sierra Negra caldera.

Built-up cover in the Highlands ISA increased only slightly during the study period (2.45 ha), and accounted for 0.3% of the study area in 2004 and 2010. Within Santo Tomás an additional 2.91 ha (13.9%) of land were converted to built-up uses, such as roads, homes, and farm structures. In contrast, built-up cover in the National Park, which consisted of roads and a few structures maintained by the Galápagos National Park Service, declined in area by 0.45 ha (17.2%).

3.6.3 Pattern Metrics

Landscape metrics for the Highlands ISA, by management zone, are presented in Table 3.19. Landscape fragmentation occurred in the Highlands ISA between 2004 and 2010, as indicated by an increase in the number of patches and edge density, and a decrease in mean patch size. Interestingly, the distance between patches declined and the proportion of the landscape occupied by the largest patch increased, which signifies spatial consolidation. Interspersion increased slightly, however, further supporting fragmentation. Pattern metric results indicating both fragmentation and consolidation could be the result of a heterogeneous response among LULC classes. Santo Tomás and the Galápagos National Park exhibited the same trends in spatial pattern, although they show a decrease in the largest patch index (also supporting fragmentation). Large patches in some classes were likely perforated by patches from other classes, and as a result, the largest patch index declined and the distance between patches decreased.

Table 3.19 Landscape metrics for the Highlands ISA, by management zone, 2004-2010

	Highlands ISA		Santo Tomás		Galápagos National Park	
Metric	2004	2010	2004	2010	2004	2010
NP	4211	8985	3113	6612	1739	3187
MPS	1.79	0.84	1.45	0.68	1.74	0.95
PSCV	1539.38	2364.99	1499.06	2065.53	1103.07	1502.51
LPI	10.27	11.86	21.46	20.21	19.36	15.95
ED	150.05	211.08	253.41	361.69	194.90	267.01
ENN	39.08	25.89	36.45	25.31	43.43	26.60
NNCV	210.15	209.29	214.84	206.31	415.33	403.51
IJI	61.57	64.97	58.35	65.94	57.52	57.95

Metrics: NP = number of patches; MPS = mean patch size (ha); PSCV = patch size coefficient of variation; LPI = largest patch index (%); ED = edge density (m/ha); ENN = Euclidean nearest neighbor distance (m); NNCV = nearest neighbor coefficient of variation; IJI = interspersion and juxtaposition index.

Patch dynamics varied by LULC class within the management zones; class metrics, by management zone, are given in Table 3.20. The forest/shrub class was fragmented into smaller patches in Santo Tomás and in the National Park between 2004 and 2010. Forest/shrub cover expanded in Santo Tomás, while it slightly declined in abundance within the National Park over the same period. In both zones, forest/shrub patches became smaller and more numerous, and had higher edge densities. Forest/shrub patches in the National Park were larger (1.13 ha, in 2010), on average, than forest/shrub patches in Santo Tomás (0.47 ha). The largest patch also accounted for a greater proportion of the National Park, suggesting that forest/shrub patches in the protected area are larger and more spatially cohesive than in the private lands.

Dry grassland fragmentation also increased in Santo Tomás and in the National Park during the study period, despite opposing changes in abundance. In Santo Tomás, dry grassland patches became more numerous, slightly smaller, and had more edges. The number of patches nearly tripled (186.3%), and mean patch size declined by one-tenth (8.2%) during the study period. Edge density rose from 15.12 in 2004 to 42.71 in 2010. The areal expansion of this class and changes in patch configuration provide evidence for fragmented growth of

Table 3.20 Class metrics for the Highlands ISA, by management zone, 2004-2010

Santo Tomás

	NP		MPS		PSCV		LPI	
Class	2004	2010	2004	2010	2004	2010	2004	2010
Agriculture/Grassland	760	1510	1.91	0.68	586.03	904.64	3.65	3.46
Barren	206	587	0.24	0.15	281.11	287.59	0.09	0.14
Built-up	251	435	0.08	0.06	197.82	234.31	0.03	0.02
Dry grassland	175	501	0.47	0.43	263.89	320.71	0.21	0.30
Forest/shrub	935	2031	0.85	0.47	761.88	937.47	2.57	3.42
Guava	766	1412	2.69	1.49	1549.64	1964.47	21.46	20.21
Rose apple	20	136	2.49	0.58	192.98	372.71	0.43	0.42

	ED		ENN		ENNCV		IJI	
Class	2004	2010	2004	2010	2004	2010	2004	2010
Agriculture/Grassland	172.64	188.11	22.37	19.58	141.73	165.23	56.80	67.11
Barren	11.59	29.35	97.89	55.83	161.53	147.98	78.72	80.69
Built-up	16.01	19.47	60.73	46.36	174.95	175.86	71.55	81.83
Dry grassland	15.12	42.71	97.76	44.30	173.88	190.97	80.68	74.33
Forest/shrub	112.47	215.23	29.95	18.14	151.96	147.73	63.09	68.20
Guava	172.59	215.45	19.53	14.69	205.10	284.21	52.26	54.74
Rose apple	6.41	13.04	48.75	37.36	159.55	204.36	61.88	53.15

Galápagos National Park

	NP		MPS		PSCV		LPI	
Class	2004	2010	2004	2010	2004	2010	2004	2010
Agriculture/Grassland	360	945	1.99	0.57	557.27	808.60	3.11	3.35
Barren	356	380	0.45	1.00	1073.63	1091.05	2.42	5.47
Built-up	6	17	0.44	0.13	130.19	234.14	0.04	0.03
Dry grassland	330	269	1.02	0.23	945.39	248.64	4.51	0.18
Forest/shrub	397	1027	3.01	1.13	1216.19	1722.16	19.36	15.95
Guava	289	541	2.13	1.64	429.23	1162.33	2.24	11.27
Rose apple	1	8	0.01	0.10	0.00	110.27	0.00	0.01

	ED		ENN		ENNCV		IJI	
Class	2004	2010	2004	2010	2004	2010	2004	2010
Agriculture/Grassland	95.58	118.69	28.43	23.00	248.03	189.26	38.35	46.21
Barren	29.60	55.20	38.91	35.31	207.14	277.03	42.89	45.21
Built-up	2.07	2.25	2148.0	327.73	86.29	366.34	72.60	72.51
Dry grassland	59.95	26.92	43.36	53.00	153.88	192.90	42.79	52.46
Forest/shrub	104.14	179.03	39.91	18.99	199.60	167.79	72.78	71.74
Guava	98.46	151.65	28.93	18.47	215.74	234.22	41.49	46.16
Rose apple	0.00	0.29	N/A	37.81	N/A	224.89	0.00	53.86

Metrics: NP = number of patches; MPS = mean patch size (ha); PSCV = patch size coefficient of variation; LPI = largest patch index (%); ED = edge density (m/ha); ENN = Euclidean nearest neighbor distance (m); NNCV = nearest neighbor coefficient of variation; IJI = interspersion and juxtaposition index.

dry grasslands in Santo Tomás. In contrast, dry grassland cover declined sharply within the National Park, and was accompanied by fewer, smaller patches with less edge. A decline in the number of patches is often accompanied by an increase in mean patch size, but in this case the average size of dry grassland patches declined from 1.02 ha to 0.23 ha. The increase in the number of dry grassland patches occurred because large patches of dry grassland were broken up or converted to other cover types, as evidenced by the decline in largest patch index from 4.5% to 0.18%. The patches that remained were smaller (and had sizes that were less varied) and more isolated, as indicated by an increase in nearest neighbor distance and a decrease in the interspersion-juxtaposition index.

Declines in the abundance of agriculture/grassland in both management zones were accompanied by greater fragmentation of this class, as evidenced by decreases in mean patch size, and increases in the total number of patches and edge density. Mean patch size was fairly consistent between the two zones, declining from 1.91 ha to 0.68 ha in Santo Tomás, and from 1.99 ha to 0.57 ha in the National Park. Edge density increased in both management zones, with higher amount of edge observed in Santo Tomás. Agriculture/grassland patches become more interspersed during the study period as well, although patches within the National Park were less interspersed among other classes than patches in Santo Tomás. Agriculture/grassland patches in both management zones are likely to continue to experience fragmentation and changes in abundance as increases in the amount of edges and interspersion among other classes increase the likelihood for future change (rather than stability).

Guava patches became smaller and more numerous throughout the study area. Mean patch size declined by 44.6% in Santo Tomás and by 22.8% the National Park, while the number of patches increased by similar proportions in both zones. Edge density of guava patches increased in both management zones as well. The increase in guava abundance and changes in guava patch configuration provide evidence for the diffuse expansion of guava in Santo Tomás and in the National Park. Although guava cover became more fragmented between 2004 and 2010, the pattern metrics indicate that it was spatially cohesive compared to other classes in the highlands. Guava patches were, on average, larger than patches of other classes; in 2010, the mean size of guava patches in the National Park and Santo Tomás were 1.64 ha and 1.49 ha, respectively. The proportion of the National Park covered by the largest guava patch increased from 2.2% in 2004 to 11.3% in 2010. The largest guava patch in Santo Tomás was relatively unchanged, but nonetheless covered approximately one-fifth (20.2%) of land in the community.

3.7 Discussion

As expected, built-up land increased within southern Isabela, primarily in the Coastal ISA. In Puerto Villamil, built-up land use increased in area by 134.1% in a seven year period. These findings support a recent study by Walsh et al. (2010) that concluded the number of buildings and the extent of roads in Puerto Villamil increased between 2003 and 2009. Growth of this class occurred throughout the community, with development expanding to the north and east. The expansion of the community to the north occurred during a period of diffusive growth (Dietzel et al., 2005) from 2003 to 2008 that followed the opening of new lands for development.

In 2001, the National Park turned over 22 ha of land in the lava fields adjacent to Puerto Villamil (considered to have low ecological value) to the Municipality of Isabela, in exchange for 11 ha of lagoons and mangrove forest within the community (with high ecological value) (González and Chávez, 2003). These lagoons and mangroves were ultimately included as part of the Sur de Isabela Ramsar wetlands site. The land acquired by the municipality was divided into two developments – one to the west of the road to Sierra Negra, which was already beginning to be converted into homes, shops, restaurants, roads etc in 2004; and the other to the east which was developed after 2004.

As additional lands were converted to urban infrastructure, the built-up areas grew together to form large patches that were less numerous, but that covered larger areas. The increase in built-up area and the consolidation of built patches between 2008 and 2010 are indicative of a phase of coalescent growth in the community (Dietzel et al., 2005). Buildings in the town are increasingly being constructed with multiple stories and growth in the future will likely include upward expansion and continued in-filling (Walsh et al., 2010). Although Puerto Villamil's footprint remains fairly small, the town appears to be undergoing a process of urbanization, with phases of diffusion and coalescence in urban growth (Dietzel et al., 2005).

National Park land within the Coastal ISA was not immune to development during the study period as the area of built-up land expanded by 40%. The increase in built-up cover occurred along existing transportation infrastructure, with the largest increases located within 20 m of roads (Figure 3.9). The National Park has established buffers in protected areas around human-use areas, known as impact reduction zones. In these sites a limited number of non-conservation land uses are permitted at designated sites – such as rock quarries, landfills, roads, water extraction, and waste disposal. The gravel mine in the Coastal ISA, located within this zone, expanded and a number of roads were added to allow extracted materials to

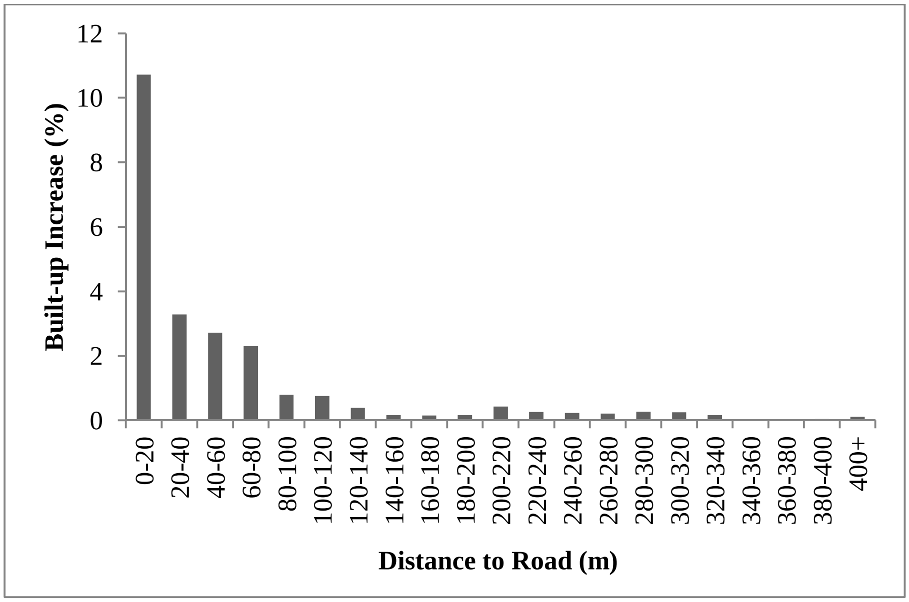

Figure 3.9 Percentage of land in each distance interval converted to built-up cover in the Coastal ISA

be transported to Puerto Villamil for construction and road paving activities. The effect of extractive activities on southern Isabela's ecosystems is not well known, but mining has endangered plants and endemic snails elsewhere in Galápagos (Snell et al., 2002). A wastewater treatment facility for the community was also constructed in the National Park during this period. It hasn't functioned properly since its installation, so untreated effluence from Puerto Villamil is dumped directly into cracks in the surrounding lava field (Walsh et al., 2010). The increase in development within Puerto Villamil, and the resulting demand for resources (e.g., water and construction materials) and need for waste disposal, has led to direct changes in land use and cover within the protected area.

Interestingly, the amount of built-up land in the highlands changed little between 2004 and 2010. Built-up uses, consisting of homes and buildings for livestock, unpaved roads and trails, and ranger stations, occupied a small portion of the highlands. In some parts of San Cristóbal and Santa Cruz Islands, land that was formerly devoted to agricultural uses has been converted to residential housing (Kerr et al., 2004). In Isabela, development has occurred only within the port town likely because of the lack of infrastructure and services (e.g., schools, water infrastructure, electricity, etc.) in Santo Tomás, and the availability of non-agricultural employment opportunities within Puerto Villamil. So, while the coastal community has become more built-up and developed over time, the highlands community has remained rural.

Vegetation cover decreased in area somewhat within Puerto Villamil, as hypothesized. Coastal and upland vegetation was cleared and converted to barren cover and built-up use. In one such case, portions of a mangrove forest in an area known as El Embarcadero was cleared in 2007 by the municipality to construct a new dock for tourists (El Comercio, 2007). Clearing of coastal vegetation for built-up uses is particularly troubling as federal and local laws prohibit the cutting of mangrove forests, even on private or municipal land (Valarezo, 2008). Contrary to expectations, upland and vegetation cover grew in extent within the National Park over the same period. Although vegetation patches in both management zones were increasingly fragmented over the study period, coastal and upland vegetation patches in the National Park were nearly four to eleven times larger than those within Puerto Villamil. While the transition from coastal vegetation to other uses and covers occurred over a relatively small area, this change has a high impact on functioning of the coastal zone. Loss and fragmentation of vegetation in the Coastal ISA is a concern for the continued functioning of the landscape as mangroves in southern Isabela provide important habitat for endemic species, such as the critically endangered mangrove finch (Fessl et al., 2011), and provide protection for Puerto Villamil from damaging wave action (Chávez and Cruz, 2002).

Lagoons shrank in extent by more than 18% between 2003 and 2010, even though the majority of lagoons are located within the protected area. Changes in extent were concentrated along lagoon edges, suggesting that declining water levels exposed mud flats, some of which were consequently colonized by coastal vegetation. Several factors may have contributed to reductions in lagoon extent in southern Isabela. First, the expansion of Puerto Villamil has led to increased water extraction from shallow underground reservoirs (Walsh et al., 2010). The lagoons are fed by a combination of freshwater springs (connected to the reservoirs) and ocean water (Seddon et al., 2011). Over-pumping may have caused the water table to drop, leading to lower water levels within the reservoirs and coastal lagoons. Second, construction of roads and buildings along the beach have blocked the connection between the lagoons and the bay, which supplies the lagoons with ocean water during periods of high tide (Walsh et al., 2010). Reductions in precipitation associated with a La Niña event in 2010 could have also reduced water inputs for the lagoon. According to the National Weather Service Climate Prediction Center (NWS CPC), October 2010 coincided with a weak La Niña period (CPC, 2012) which is generally associated with cooler, drier conditions in the Galápagos (Trueman and d'Ozouville, 2010). However, according to precipitation data provided by the Charles Darwin Foundation (CDF), rainfall in the Galápagos during the month preceding image acquisition was normal (CDF, 2012). The effect of community development, water extraction, and climate on coastal lagoons warrants further investigation. Regardless of the mechanism, changes in lagoon extent and depth have serious implications for avian fauna and aquatic species that depend on coastal lagoons (Gelin and Gravez, 2002).

At the same time the Coastal ISA became more developed, the Highlands ISA witnessed the loss of agriculture/grasslands and the expansion of invasive plant cover. As hypothesized, agricultural land use declined in Santo Tomás. Although the results show that some areas were newly cleared for agriculture between 2004 and 2010, the net effect was a nearly 30% decrease in agriculture during this period. Changes in this class were, for the most part, distributed throughout the community, although less so to the west where little agricultural land was present and in 2004. Conversion of agricultural land to guava, forest/shrub, and dry grassland covers resulted in the fragmentation of agriculture into smaller and more numerous patches with increased edges. These changes seem to indicate a process of agricultural abandonment in the highlands.

This trend is not new to the last decade, but instead is part of an ongoing process of land abandonment that began in the Galápagos in the late 1980s (Kerr et al., 2004; Chiriboga and Maignan, 2006). Fields, and in some cases entire farms, are allowed to lie fallow for extended periods of time or are permanently abandoned. Guava and other invasive plants can quickly spread to abandoned fields and farms. An analysis of fossil pollen from Galápagos indicated that declines in agriculture and intensive grazing during the 1970s and 1980s were associated with invasions by exotic plants rather than the return of native and endemic flora (Restrepo et al., 2012).

In Santo Tomás, abandonment is indicated by the conversion of large areas of agriculture to guava. Forest expansion can also occur in fields and pastures following agricultural abandonment (Poyatos et al, 2003; Rudel et al., 2005). It is unclear to what degree the increase in forest cover within Santo Tomás is attributable to secondary succession of native and introduced trees and shrubs, such as native *Jaboncillo* trees (*Sapindus saponaria*); or to the cultivation of introduced hardwoods (afforestation), such as *Fernán Sánchez* (*Triplaris cumingiana*), which is used in local construction. The distinction could have different impacts on biodiversity and landscape function, with the former signaling abandonment, and the latter indicative of a shift toward less intensive land use.

Guava cover only increased slightly in Santo Tomás between 2004 and 2010, contrary to expectations. However, by 2010 nearly one-half (46.7%) of land within the community was invaded by guava. Guava cover was spatially cohesive, evidenced by large patch sizes and by the fact that the largest contiguous patch covered 20% of the community. The large, cohesive areas of invasion likely coincide with dense patches of guava on farms and agricultural fields that are not actively managed (i.e., abandoned) (Walsh et al., 2008). Land that is no longer actively farmed is not only susceptible to invasive plants, as previously mentioned, but also facilitates the propagation of invasive species throughout the highlands and into the National Park (Gonzalez et al., 2008; Gardener et al., 2010a). Animals, including livestock, endemic finches, and giant tortoises, as well as humans disperse seeds from invaded fields to adjacent farms and into the National Park (Rentería et al., 2006; Blake et al., 2012).

In contrast to Santo Tomás, the National Park, experienced a substantial increase in guava cover, with the invasive plant expanding by 44% to cover nearly one-third (29.3%) of the protected area. The proportion of National Park land invaded by guava was highest within 100 m of the border with Santo Tomás, and generally declined with distance (Figure 3.10). This pattern seems to suggest a spillover effect whereby guava that has invaded farms and fields within Santo Tomás easily permeates the National Park border to spread across the protected area, and vice versa. Park rangers have indicated that they regularly clear guava on the National Park side of the border, on the order of every three to six months (Galápagos National Park staff, personal communication, 2008). However, the results show that many

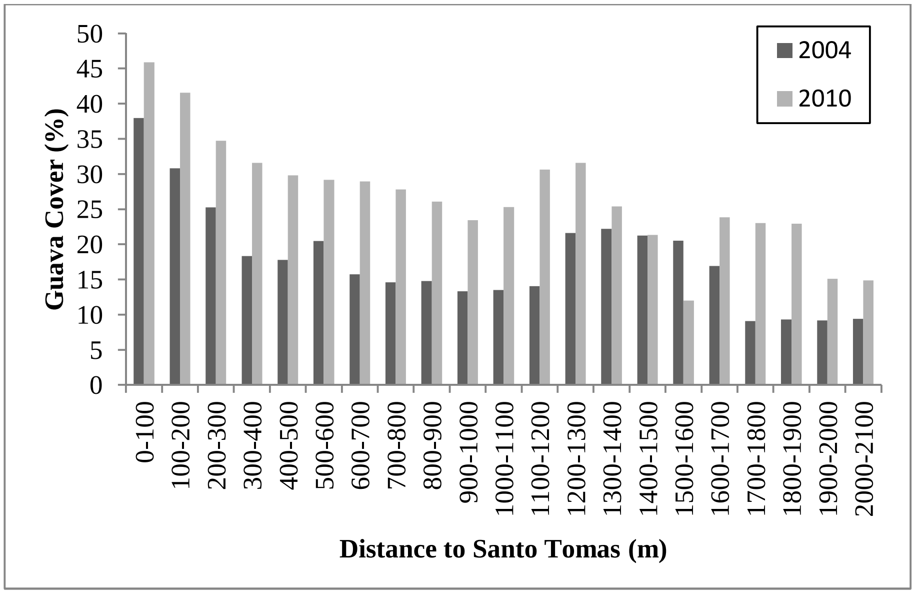

Figure 3.10 The percentage of Galápagos National Park land covered by guava in 2004 and 2010 (y-axis) at 100 m distance intervals to the border with Santo Tomás (x-axis)

patches persisted over the six year study period, or were re-established in that time, yielding a pattern that appears more indicative of the natural spread of the invasive plant rather than of active management. Interestingly, the greatest increases in guava cover (as a percentage of the amount of guava present in 2004) occurred farther away from the border, at distances of 1700-1900 m (Figure 3.11). This may indicate that guava is spreading into more protected areas of the park, especially to the west. Guava did not expand eastward or to the far north, likely because the drier climate in these areas prevents its establishment (Chiriboga and Maignan, 2006).

Rose apple cover also increased within the Highlands ISA. While most of the expansion of this invasive tree occurred within Santo Tomás, by 2010 it had clearly invaded the National Park. Rose apple covers a small area on Isabela, but it is invasive on other islands in the archipelago (Rentería, 2007). The presence of guava and rose apple throughout much of the Highlands ISA is problematic because these species negatively impact and

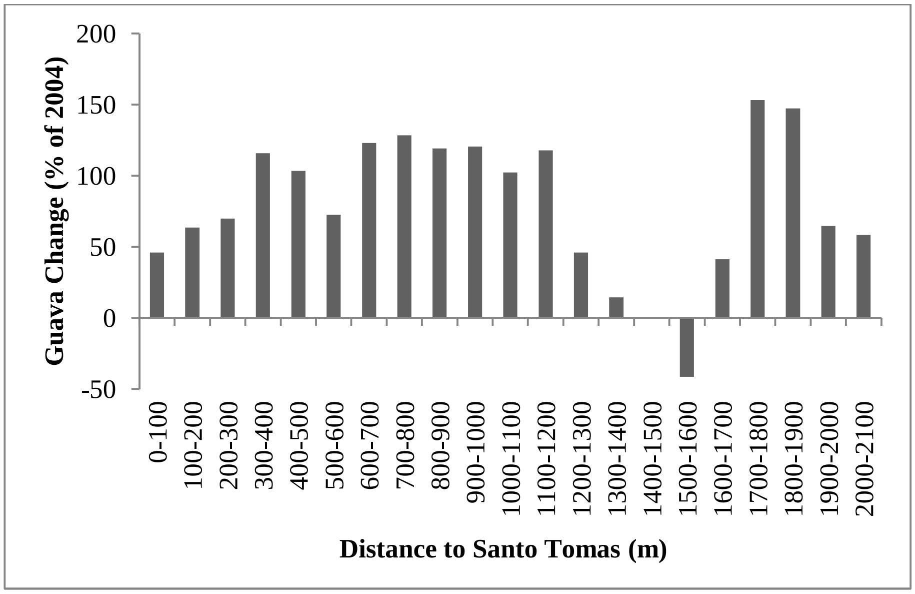

Figure 3.11 Change in guava cover between 2004 and 2010 (% relative to 2004) in the Galápagos National Park (y-axis) at 100 m distance intervals to the border with Santo Tomás (x-axis)

transform managed and natural ecosystems (Tye et al., 2002). The growing number and impact of invasive plant and animal species in the Galápagos, and the threat of ongoing introductions, was one of the reasons cited for the archipelago's placement on UNESCO's In Danger list in 2007. The expansion of trees into the naturally treeless fern-sedge community of the humid zone of the National Park (e.g., around the Sierra Negra caldera) reduces the cover of endemic and native grasses, and results in declines in species richness (Jäger et al., 2007). These and other invasive plants also affect landowners because they decrease the profits that can be derived from agricultural production and increase the labor and time required to maintain functioning farms (Chiriboga and Maignan, 2006). Private landowners are solely responsible for controlling invasive plants on their properties in Galápagos, and their removal can be labor intensive and costly.

Without more substantial control efforts, both species are likely to continue to expand in Santo Tomás and the National Park. Total eradication of guava is not a feasible solution given that such a large areas is already invaded (Rejmanek and Pitcairn, 2002), but a concerted control program that involves the Galápagos National Park and private landowners in southern Isabela should be considered. Rose apple, on the other hands, is still in the early stages of invasion and could be removed from the highlands. It was slated for eradication from Isabela in the last decade, but the project was never started due to incomplete information on its distribution (Gardener et al., 2010b). Efforts to eradicate rose apple should be re-evaluated based on the distribution data provided by this study.

To put the results of this study in context, recent LULC changes observed in southern Isabela are discussed relative to other inhabited islands in Galápagos using the most complete map of LULC in the archipelago (TNC and CLIRSEN, 2006) and changes reported in the literature. In 2000, Puerto Villamil had the third largest footprint of coastal towns (84 ha), after those on Santa Cruz Island (Puerto Ayora, 171 ha) and San Cristóbal Island (Puerto Baquerizo Moreno, 142 ha); Floreana's port town had the smallest footprint at 22 ha (ibid.). Although this particular map of Galápagos doesn't provide information on how much of the land set aside for the communities was built-up, evidence from the literature suggests that the coastal towns on Santa Cruz and San Cristóbal have rapidly urbanized and that little land remains for future development (Kerr et al., 2004; Mena, 2009). The Galápagos National Park and the Municipality of Santa Cruz recently completed a land swap that adds 70 acres of land to Puerto Ayora for a large housing development called El Mirador. Isabela Island, with more than 144 ha of land set aside for Puerto Villamil and its own recent land swap, appears to be following the trajectory of increasing development observed on Santa Cruz and San Cristóbal Islands.

The TNC and CLIRSEN (2006) maps also show that agricultural land uses (including crops and pastures) dominated the highland communities of Isabela (Santo Tomás, 76%), Santa Cruz (Bellavista and Santa Rosa, 68.5%), and Floreana (66.7%) in 2000. Less than one-third (30.9%) of land in San Cristóbal's highland community was devoted to agriculture at that time, signaling significant agricultural abandonment. This study has shown that by 2010, very little land in Isabela's highlands was still used for agriculture. These findings support the notion of declining agricultural production and a process of land abandonment in the archipelago over the last two decades (Kerr et al., 2004; Chiriboga and Maignan, 2006).

The maps further demonstrate that the highland communities of the inhabited islands were invaded by a number of introduced plants. Invasive plants covered nearly one-half of San Cristóbal (48.9%), one-quarter of Santa Cruz (25.3%), and approximately one-tenth of Isabela (14%). Villa and Segarra (2010) found that between 1987 and 2000, large areas of agricultural land on San Cristóbal were invaded by guava, rose apple, and hill raspberries. They also found that while invasive plants weren't noted on maps of Santa Cruz in 1987, a number of introduce plants were present in the island's highlands by 2000. Invasive plant spread is not only an issue on Isabela, but also on other inhabited islands in the archipelago.

3.8 Conclusions

This chapter quantified LULC change in southern Isabela Island using a time series of QuickBird and WorldView-2 satellite images from 2003/2004 to 2010. The images, covering two ISAs, were classified into twelve LULC categories using an object-based image analysis (OBIA) classifier. Landscape composition was quantified from the classified maps, and landscape configuration was described from pattern metric analysis. Change between image dates was assessed using a post-classification change detection approach, and quantified with from-to change matrices. This study shows that substantial changes in the composition and spatial configuration of LULC occurred in southern Isabela Island in a relatively short period of time. Four main land cover transformations were observed: (1) built-up expansion (urbanization) within the coastal community of Puerto Villamil, which included a period of diffuse growth (2004-2008), followed by the coalescence of built-up areas (2008-2010); (2) agricultural contraction in the highland community of Santo Tomás, accompanied by fragmentation of agricultural land use; (3) the spread of invasive plants; and (4) the expansion of forest and shrub cover in the highlands. These changes coincide with a period of international and national concern about the impacts of human activities on the environment in Galápagos.

Differences in the pattern of LULC change in the two management zones – private lands within the communities and protected areas in the Galápagos National Park – were observed. As expected, land use change was more extensive in the two communities, particularly with the increase of built-up areas (in the Coastal ISA) and declines in agriculture (in the Highlands ISA). The protected areas were subject to indirect land cover modifications resulting from land use changes in the adjacent communities, such as the shrinking of lagoons due to increased water extraction in Puerto Villamil, and the spread of invasive plants from abandoned farms in Santo Tomás. A number of direct changes to land cover were also observed in the coastal protected area, including the conversion of park land to more developed uses (e.g., roads, wastewater treatment facilities, etc.), to support the growing community of Puerto Villamil. The destruction and degradation of habitat for endemic and native species (e.g., cutting of mangrove forests; replacement of native flora by introduced plant species), and alterations to the flow of materials (e.g., lagoons cut off from regular ocean flows by development) in and around the protected areas of southern Isabela may have implications for the biodiversity and ecosystem functions that the National Park was established to protect, and on which people rely for the livelihoods and well-being.

This study is not without its limitations. First, the accuracy of agriculture/grassland, forest/shrub, and guava classes in the highlands was below the standard 85% threshold, likely due to a time lag between image acquisition and field data collection, the classification of mixed objects, and a limited number of training samples. Further, a lack of reference data hampered efforts to determine the accuracy of all classified maps, and to quantify error propagation in the change analyses. Second, a lack of cloud-free imagery prevented the change detection analysis from being carried out in some areas. Cloud cover is nearly constant in parts of the highlands, and the coastal area is sometimes obscured by clouds depending on the season. Additional imagery in the future will not only permit an analysis of landscape dynamics, but may also allow LULC changes to be assessed in all areas, even if clouds are present in some scenes (using panel analysis). Finally, the post-classification change detection approach adopted here is limited by the fact that it only captures categorical changes in LULC (i.e., change from one type of LULC to another) (Macleod and Congalton, 1998). Future work should consider assessing within-class changes, such as the density of coastal vegetation, as a way to better understand landscape function.

This study contributes to what is known about LULC change in southern Isabela by characterizing LULC change over the last decade, considering transitions in the rural and urbanizing communities, and contrasting changes within and outside of protected areas on the island. The differences between and similarities among changes in these sites have implications for how human-use and protected areas are managed in Galápagos. Further, several of the change processes highlighted in this study, such as the abandonment of agriculture, the expansion of forest/shrub cover, and the spread of invasive plants following land abandonment, are of increasing concern and debate among researchers and policy makers (Rey Benayas et al., 2007; Diaz et al., 2011).

The remote sensing and landscape configuration analyses presented here could be used as a tool for monitoring LULC change in the Galápagos Islands, or elsewhere in the tropics. High spatial resolution data, such as QuickBird and WorldView-2, make it possible to capture changes that are important for land managers and decision-makers, but which occur over small spatial extents. Satellite imagery in conjunction with a knowledge-based OBIA classifier can provide timely and accurate LULC data for areas with sparse information and where field based data collection on a large scale is prohibitive. Pattern metric analyses allow studies to move beyond changes in landscape composition to also consider changes in configuration of land cover types. Several applications of LULC change information for the Galápagos Islands have been identified. For example, current LULC maps could be used for regional planning and natural resource management in and around communities (Villa and Segarra, 2010). Invasive species distribution information provided by detailed LULC maps could also be used to develop a plant invasion risk assessment system (Tye et al., 2002) and to design control and eradication programs (Gardener et al., 2010a).

More generally, this research contributes to the ongoing discussions of LULC change in and around protected areas. This case study expanded previous work on the topic to a site that includes a large protected area that surrounds small-footprint communities; large parks are generally less susceptible to change because they can slow LULC modification occurring along their borders (Maiorano et al., 2008). Despite fairly strict rules about land use within and outside of the National Park, and increased support for conservation of the archipelago following UNESCO's In Danger listing, direct and indirect changes in land cover occurred within the protected area nevertheless. Although this study only considered those portions of the protected area immediately surrounding the communities, it is likely that some of the observed LULC transitions extended farther into the National Park. The Galápagos National Park Service and local stakeholders (e.g., municipalities, private landowners, conservation organizations, etc.), therefore, should work together to develop conservation and development strategies that consider the Galápagos Islands as a coupled human-natural system, and that balance the desire for continued conservation of the archipelago with development that supports local livelihoods.

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CHAPTER 4: Patterns and Drivers of Agricultural Abandonment, Plant Invasion, and Forest Expansion in Isabela Island

4.1 Introduction

A substantial amount of effort among land change researchers has been dedicated to not only observing and monitoring patterns of land use change across spatial and temporal scales, but also to gaining a better understanding of the social, political, and environmental factors that underlie these changes (Gutman et al., 2004; Rindfuss et al., 2004a; Rindfuss et al., 2004b; Turner et al., 2007). Studies of the expansion of agriculture, deforestation, and urbanization have dominated the literature on this topic (Lambin et al., 2001; Ramankutty et al., 2006). As a result, processes of land use intensification, particularly agricultural extensification and deforestation in the tropics, are fairly well understood (Geist and Lambin, 2002; Hansen et al., 2008). Some regions across the globe, however, have seen the amount of land devoted to crops stabilize, and a few areas have witnessed declines in agriculture (Ramankutty and Foley, 1999a; Ramankutty et al., 2006).

Agricultural land abandonment is not a new process as evidenced by studies documenting abandonment and forest transitions in the United States (Foster, 1992; Ramankutty and Foley, 1999b) and Western Europe (Mather, 2001; Gellrich et al., 2007) in the 19th and 20th century; forest transitions involve shifts from periods of forest loss to periods of net gains (Mather, 1992). Abandoned land is becoming more widespread, however, and rates of abandonment appear to be on the rise (Baudry, 1991; Gellrich and Zimmermann, 2007; Hobbs and Cramer, 2007). Studies of agricultural abandonment are beginning to emerge from Mexico, Central America and the Caribbean (Nagendra et al., 2003; Schneider and Geoghegan, 2006; Parés-Ramos et al., 2008); South America (Izquierdo and Grau, 2009; Diaz et al., 2011; Eraso et al., 2012); and Asia (Khanal and Watanabe, 2006; Leblond, 2008; Ostwald et al., 2009). However, the patterns, drivers, and impacts of land abandonment and forest transition remain poorly understood (Gellrich and Zimmerman, 2007; Sluiter and de Jong, 2007; Baumann et al., 2011).

The negative consequences of agricultural abandonment for rural households and the environment are of increasing concern and debate among researchers (Diaz et al., 2011). The impacts of abandonment can include increased erosion when soil conservation measures are abandoned (Harden, 1996), food insecurity due to decreased agricultural production (Zaragozí et al., 2012), the loss of the traditional livelihoods (Khanal and Watanabe, 2006), and the invasion of former cropland by introduced species (Schneider and Geoghegan, 2006). Land abandonment can also have positive outcomes, however, such as the recovery of native biodiversity and ecosystem services if natural vegetation regrowth occurs (Aide and Grau, 2004; Hobbs and Cramer, 2007; Izquierdo and Grau, 2009), improvement in soil properties to pre-cultivation levels (Lesschen et al., 2008), and increased carbon sequestration in forested areas (Houghton et al., 1999).

Agricultural land abandonment has been documented on the inhabited islands of the Galápagos archipelago over the last three decades (MacFarland and Cifuentes, 1996; Chiriboga and Maignan, 2006; Maignan, 2007). A gradual abandonment of agricultural land and farming activities was first reported in Galápagos in the 1980s (Rodriguez, 1993; González et al., 2008). In the last two decades, the rate of agricultural abandonment and the prevalence of abandoned farms seems to have increased (Chiriboga and Maignan, 2006;

Maignan, 2007). Several reasons for this process have been proposed, including a shift toward a more market-oriented economy based on tourism rather than traditional livelihoods (e.g., fishing and agriculture); migration of farm households to the coastal communities to take advantage of these new opportunities; and declines in available labor to maintain productive farms. Agricultural land abandonment has been identified as an important landscape change process in southern Isabela Island in the previous decade (Chapter 3). Forest expansion and the invasion of introduced plants, two processes linked to land abandonment elsewhere, have also been observed in southern Isabela in this same period.

4.1.1 Study Aims

The goal of this chapter is to identify patterns and potential drivers of agricultural land abandonment and resultant land cover changes (plant invasion and forest expansion) in Isabela Island during the recent "social-ecological crisis[1] in Galápagos (González et al., 2008: 7). Three research questions are addressed in this study:

1) What are the patterns of agricultural land abandonment, plant invasion, and forest expansion in Isabela Island, at the farm and community level, between 2004 and 2010?

   Previous work has shown that the amount of land devoted to agricultural land use declined in southern Isabela between 2004 and 2010 (Chapter 3). It is expected that small fields, rather than entire farms, were abandoned in the period, with losses primarily concentrated on the largest farms. Guava (*Psidium guajava* L.) invasion and forest

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[1] González et al. (2008) use this term to refer to the present situation in Galápagos (1998 – 2010), which is characterized by a growing human presence, exploitation of natural resources, and social and institutional instability in the archipelago. In response to these issues, the UNESCO World Heritage Committee placed Galápagos on their list of "World Heritage in Danger" from 2007 to 2010.

expansion likely occurred where agricultural land was abandoned (i.e., in old fields), leading to similar patterns of abandonment, invasion and forest expansion.

2) How are agricultural land abandonment, plant invasion, and forest expansion related to variables representing the biophysical and geographic characteristics of southern Isabela?

   Agricultural abandonment is hypothesized to be associated with marginal sites located at lower elevations and on steeper slopes, where the geomorphic substrate is rocky, and in remote areas (i.e., farther from roads and the market center, Puerto Villamil) where the cost of production is greater. Guava can adapt to a range of environments and climatic conditions, so it is expected that guava invasion will be associated with all but the lowest elevations, regardless of slope or aspect, and in the least accessible sites. Forest expansion is expected to be associated with higher elevation sites, in areas where the substrate is less rocky, and in remote sites far from roads and Puerto Villamil.

3) In what ways have socio-economic and demographic characteristics of the island's communities changed between 2000 and 2010, and how might these factors be associated with agricultural abandonment?

   As a result of agricultural land abandonment, crop harvests and livestock production are expected to decline. It is hypothesized that increased off-farm employment opportunities will result in a larger proportion of the island's population residing in Puerto Villamil. The proportion of farms employing agricultural laborers is not expected to rise, however, due to declines in the profitability of agriculture.

This research uses spatial analyses of land use and land cover (LULC) change, statistical models of the environmental drivers of change, and descriptions of key social and demographic trends to address these questions. The composition and spatial configuration of

LULC change is assessed in the period from 2004 to 2010 in Santo Tomás to understand recent patterns of agricultural abandonment, guava invasion, and forest expansion in the community (Question 1). Land parcel boundaries are superimposed on the LULC transition maps in a Geographic Information Systems (GIS) database to summarize the number of farms that experienced each type of change, the proportion of farms affected, and the magnitude of changes across the entire agricultural zone. The LULC change maps were generated through post-classification change analysis of QuickBird and WorldView-2 satellite images (2004-2010) in Chapter 3.

Logistic regression models are then developed to assess how agricultural abandonment, guava invasion, and forest expansion are related to a set of biophysical and geographic factors (Question 2); one model is generated for each LULC transition. The dependent variable for each model (presence/absence of the LULC transition) is taken from the aforementioned LULC change maps. The set of explanatory variables is drawn from data layers organized in a GIS database that represent biophysical conditions (e.g., topography and geomorphology) and geographic accessibility (e.g., distance to roads and market) in the study area.

Descriptive statistics and cross-tabulations of secondary data are generated to assess changes in the socio-economic and demographic characteristics of the rural agricultural community of Santo Tomás and the coastal town of Puerto Villamil between 2000 and 2010 (Question 3). The secondary data include national population censuses (INEC, 2002; 2011), a national agricultural census (INEC and MAG, 2001), and a living standards survey of Galápagos (INEC, 2010). The secondary demographic and agricultural data are supplemented by information from interviews of 45 Santo Tomás landowners conducted in

2008; these interviews are used to contextualize the quantitative analyses and to provide a deeper understanding of LULC transitions and population change in southern Isabela. The lack of fine-level spatial information for the secondary data sets prevents quantitative modeling of the socio-economic and demographic drivers of agricultural abandonment, plant invasion, and forest expansion. The goal, rather, is to generate hypotheses about the social factors responsible for land change in Isabela.

Isabela Island offers a unique opportunity for exploring the process of land abandonment in Galápagos. At the beginning of the last decade, participation in the agricultural industry was highest on Isabela (Larrea, 2007). Although recent studies have suggested that abandonment is becoming increasingly common (Chiriboga and Maignan, 2006; Maignan, 2007), it may still be early enough in the process to capture important changes in agricultural production and the socio-economic and demographic factors that determine land abandonment.

A better understanding of the patterns and drivers of agricultural land abandonment and resultant land cover changes in Isabela will be of interest to not only local landowners but various stakeholders groups including the Galápagos National Park Service (GNPS), the Ministry of Agriculture, Livestock, and Fisheries (MAGAP), and FUNDAR Galápagos, an NGO that works with local communities on alternative and responsible approaches to development. These groups are interested in improving agricultural production in Galápagos through education and best practices that improve quality of life for rural residents and promote food sovereignty in the region (GNPS, 2011). Food is increasingly imported from mainland Ecuador to supplement increasing declines in local production. Imported food items are not only expensive because reflect the cost of transportation from the mainland, but they increase the risk of pest and disease introductions (Borja, 2007; González et al., 2008; Gardener and Grenier, 2011). These stakeholders are also interested in promoting active farming as a mechanism for controlling invasive plants in the human use zone as well as in adjacent areas of the National Park (PNG, 2005). The findings from this work will also contribute to the debate on the patterns, causes, and consequences of agricultural land abandonment, an important addition to the broader study of land use change.

4.2 Agricultural Land Abandonment

A single definition of agricultural land abandonment has not been widely adopted. Rather, studies of land abandonment have adapted general definitions to fit the characteristics of the particular agricultural system being investigated. This extends to not only defining which activities and land covers constitute agricultural land use (e.g., crops, hay production, livestock grazing), but in describing the resultant land cover states that are indicative of abandonment (e.g., uncultivated land, forest cover, shrubs). Land abandonment is defined by Baudry (1991) as a change from a traditional or recently established pattern of agricultural use to a less intensive pattern, or as the total termination of land management. In this chapter, land abandonment is viewed as a process that involves the transformation of land from an agricultural use (crops or pasture) towards uncultivated vegetation (invasive plants, forests, and shrubs).

Agricultural land abandonment is not a new phenomenon, as land abandonment and forest recovery were documented in the United States (Foster, 1992; Ramankutty and Foley, 1999b) and Western Europe (Mather, 2001; Gellrich et al, 2007) during the late 1800s and early 1900s. However, abandoned land is becoming more widespread and rates of land abandonment are on the rise (Baudry, 1991; Gellrich and Zimmermann, 2007; Hobbs and Cramer, 2007). While agricultural extensification and deforestation remain prominent change processes in many parts of Latin America, an increasing number of places are witnessing the abandonment of marginal agricultural lands and the subsequent recovery of ecosystems (Ramankutty and Foley, 1999a; Aide and Grau, 2004; Grau and Aide, 2008). Further, the proportion of the population living in rural areas has declined over the past 40 years as people migrate to urban areas (Aide and Grau, 2004). As a result, fewer households derive their livelihoods from agriculture, fishing, or forestry (ibid.).

While agricultural land abandonment occurs globally, the majority of research to date has been carried out in North America, Western Europe, and Eastern Europe. In a review of forty-five independent studies of agricultural abandonment, Rey Benayas et al. (2007) found that a number of social and biophysical factors have been cited as important determinants of land abandonment. Socio-economic and demographic drivers include rural depopulation decline (Aide and Grau, 2004; Khanal and Watanabe, 2006), off-farm employment and new economic opportunities (Romero-Calcerrada and Perry, 2004; Gellrich et al., 2007; Diaz et al., 2011), land tenure (Mottet et al., 2006), and agrarian policies (MacDonald et al., 2000). Important biophysical and geographic drivers of abandonment include topography (elevation, slope, aspect) (Braimoh and Vlek, 2005; Peña et al., 2007), soil quality (Douglas et al., 1994), and proximity to roads and market centers (Braimoh and Vlek, 2005; Peña et al., 2007). Based on their review, Rey Benayas et al. (2007) concluded that agricultural abandonment is primarily driven by rural-urban migration as rural people take advantage of emerging off-farm economic opportunities in urban places. The authors note, however, that agricultural lands with physical conditions that limit production, such as poor soils or steep slopes, are more prone to abandonment if socio-economic factors act.

In recent years a number of studies have emerged that examine the patterns, causes, and consequences of agricultural abandonment in Latin American countries. Diaz et al. (2011) assessed the drivers of agricultural land abandonment on an island off the coast of Southern Chile. The pattern of land abandonment in their study area was primarily driven by socio-economic and geographic factors. Abandonment occurred in remote areas, far from secondary roads, and on small farms with few productive assets (e.g., livestock and pasture). Off-farm employment in the emerging tourism and aquaculture industries had a positive effect on abandonment. Farmer demographics (age, education, and residency on/off the farm) were not significantly associated with abandonment, but the authors noted that older and uneducated farmers were forced to maintain the cultivation of marginal lands as few other options were available to them. Although marginal lands, those having high input costs and low yields, were more often abandoned in the study area, the authors found that biophysical conditions were not as important in determining land abandonment patterns as the aforementioned social factors.

In contrast, Eraso et al. (2012) found that abandonment in the Colombian Andes was almost wholly determined by biophysical and geographic factors, including elevation, slope, soil fertility, and distance to roads and cities. Population displacement due to conflict, was the only significant social predictor of abandonment. Secondary forest cover increased as a result of abandonment, which promoted ecosystem recovery in the study area.

Taking a slightly different approach, Schneider and Geoghegan (2006) examined the factors that affect whether farmers abandon or continue cultivating plots that have been invaded by bracken fern. Larger land holdings and plots that were continuously cultivated were less likely to be abandoned. Farmers with any level of formal education, which was associated with greater off-farm employment opportunities, were also more likely to abandon invaded fields. Interestingly, the total number of household members, a proxy for labor availability, had no effect on the probability of abandonment.

In many places, succession of abandoned fields follows an often observed and repeatable trajectory (Cramer et al., 2008). Vegetation composition following abandonment is determined by the history of cultivation, soil characteristics, and the presence of vegetation communities that existed prior to clearing (Hobbs and Cramer, 2007). Cramer et al. (2008) give three examples of succession trajectories that commonly occur following abandonment. First, land cultivated with traditional row crops, such as sites in the forests and savannas of eastern North America, transition from short-lived herbaceous species to longer-lived woody plants. Second, where extensive forest clearing has occurred, such as in the tropical forests of Central America, the succession of pasture grasses to woody species is somewhat delayed due to the lack of seeds for tree establishment, competition with grasses, herbivory, and fire. Third, on land that was subject to rapid clearing and where environmental conditions favor vegetation communities with high levels of local endemism, as in the eucalypt woodlands of Western Australia, the recovery of woody vegetation is slow due to the invasion of exotic species. Without some type of intervention, invasive species can dominate old fields for decades, leading to a degraded but stable state of land cover (e.g., Brown and Lugo, 2006).

Although forests can regenerate spontaneously following agricultural land abandonment, forest transitions can also occur through the establishment of forest plantations, or when people engaged in agroforestry plant trees in areas near their home

(Rudel, 2010). While the majority of studies focus on forest transitions following abandonment, descriptions of succession patterns in landscapes that were not dominated by woody species prior to cultivation (e.g., semi-natural grasslands or scrub communities) are largely absent from the literature. An early study of natural vegetation regeneration following abandonment in Colorado described a process of succession whereby formerly cultivated fields were replaced by perennial forbs and grasses in the first few years, followed by a more stable mix of longer-lived grasses, forbs, and a few shrubs in the 25-40 years after abandonment (Costello, 1944). In a more recent example from China, an increase in annual and biennial forbs was observed in the initial period after agricultural abandonment, followed by species compositions similar to natural grasslands within 14 years (Zhao et al., 2005).

4.3 Study Area

The study area consists of two parishes in the southern part of Isabela Island (Isabela Canton), Galápagos (Figure 4.1): the urban parish of Puerto Villamil, and the rural parish of Tomás de Berlanga (Santo Tomás, locally). Cantons, administrative divisions in Ecuador equivalent to the county-level in the United States, are sub-divided into parishes (*parroquias*) that are classified as urban if they include the provincial capital or the cantonal head, and rural otherwise. These parishes make up only 1.1% of Isabela's terrestrial area, with the remaining 98.9% of land on the island protected under the Galápagos National Park.

Elevation in the study area, which lies along the flanks of Sierra Negra Volcano, varies from sea level to 1040 m above mean sea level (AMSL). It has a semi-arid and subtropical climate with distinct wet and dry seasons; mean monthly temperature range from 19 to 30°C, and average monthly precipitation varies from 11 to 48 mm per month

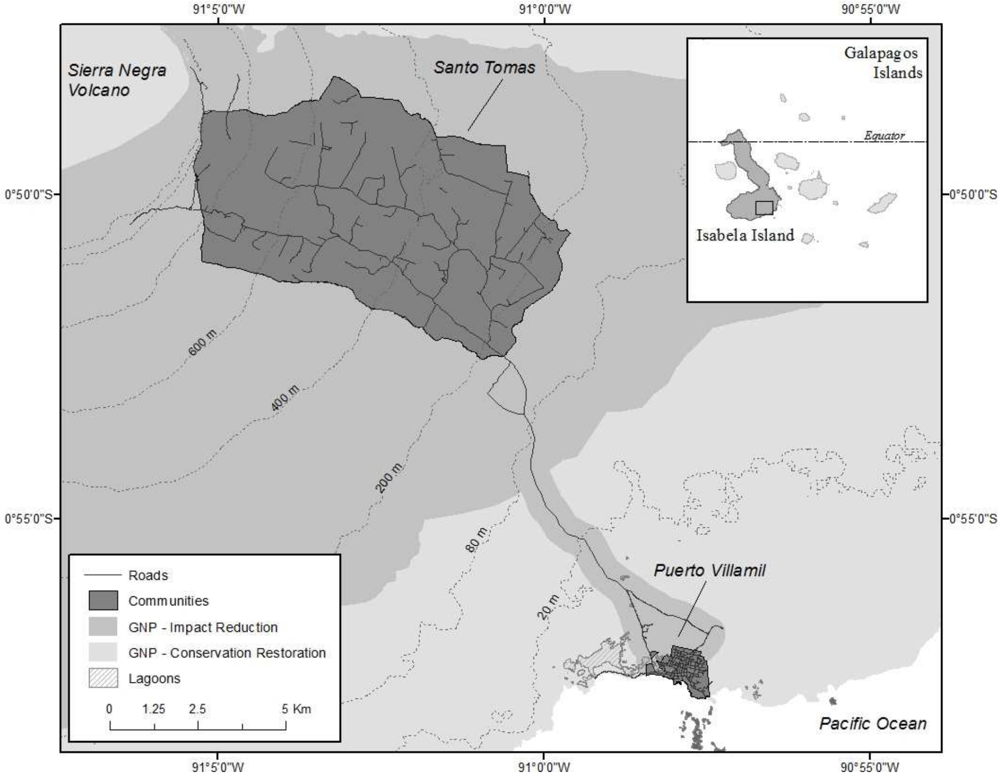

Figure 4.1 Study area on southern Isabela Island includes the the communities of Santo Tomás and Puerto Villamil, as well as land protected by the Galápagos National Park (GNP)

(Guézou et al., 2007). Vegetation communities are organized along an elevation gradient, from xerophytic plants in the dry lowlands to evergreen species in the humid highlands. The parent geological material is primarily basaltic lava flows and pyroclastic materials, with extremely shallow sandy soils dominating the lowlands, and clayey loams up to several meters in depth in the highlands (Laruelle, 1966; Franz, 1980; Valarezo, 2008).

The history of human settlements in Isabela, as in the rest of Galápagos, is relatively short. In the late 1890s, a small number of families and individuals settled Isabela Island. Although a few people resided in the port town of Puerto Villamil located on the island's southeastern coast, the majority of households lived and worked on a large hacienda established in the humid highlands near what is now Santo Tomás (Perry, 1984; Ospina-Peralta, 2006; Chiriboga and Maignan, 2006). Settlement of Isabela coincided with

Ecuadorian policies meant to populate Galápagos to cement the state's territorial claims to the remote archipelago (Constantino, 2007).

Within thirty years of its establishment, the hacienda was dissolved and its land was redistributed among former laborers, each of whom received between 10 and 20 ha of land (Chiriboga and Maignan, 2006). These small, family farms were characterized by subsistence-based agricultural production that included annuals like yucca, potatoes, and vegetables, small numbers of domesticated animals grazing on natural pastures, and shade-grown coffee (a legacy of the hacienda) (Perry, 1984; Chiriboga and Maignan, 2006; Ospina-Peralta, 2006). Extensification of agriculture and ranching continued throughout the 1970s, primarily driven by the slow influx of immigrants from mainland Ecuador; artisanal fishing along the coast became a secondary economic activity (MacFarland and Cifuentes, 1996). Large areas of native vegetation were cleared in the highlands and replaced by cultivars and other plants introduced from the mainland. In 1974, fifteen years after the Galápagos National Park was established, the boundaries of the protected area were formalized (Maignan, 2007; Villa and Segarra, 2010). Existing settlements, including Santo Tomás and Puerto Villamil, were excluded from the National Park; human activities, including agriculture, were restricted to areas that had already been cleared, developed, or otherwise modified.

In the two decades that followed, Isabela's economy diversified and jobs outside of traditional industries (i.e., agriculture and artisanal fishing) increased (Ospina-Peralta, 2006; MacFarland and Cifuentes, 1996). A substantial number of administrative jobs in local government agencies and institutions were created after Galápagos was incorporated as the 22nd province of Ecuador (Epler, 2007). Expansion of land-based tourism on the island led to increased employment opportunities in construction and in businesses catering to tourists (e.g., hotels, restaurants, tour operators) (González et al., 2008). The majority of these new jobs were located in Puerto Villamil, where the central government funded development projects to enhance infrastructure and public services, such as electricity, water, and schools (Epler, 2007). Lucrative off-farm job opportunities combined with declining agricultural profits attracted many people to move to Puerto Villamil (Chiriboga et al., 2007). Between 1974 and 1990, the population of Puerto Villamil quadrupled (from 170 to 696 residents) as people left the highlands to establish homes along the coast (Rodriguez, 1993). Landowners increasingly invested less time and money in agricultural production, and as a result, marginal agricultural lands were abandoned (PNG, 2005; Chiriboga and Maignan, 2006; González et al., 2008).

A fishing boom in Galápagos during the 1990s, coupled with poor economic conditions in mainland Ecuador, resulted in new waves of immigration to Isabela, as people sought to profit from commercial fisheries (Bremner and Perez, 2002; Boersma et al., 2005; Watkins and Cruz, 2007). The Ecuadorian government, in response to concerns that population growth and increasing tourism were leading to environmental degradation and social conflicts in the archipelago, passed the Special Law for Conservation and Sustainable Development of Galápagos[2] in 1998. The Special Law, which provided a legal framework to ensure the continued protection of biodiversity in Galápagos, included strict immigration and residency restrictions aimed at limiting future population growth. These restrictions had the effect of driving up the wages of local laborers and increased the cost and complexity of hiring workers from mainland Ecuador (Borja, 2007). As a result, it became more difficult

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[2] Ley de Régimen Especial para la Conservación y Desarrollo Sustentable de la Provincia de Galápagos (LOREG), Registro Oficial No. 278, 18 March 1998, Ecuador.

for landowners engaged in off-farm activities to hire laborers to maintain their farms and preserve previous levels of agricultural production.

4.4 Methods and Data

4.4.1 Patterns of LULC Change

The composition and spatial configuration of LULC in Santo Tomás between 2004 and 2010 was assessed to understand recent patterns of agricultural land abandonment, guava invasion, and forest expansion in southern Isabela. Land cover change is generated from the complex interaction of social and biophysical processes operating across spatial and temporal scales (Gardner et al., 1987; Urban et al., 1987; Gustafson, 1998). Therefore, information on spatial and temporal patterns of land cover can aid in the inference of processes that underlie land use change (Brown et al., 2000; Crews-Meyer, 2004).

In this study, LULC maps of the study area derived from a time series of high spatial resolution satellite images were used to characterize LULC change in Santo Tomás between 2004 and 2010 (see Chapter 3). QuickBird data acquired on October 22, 2004 and WorldView-2 data acquired on October 23, 2010 were selected to coincide with the recent "social-ecological crisis" in Galápagos (González et al., 2008: 7), and correspond to the season of peak agricultural production in southern Isabela (Brewington, 2011). Using an object based image analysis (OBIA) technique, seven LULC classes were derived from the satellite images: agriculture (includes crops and pastures), barren, built-up, dry pasture, forest (including shrubs), invasive guava (*Psidium guajava* L.), and invasive rose apple (*Syzygium jambos* (L.) Alston). The 2010 classification had an overall accuracy of 88.7% (kappa = 0.87); data to assess the accuracy of the 2004 classification were not available, but visual

Table 4.1 LULC change classes that comprise agriculture, guava, and forest transitions in Santo Tomás

Agriculture Transitions		
Stable Agriculture	Agricultural Abandonment	Agricultural Intensification[1]
Agriculture → Agriculture	Agriculture → Forest	Forest → Agriculture
Agriculture → Barren	Agriculture → Guava	Forest → Dry pasture
Agriculture → Dry pasture	Agriculture → Rose apple	Guava → Agriculture
Barren → Agriculture	Dry pasture → Forest	Guava → Dry pasture
Dry pasture → Agriculture	Dry pasture → Guava	Rose apple → Agriculture
	Dry pasture → Rose apple	Rose apple → Dry pasture
Guava Transitions		
Stable Guava	Guava Contraction	Guava Invasion
Guava → Guava	Guava → Agriculture	Agriculture → Guava
Guava → Rose apple	Guava → Barren	Barren → Guava
Rose apple → Guava	Guava → Dry pasture	Dry pasture → Guava
	Guava → Forest	Forest → Guava
Forest Transitions		
Stable Forest	Deforestation	Forest Expansion
Forest→ Forest	Forest→ Agriculture	Agriculture → Forest
	Forest→ Barren	Barren → Forest
	Forest→ Dry pasture	Dry pasture → Forest
	Forest→ Guava	Guava → Forest
	Forest→ Rose apple	Rose apple → Forest

[1] In this study, agricultural intensification refers to long-fallow or abandoned lands within the existing agricultural zone (Santo Tomás) that have been brought back into production.

assessment indicated that invariant features, such as main roads, were correctly classified.

A categorical map of LULC change was produced with post-classification change detection analysis and map algebra, such that each pixel was coded to indicate its land cover history (e.g., agriculture → forest). The resulting change classes were then combined and recoded to map agriculture, guava, and forest transitions (Table 4.1). Pixel histories involving agriculture, guava, and forest cover that were inconsistent with these transitions were excluded as they were deemed to be artifacts of the classification rather than logical changes.

Landscape pattern was then assessed by calculating pattern metrics for each LULC transition. Most analyses of landscape pattern calculate metrics describing the composition and spatial configuration of LULC from individual classified images that are then compared across time to infer change processes (Southworth et al., 2002; Crews-Meyer, 2002).

However, pattern metrics can also be generated for LULC change classes. The extent and configuration of each transition was assessed by calculating five class level metrics[3] from the transition maps in FragStats 4.0 software package (University of Massachusetts, Amherst, MA):

(1) *Class Area (CA)*: total area (abundance) of each LULC transition
(2) *Percentage of landscape (PLAND)*: proportion of the landscape (i.e., Santo Tomás) occupied by each LULC transition
(3) *Number of patches (NP)*: total number of patches of each LULC transition
(4) *Mean patch size (MPS)*: average patch size of each transition, in hectares
(5) *Patch size coefficient of variation (PSCV)*: patch size standard deviation normalized by mean patch size; a measure of patch size distribution that is more robust against outlier values than standard deviation (McGarigal et al., 2012).

The pattern of LULC transitions was also assessed at the farm-level to understand the prevalence of farms undergoing net agricultural abandonment, guava invasion, and forest expansion. A spatial data layer representing parcel boundaries was generated using sketch maps and Global Positioning System (GPS) measurements of farm locations in 2008 and 2009 to improve an outdated and incomplete map of farms provided by the Isabela Municipality. Ownership of each parcel was determined through interviews with Santo Tomás landowners in 2008 (described in section 4.3.3) and discussions with Isabela residents in 2009. Some farms were composed of multiple, spatially discontinuous parcels, so ownership information was used to aggregate LULC transition information across all parcels held by a landowner. The resulting boundary map included 243 land parcels with 187 different owners.

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[3] Equations for the calculation of the metrics, along with fuller descriptions are provided by McGarigal et al. (2012).

Farm parcel boundaries were superimposed on the LULC transition maps in a GIS database to determine the following:

(1) Average amount and percentage of land on farms that was used for agriculture, covered by guava, or covered by forest in 2004 and 2010;

(2) Number and percentage of farms that experienced (a) net agricultural abandonment or intensification, (b) net guava contraction or invasion, and (c) net deforestation or expansion;

(3) Frequency (number and percent of farms) and average extent of farm change (area, percent of property), by the farm's dominant type of transition (gain/loss) in (a) agriculture, (b) guava, and (c) forest.

4.4.2 Linking LULC Transitions to Biophysical and Geographic Factors

Binary logistic regression was used to model the probability of observing agricultural abandonment, guava invasion, or forest expansion at the pixel level in Santo Tomás as a function of explanatory variables representing the biophysical and geographic characteristics of southern Isabela. Logistic regression models have frequently been employed to explore the social, biophysical, and geographic drivers of agricultural land abandonment and forest transitions (Braimoh and Vleck, 2005; Gellrich et al., 2007; Van Doorn and Bakker, 2007; Müller and Munroe, 2008; Diaz et al., 2011). Three regression models were specified - one each for agricultural abandonment, guava invasion, and forest expansion. The dependent variable for each model was the presence or absence of the particular LULC transition in a pixel (e.g., presence/absence of agricultural abandonment), where y=1 when a given trajectory was observed in a pixel, and y=0 otherwise. The logistic regression model took the following form:

$$p(Y = 1) = \frac{e^{\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n}}{1 + e^{\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n}} \qquad (1)$$

where $p(Y=1)$ is the probability that the dependent variable is 1 (i.e., a particular LULC is observed); $X_1 ... X_n$ are explanatory variables; β_0 is the constant term; and $B_1 ... B_n$ represent the parameter estimates.

The biophysical and geographic independent variables included in the models (Table 4.2) were selected based on their importance to the processes of agricultural abandonment and forest expansion in Latin America, and their hypothesized association with LULC change in Galápagos. The elevation variable (*Elev*), included here as a proxy for climate, was determined from a 20 m resolution digital elevation model (DEM) constructed from a 1:25,000 scale digital topographic map of Isabela (IGM, 2009). Climate conditions at higher elevations on Isabela are generally cool and wet, while lower elevations are warm and dry. A negative relationship between *Elev* and the probability of agricultural land abandonment, and a positive relationship between *Elev* and forest expansion is expected; as guava is a habitat generalist, guava invasion is not expected to significantly vary with elevation.

Table 4.2 Description of independent variables and their sources

Category	Variable	Description	Source
Biophysical	Elev	Elevation; Digital Elevation Model (DEM) derived from contour lines and control points (meters AMSL)	1:25,000 topographic map (IGM, 2009)
	Slope	Slope angle (degrees); direction the maximum slope faces, calculated from DEM	1:25,000 topographic map (IGM, 2009)
	Aspect	Aspect (degrees); calculated from DEM	1:25,000 topographic map (IGM, 2009)
	Geom	Geomorphic substrate; mapped as binary layer with GEOM=1 if soil substrate, and 0 otherwise	1:100,000 geomorphology map (PRONAREG et al., 1987)
Geographic	Dist_Rd	Euclidean distance to nearest road (m)	Field work and 1:25,000 topographic map (IGM, 2009)
	Dist_GNP	Euclidean distance to Galápagos National Park border	1:25,000 topographic map (IGM, 2009)
	Dist_PV	Distance traveled by road to Puerto Villamil (m)	Field work and 1:25,000 topographic map (IGM, 2009)

Slope (*Slope*) and slope aspect (*Aspect*) were also calculated from the DEM. *Slope* is used as a proxy for the difficulty of land use maintenance, as land clearing and cultivation activities are more difficult on steeper slopes. A positive relationship between *Slope* and the probability of agricultural abandonment is hypothesized. *Aspect* is included as a proxy for moisture availability (Shimizu, 1997). It is expected that south-facing slopes will be negatively related to the probability of agricultural abandonment.

The distance to nearest road variable (*Dist_Rd*), was calculated as the straight-line distance to the nearest road. Road features included on the topographic map of southern Isabela (IGM, 2009) were cleaned and updated using GPS data of road locations to generate a road network for this analysis. The *Dist_Rd* variable is included in the model as a proxy for accessibility, with the most remote sites being those farthest from roads. Being far from roads increases the time and cost associated with traveling to town (Puerto Villamil). Therefore, positive relationships between *Dist_Rd* and the probability of agricultural abandonment, guava invasion, and forest expansion are expected.

Euclidean distance to the Galápagos National Park border (*Dist_GNP*) is an indicator of the influence of conservation strategies on land management outside the park. The relationship between *Dist_GNP* and the transitions is difficult to determine, so it was included in the model to determine its relation to agricultural abandonment, guava invasion, and forest expansion rather than to test specific hypotheses.

Distance to Puerto Villamil (*Dist_PV*), the distance traveled along the road network to the center of Puerto Villamil, was included as a proxy for distance to market and the cost associated with agriculture. Positive relationships are hypothesized between *Dist_PV* and the probability of agricultural abandonment, guava invasion, and forest expansion.

A binary geomorphology variable (*Geom*) was included in the model as a proxy for soil quality. Geomorphic substrate types were digitized from a map of Isabela Island geomorphology (PRONAREG et al., 1987), and recoded into two types. *Geom* equaled 0 for rocky substrates with little weathering and shallow soils, and 1 for soil substrates with fewer rocks and deeper soils. A negative relationship between *Geom* and agricultural abandonment is expected.

Each logistic regression was performed on an independent sample of 100 pixels randomly selected from the appropriate binary transition map – agricultural abandonment, guava invasion, or forest expansion. The pixels in each sample were spaced at least 350 m apart due to the presence of spatial auto-correlation in the data. Spatial autocorrelation was tested using Moran's I, a measure of feature similarity based on location and value, and semivariograms were generated to determine the optimal spacing between observations. The values of the dependent variable and the set of independent variables were recorded for each sampled pixel. Multicollinearity was assessed by calculating Spearman's rank correlations (r_s) for each variable pair. When r_s exceeded 0.8 (Menard, 1995) the variable that was more correlated with the modeled transition was retained. Five of the seven variables were retained for modeling (Table 4.3). Model performance was assessed with a pseudo-R^2 measure and

Table 4.3 Independent variables retained in each regression model and hypothesized effect on LULC transitions

	Agricultural Abandonment			Guava Invasion			Forest Expansion		
	Mean	SD	Effect	Mean	SD	Effect	Mean	SD	Effect
Elev (m)	463.04	216.26	(-)	557.99	179.61	(+)	400.10	167.10	(+)
Slope (°)	4.41	2.44	(+)	4.95	2.77	(+/-)	4.45	34.67	(+/-)
Aspect (°)	112.21	22.11	(-)	108.56	34.95	(+/-)	110.77	2.43	(+/-)
Dist_Rd (m)	275.65	299.00	(+)	340.91	286.65	(+)	265.04	224.18	(+)
Dist_GNP (m)	1083.55	709.59	(+/-)	1042.93	671.12	(+/-)	986.29	697.68	(+/-)

the percentage of correct predictions. The logistic regression models were estimated in SPSS Statistics v.20 (IBM SPSS Statistics, Chicago, IL).

4.4.3 Descriptive Analysis of Socio-economic and Demographic Factors

Descriptive statistics and cross-tabulations of socio-economic, demographic, and agricultural production data were generated to assess changes in the characteristics of Isabela’s two communities during the previous decade (2000-2010). The secondary data used in this study come from four publicly available data sets collected and published by the National Institute of Statistics and Censuses in Ecuador (INEC)[4] – Population and Housing Census of 2001 and 2010, National Agricultural Census III in 2000, and Galápagos Living Standards Survey in 2009. The agricultural census and living standards survey provide information on agricultural land use and farm productivity in Santo Tomás, while the population and housing censuses contain information on the demographic and socio-economic characteristics of Santo Tomás and Puerto Villamil.

Variables included in the analysis were selected based on theories of agricultural abandonment and forest expansion in Latin America, and factors unique to Galápagos. Statistical analysis of the variables was carried out in SPSS v.20. The lack of fine-level spatial information in the secondary data sets prevented quantitative modeling of the relationship between land use transitions and socio-economic and demographic factors. The goal of this part of the study, therefore, was to generate hypotheses about the social factors responsible for LULC change in southern Isabela Island.

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[4] The data sets, including the survey instruments and details of the data collection methods, can be accessed from INEC’s website: http://www.inec.gob.ec/home/.

4.4.3.1 Agricultural Productivity

The Third National Agricultural Census (INEC and MAG, 2001) was conducted throughout Ecuador and the Galápagos Islands by INEC, in collaboration with the Ministry of Agriculture and Livestock (MAG). Agricultural production units (*unidades de producción agropecuaria*, UPAs) on Isabela were visited between October 1, 1999 and September 30, 2000. UPAs are rural land holdings 0.05 ha or larger that are totally or partially devoted to agricultural production, and operate as an economic unit under the direction of a single manager (e.g., a household or cooperative); in essence, a UPA is a farm, hacienda, or other agricultural property that comprises one or more land parcels. The questionnaire, which was administered to each household that managed a UPA, included questions on land holdings, land use in the previous twelve months, livestock holdings, and hired labor. A total of 108 UPAs were censused on Isabela.

The Galápagos Living Standards Survey (INEC and CGREG, 2010) was carried out in the Galápagos Islands between October 17 and December 15, 2009 by INEC and the Galápagos Governing Council (CGREG). In Puerto Villamil, a probability sample of 180 households was randomly drawn from the six census sectors that cover the community. Because the number of households in Santo Tomás was smaller than the average number of households in a rural census sector (N = 80), all 62 households were included in the survey; a total of 242 households were surveyed on Isabela Island. Administered by interviewers over several visits, the 74 page questionnaire included several questions about agricultural activities, such as land holdings, land use in the past twelve months, loss of land to invasive plants, livestock holdings, and hired labor. Many of the agricultural questions were taken directly from the National Agricultural Census, which facilitates comparison of the results from the Agricultural Census and Living Standards Survey. Factor weights included in the data set were applied to responses to estimate population-level characteristics.

To understand how agricultural productivity changed between 2000 and 2009, several descriptive statistics were calculated from the Agricultural Census and Living Standards data sets:

(1) *Farm Demographics:* (a) number of farms; (b) area of land holdings, by size; (c) proportion of landowning households residing on farm

(2) *Crop Harvest:* (a) proportion of farms that harvested annual or perennial crops (any amount) in the previous 12 months; (b) average number of crops cultivated, in the previous 12 months; percentage of harvested crops sold outside the household, in the previous 12 months

(3) *Livestock:* (a) number of farms with cattle, pigs, or horses in the previous 12 months; (b) average number cattle, pigs, or horses raised by households in the previous 12 months

(4) *Labor:* (a) average age of the head of household, by place of residence (parish); (b) proportion of farms with hired labor (permanent or occasional); (c) average number of permanent and occasional laborers contracted per farm

4.4.3.2 Socio-economic and demographic characteristics

The National Population and Housing Census is conducted approximately once every 10 years in Ecuador and the Galápagos Islands by INEC. The 2001 census (INEC, 2002) included everyone that was present in Ecuador, regardless of their usual place of residence, from the night of November 24 to the morning of November 25, 2001. Similarly, the 2010 census (INEC, 2011) enumerated everyone in Ecuador from the night of November 27 until the morning of November 28, 2010. Census enumerators administered a questionnaire to each household in the country, collecting information from respondents about the demographic makeup of the household and occupation, among other topics.

To assess how socio-economic and demographic characteristics of Santo Tomás and Puerto Villamil changed between 2001 and 2010, several descriptive statistics were calculated from the Census data sets:

(1) *Population Characteristics:* (a) population (number and percentage), by parish (i.e., Santo Tomás and Puerto Villamil); (b) population by age and sex, according to parish; (c) number of households, by parish; (d) average household size, by parish

(2) *Occupation:* economically active population by industry, according to parish

Both censuses employed a *de facto* method for enumerating the country's population, which apportions persons based on their location at enumeration. Therefore, people present in Galápagos on census day, including tourists and other visitors, were assigned to Galápagos, while Galápagos residents present elsewhere in Ecuador were assigned to the mainland; usual residents of Galápagos who were outside of the country at the time of enumeration were not captured by the census. In this study, the data were analyzed based on a person's usual place of residence, as reported in the census.

4.4.3.3 Qualitative analysis of household interviews

Santo Tomás was first visited in 2006, with a follow-up visit in 2007, to gather data on invasive species and to conduct preliminary interviews on land use with a small number of landowners in the highlands. During July and August 2008, interviews were conducted with 45 landowning households. A random sample of potential respondents was originally drawn from a cadastral map of farms produced by the Galápagos National Institute

(INGALA; now CGREG). During beta-testing of the questionnaire[5], however, landowners pointed out that the cadastral map was more than 30 years old and no longer accurate. In response, potential interviewees were identified by other landowners who had been interviewed during beta-testing and in earlier field visits, and through discussions with Isabela residents. A purposeful sample of respondents was then selected so that many of the households with active farms, defined as those devoting all or most of their time to agricultural activities, were interviewed; landowners residing in Puerto Villamil and engaged in other activities were then included to approximate planned sampling levels; the final sample represented approximately 24% of households with land in Santo Tomás.

Interviews were structured using a questionnaire containing closed- and open-ended questions designed by the author (Appendix I). The questions addressed land use, constraints on agriculture (problems faced by the farm), occupation, invasive plants, and respondent observations about development in Puerto Villamil. With help from respondents, the general boundaries of land parcels owned by the household were sketched onto an incomplete map of properties provided by the Isabela Municipality. GPS coordinates of farm boundaries were also captured, when possible, for use in constructing a complete parcel map for Santo Tomás. Interviews were conducted in Spanish with the household head or another member of the household with knowledge of the farm when the head was not available. Most interviews lasted between one and two hours.

The information provided by these interviews was used to contextualize findings from the secondary data analyses, and to provide a deeper understanding of land use transitions and socio-demographic changes in southern Isabela. Data from the structured

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[5] The questionnaire was beta-tested with five households from the sample in July 2008. The early interviews identified several questions that were confusing or topics that were not particularly salient; these questions were excluded from subsequent interviews.

questions were entered into an Excel spreadsheet so that information on land use, occupation, and place of residence could be quickly compared across farms. Common responses to the open-ended questions were grouped together and categorized in an effort to understand the major problems dealt with by farmers that constrain agricultural production, landowner perspectives about invasive plants, and their observations on development in Puerto Villamil that may help explain emigration from Santo Tomás.

4.5 Results and Discussion

4.5.1 LULC Change Patterns

Between 2004 and 2010, a total of 633 ha of agricultural land were abandoned in Santo Tomás (Table 4.4). Land abandoned in this period accounted for 14% of the study area, making it one of the most expansive transitions mapped. Although 354 ha of land were converted to agricultural uses (agricultural intensification), the net result of agricultural changes in the study area was a loss of nearly 280 ha of agricultural land. Land abandonment was somewhat more spatially cohesive than agricultural intensification, evidenced by a smaller number of larger patches. This pattern suggests that while small areas of land continued to be cleared and cultivated in Santo Tomás, slightly larger areas of productive land were abandoned.

At the farm level, one-third (33%), or 8 ha, of each property was dedicated to agriculture in 2004 (Table 4.5). By 2010, agricultural land use declined to less than one-quarter (22%), resulting in farms primarily dedicated to other uses. The amount of land is set aside for agricultural use is fairly small considering it encompasses both small areas for crop cultivation and pasture lands that are generally more extensive. Of the 185 farms included in

Table 4.4 Class metrics for LULC transitions

	LULC Transition		
Metric	Stable Agriculture	Agricultural Abandonment	Agricultural Intensification
CA	892.80	632.84	354.49
PLAND	20.3	14.4	8.1
NP	3276	7739	8202
MPS	0.27	0.08	0.04
PSCV	1195.11	695.75	511.95
	Stable Guava	Guava Contraction	Guava Invasion
CA	1488.06	572.02	635.60
PLAND	33.9	13.0	14.5
NP	4140	8159	7721
MPS	0.40	0.07	0.08
PSCV	2576.01	956.24	1107.75
	Stable Forest	Deforestation	Forest Expansion
CA	393.32	400.93	566.23
PLAND	9.0	9.1	12.9
NP	3583	5359	6311
MPS	0.11	0.07	0.09
PSCV	1283.99	1167.13	555.28

Metrics: CA = class area (ha); PLAND = percent of landscape (%); NP = number of patches; MPS = mean patch size (ha); PSCV = patch size coefficient of variation

Table 4.5 Area (A) and percent of farm property (B) used for agriculture, invaded by guava, or covered by forest

	2004				2010				
N=185[a]	Mean	SD	Min	Max	Mean	SD	Min	Max	Difference[b]
(A) Area (ha) of farm covered by:									
Agriculture	8.05	13.88	0.00	113.50	6.60	12.09	0.00	79.70	-1.46***
Guava	10.99	18.50	0.00	103.37	11.28	19.66	0.00	126.27	0.28
Forest	4.16	8.39	0.00	54.74	5.08	8.17	0.00	60.31	0.92***
(B) Percent of farm (%) covered by:									
Agriculture	33.3	26.9	0.0	100.0	22.2	22.8	0.0	94.7	-11.1***
Guava	36.8	29.9	0.0	99.7	30.6	27.0	0.0	97.0	-6.3***
Forest	26.2	26.2	0.0	100.0	24.8	20.1	0.0	90.1	-1.4

a Two farms were excluded from the analysis because they lack LULC data (due to cloud cover).

b Wilcoxon signed rank tests were performed to determine if 2004 and 2010 averages are significantly different. *** Significance level of W statistic: 0.001

the analysis, 118 (64%) exhibited net agricultural land abandonment between 2004 and 2010 (Table 4.6). These farms lost 3 ha of agricultural land, on average, comprising approximately 17% of the farm property. The 33% of farms that were dominated by agricultural intensification saw an average increase of less than 2 ha.

Figure 4.2 shows farm boundaries superimposed on the spatial distribution of stable agriculture (grey) and transitions involving the abandonment (red) and intensification (green) of agriculture. Abandoned patches appear to increase in size moving from south-southeast to west-northwest. In some cases the larger patches seem to coincide with fields visible in the satellite imagery. It is interesting to note that several farms appear to have devoted little to no land to agriculture in either year (areas in white). It is likely that these farms were abandoned prior to 2004.

The pattern of guava invasion was compositionally and spatially similar to that of agricultural abandonment. Over the course of six years, guava invaded 636 ha of land over

Table 4.6 Frequency and mean extent of change, by the farm's dominant type of change, for agriculture, guava, and forest

	Frequency		Mean Change [a]	
	Number of Farms	Percent of Farms (%)	Area (ha)	Percent of Property (%)
Dominant Change in Agriculture:				
Agricultural Abandonment	118	63.8	3.12 (5.19)	16.8 (18.8)
Agricultural Intensification	61	33.0	1.62 (2.91)	10.4 (12.3)
Dominant Change in Guava:				
Guava Contraction	100	54.1	2.66 (4.28)	14.5 (13.9)
Guava Invasion	74	40.0	4.31 (7.64)	20.1 (19.6)
Dominant Change in Forest:				
Deforestation	62	33.5	2.25 (5.37)	15.3 (18.3)
Forest Expansion	121	65.4	2.56 (3.51)	15.1 (14.2)

a Standard deviation listed in parenthesis.

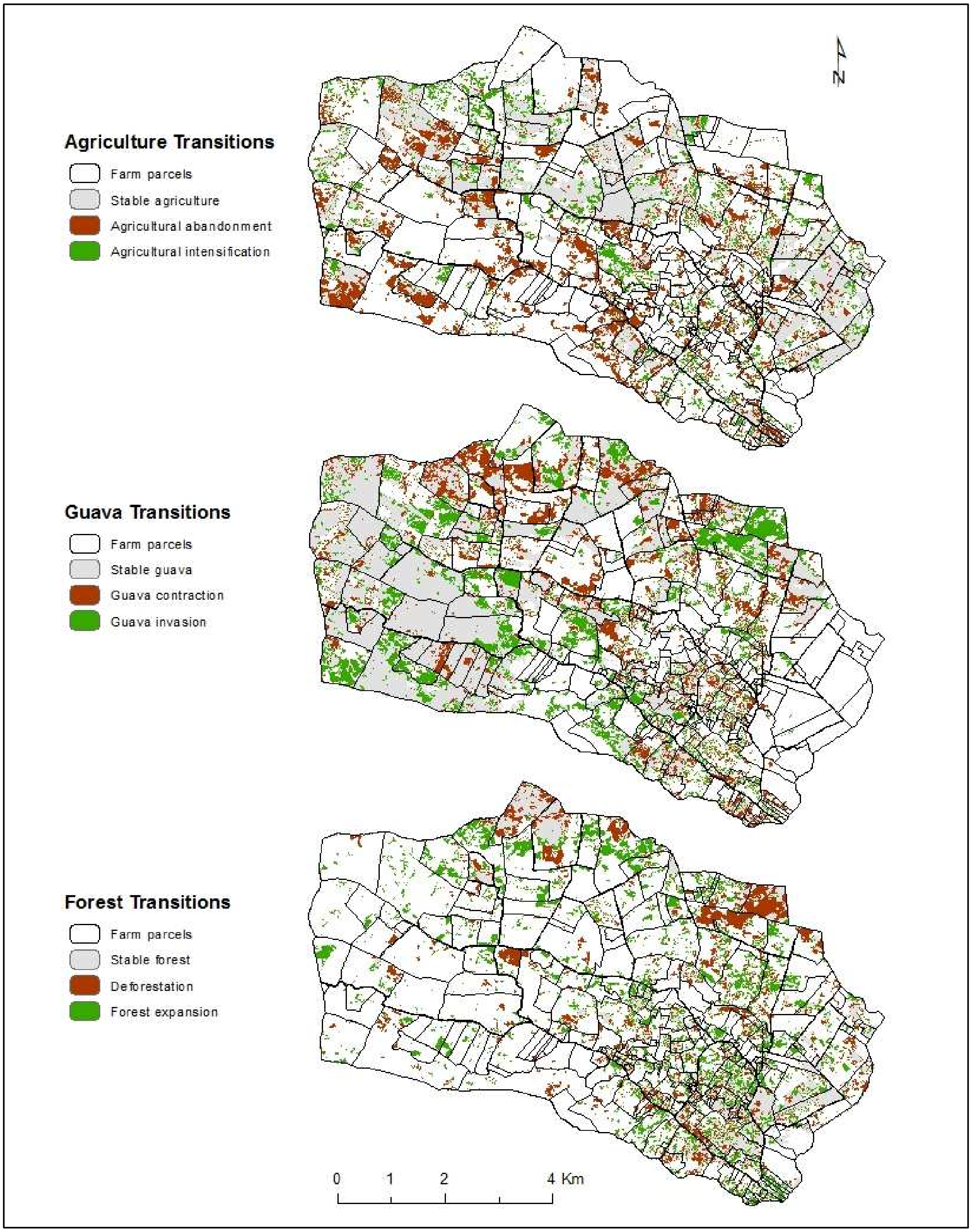

Figure 4.2 Farm parcel boundaries superimposed on maps of agriculture, guava, and forest transitions in Santo Tomás, 2004-2010

14% of the study area (Table 4.4). Guava cover also contracted by 572 ha during this period, primarily from clearing by landowners, resulting in a net increase of just 64 ha of guava. Patches of land invaded by guava were, on average, identical in size to patches where agriculture was abandoned for other uses. However, the patch size coefficient of variation (PSCV) metric indicates greater variability in the size of invaded patches compared to abandoned patches.

The farm-level results show that the average farm area covered by guava did not significantly increase between 2004 and 2010, although the proportion of each farm covered by guava declined slightly (Table 4.5). The map depicting guava change (Figure 4.2) suggests that more of the small farms cleared guava (red) than did large ones in this period, leading to a shift in the average proportion of each farm covered by guava but no significant change in its average areal extent. Forty percent of farms experienced a net increase in guava cover, averaging just over 4 ha of land. The contraction of guava was much more prevalent, occurring on 54% of farms, but the areas cleared of guava averaged only 2.66 ha (Table 4.5). The map also shows that guava continued to spread across farms in western Santo Tomás (green), which were already dominated by guava in 2004. The pattern of invasion and contraction is fragmented on farms in the central area, while farms farther to the south are mostly free of guava (white). Field observations suggest that there are a number of active farms in the south, which seem to be doing a good job of keeping guava from becoming established.

From 2004 and 2010, 566 ha of land were converted to forest cover, accounted for 13% of the study area (Table 4.4). Gains in forest cover were accompanied by the loss of formerly forested land (deforestation), leading to a 165 ha net increase in forest cover. Forest expansion was the most spatially cohesive of the LULC transitions analyzed, evidenced by a small number of larger patches (NP=6311; MPS=0.09 ha). However, forests were less abundant than both guava and agricultural land in Santo Tomás.

The lower prevalence of forest cover was also evident at the farm level, where forests ranged from 26% to 25% of land cover on farm properties between 2004 and 2010 (Table 4.5). However, the average amount of forest cover on farms increased from just over 4 ha to 5 ha in the same period. Of the 185 farms analyzed, most (65%) experienced net forest expansion (Table 4.6). These farms gained 2.56 ha of forest cover, on average, comprising approximately 15% of each property. The nearly one-third of farms that were dominated by deforestation, however, lost a similar amount of forest (2 ha). The map of forest stability and change (Figure 4.2) illustrates that forest transitions were more prevalent in the eastern half of Santo Tomás. However, forest expansion does not seem to follow an easily observable pattern as farms exhibiting forest expansion appear among those undergoing deforestation.

The farm level agricultural land use data confirm that abandonment occurred in Santo Tomás prior to 2004 as the average farm only devoted one-third of its land to cultivation by that year. Yet the results also show that the process of agricultural land abandonment continued over the last decade. In most cases, abandoned agricultural land was replaced by guava as part of a transition from a landscape cultivated with herbaceous species (i.e., crops) to one dominated by invasive woody plants.

4.5.2 Biophysical and Geographic Determinants of LULC Change

The results of the logistic regression models for agricultural land abandonment, guava invasion, and forest expansion are presented in Table 4.7. Positive regression coefficients (β)

Table 4.7 Logistic regression models for agricultural abandonment, guava invasion, and forest expansion

	Coefficient (β)	Standard error	Significance (p-Value)	Odds ratios (Exp (β))
(A) Agricultural abandonment (n=100)				
Elev	.001	.001	.279	1.001
Slope	-.028	.119	.813	.972
Aspect	.020	.010	.060	1.020
Dist_Rd	.001	.001	.246	1.001
Dist_GNP	.000	.000	.954	1.000
Intercept	-3.278	1.534	.033	.038
pseudo R^2	.105			
Correct Predictions (%)	64.0			
(B) Guava invasion (n=100)				
Elev	-.001	.002	.414	.999
Slope	-.112	.116	.334	.894
Aspect	-.006	.007	.368	.994
Dist_Rd	.000	.001	.882	1.000
Dist_GNP	.000	.000	.397	1.000
Intercept	1.248	1.175	.288	3.482
pseudo R^2	.070			
Correct Predictions (%)	72.0			
(C) Forest expansion (n =100)				
Elev	.005	.002	.009**	1.005
Slope	-.017	.122	.886	.983
Aspect	.004	.007	.555	1.004
Dist_Rd	.000	.001	.903	1.000
Dist_GNP	.001	.000	.088	1.001
Intercept	-1.927	1.187	.104	.146
pseudo R^2	.192			
Correct Predictions (%)	75.0			

pseudo R^2 = Nagelkerke R squared; **Significant at the $p < 0.01$ level

indicate that higher values of the independent variable increase the probability of observing the LULC transition, while the opposite is true for negative coefficients. The coefficient values cannot be directly interpreted as a measure of change in the dependent variable because they are in log units, so odds ratios (e^{β}) are also presented in the table. Odds ratios measure the likelihood of observing the transition given a one unit increase in the independent variable. When the odds ratio is greater than one, the odds of observing the

LULC transition increase, and when the odds ratio is less than one the likelihood of observing the transition decreases; when odds ratio values are equal to one, the likelihood of observing the trajectory is not affected by a change in the independent variable.

Pseudo-R^2 values ranged from 0.07 for guava invasion to .19 for forest expansion; pseudo-$R^2 > 0.2$ indicate good model fit (Clark and Hosking, 1986). The percent of cases correctly predicted by each model ranged from 64% for agricultural abandonment to 75% for forest expansion. These measures indicate that each of the three models performed poorly in explaining LULC transitions at the pixel level. Further, the set of biophysical and geographic variables included in the model do not significantly explain the likelihood of observing agricultural land abandonment or guava invasion ($p > 0.05$).

Elevation, however, was significant in the forest expansion model ($p < 0.05$). The positive (β) coefficient for elevation indicates that higher elevation values increase the probability of observing forest expansion. A one-meter increase in elevation multiplies the odds of forest expansion by a factor of 1.005. However, the pseudo-R^2 value (.192) was just below the acceptable threshold for good model fit, and the accuracy of predictions was low (72%). The pattern of forest expansion is, therefore, determined in part by other biophysical or social factors not captured in this model.

These results seem to indicate that agricultural land abandonment, guava spread, and forest expansion in Santo Tomás are not determined by the biophysical or geographic characteristics of southern Isabela. This is somewhat surprising as it was hypothesized that agricultural abandonment is associated with marginal environmental conditions determined by topography and accessibility. One reason may be that there is not a sufficient amount of variation among the biophysical and geographic variables of interest across the small study area. Further, the effects of biophysical and geographic factors on LULC transformation may not be observable given that the models rely on a limited sample size (100 pixels per model) and are specified with a large number of independent variables relative to the number of sample.

It is also possible that other important environmental factors that determine the presence of land abandonment, plant invasion, and forest expansion were not captured by the set of explanatory variables included in these models. For example, several of the landowners surveyed for this study indicated that the drier conditions found at lower elevations in Santo Tomás limit the type and quantity of crops that can be grown. While elevation was used as a proxy for climate in this study, explicit data on precipitation may be more useful for understanding the heterogeneity of water availability across Santo Tomás.

Other landowners noted that rocky soils are difficult to farm because they provide poor soil conditions for crop cultivation and cannot be cleared or planted with tractors. Poor soil conditions (shallow depth, clayey or rocky textures, and limited nutrient content), which were not well captured by the geomorphology variable included in these models, are positively associated with land abandonment and forest expansion elsewhere (Bürgi and Turner, 2002; Bakker et al., 2005). Distance to the nearest road, which was included in the models as a measure of accessibility, may not adequately capture the costs and time required to transport agricultural products from Santo Tomás to Puerto Villamil for sale. For five of the 45 landowners interviewed for this study, the lack of transportation options is a major problem. Most households do not own vehicles, and as a result they must pay a driver to transport their goods to market. The Isabela Municipality operates daily bus service between Santo Tomás and Puerto Villamil to facilitate travel between the communities, but some farms are a 45 minute walk from the nearest stop. Therefore, accessibility measures that more accurately capture transportation costs and accessibility may be better predictors of land use change than those included in the models.

4.5.3 Changes in Socio-economic and Demographic Factors

Descriptive statistics on various aspects of agricultural production calculated from the National Agricultural Census (2000) and the Galápagos Living Standards Survey (2009) are presented in Table 4.8. The farm demographics data reveal that the number of farms in Santo Tomás increased between 2000 and 2009, and the distribution of landholdings shifted toward small to medium-sized farms (< 0.5 to 20 ha). Figure 4.3 illustrates the distribution of farm sizes and area of land holdings in various size classes. The average area of landholdings decreased from 44 ha to 19 ha, and the number of farms increased from 108 to 182 over this period (Table 4.8).

The additional farms did not result from an increase in the spatial extent of Santo Tomás, whose limits were fixed when the Galápagos National Park's boundaries were formalized in the 1970s. Rather, as Isabela residents explained during an effort to map farm and parcel boundaries in 2009, many owners of large farms subdivided them over the last decade, giving parcels to adult children or selling them to recent migrants. Figure 4.3 shows that none of the 12 farms with landholdings greater than 100 ha in 2000 remained intact by 2009. The subdivision of these and other moderately large farms into smaller ones can also be seen in the increased prevalence of small to medium-sized farms (< 0.5 to 20 ha) (Figure 4.3). Large farms, particularly those over 20 ha, are difficult to cultivate as they require large amounts of time and labor to keep them productive (Chiriboga et al., 2007). One possible

Table 4.8 Descriptive statistics on agricultural production in Santo Tomás

	2000[a]			2009[b]		
Agricultural Production Characteristics	Value	Mean	SD	Value	Mean	SD
(A) Farm Demographics						
Total number of farms (N)	108	-	-	182	-	-
Landowner resides on farm (%)	40.7	-	-	22.3	-	-
Farm area (ha)	108	44.44	50.75	130	18.78	21.23
(B) Crop Harvest [c]						
Farms harvesting any crops (%)	29.6	-	-	39.2	-	-
Harvest sold (%)	61.7	-	-	21.1	-	-
Crop types harvested (N)	32	18.19	12.18	51	7.4	3.7
(C) Livestock rearing						
Cattle (N)	67	29.43	34.67	43	20.50	24.83
Pigs (N)	44	5.36	5.72	27	3.96	2.78
Horses (N)	115	3.09	2.50	31	5.51	5.71
(D) Labor[a]						
Age of household head, residence in Puerto Villamil (years)	64	48.06	10.90	92	46.73	12.93
Age of household head, residence in Santo Tomás (years)	40	53.98	17.52	28	53.00	14.50
Farms with any paid laborers (%)	37.0	-	-	25.4	-	-
Permanent paid laborers (N)	23	1.39	.941	16	1.40	.507
Occasional paid laborers (N)	17	1.18	.529	12	1.00	.000

a Calculated from the National Agricultural Census (2000)
b Calculated from the Living Standards Survey (2009)
c The Living Standards Survey recorded 182 farms in 2009. Information on farm size, crop harvest, and labor were not recorded for 52 farms that listed their primary agricultural activity as only livestock production or only agroforestry.

explanation for subdivision is that by breaking up large farms and either selling off parcels or gifting them to children, farmers can some maintain productivity without the need to hire laborers.

Agricultural abandonment can be characterized by not only a reduction in the amount of land devoted to agriculture but also by changes in farm productivity. The crop cultivation data (Table 4.8) revealed an unexpected increase in the proportion of farms that harvested crops (not including pasture), from 30% in 2000 to 39% in 2010. Although the increase was small, it is nonetheless interesting given that the LULC analysis presented here indicate that

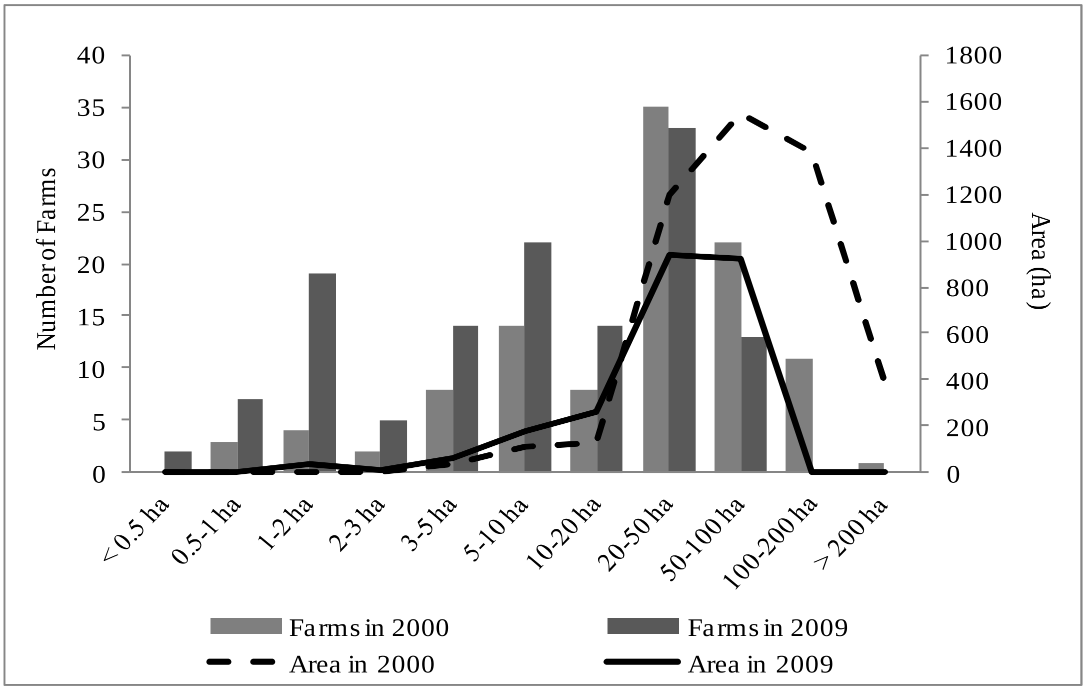

Figure 4.3 Number of Santo Tomás farms and area of land holdings in in each size class, 2000 and 2009

the total amount of cultivated land in Santo Tomás (including crops and pasture) declined between 2004 and 2010. These seemingly contrasting results could be explained an increase in the number of farms harvesting existing perennials (e.g., fruit from citrus and avocado trees), even if they abandoned other cultivated land. Another possible explanation is that the declines in agricultural land resulted primarily from the loss of pasture, which was included in the LULC analysis but not in the production statistics presented here. The Living Standards Survey, however, did not collect specific information on cultivation (planting) or pastures so it is difficult to explore these possibilities.

In any case, the harvest data also indicate that a smaller variety of crops were harvested in 2009 than in 2000, likely due to decreased variety in the type of products cultivated. Farms harvested, on average 18 different crops in 2000, but only 7 in 2009. In 2000, more than half (62%) of all annual and perennial crops harvested over the previous year were destined for sale. In contrast, nearly three-quarters (79%) of the crops harvested in 2009 were consumed by farm households or fed to livestock. The prevalence of livestock also declined over this period, with fewer households raising cattle, pigs, or horses by 2010. With the exception of horses, the average number of animals kept by farms also fell.

Declines in productivity may be related to several factors identified during interviews with landowners in 2008 and from observations of Santo Tomás from 2007-2009. Isabela Island lacks a market for locally grown agricultural products beyond limited sales to small stores and restaurants in Puerto Villamil. When landowners were asked to describe the most important problems faced by the farm, seven (~ 15%) noted the lack of market opportunities in Isabela. In the summer of 2008 several producers started a Saturday morning farmer's market in Puerto Villamil in an effort to increase sales. One landowner noted, however, the farmer's market is short because there are few products for sale and farmers tend to sell out quickly. Another farmer remarked that there isn't much demand for locally grown products because people in Puerto Villamil prefer to buy food imported from the mainland. There is also a great deal of repetition in the products that are offered and harvests can be inconsistent from year to year. As a result, products grown on Isabela are not marketed to tourist vessels and are rarely sold elsewhere in Galápagos.

As the LULC change analysis demonstrated, invasive plants have become widespread throughout much of Santo Tomás. The presence of invasive plants reduces the productivity and profitability of agriculture because farmers must devote a significant amount of time, labor, and money to clearing them (Chiriboga and Maignan, 2006). During interviews, farmers were shown photographs of a number of introduced and invasive plants (e.g., guava, passion fruit, elephant grass, etc.) and asked to comment about the presence of these plants on their land and whether they make an effort to control their growth. Guava, which was present on more than 90% of farms, was frequently referred to as a plague (*plaga*) by landowners. One farmer, whose property had large amounts of land invaded by guava, explained that guava was not a problem on the farm because he wasn't trying to cultivate anything in those areas, and that his livestock had no problems grazing in the guava patches. Most farmers, however, have adopted a variety of methods to control its growth, such as cutting small plants three to four times per year or exposing the bark of mature trees, all of which require extensive amounts of manual labor. One such landowner commented that he does his best to control the plant in his fields but believes he is, "not winning the fight" against guava. Gardener et al. (2010) estimate that it costs between $500 and $2500 USD per hectare to remove invasive species from farmland, and an additional $500 to $1000 USD per hectare, per year, for maintenance. The interviews also highlighted other possible reasons for reduced agricultural production, such as limited labor and the rise of off-farm economic opportunities.

Farm demographic statistics from the Agricultural Census and Living Standards Survey indicate that although there were more farms in Santo Tomás in 2009 than in 2000, fewer people were living on them (Table 4.8). Forty-one percent of landowners resided on their farm properties in 2000, but by 2010, nearly 80% of landowners lived elsewhere. Interviews with landowners confirmed that in most cases these households emigrated to Puerto Villamil, rather than to other islands or mainland Ecuador. According to data from the National Population and Housing Censuses, a larger proportion of Isabela's population lived in Puerto Villamil in 2010 than in previous years (Table 4.9). In 2001, 88% of Isabela's population resided in the town, and by 2010 the proportion living in Puerto Villamil had

Table 4.9 Descriptive statistics of Isabela Island's population

	Isabela Island		Puerto Villamil		Santo Tomás	
Population Characteristics[a]	2001	2010	2001	2010	2001	2010
Population (N)	1593	2164	1397	1999	196	165
Population (%)	100	100	87.8	92.4	12.3	7.6
Households (N)	463	681	397	627	66	54
Mean household size (persons)[b]	3.38 (1.88)	3.17 (1.76)	3.45 (1.85)	3.19 (1.76)	2.97 (2.02)	3.04 (1.77)

a Usual residents of Isabela Island (excludes floating population); calculated from the National Population and Housing Census (2001, 2010)
b Standard deviation in parenthesis

grown to more than 92%. These data also show that although the total population of Isabela Island increased between 2001 and 2010 (from 1,593 to 2,164 persons), the number of people living in Santo Tomás fell from 196 to 165 persons. These population changes seem to be indicative of rural-urban migration (or more appropriately, rural-rural migration given Puerto Villamil's small size) and rural depopulation, which have been identified as important determinants of agricultural land abandonment elsewhere (Aide and Grau, 2004; Khanal and Watanabe, 2006; Rey Benayas et al., 2007).

Increased participation in off-farm employment has been found to have a positive effect on land abandonment as it limits the amount of time households have to dedicate to agricultural activities and decreases the labor pool available for farming (Diaz et al., 2011). The Population Census data reveal an increase in non-agricultural activities in Puerto Villamil and reductions in the proportion of the economically active population (aged 15-64) who listed agriculture as their primary occupation (Figure 4.4). In 2001, more than 80% of working-age Santo Tomás residents listed agriculture and fishing as their primary occupation, but by 2010 fewer than 70% of residents were engaged in these traditional activities. The 30% of Santo Tomás residents working outside of the farm were employed in a variety of sectors including public administration and retail. The situation in Puerto Villamil was quite different, as few people (less than 10%) reported agriculture or fishing as

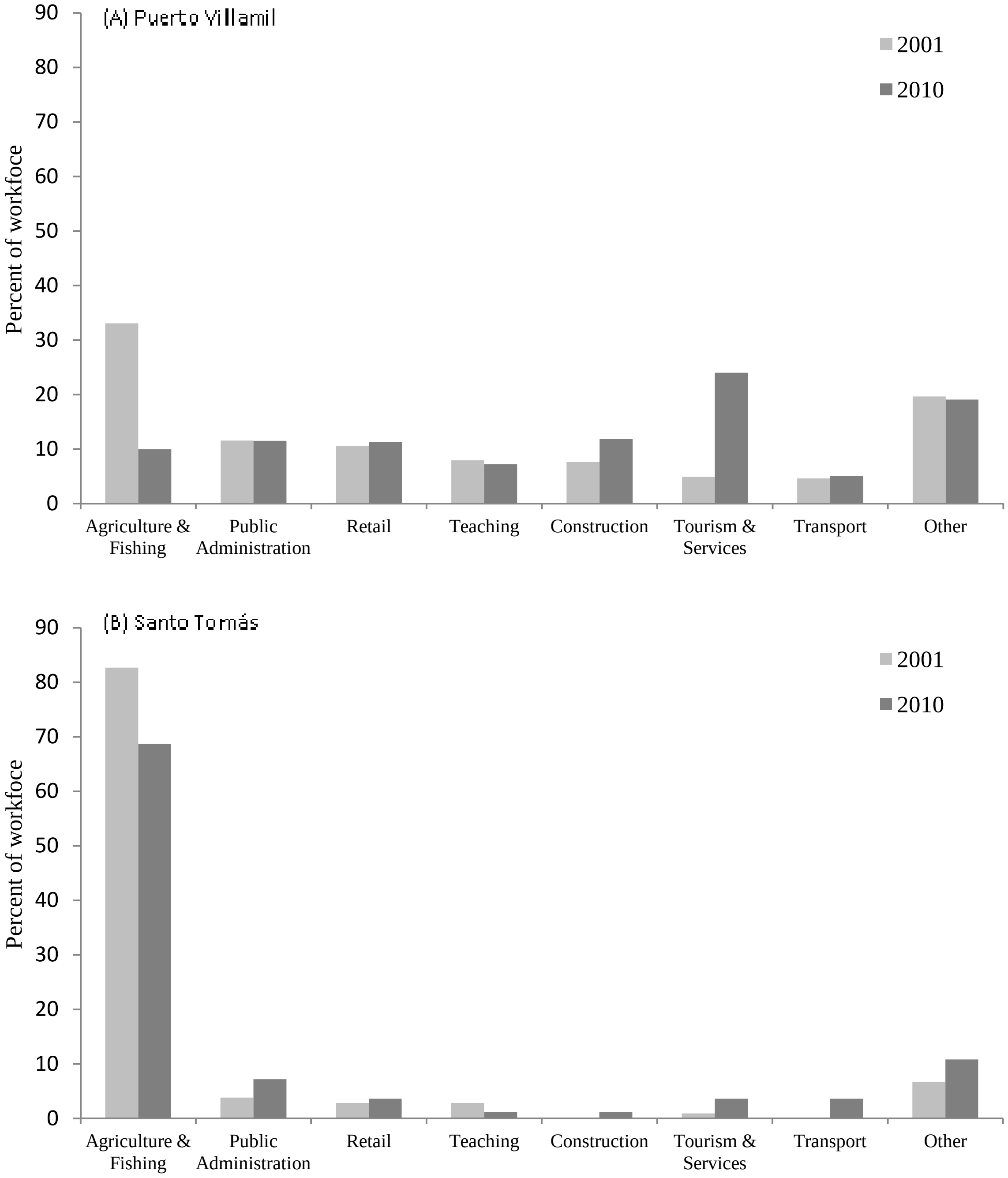

Figure 4.4 Percent of economically active population (aged 15-64) of (A) Puerto Villamil and (B) Santo Tomás employed in various sectors in 2001 and 2010

their primary occupation. More than 198 jobs were created in tourism (which includes services provided by tour operators, hotels, and restaurants), and construction employment grew by 67 persons between 2001 and 2010 (Figure 4.4).

Labor availability is also an issue for landowners who wish to maintain productive farms. Household labor is limited owing to small households that average between 2.97 and 3.45 individuals (Table 4.9). Children, particularly those in school, aren’t generally expected to help with farm activities according to several landowners interviewed for this study. Further, many older children are absent from Galápagos for several years while they attend secondary school on the mainland; this absence is reflected in the 15-19 age group of the population pyramids presented in Figure 4.5.

Landowners (heads of households) who resided in Santo Tomás were, on average, older than their counterparts in Santo Tomás (Table 4.8). Diaz et al. (2011) found that older landowners were forced to continue farming marginal lands in Chile because they didn’t have the resources to work in other sectors. In addition, fewer landowners are hiring laborers to assist with agricultural activities because of the high wages demanded by local workers, and the expense and bureaucracy involved in contracting laborers from mainland Ecuador. In

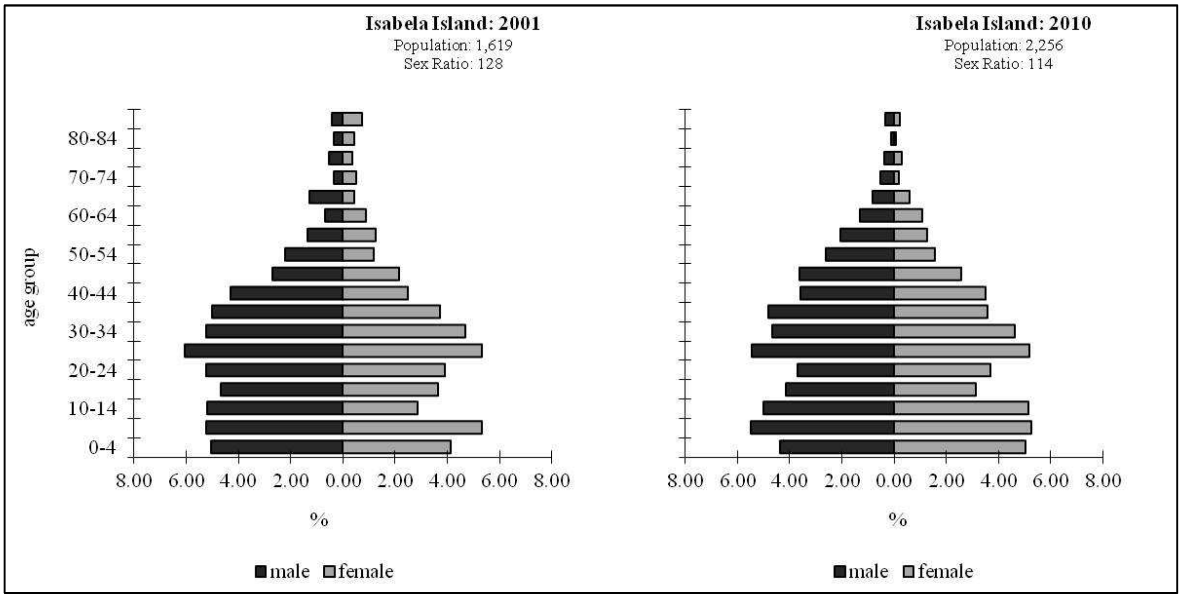

Figure 4.5 Population pyramids for Isabela Island in 2001 and 2010, calculated from the National Population and Housing Census (2001, 2010)

2000, 37% of farms hired workers, while in 2010 only 25% of farms had any paid laborers (Table 4.8). Due to residency restrictions put in place by the Galápagos Special Law, hiring someone from the mainland requires substantial fees and paperwork. One landowner who has hired family members from the mainland to help with clearing and planting activities on his farm explained that he pays approximately $180 USD annually (in 2008) in fees for each mainland worker he contracts. For the most part, landowners have not adopted labor-saving technologies as a means of dealing with the limited labor pool. Tractors, certified seeds, and irrigation systems are expensive and not affordable for most farms given their low profitability.

The results indicate that agricultural land abandonment in southern Isabela Island has continued in the last decade owing to several socio-economic and demographic factors including rural-urban migration due to economic opportunities in tourism and related services; declining profitability of agriculture due to (a) the limited market for locally grown products, and (b) the increased abundance of invasive species; and (c) small labor pools due to rural depopulation and immigration restrictions. Although abandonment has been met with declines in agricultural productivity, it seems clear from the interviews that most landowners retain ownership of their parcels after emigrating from Santo Tomás. They may visit their properties on the weekend or during holidays, but most of their time is spent relaxing or harvesting existing products (e.g., citrus fruit) than on clearing land or planting new crops. Some landowners who own businesses in Puerto Villamil use the money generated from these enterprises to hire full-time workers to maintain their farms. One such landowner interviewed for this study uses the money earned from a hotel in Puerto Villamil to hire laborers from mainland Ecuador to grow food for the hotel restaurant and care for horses that hotel guests ride during visits to the Sierra Negra Volcano. These examples suggest that there remain feedbacks between life in the coastal towns and farms in the highlands of Galápagos following agricultural land abandonment.

In San Cristóbal Island there is evidence that landowners who had previously abandoned farms and immigrated to the coast are now considering returning to life in the highlands in response to cost of living increases (Mena, personal communication 2012). It is unclear what effect this would have on agriculture since re-cultivation of old fields is costly once forests or other woody species become established (Larsson and Nilsson, 2005). Landowners on Isabela did not mention the possibility of returning to life in Santo Tomás during visits in 2008 or 2009. However, it is possible that as Puerto Villamil becomes more developed and as tourism becomes a more prominent component of the local economy, cost of living increases will force landowners to rethink life along the coast.

4.6 Conclusions

This chapter identified patterns and potential drivers of agricultural land abandonment and related land cover transitions in southern Isabela Island between 2004 and 2010, during a period of social and environmental crisis in Galápagos. Patterns of agricultural land abandonment, guava invasion, and forest expansion at the farm and community level were assessed through pattern metric and overlay analyses of categorical LULC change maps of each transition. The results show that over 14% of agricultural land was abandoned in Santo Tomás between 2004 and 2010, indicating that the process of land abandonment that slowly began in the late 1980s has continued into the 2000s. Land was abandoned in patches corresponding to fields, particularly in the west-northwest portion of the community, and in smaller patches to the southeast. Most farms exhibited some level of net abandonment, losing on average 3 ha of agricultural land. This is an interesting finding as it points to the fact that agricultural abandonment is widespread throughout Santo Tomás. In most cases, abandoned agricultural lands transitioned from fields covered by herbaceous species (crops, pasture) to old fields dominated by guava (and to a lesser extent, forest cover).

Logistic regression models were developed to assess how agricultural land abandonment, guava invasion, and forest expansion in this period were related to the physical characteristics of southern Isabela Island (e.g., elevation, slope, distance to roads and Puerto Villamil). The results indicated that the biophysical and geographic variables included in the models did not significantly explain patterns of agricultural abandonment or guava invasion at the pixel level. Elevation was a significant component of the model of forest expansion but this factor alone was not a robust predictor of forestation. Previous research on agricultural land abandonment has demonstrated that in many places abandonment is primarily driven by social factors, such as rural-urban migration and changing economic opportunities, while environmental factors play only a secondary role in driving land abandonment (Rey Benayas et al., 2007). In this study, however, it is not clear how biophysical and geographic factors influence land abandonment and related LULC transitions due to issues with model specificity (i.e., small sample size and relatively large number of variables).

Finally, descriptive statistics of secondary data were generated to assess possible shifts in agricultural production due to abandonment, and to examine changes in the socio-economic and demographic characteristics of Santo Tomás and Puerto Villamil between 2000 and 2010 in order to generate hypotheses of the social determinants of LULC change. The results indicate that the abandonment of land devoted to agriculture was accompanied by declines in production that included a smaller number of livestock and fewer crops for sale. They also show that agricultural land abandonment in southern Isabela results from a combination of several socio-economic and demographic factors, including rural-urban migration due to the rise of economic opportunities in tourism and related services; declining profitability of agriculture owing to low demand for local produce and increased abundance of invasive species; and limited options for farm labor due to small households, rural depopulation, and immigration restrictions.

This chapter has several limitations. First, agricultural land abandonment and other LULC change processes were assessed over a relatively short period of time (6 years), using just two image dates for comparison. Given these restrictions, it is not possible to separate temporary land abandonment (i.e., long fallow) from permanent agricultural abandonment, or to discern longer-term patterns of cultivation, abandonment, and succession. Second, the temporal mismatch between the LULC change analysis (2004 to 2010) and the secondary social data (2000 to 2010) could have led to incorrect assumptions about the relationship between land abandonment and socio-economic and demographic factors.

The possible determinants of LULC change identified in this study should be more formally examined, possibly by linking patterns of land abandonment at the farm level to household level socio-economic and demographic characteristics. Future research on this topic should also expand the analysis to explore the impacts of conservation and agrarian policies on LULC. For example, the quarantine system established by the Galápagos Special Law to protect ecosystems in Galápagos from further species introductions prohibits some fresh foods and live animals from being imported. It is unclear whether this has an impact on farm productivity or land abandonment. A recently developed stylized agent-based model of livelihoods and land use in Galápagos demonstrates that farm subsidies may be successful in controlling guava in the highlands by maintaining agricultural livelihoods (Miller et al., 2010). The effects of exogenous factors on LULC change in the archipelago should also be considered, such as food prices set in external markets (i.e., mainland Ecuador) and El Niño / La Niña events.

This study contributes to a better understanding of the patterns and drivers of agricultural land abandonment and resultant land cover changes in southern Isabela and the Galápagos Islands, which is important for conservation planning and land management in the region. The results of this study indicate that agricultural land abandonment continues in Santo Tomás, resulting in reduced farm productivity and land parcels dominated by invasive species. The findings from this work also contribute to the debate on the patterns, causes, and consequences of agricultural land abandonment in Latin America. The results presented here seem to indicate that biophysical and geographic factors are not significant in explaining patterns of agricultural abandonment, plant invasion, or forest expansion in southern Isabela Island. This supports the theory that agricultural land abandonment and forest transitions are primarily determined by social processes.

LULC change in Galápagos has important implications for food sovereignty, conservation of protected areas, and community development. To deal with food shortages caused by declines in agricultural production, an increasing amount of fresh food is imported by planes and cargo ships from mainland Ecuador, risking further species introductions and raising the cost of basic food items (Borja, 2007; González et al., 2008; Gardener and Grenier, 2011). Food shortages in the archipelago are also a growing problem as food makes up a very small portion of the cargo arriving in Galápagos each week (Zapata and Martinetti, 2010). The problem is exacerbated when cargo ships break down or when they are prevented from entering the archipelago due to quarantine issues (Luna, 2008).

Agricultural activities in Galápagos occupy important ecosystems within the humid highlands, and productive farms act to maintain the hydrologic system and control the spread of invasive species (González et al., 2008). While this study focused on the patterns and determinants of LULC change in the communities, it should be noted that land use change within the human use zones affects land cover in the Galápagos National Park, and vice versa (see Chapter 3). For example, abandoned agricultural land is often quickly invaded by guava and other introduced species, facilitating the spread of exotic plants to neighboring farms and adjacent protected areas (González et al., 2008; Gardener et al., 2010). However, land cover changes within the National Park can feedback to alter LULC on nearby farms. According to landowners, when guava is not regularly cleared in areas of the National Park bordering Santo Tomás, birds and tortoises inadvertently spread its seeds into the agricultural zone. Although management of the Galápagos Islands has historically focused on regulating the protected areas of the archipelago, with little attention paid to local communities (Epler, 2007; Hennessy and McCleary, 2011), it is clear that simultaneous attention to and management of human use zones and protected areas is necessary.

4.7 APPENDIX I: Landowner Questionnaire

Questionnaire ID: [ ] [ ]

Investigator: Amy L. McCleary
University of North Carolina – Chapel Hill
Survey of Population and Land Use in Isabela Island, Galápagos, 2008

Household Questionnaire for Landowners

Day/Month/Year of Interview: . . . .

Start Time of Interview: . . . . Time Finished: . . . .

Observations during Interview: . . . .

. . . .

. . . .

. . . .

Identification of Household and the Farm/Land

1. Name of the head of household ____

2. Name of the spouse of the head of household ____

3. Name of the respondent, if not the head of household __________________________________

Household Composition

4. Indicate the names of all persons that normally live in this house, beginning with the head of household, and then for all others.

a.	b.	c.	d.	e.	f.	g.	h.
ID #	First and last name of household member	Sex M = 1 F = 2	Relationship to Head of Household (use codes)	Age (in years)	Where was this person born?	What education level has this person finished?? (use codes)	Marital status (use codes)
1.							
2.							
3.							
4.							
5.							
6.							
7.							
8.							
9.							
10.							

Relationship	Education Level	Marital Status
Head……….…..…1	None……….……..…1	Single……...……..…1
Spouse…………….2	Literacy Center…..….2	Married…..………....2
Child………………3	Primary………....……3	Cohabiting…….……3
Father / Mother…....4	Secondary…………...4	Separated…………...4
Step-parent…….….5	Baccalaureate……..….5	Divorced……….….…5
Sibling…………….6	Graduate…………….6	Widowed…….…….6
Other………………7	Postgraduate………...7	

Occupation

5. Indicate the primary and secondary occupations of all persons > 12 years old that normally live in this house. Indicate if these jobs are done all year long, or if they happen at particular times of the year.

a.	b.	c.	d.	e.	f.
ID #	First and last name of household member (copied from 4)	What is this person’s primary occupation?	What time of year does this activity take place?	What is this person’s secondary occupation?	What time of year does this activity take place?
1.					
2.					
3.					
4.					
5.					
6.					
7.					
8.					
9.					
10.					

Land Use

6. I'd like to talk to you about the land you own in the highlands. Do you live in a house on this land?
    a. Yes
    b. No

7. What is the name of the community where your house (dwelling unit) is located? __________ ____

   (If a household has multiple houses on the Island, this question refers to the one where they normally live or where they spend most of their time.)

8. If your house is not part of a community, what is the name of the nearest community to you?_ ____

A parcel is a single, continuous piece of land. The next set of questions will be about parcels this household uses (to grow crops, raise livestock, graze horses, etc.) in the highlands.

9. During the last year, how many total land parcels did your household use on Isabela Island (including the parcel where your house is located)? ____________________________

10. Where are these land parcels located on Isabela?
    (Use separate sketch map / satellite imagery to show location; multiple locations or parcels should be numbered on the map.)

11. Now I would like to ask you about each of the land parcels you own or use on Isabela, beginning with the one where your house is located (parcel 1). (Refer to sketch map with numbered parcels to make it clear which parcels are being discussed)

a.	b.	c.	d.	e.
Parcel #	How many Ha is this parcel?	Land tenure of this parcel? (use code)	How long have you owned or used this parcel?	What did you do with this parcel in the last year (June 2007 – present)?
1.				
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				

Land Tenure

Owned…………..….1	Rented to others.….3	For services…….….5
Rented……….……..2	Free……………….4	Other…………..…..6

11. *Continued*

	f.	g.
Parcel #	Who makes the decisions about how this parcel is used (e.g., what crops to plant, how to graze livestock, etc.)?	What will you do with this parcel in the next year (present – June 2009)
1.		
2.		
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

12. What do you consider to be the most important problems confronting your farm / land?

Introduced Plants

Note: These questions are meant to aid in open-ended discussions around the topic of introduced plants, rather than to serve as quantitative measures.

I am interested in how farmers here deal with different kinds of plants. I would like to show you some photographs of different plants and then ask you some questions to better understand them.
[Photographs: guava, blackberries, elephant grass, cedar, and lantana]

13. Are any of these plants present on the land parcels you have? If they are, did you try to grow these plants for a specific reason?

14. Do you ever try to control or remove any of these plants from your land? If so, what methods do you use to control the plants? How often do you use these methods to control the specific plants? Were these methods successful?

El Niño

Note: These questions are meant to aid in open-ended discussions around the topic of El Niño, rather than to serve as quantitative measures.

15. Have you heard of the term El Niño? If so, what is the weather in Isabela like during periods of El Niño?

16. The last strong El Niño happened in 1997-98. Were you in the Galápagos during this time? If so, do you remember this 1997-1998 El Niño? Can you think of other recent El Niño events?

17. What happens to crops or animals during El Niño events?

18. Are there changes in the amount of invasive plants [name some from earlier in the interview] on your land during or after an El Niño event? Are they less difficult or more difficult to control?

19. Does the El Niño make it difficult to manage your land or carry out normal household activities? Explain.

Tourism & Community Development

Note: These questions are meant to aid in open-ended discussions around the topic of tourism & community development, rather than to serve as quantitative measures.

20. How has Puerto Villamil changed in the last 10-15 years?

21. Do you ever work directly with tourists or provide services to them?

22. Have you noticed changes in the number or types of tourists on Isabela in the last five years?

23. Do you know of sites on Isabela Island that are being developed for tourists to visit? Are these sites outside of the Park that tourists could visit to see natural sites or animals such as tortoises? Where are these sites located?

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CHAPTER 5: Conclusions

5.1 Research Summary

This dissertation examined patterns and determinants of contemporary land use and land cover (LULC) change in the communities and adjacent protected areas of Isabela Island to gain a better understanding of human-environment interactions in the Galápagos Archipelago. Research topics specifically addressed in the chapters include (a) an evaluation of classification approaches for mapping LULC via high spatial resolution remotely sensed data, (b) an assessment of the recent patterns of LULC change in the human use zones and protected areas, and (c) an examination of the patterns and determinants of agricultural land abandonment, exotic plant invasion and forest expansion.

Two supervised classification approaches, SVM and OBIA, were evaluated in this dissertation for their ability to distinguish among and map several types of LULC from high spatial resolution satellite imagery (Chapter 2). Pixel-based (SVM) and object-based (OBIA) classifiers were applied to a WorldView-2 satellite image from the highlands of southern Isabela Island to map eight LULC types; the accuracy of each classification was evaluated with *in situ* LULC data. The results show that the OBIA classification approach yields an overall accuracy that is significantly better than the classification derived from the SVM approach. Individual class accuracies are also higher with the OBIA classifier, except for guava which has a higher producer's accuracy with the SVM approach. The two classifications also produce different estimates of LULC composition, particularly with respect to forest/shrub and guava cover types. The OBIA classification produces a higher estimate of forest/shrub cover than the SVM classification, due to OBIA's ability to better differentiate between shadowed forest areas and guava. The estimate of guava cover is higher in the SVM map, likely because guava is over-classified with SVM, and under-classified with OBIA.

These results are consistent with previous studies that found object-based classifications generally outperform pixel-based assessments of LULC using remotely sensed data (e.g., Wang et al., 2004; Conchedda et al., 2008; Cleve et al., 2008). This study has extended the comparison to a non-parametric pixel-based classifier (SVM) that has shown potential to accurately map LULC. Further, performance of the classifiers is evaluated with a classification scheme that includes a range of vegetation types and man-made features, rather than a single target. This study also provides one of the first applications of the newly launched WorldView-2 sensor for LULC research, demonstrating the potential of this new imagery and its additional spectral bands for vegetation discrimination.

Several issues related to each approach were identified. OBIA offers analysts greater control in selecting and adjusting classification parameters, such as which spectral or contextual information is included in the classification rules. With the inclusion of contextual information in the classification itself, it is easier to separate land use from land cover when two features that differ in function (e.g., roads and bare soil) are spectrally similar. However, SVM requires less front-end processing time, limited mainly to the selection of appropriate kernel and error parameters. If only a few images need to be classified and processing time needs to be minimized, the SVM approach may be more appropriate.

This dissertation also quantified contemporary LULC change in southern Isabela Island using a time series of QuickBird and WorldView-2 satellite images from 2003/2004, 2008, and 2010 to understand (1) how the composition and spatial configuration of LULC changes; and (2) how LULC patterns differ between the communities and protected areas (Chapter 3). The images, covering two ISAs, were classified into twelve LULC categories using an OBIA classifier. Landscape composition was quantified from the classified maps, and landscape configuration was described from pattern metric analysis. Change between image dates was assessed using a post-classification change detection approach, and quantified USING from-to change matrices.

The results indicate that substantial changes in the pattern of LULC occur in southern Isabela Island in a relatively short period of time. Four main land cover transformations are observed: (1) built-up expansion (urbanization) within the coastal community of Puerto Villamil, that includes a period of diffuse growth (2004-2008), followed by the coalescence of built-up areas (2008-2010); (2) agricultural contraction in the highland community of Santo Tomás, accompanied by fragmentation of agricultural land use; (3) the spread of invasive plants; and (4) the expansion of forest and shrub cover in the highlands.

As expected, land use change is more extensive in the two communities, particularly with the increase of built-up areas in the Coastal ISA and declines in agriculture in the Highlands ISA. The protected areas are subject to indirect land cover modifications resulting from land use changes in the adjacent communities, such as the shrinking of lagoons due to increased water extraction in Puerto Villamil, and the spread of invasive plants from abandoned farms in Santo Tomás. A number of direct changes to land cover are also observed in the coastal protected area, including the conversion of park land to more developed uses (e.g., roads, wastewater treatment facilities, etc.), to support the growing community of Puerto Villamil. The destruction and degradation of habitat for endemic and native species (e.g., cutting of mangrove forests; replacement of native flora by introduced plant species), and alterations to the flow of materials (e.g., coastal lagoons cut off from regular ocean flows by development) in and around the protected areas of southern Isabela has implications for biodiversity and ecosystem functions that the National Park was established to protect, and which people rely for their livelihoods and general well-being.

The remote sensing and landscape configuration analyses presented in this study can be used as a tool for monitoring LULC change in the Galápagos Islands, or elsewhere in the tropics. High spatial resolution data, such as QuickBird and WorldView-2, make it possible to capture changes over small spatial extents that are important to land managers and decision-makers. Satellite imagery in conjunction with a knowledge-based OBIA classifier provides timely and accurate LULC data for areas with sparse information and where field based data collection on a large scale is prohibitive. Pattern metric analyses allow studies to move beyond changes in landscape composition to also consider changes in configuration of land cover types.

Finally, this dissertation identifies patterns and potential drivers of agricultural land abandonment and related land cover transitions in southern Isabela Island between 2004 and 2010, during a period of “social and environmental crisis” in the Galápagos Islands (Chapter 4). Patterns of agricultural land abandonment, guava invasion, and forest expansion at the farm and community level were assessed through pattern metrics and overlay analyses of categorical LULC change maps of each transition. The results indicate that the process of land abandonment that began slowly in the late 1980s has continued into the 2000s, and that agricultural abandonment is widespread throughout Santo Tomás. In most cases, abandoned lands are invaded by guava, and to a lesser extent are colonized by forests.

Logistic regression models were developed to assess how agricultural land abandonment, guava invasion, and forest expansion in this period are related to the physical characteristics of southern Isabela Island. The results indicate that the biophysical and geographic variables included in the models are not important in explaining patterns of agricultural abandonment or guava invasion at the pixel level. Elevation is a significant component of the model of forest expansion but this factor alone is not a robust predictor of forestation. This is an important finding as policies and projects aimed at improving the physical conditions of agricultural production are unlikely to halt or reverse land abandonment in the region.

Finally, descriptive statistics of secondary data were generated to assess possible shifts in agricultural production due to abandonment, and to examine changes in the socio-economic and demographic characteristics of Santo Tomás and Puerto Villamil between 2000 and 2010 to generate hypotheses of the social determinants of LULC change. The results indicate that the abandonment of land devoted to agriculture is accompanied by declines in production that include a smaller number of livestock and fewer crops for sale. They also show that agricultural land abandonment in southern Isabela results from a combination of several socio-economic and demographic factors, including rural-urban migration due to the rise of economic opportunities in tourism and related services; declining profitability of agriculture owing to low demand for local produce and increased abundance of invasive species; and limited options for farm labor due to small households, rural depopulation, and immigration restrictions

This study contributes to a better understanding of the patterns and drivers of agricultural land abandonment and resultant land cover changes in southern Isabela and the Galápagos Islands, which is important for conservation planning and land management in the region. For example, agricultural activities in Galápagos occupy important ecosystems within the humid highlands, and productive farms act to control the spread of invasive species and to maintain the hydrologic system (González et al., 2008). Abandoned lands become invaded fairly quickly, facilitating the spread of exotic plants to neighboring farms and protected areas (González et al., 2008; Gardener et al., 2010). To deal with food shortages caused by declines in agricultural production, an increasing amount of fresh food is imported by plane and cargo ship from mainland Ecuador, risking further species introductions and raising the cost of basic food items (Borja, 2007; González et al., 2008; Gardener and Grenier, 2011). Understanding when and where agricultural abandonment and related land cover change occurs can facilitate projects that are better designed to deal with such issues.

5.2 Challenges

Several factors were encountered that presented challenges for this research, particularly with respect to data and methods. First, a lack of archived satellite imagery or historic aerial photographs limited the time series available for analysis and constrained the LULC change analysis to a contemporary period. Further, cloud cover is nearly constant in parts of the highlands of Isabela, and the coastal area is sometimes obscured by clouds depending on the season, making it difficult to obtain remotely sensed data for some parts of the islands and during particular times of the year. As a result, agricultural land abandonment and other LULC change processes are assessed over a relatively short period of time (6 years), using just two image dates for comparison. Given these restrictions, it is not possible to separate short-term processes, like temporary land abandonment (i.e., long fallow), from long-term processes, such as permanent agricultural abandonment; it also limits the possibility of discerning landscape dynamics, such as patterns of urban expansion and coalescence, or patterns of cultivation, abandonment, and succession.

Other limitations of this research are related to temporal mismatches between the satellite image time series, social surveys and census data, and *in situ* data. For example, a time lag between satellite image acquisition (2003/2004, 2008, and 2010) and field data collection (2008, 2009) may impact the accuracies of the LULC maps. Temporal mismatches between the LULC change data (2003/2004 to 2010) and the secondary social data (2000 to 2010) could impact the relationship between LULC change processes and socio-economic and demographic factors that are hypothesized here. Unfortunately, temporal and spatial constraints on data availability, and the spatio-temporal mismatches that often result from combining image time series data acquired at a particular temporal and spatial scale with survey or census data collected at other scales, are not uncommon problems in the study of land use change (Rindfuss et al., 2004).

The accuracy of the LULC classifications was also impacted by factors beyond the temporal mismatch of data collection. The overall accuracies of the LULC classifications are generally acceptable, but some classes (i.e., agriculture/grassland, forest/shrub, and guava) have accuracies that fall below the standard 85% threshold, likely due to the classification of mixed objects and a small training data set. A lack of reference data hampered efforts to determine the accuracy of some maps in the time series and to quantify error propagation though the change analyses. Data collection was complicated by the fact that some sites within the Galápagos National Park were not accessible due to difficult terrain, while access to some properties within the communities was restricted.

5.3 Contributions

The research presented in this dissertation contributes to a better understanding of contemporary LULC change in Isabela Island, provides insights into human-environment interactions in the Galápagos Islands, and adds to discussions within the land change science community about the nature of LULC change in and around protected areas, and about the patterns, causes, and consequences of agricultural land abandonment. Data on LULC and LULC change in the Galápagos Islands, including Isabela, are limited (González et al., 2008), and the information that does exist is often incomplete and outdated. For example, the first archipelago-wide maps of land use produced in 1987 as part of an effort to inventory features of the natural environment (PRONAREG et al., 1987) did not include land use maps for Isabela Island. This has hampered previous efforts to assess changes in land use and vegetation cover within local communities (Villa and Segarra, 2010), and to quantify areas transformed by human activities (Watson et al., 2009). The remote sensing and GIS methods employed here, in combination with the LULC maps and LULC change information generated by this research, has several applications in the Galápagos Islands. For example, current LULC maps can be used for regional planning and natural resource management in local communities (Villa and Segarra, 2010). Invasive species distribution information provided by detailed LULC maps can also be used to develop a plant invasion risk assessment system (Tye et al., 2002) and to design control and eradication programs (Gardener et al., 2010).

This research contributes to the understanding of human-environment interactions in the Galápagos Islands using an approach that is informed by interdisciplinary theories on land use change which integrates social and environmental data using quantitative and qualitative methods. The majority of research in Galápagos has focused on describing the biological and physical aspects of the archipelago (Santander et al., 2009). Less work, however, has been done to understand the human dimension and its connection to the environment. This research also demonstrates that important feedbacks exist between land use in the communities and land cover in the National Park. Management of the Galápagos Islands has historically focused on regulating the protected areas of the archipelago, with little attention paid to local communities (Epler, 2007; Hennessy and McCleary, 2011). Going forward, the Galápagos National Park Service and local stakeholders (e.g., municipalities, private landowners, conservation organizations, etc.) should work together to develop conservation and development strategies that consider the Galápagos Islands as a coupled human-natural system (González et al., 2008), and that balance the desire for continued conservation of the archipelago with development that supports local livelihoods.

More generally, this research contributes to the ongoing discussions of LULC change in and around protected areas. Previous work on the topic was expanded to a site that includes a large protected area that surrounds small-footprint communities; large parks are generally considered less susceptible to change because they can slow LULC modification occurring along their borders (Maiorano et al., 2008). Despite fairly strict rules about land use within and outside of the National Park, and increased support for conservation of the archipelago following UNESCO's "In Danger" listing, direct and indirect changes in land cover occur within the protected area. This research considers those portions of the protected area immediately surrounding the communities, but discussions with park rangers confirm that some of the observed LULC transitions (e.g., the presence of invasive plants) extend farther into the National Park.

The findings from this dissertation also contribute to the debate on the patterns, causes, and consequences of agricultural land abandonment in Latin America. The results presented here indicate that biophysical and geographic factors are not important in explaining patterns of agricultural abandonment, plant invasion, or forest expansion in southern Isabela Island. This supports the theory that agricultural land abandonment and forest transitions are primarily determined by social processes, such as urban-rural migration and increased participation in off-farm employment.

5.4 Future Research

Differentiating agriculture and grasslands (pasture), and separating shrubs from forest cover is challenging, because these LULC types have similar spectral signatures. Therefore, mixed classes of agriculture/grassland and forest/shrub are included in the LULC assessments. Although they have similar spectral characteristics, they indicate different land uses. Future research will target the separation of these classes, possibly with the use of additional field data or hyperspectral image analysis to improve spectral separability between the classes.

The results of the LULC analysis indicate that some of the errors in the OBIA classifications result from the assignment of mixed objects, those containing pixels from more than one LULC type, to a single class. The OBIA classification algorithm works by evaluating the membership value of each image object against the list of classes (i.e., fuzzy classification), and the class with the highest membership value (ranging from 0 to 1) is assigned to the object (i.e., discrete classification). Future research will consider exploring the fuzzy classifications that are produced in the object-based analysis, as they could offer a potential solution to mixed objects, and may provide additional information about the landscape that is not captured in discrete LULC maps.

Additionally, in some cases the LULC maps produced with the SVM approach had higher individual class accuracies than the OBIA maps (e.g., guava cover). Future research should consider integrating the two classifiers by applying SVM at the object-level. Tzotsos and Argialas (2008) found that an integrated SVM-OBIA approach for multi-class classification produced classifications with higher accuracies than nearest neighbor object-based classifiers. This approach may produce classifications that are accurate and more quickly implemented than those produced from knowledge-based OBIA alone.

Further, the analyses presented in this dissertation should be expanded to other inhabited islands in Galápagos to compare and contrast the patterns and determinants of LULC in the communities and protected areas throughout the archipelago. On Santa Cruz and San Cristóbal Islands, for example, development of coastal towns has been more substantial, while most of the farms on Floreana Island remain productive (Villa and Segarra, 2010). Additionally, the possible determinants of LULC change identified in this study should be formally examined, possibly by linking patterns of land change at the farm level to household level socio-economic and demographic characteristics.

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