THESIS

LAND TENURE SECURITY AND LAND-COVER CHANGE: A CASE STUDY FROM PROTECTED AREA BUFFER ZONE COMMUNITIES IN MADAGASCAR

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ABSTRACT

LAND TENURE SECURITY AND LAND-COVER CHANGE: A CASE STUDY FROM PROTECTED AREA BUFFER ZONE COMMUNITIES IN MADAGASCAR

Tenure and property rights define the relationship that people have with land and natural resources. Customary tenure systems are predominant in Madagascar, where locally administered rule systems have the flexibility to adapt to changing conditions, inherent conflict resolution mechanisms, and often, community buy-in. However, laws and regulations at different governmental levels throughout the country's history have often caused tenure systems to overlap in rural areas, which, in turn, often causes conflict and tenure insecurity. One important alteration to existing land and natural resource tenure systems is the creation of protected areas, which are commonly created to preserve the endemic biodiversity of the country. Many investigations have attempted to link land tenure to land-cover change using earth observing satellite imagery, but the study reported here is the first of the kind for Madagascar. This study addresses the following questions: if and how a land tenure system and its relative security influence land-cover change within a community and if and how land tenure outside of a protected area influences change within. Land cover classifications created from the Landsat TM and ETM+ images achieved high accuracies despite low image availability due to the period during which the study took place and the significant cloud cover found over the study sites. Findings of the study show that protected areas are relatively unaffected by surrounding land-use and land tenure security in the villages near the protected areas, and that the protected areas are effective at conserving the forests within their boundaries. Within each community, however, conflict and tenure insecurity are associated with elevated conversion of forest areas to other land-covers, regardless of tenure. These results

highlight the need to prioritize land tenure security to both ensure local communities access to land and natural resources and meet widespread goals related to conserving biodiversity held by the international conservation community through the support of customary tenure systems and the promotion of socially responsible agricultural transitions.

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INTRODUCTION:

Land Tenure

Humans profoundly influence the landscapes they inhabit, often resulting in significant effects on the livelihoods of local communities and the functionality of natural ecosystems. Generally, land tenure is referred to as the right to access, use, alter, and possess land, which is influenced by rules or systems implemented at various levels from local communities to the national government. The Food and Agriculture Organization defines land tenure as “the relationship, whether legally or customarily defined, among people, as individuals or groups, with respect to land” and its associated natural resources (FAO 2002). Globally, land tenure systems have highly diverse forms and function, making it difficult to implement uniform land tenure policies in many circumstances. Understanding the different forms of land tenure systems is essential to forming effective land management strategies at all levels of society.

Property rights are an important aspect of land tenure systems, and these rights also contain considerable variation depending on regional and local conditions. The group that holds primary rights to land or its governance often determines the type of land tenure. Private land rights are possessed by a single entity or individual, whereas communal rights can be held by a group of people (or even a village). State or government ownership of land often, in the case of protected areas, restricts the rights of people to land and resources, but, if government ownership is not respected, this may also lead to an open-access scenario with few restrictions on land or resources. For example, when state rule systems overlap with local or regional ones, both systems can be delegitimized, and communities may not adhere to restrictions on land use (Leisz et al 1995, Robinson et al 2018). High-income countries have predominantly implemented top-down, private land tenure systems with some holdings by the state, but these systems are far less prevalent or effective in lower-incomed countries.

Different types of land tenure are sometimes denoted by the entity that administers a rule system. Customary land tenure systems generally include long-established governance systems administered by the community that have inherent conflict resolution mechanisms and are flexible and can change according to local needs (Larson et. al 2010, Leisz et. al 1995). Often, and as is the case in this study, these systems are comprised of communal rights to pastures but exclusive private rights to agricultural parcels (FAO 2002). These types of land tenure systems may or may not be recognized by state institutions (Larson et al 2010), and they are increasingly threatened by changing land management policy and global market pressures (Chimhowu 2019, Unruh 2008). Although there is considerable variation and complexity, rural landscapes in many low-income countries are dominated by agricultural smallholdings (Rudel and Hernandez 2017), and in Africa, these landscapes are dominated by *customary tenure* (Chimhowu 2006). Establishing an understanding of the way customary land tenure systems affect land-use and land-cover change is a complex, but necessary step in effective land management.

Land tenure security can be thought of as the confidence that tenants hold in their sustained access to or use of land. A theory promoted in agricultural and economic development is that when tenants feel confident in their access to land, they are more likely to invest in agriculture on that land and intensify production, allowing users to increase their income without seeking additional land to clear (Aregay Gebreeyosus et al 2020). This leads to the view that to avoid further degradation of natural resources, land management strategies should aim to reinforce land tenure security in rural communities.

Customary tenure systems can and have provided communities with significant feelings of security in land access because local stakeholders are usually involved in their governance and longevity (Bruce and Migot-Adholla 1994; Leisz et al 1995). It is important for contemporary land policy to reinforce this security. Historically, there have been efforts to achieve this by issuing titles to landholders, sometimes also called land registration. Land titling has been touted to increase farmers' access to credit and thus stimulate investment in the land and increase agricultural productivity (Feder and Onchan 1986, Atwood 1990, Feder and Feeny 1991, Feder and Nishio 1998). However, efforts to title or register land often see mixed success in reaching rural communities and increasing land tenure security (Chimhowu 2006, Singirankabo and Ertsen 2020).

Customary land tenure can also conflict with state-implemented land tenure systems in low and middle-income countries (Brottem and Unruh 2009, Leisz et. al 1995). Land tenure interventions are often undertaken by national governments and development agencies, but if these actions do not allow space for the functioning of existing systems, they can lead to conflict. The implementation of national land tenure systems in many African nations, for example, often results in a "pervasive disconnect between customary and statutory land rights" (Unruh 2008). Examples of situations that can give rise to this conflict include the creation of nature reserves or the nationalization of forests (Naughton-Treves et al 2005, Ralk 2007, Thapa and Weber 1990). However, conflict between state and customary land tenure systems is not pre-ordained. State land tenure laws in some cases can support local land tenure systems (Budiman et al 2020, Leisz et al 1995). For example, in Colombia, the government-sponsored collective titling program increased the tenure security of communities with historical claims to land while allowing the rules of customary systems to remain in place (Velez 2011). Community or collective titling programs in several African countries have also lent legitimacy to customary tenure systems (Chimhowu 2019). The interaction between land tenure systems at different levels of government may also influence land-cover change, and, as a result alter the impact of land management strategies.

Clarifying land tenure and its relationship to land-cover change is an important step to ensure the effective implementation of conservation strategies. Global conservation or development strategies are often impacted by land tenure security in low-income countries. Because of the ability of tropical forests to sequester large amounts of carbon, their conservation or restoration is seen as an important tool in the effort to slow greenhouse gas emissions. The conversion of forests to agriculture or pasture is still a major threat worldwide (Kirschbaum et al 2013). Global carbon management schemes such as Reducing Emissions from Deforestation and Degradation (REDD+) or other payment for ecosystem service (PES) schemes also rely on the accurate identification of local stakeholders and the understanding of local land use policy (Naughton-Treves and Wendland 2013).

Protected Areas

A common type of land tenure intervention that has the potential to alter existing customary systems and influence land-cover change is the creation of protected areas. Over the last fifty years, the creation of nature reserves has been one of the primary tools used to meet the conservation goals of the international development community and support the economic development of local communities. In the late 1960s and early 70s, the United Nations Education, Scientific and Cultural Organization (UNESCO) created the Man and Biosphere program (MAB), which has the goal of integrating scientific research, conservation goals, and community economic development (Dyer and Holland 1988). The main tool in achieving the program's goals was the implementation of biosphere reserves, which protect a central core zone of natural resources surrounded by a designated buffer zone where restricted resource use can take place (UNESCO 2009). The goal of a buffer zone is to allow for some resource use by communities, while still promoting adequate habitat for wildlife and buffering the core area from human impact (UNESCO 2009). Around the world, the adoption of protected areas increased dramatically from 1970-2000 (Naughton-Treves et al 2005). Since the concept of buffer zones was first described, their implementation to support the conservation of a protected area has become quite popular. Although few protected areas are officially MAB reserves, many protected areas created since this time have been similarly structured and governed (Neumann 1997, Wells and Brandon, 1993).

In the context of land tenure, the creation of a protected area can be thought of as the implementation of a restrictive state land tenure system. Although many of these spaces are created in areas of low human population density, the newly imposed state land tenure rules often disrupt the existing customary land tenure system. Those already inhabiting the core areas are usually displaced and their access to land and natural resources that they previously used is impeded (Krueger 2009). This conflict can lead to negative views of a protected area in the local community (Holmes 2014, Macura et al 2011) and compromise the long-term success of reserves (Wells and Brandon 1993). It is also common for local entities to be unaware of the goals or rules of protected areas due to poor outreach to communities (Dimitrakopolous et al 2010, Macura et al 2011). All these factors increase the likelihood of conflict between communities near protected areas and the state management structure.

While protected areas are often effective at conserving natural resources within the core protected area (Nagendra 2008, Naughton-Treves et al 2005), land-cover in the buffer zones often undergoes change. To understand the true impact that protected areas and the associated state land tenure system have, it is important to also monitor the buffer zone areas in addition to the park interior for land-cover change (Naughton-Treves et al 2005). To do this, researchers must have an accurate way to measure changes in land-cover and land use in regions of the world that are often difficult or costly to survey.

Remote sensing and land-cover change

The availability of high and moderate resolution satellite imagery has allowed for the interpretation of land-cover and land-cover change without extensive, and sometimes cost-prohibitive, field sampling. A wide array of sensors collect imagery at various spatial, spectral, and temporal resolutions, allowing for unprecedented examinations of land-cover change. One prominent earth observation system is the Landsat satellite program. Starting with Landsat 4 in 1982 and continuing through today with Landsat 9, the Thematic Mapper (TM), Enhanced Thematic Mapper+ (ETM+), and Operational Land Imager (OLI) sensors have collected multispectral imagery with global coverage at moderate resolution (30 meters for most bands) which is free to the public and researchers (Houska 2012, Woodcock et al 2008). Other prominent sensors often used for land-cover monitoring offer different resolutions than Landsat. Starting in 1979, the Advanced Very High Resolution Radiometer (AVHRR) provides multispectral imagery at 1.1km resolution for local area coverage (Malingreau et al 1989), while the newer Sentinel-2 (beginning in 2015) mission provides similar wavelengths to the three Landsat sensors mentioned above sensors but at 10-meter resolution (Gascon et al 2014).

The use of classification algorithms and satellite imagery has allowed for the categorization of land-cover across large geographic areas without exhaustive field surveys. To achieve this, training datasets must be created to inform classification algorithms to predict land-cover types. These training datasets are often points or polygons containing the known identity of land-cover at each location from which the relevant spectral or ancillary data values are also extracted. The classification algorithm then uses this information to classify land-cover across a larger region of interest.

While no classification techniques can perfectly categorize land-cover, bias can be reduced by prudent management of training and validation datasets. Spatial autocorrelation is the likelihood that nearby features will be more like each other than ones further away (Dormann et al 2007). If the classification algorithm uses proximity as a determining factor for prediction, such as with object-based image analysis, this can cause the algorithm to 'memorize' the training data and can, as a result, lead to artificially high classification accuracy. One way to minimize this risk is to select training samples randomly across the intended classification extent. Following this protocol, samples from each land-cover class will be randomly distributed across the landscape, limiting the classifier's spatial bias and ensuring that the algorithm has a representative distribution of the spectral information on the landscape (Lillesand et al 2015).

However, the creation of training data and validation of the results of this process often still rely on limited field sampling within a landscape to ensure the accurate identification of land-cover classes.

In place of such sampling, some studies rely on imagery of a higher resolution than the images with which they are categorizing land-cover (Knorn et al 2009, Yuan et al 2009). For example, a land-cover classification on a 30-meter dataset could reasonably rely on training datasets derived from imagery of 1-meter resolution for the accurate portrayal of a landscape. Sensors with 5-meter resolution or finer did not become widely available until the year 2000 or later, and newer web-based platforms that display imagery, such as Google Earth, offer a spatially referenced interface with which to survey and manipulate this imagery for remote sensing applications (Gong et al 2013, Yu and Gong 2012, Li et al 2020) and provide a resource from which training data for moderate resolution imagery can be obtained. Image processing techniques have also advanced to handle the wealth of data from different sensors. Modern satellite imagery and highly effective classification algorithms yield LULCC analyses suitable for a wide range of applications in monitoring and management.

Over the last fifteen years, the use of machine learning classifiers has been shown to produce highly accurate land-cover maps (Sheykhmousa et al 2020). The advantage of these methods is that they can digest large volumes of multi-spectral imagery from numerous dates to classify complex landscapes. For land-use / land-cover change (LULCC) analyses, some of the most common algorithms include random forest, support vector machine, and artificial neural networks (Sheykhmousa et al 2020, Talukdar et al 2020). Random forest is an ensemble machine learning tool commonly used in land-cover classification. The technique makes use of multiple decision trees and bagging to make predictions based on a training dataset (Gislason et al 2006), and it has been shown to produce highly accurate land-cover predictions in highly heterogeneous tropical terrain (Grinand et al 2013, Doyle et al 2021).

Madagascar, biodiversity, and climate

Almost seventy-eight percent (78%) of Madagascar's population lives under the international poverty line of $1.90 per day (World Bank, 2020), and a large majority of Malagasy are employed or reliant on agriculture for subsistence and additional income. Madagascar has also been identified as an area of global biodiversity importance and has been a focus of international conservation and development efforts (Myers et al 2000). Most of this diversity exists in Madagascar's forests (Dufils 2003), which are under immense pressure from the growing and largely impoverished rural population.

The predominant agricultural activities of Madagascar include rice cultivation and raising livestock, followed by the cultivation of cash crops and secondary food crops (INSTAT n.d.). Rural Malagasy have often been highly vulnerable to hunger and loss of income due to their reliance on agriculture (Harvey 2014), so many farmers rely on forest resources for supplemental food, fuel, and income (Sarrasin 2013).

In Madagascar, swidden agriculture, also referred to as shifting cultivation, is a form of subsistence cultivation where a parcel of woodland is cut, cleared with fire, cultivated for a few years, and left to fallow for several more. The practice is called *tavy* in the Malagasy language, and, where practiced with low population densities and sufficient fallow periods, it can be employed sustainably. However, this is not typically the case because of the pressure of population growth and immigration on rural communities (Styger et al 2007, Lawrence et al 2010). When fallows are too short, the vegetation that regrows does not mature to forest and the soil degrades overtime. Over many of these protracted fallow cycles, forest can be replaced by secondary grassland (Brand and Pfund 1998) after which point, it can then take decades for tree cover to reestablish. The Malagasy practice of tavy has historically been seen by many rural Malagasy as a way to be spiritually connected to their ancestors (Styger et al 2007). When a community has the appropriate land and resources, paddy cultivation is often carried out in place of tavy, but the practice of tavy still often persists to an extent because of its cultural importance (Styger et al 2007, Ralk 2007).

Land tenure in Madagascar

Historically, customary land tenure systems dominated much of rural Madagascar, and there was a wide range in the degree to which these systems have overlapped with state land tenure systems (Leisz et al 1995). Property rights in Madagascar's customary land tenure systems resembles the typical pattern seen in other parts of the world where pastures are held and accessed communally, and agricultural parcels are held by individuals or families, who may gain these rights either for the period of time that they cultivate the land or according to who first cleared the field historically (Leisz et al 1995, FAO 2002). Land titling systems are implemented at various levels of government in Madagascar, but only a small portion of landholders seek a title. Locals' confidence in customary land tenure systems makes it so they do not see the need, and the cost of obtaining a title is often prohibitive (Jacoby and Minten 2007). More commonly, land rights are recorded in local offices on informal documents called "petits papiers" (Burnod et al 2012). Customary land tenure systems often have rules regulating the practice of swidden, including how long to rest fallow land, what land can be cleared, and who has access to that land (Ralk 2007).

Over the last century, the government's top-down land management strategies have often degraded local land tenure security. Customary land tenure systems in the country have been shown to afford tenants high levels of land tenure security (Leisz et al 1995, Ranjatson et al 2019), so disruptions to these systems may drive insecurity and corresponding land-cover change. If people do not feel confident in their sustained access to land, they may not see a benefit in using it sustainably and may seek to clear new lands. For example, the French colonial government created insecurity for customary land tenure systems by outlawing the burning of forests in 1930, allowing widespread logging by international companies across the country (Kull 2000), and appropriating lowlands for intensive rice cultivation (Styger et al 2007). Despite colonial interdiction, swidden continued to take place, and even increased in practice, due to rural resentment (Jarosz 1996), and much of this new swidden was driven to less suitable forested uplands. State or regional land tenure systems can also make land tenure security to swidden plots less secure. For example, *mise en valeur* rules that give land rights to tenants for putting land to use on an annual or permanent basis degrade the rights of swiddeners to their fallowed plots by allowing others access to those lands. This creates a situation where customary rights to fallow land are no longer respected, resulting in a continued degradation of the soil and vegetation of the plots. These types of policies and practices act as a positive feedback loop driving further forest loss. In Madagascar, modern government actions that have potentially degraded the security provided by customary land tenure systems include the nationalization of forest resources, land titling efforts, and efforts to repossess untitled lands (Leisz et al 1995, Ralk 2007). It is only in the last few decades that Madagascar has shifted towards enabling community-based forest management (Healy and Ratsimbarison 1998).

Protected areas in the country are numerous and varied in form in terms of restrictiveness of use within the gazetted boundaries. The goal of achieving conservation in the protected area through the economic uplifting of communities surrounding the core zone is a direct reflection of the influence of the Man and Biosphere Program on Madagascar's protected areas network (Leisz et al 1995). As a result, through Madagascar' national Environmental Action Plan, protected areas are similar in structure to the original core/buffer zone concept of the biosphere reserves where use is prohibited in the core zone while limited or restricted in the buffer zone (Neumann 1997, Shyamsundar 1996, Leisz et al 1995).

Madagascar’s protected areas network zoning allows for what is called a “protection zone” outside of the core and buffer zones where agricultural and pastoral activities are permitted if they do not harm the park or reserve (Comission SAPM, 2009). The zoning structure of Madagascar’s protected areas as defined by the can be seen in Figure 1. Another form of protected area common in the country are “Special Reserves”, which differ from national parks because sustainable use and harvest of natural resources by local communities is allowed throughout the gazetted boundaries of the reserve (Waeber et al 2018).

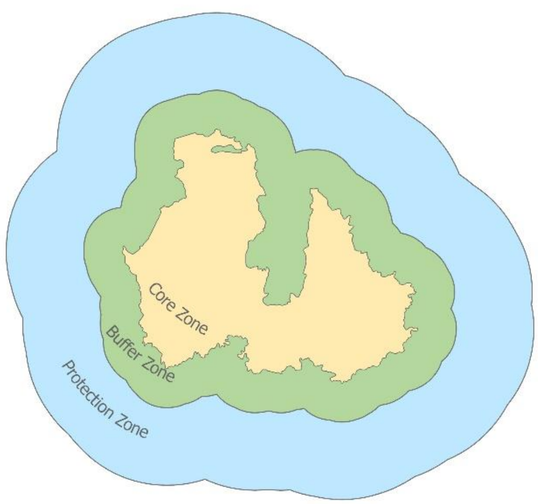

Figure 1: Conceptual zoning of protected areas in Madagascar (SAPM 2009)

Many protected areas in Madagascar have been shown to be effective at reducing deforestation (Eklund et al 2019), but natural resource dynamics in the buffer zone and protected zone of these spaces are not as well understood. To assess the efficacy of the Man and Biosphere paradigm and to understand the relationship between peripheral communities and the integral protected areas, an effective way to measure land-use and land-cover change is necessary.

Madagascar LULCC monitoring

There has been significant attention given to mapping forest cover in Madagascar due to the focus of conservation organizations on Madagascar's rare and endangered biodiversity. While forest resources in the country have been catalogued by several larger global efforts (Hansen and Defries 2004, Kim et al 2014), these global classifications often fail to accurately classify the unique dry and spiny forests in the west and southwest portion of the country that have significant phenological and structural differences when compared to humid forests (Harper et al 2007). To cope with this, some studies split forest resources on in Madagascar into different forest types and classify them separately (Nelson and Horning 1990, Harper et al 2007, Mayaux et al 2000). While forest cover maps derived from coarse-resolution imagery such as AVHRR (Nelson and Horning 1990) give a good picture of forest change on the whole island, they don't capture more local phenomena. For this reason, moderate- or even fine-resolution imagery have been used (Harper et al 2007, Mayaux et al 2010) to map forest cover across both local and national scales. Several of these studies also incorporate methods to detect change in land-cover (Grinand 2013, Zaehringer et al 2015, Vieilledent et al 2018). LULCC studies often focus on forest loss because of its importance to biodiversity, but an examination of all land-cover change offers a more complete examination of human interactions with land.

Linking land tenure and land-cover change

There have been numerous efforts to integrate land tenure data with remote sensing techniques to better understand how land rights and regulations influence land-cover change. One meta-analysis (Robinson et al 2014) attempts to establish global or regional patterns associated with the forest loss - land tenure relationship. However, with the potential for every country to have different de jure and de facto land tenure laws, it is important to examine land tenure and land-cover change in each region of interest.

Possibly because of the conservation concerns in Madagascar, several studies have tried to investigate the link between land-cover change and its potential drivers in the country. Scales (2011) demonstrated that colonial policies were an important factor driving land-cover change in the country from 1896 to 2005 using historical colonial data and satellite imagery. Another study identified proximity to human settlement and topography as important determinants of land-cover change but also suggests that different land management regimes create unique land-cover change trajectories that need further investigation (McConnell et al 2004). However, to date few studies globally, and none in Madagascar, have been identified that incorporate fieldwork investigating the level of tenure security afforded by local land tenure systems and corresponding land-cover change analysis to explore the links between land tenure systems, land tenure security, and land-cover change. Furthermore, the relationship between the land tenure systems operating in state protected areas and in local communities is not well described, and not easily generalized. Therefore, it is important to continue to assess the effectiveness of protected areas in the country and clarify the relationship of adjacent communities with the park or reserve that they border. This paper makes use of knowledge gained from fieldwork investigating land tenure systems near national parks in Madagascar, ground truth data verifying land-cover types, aerial photographs of study areas, and land-cover change data derived from satellite imagery to investigate the following research questions:

1. How does a community's land tenure system and its relative land tenure security influence land-cover change within the community's territory?
2. How does the land tenure security in a community in the buffer zone of a national park impact land-cover change in parts of a national park adjacent to that community?

MATERIALS AND METHODS

1993-94 Land Tenure Center survey overview

Between May of 1993 and May of 1994, a team of multi-national researchers in coordination with the Land Tenure Center at the University of Wisconsin-Madison carried out research in seven fokontany [1], each located in the periphery of a national park in Madagascar using rapid rural appraisal techniques (Carruthers and Chambers 1981) and surveys. Specific data gathering methods included semi-structured interviews, focus group interviews, randomized household surveys (50% of the male head of household, 50% of the female head of household), transect walks, and participatory mapping (Leisz et al. 1995). This team collected data identifying the local livelihood systems, dominant agricultural practices, effective local land and natural resource tenure system(s), physical boundaries of each site, and major land-cover types. Their results inform the different categories of land tenure systems used in this analysis, the level of land tenure security found in each fokontany, and the resulting comparison of the effect of the land tenure system and land tenure security on land-cover change. Overlap between state and customary tenure systems was present in each of the fokontany, but the most respected rule system varied between sites. As a result of the Land Tenure Center's work, each site was determined to have one of the following land tenure systems:

1. *Customary*: a system where local governance is strongest. Land tenure considered secure by the community.
2. *State*: a system where a regional or federal government system dominates. Land tenure considered secure by the community.

[1] The lowest official level of government administration in Madagascar, approximately equivalent to a county in the United States.

3. *Overlapping and conflicting land-tenure systems*: a situation where both customary and state land tenure exists, they are not complementary, and the land security of the local system is subverted. Land tenure is considered insecure by the community.

It should be noted that a pure “State tenure system” is only found within the national park boundaries, where few people live. The land-tenure systems at each fokontany contained rules that regulated the rights of access and use to the following resources at each fokontany: forests, land, water, and trees.

The survey also categorized common agricultural practices in each of the fokontany. Raising cattle and cultivating rice were the dominant practices, but there was significant variation in rice cultivation techniques and associated land-use. Rice cultivation practices are best categorized as follows:

1. *Lowland rice*: this type of rice cultivation is seasonally flooded using canal infrastructure to suppress weeds. Plots of this type are meant for permanent or semi-permanent cultivation
2. *Swidden rice*: is a system where plots of shrub or woodland are cut, burned, cultivated for one or a few years, and then left to fallow. This type of rice cultivation relies primarily on rain as a water source and is locally referred to as *tavy*.
3. *Upland rice*: this type of cultivation may be irrigated or rainfed, but it is not seasonally flooded for prolonged periods nor is it part of a swidden system, since the upland fields are cultivated yearly and not left to fallow.

The cultivation of other subsistence crops such as cassava, fruit trees, and garden vegetables also took place to a lesser extent in each fokontany.

Leisz et al (1995) documented the current and historical land tenure systems of seven fokontany each within ten kilometers of a national parks. Each fokontany had some variation of the land tenure systems listed above, and, in each case, it was confirmed that the system had been in place for decades prior to the study. Although follow-up surveys were not done in the communities following 1994, members of the original research team were still in contact with the fokontany in the following years and confirmed that there were no major political or economic shifts in the study areas.

Site overviews

From the Land Tenure Center fieldwork, results from six fokontany and three national parks are included in this study. The national parks discussed here include Montagne D'Ambre, Zahamena, and Andohahela. Additionally, to compare the effectiveness of different types of protected areas in Madagascar, the land-cover of the special reserve of Ankarana, located less than ten kilometers southwest of Montagne D'Ambre, is also included in this analysis since one of the fokontany is within ten kilometers of it. The Land Tenure Center fieldwork team randomly selected fokontany that were ten kilometers or less from the border of each national park (or special reserve). Two fokontany were selected for each national park and were labelled using their colloquial name including Ambondrona, Andonakaomby, Anosivola, Sahamalaza, Marohotro, and Montifeno. The three protected area-fokontany associations lie within separate Landsat scenes, and they are classified and referred to separately in this study. The protected areas are located across a north-south transect of Madagascar, with Montagne D'Ambre (fokontany Ambondrona and Andonakaomby) located in the northernmost part, Zahamena (fokontany Sahamalaza and Anosivola) in the middle on the eastern chain of humid forest, and Andohahela (fokontany Marohotro and Montifeno) located near the southeast corner. The only major urban center near any of the study sites or protected areas is the city of Antsiranana, which lies within ten kilometers of Montagne D'Ambre national park, to its northeast. A map of the three sites and National Parks can be seen in Figure 2.

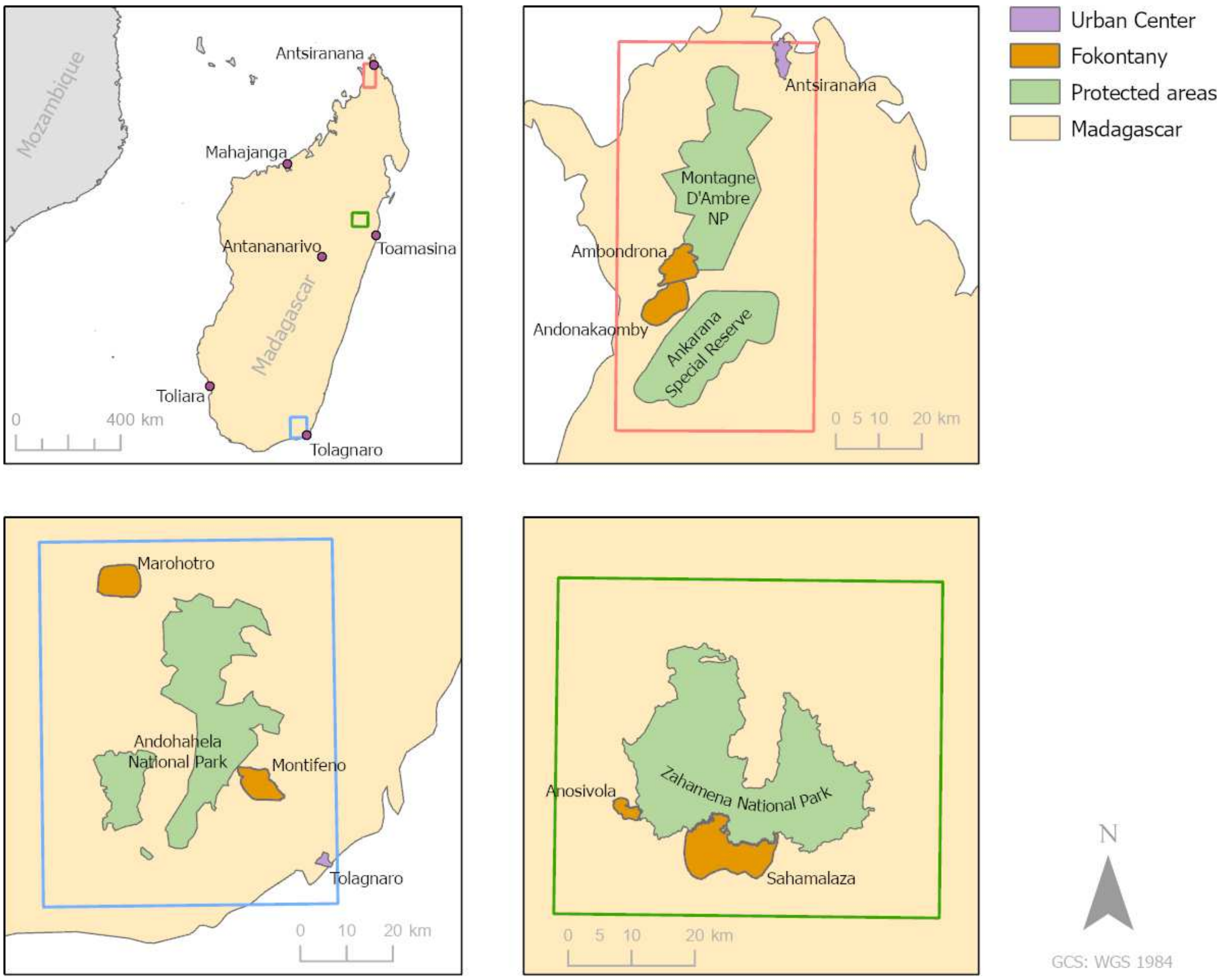

Figure 2: Map of fokontany and nearby national parks

Site ecological profiles

Montagne d'Ambre national park and the nearby fokontany of Ambondrona and Andonakaomby lie on a volcanic massif where montane rainforest in the core protected area is surrounded sparse, dry forest, pastureland, and upland rice cultivation. Originally this area was protected as a Special Reserve by the French colonial authority in 1937, then in 1958 it was further protected as a National Park ((Goodman et al 2018). The core of the park is comprised primarily of forest, but also has several volcanic lakes and waterfalls. The area has a rich biodiversity of flora and fauna, some of which are endemic to the park. The special reserve of Ankarana, created in 1956, contains unique rock formations called *tsingy* in Malagasy and pockets of humid and dry forests (Goodman et al 2018).

Zahamena national park is a large remnant of primary montane humid forest in the eastern portion of the country. The park, created in 1927 by the French colonial government, sits along a spine of humid forest that stretches almost the entire north-south extent of the country. It is bordered to the east by humid lowland forest and to the west by Madagascar's drier central highlands (Goodman et al 2018). The protected area lies at the northern end of an important corridor of continuous, remnant forest called the Ankeniheny-Zahamena corridor (Rosimeiry et al 2012).

Andohahela national park lies at the southernmost extent of the same humid forest spine as Zahamena. The park, created in 1939 by the French colonial government, displays the extreme climatic gradients that exist in Madagascar. The eastern parcel is made up of mostly humid montane forest, while the western parcel protects a substantial amount of spiny forest. The spiny forest biome receives substantially less rainfall, and contains an extremely high proportion of endemic plants, even compared to other vegetation types in Madagascar. Spiny forest vegetation is also extremely slow growing, leaving it particularly vulnerable to logging or the harvest of timber for charcoal (Goodman et al 2018).

Site land tenure systems

Using randomized, semi-structured household interviews, the Land Tenure Center team examined the land tenure rules and regulations associated with a bundle of four different resources at each fokontany including forests, water, trees, and land. Their resulting report describes how land tenure security varies by each site and for each resource. The following trends were evident in their findings. Forests and water are often held as common resources in customary tenure systems, whereas individual trees and land are often owned or accessed by individuals or single households (except for pastureland). Because of Madagascar's state forest code, there are overlapping tenure rules and regulations between state and customary systems in each of the surveyed fokontany, but the degree to which this affects tenure security to forests varied by fokontany based on the forest use. Smaller, pocket forests often fell outside of the interest of or enforcement by local forest agents from Madagascar's Department of Water and Forests, but in larger forest areas where the code is enforced, community members reported feelings of insecure tenure to the forests that in many cases their ancestors had been using for generations. Logging permits were issued to loggers from outside the community for the customary forests of several of the surveyed fokontany, and those communities often felt that they had limited or no access to the forest resources. Both water and individual trees were managed under customary tenure systems in all fokontany, and individuals typically felt a high degree of security in their access to those resources. Finally, land tenure scenarios varied the most significantly between fokontany. Two of the sites, Anosivola and Sahamalaza, reported insecure land tenure, while the other four fokontany are categorized as following the customary land tenure and believing that they have secure rights to access, use, and manage land. In summary, community members typically expressed some degree of insecurity to forest resources, water and tree resources are confirmed as secure, and rights to land were either secure or insecure depending on the fokontany.

Because rights to forest was not discretely categorized as secure or insecure by the Land Tenure Center report, and because water and tree tenure did not vary between the sites, this study examines only the effect of land tenure security on land-cover change. A dominant customary land tenure system indicates tenure security, while an 'overlapping and conflicting' tenure scenario indicates insecurity. As noted above, Anosivola and Sahamalaza were found to have land-tenure systems that are 'overlapping and conflicting' between the local, customary, system and the national government's land tenure systems. This situation has created conflict and uncertainty. An example of this is seen in Anosivola, where the national government's rules granting rights to land to people who are actively cultivating the land, as opposed to recognizing land rights of households who have fallow land, has allowed more wealthy community members to claim other farmers fallow plots (Leisz et al 1995).

Site agricultural practices

Agricultural practices at each site varied by region and climate. In the northernmost fokontany of Ambondrona and Andonakaomby, there is little irrigated rice due to the lack of water resources. Cattle husbandry, as well as upland and rainfed rice are the primary agricultural activities. There is substantial rainfall throughout the growing season in these regions, which allows for this style of cultivation that often requires lower amounts of irrigation and lower investment of labor or income into agricultural infrastructure. In the eastern communities of Anosivola and Sahamalaza, there is a mix of practices taking place. For Anosivola, there are established lowland irrigated rice fields, pasture for cattle, and swidden rice. In Sahamalaza, where there is no flat land that can be used for irrigated or flooded rice cultivation, swidden is the dominant form of rice cultivation, while raising cattle is also common. Finally, in Marohotro and Montifeno in the southernmost portion of the country, cattle husbandry and lowland irrigated or flooded rice cultivation are the dominant agricultural activities. In each of these communities, other forms of agriculture and rice cultivation took place to a lesser extent but did not have a significant impact on land-cover because of their scarcity.

Swidden took place in all of the fokontany to a certain extent, but it was designated as the dominant agricultural practice only in Sahamalaza. A summary of the land tenure scenario, agricultural practices, and associated protected areas for each fokontany is shown in Table 1.

Table 1: Summary of agricultural practices, dominant tenure system, level of tenure security reported by residents, and the associated protected area. *Ankarana is the only protected area that is not a national park. (Leisz et al. 1995)

Site	Dominant Agricultural Practice	Dominant Land Tenure System	Level of tenure security reported by residents of the fokontany	Associated Protected Area
Ambondrona	Upland rice, cattle	Customary	High – confidence in secure access to land and resources	Montagne D'Ambre, Ankarana*
Andonakaomby	Upland rice, cattle	Customary	High – confidence in secure access to land and resources	Montagne D'Ambre
Anosivola	Lowland rice, cattle	Overlapping and conflicting	Medium – confidence in secure access to irrigated and lowland rice plots; low confidence in secure rights to upland/dryland fields and forest areas	Zahamena
Sahamalaza	Swidden rice	Overlapping and conflicting	Low - low confidence that they have secure rights to upland/dryland fields, shrub/grass, and forest areas	Zahamena
Marohotro	Lowland rice, cattle	Customary	High – confidence that they have secure access to land and resources within their fokontany	Andohahela
Montifeno	Lowland rice, cattle	Customary	High – confidence that they have secure access to land and resources within their fokontany	Andohahela

Data and geoprocessing

Geoprocessing was carried out in QGIS and RStudio (RStudio Team 2022). Protected area core zone boundaries were obtained from Protected Planet (n.d.). A ten-kilometer buffer around each of the protected area boundaries to mirror a buffer zone and a five-kilometer buffer for each fokontany to examine the full potential footprint for each was made. After merging the buffers, the resulting polygon was the full analysis extent. Figure 3 illustrates this process. Each national park-fokontany complex are contained within a single Landsat scene and the classification for those analysis extents is further referred to in this study as a classification region. The Zahamena and Andohahela analysis extents were used as final classification extents without further editing. The analysis extent polygon for Montagne D'Ambre was cropped to remove the analysis extent that intersected with the ocean, that intersected with major urban centers, or that contained significant cloud cover. The areas removed did not intersect with the surveyed fokontany, so the loss of data was deemed acceptable. The extra processing for the Montagne D'Ambre classification region can be seen in Figure 4.

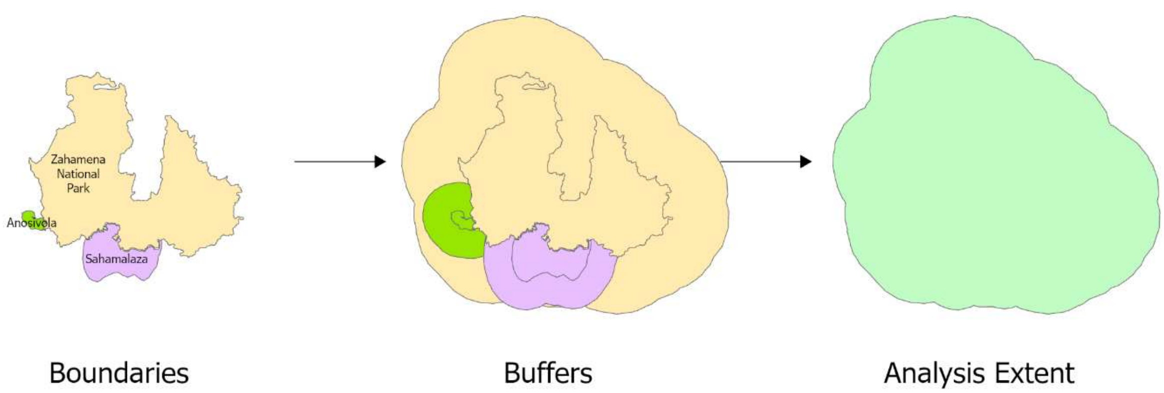

Figure 3: Buffering, and merging of buffers to form the analysis extent for land-cover classification

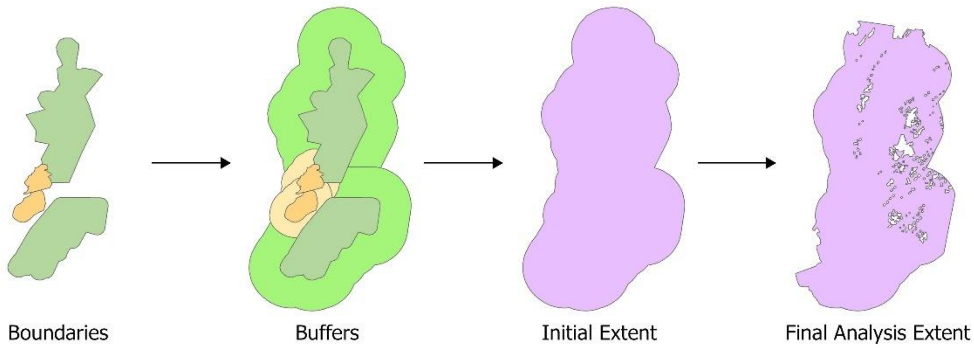

Figure 4: Additional aggregation of the Montagne D'Ambre classification region and resulting extent

Landsat scenes were acquired through the United States Geological Survey's Earth Explorer portal (Houska 2012) for the three national parks regions. Land-cover was classified for three separate dates, 1990, 1995, and 2000, within a ten-year period, resulting in nine total land-cover classifications. The one exception was the earliest classification for the Montagne D'Ambre region, where the earliest classification date was changed to 1985 because of lack of imagery in 1990 due to extensive cloud cover. This region consists of montane, humid tropical forest, and it is difficult to find cloud-free imagery for the region. For each classification region and date, scenes prior to and within a six-month range of the target year constituted the whole range of imagery for each date. The scenes included in all nine classifications can be seen in Table 2.

Table 2: Classification region and the scenes/date included in the analysis for each classification year of the study

Site	1985 or 1990	1995	2000
Montagne D'Ambre	19840625	19940520 19950710	19980702 20001011
Andohahela	19900705 19900923 19910302 19910521	19910724 19921217 19930526 19930729 19940630 19950905 19960212	19960907 19961009 19970521 19970724 19980727 19981116 20000716 20000902 20001020 19990908 19991111 20000910
Zahamena	19900619	19930408 19941121	20050425 20040711 19970724 19971129 19971215 19991229 20000419

From Landsat Thematic Mapper and Enhanced Thematic Mapper scenes, spectral bands one through seven, which cover the blue, green, red, near-infrared, mid-infrared, and thermal wavelengths, were included in the analysis for each date and classification region. Because of the ability of random forest models to digest many dimensions of data and retain high accuracies (Fox et al 2017), there was no reason to exclude any of these bands from the analysis. Additional datasets used to inform the land-cover classifier were either obtained from other sources or derived. Three spectral indices were calculated for each Landsat scene to accentuate differences between land-cover. These include the normalized difference vegetation index (NDVI), the enhanced vegetation index (EVI), and the normalized difference moisture index (NDMI). NDVI and EVI are both measures of photosynthetic activity, but studies have shown that EVI is more sensitive in areas of dense vegetation (Qiu et al 2018). NDMI is a good proxy for vegetation moisture content (USGS n.d.), which is important in distinguishing vegetation types in areas with abrupt climactic gradients such as those found in Madagascar. Both are included in this study because of the wide array of vegetation types across sites. An elevation dataset was obtained from the Shuttle Radar Topography Mission (SRTM), and from this DEM, a slope dataset was derived and included in the land-cover classification analysis.

Land-cover change analysis

Variation in agricultural activity and ecosystems across Madagascar led to slight differences in the classification scheme used for each of the sites. For all sites, dense tree cover, sparse tree cover, shrub/pasture, and water were classified. For the Montagne d'Ambre analysis extent, upland agriculture and bare rock were additional classes due to the prevalence of rock spires, called *tsingy* in Malagasy, within the special reserve of Ankarana. For the Zahamena analysis extent, both lowland agriculture and upland agriculture were also classified. Finally, for Andohahela analysis extent, lowland agriculture, upland agriculture, and spiny forest were added to the classification. The land-cover classification scheme for each of the classification regions can be seen in Table 3.

Table 3: Land-cover classification scheme for each national park region.

Andohahela	Montagne d'Ambre	Zahamena
Dense tree cover Sparse tree cover Shrub/grass Water Lowland agriculture Upland agriculture Spiny Forest	Dense tree cover Sparse tree cover Shrub/grass Water Upland agriculture Bare rock	Dense tree cover Sparse tree cover Shrub/grass Water Lowland agriculture Upland agriculture

Although some ground truth field data with GPS coordinates was available from the Land Tenure Center field work, because the bulk of training datasets were derived from aerial photography and satellite imagery, it was necessary to translate different land-use strategies into observable land-cover classes. In the resulting classification scheme, rangeland was assumed to be identified as the 'shrub/grass' class, lowland rice as 'lowland agriculture', and, finally, upland rice or swidden rice as 'upland agriculture'.

Training datasets for the earliest classification date for each analysis extent (1985 and 1990) were derived from ground truth points from Leisz. et al (1995) and aerial photography from the "Institut Géographique et Hydrographique de Madagascar". For the year 2000, training datasets were derived from high-resolution satellite imagery on Google Earth. Because neither aerial photography nor high-resolution imagery were available for any date near 1995, the training dataset for this timestamp was derived by verifying points identified as the same land-cover class in both 1990 and 2000 and then by comparing spectral indices from all timestamps to verify stability of training points. Following this, for each of the training points with known land-cover identity, values for each of the spectral Landsat bands, spectral indices, and ancillary data were extracted to a table with which to fit a random forest model. This model was finally used to create classified land-cover maps for each of the national park regions and associated fokontany. This process was carried out using the randomforest package (Liaw and Wiener 2002) in RStudio. This process also yields values of the decrease in Gini importance. The Gini importance used in the randomforest package measures a mean decrease in impurity, for each variable in the model. A higher decrease indicates a more 'important' variable for the classifier, so it is possible to say what data the random forest models relied on the most consistently when predicting land-cover (Krishna et al 2018). This allows the algorithm to decide what variables to rely on for prediction, and there is evidence that shows the removal of less important variables in this process does not yield higher predictive accuracies (Fox et al 2017). For this reason, variables were not iteratively removed from the modeling and classification process in this study.

Accuracy of the resulting land-cover maps was assessed using confusion matrixes demonstrating how predicted land-cover aligned with validation data (Lillesand et al 2015). An example of an empty confusion matrix is shown in Table 4. For each land-cover class, the number of correctly classified validation points lies in the intersect of the row and column. Any mis-identified points have different column and row headings. Using this information, you can calculate both the user's and producer's accuracy for both classes as well as the overall accuracy for the classification. Producer's accuracy for a class is the total number of correctly classified validation points divided by the actual number of validation points that should've been identified as that class. User's accuracy Is the total number of correctly classified validation points divided by total number classified as that class, either correctly or incorrectly.

Table 4: Empty confusion matrix showing the configuration for accuracy assessment

		Truth Data							
		Dense Tree Cover	Sparse Tree Cover	Shrub/Pasture	Water	Upland Agriculture	Bare Rock	Sum	User's Accuracy
Classification	Dense Tree Cover								
	Sparse Tree Cover								
	Shrub/Pasture								
	Water								
	Upland Agriculture								
	Bare Rock								
Sum								Overall Accuracy:	
Producer's Accuracy									

The area of each land-cover type for each analysis extent was calculated. To examine land-cover change in the national parks closest to each fokontany, areas of each land-cover within the intersect of the national park and a five-kilometer buffer of each fokontany boundaries were noted. This included only five of the fokontany because the community of Marohotro lies between five and ten kilometers of Andohahela national park. Land-cover in each analysis extent were converted to percentages for each to aid in comparison between the analysis extents. The land tenure situation and land-cover change for each fokontany were noted and are discussed further in the discussion portion of this paper.

After classification, raster math was used to determine where and what type of change was taking place on the landscape. For each of the change rasters produced, the quantity of each type of land-cover change for each park area was noted, and the various change types were lumped into the following broader categories to better demonstrate trends on the landscape:

- **Tree cover loss/degradation**: change from a tree cover type to one of the following: upland agriculture, lowland agriculture, bare rock, or shrub/grass. Or change from dense tree cover to sparse tree cover.
- **Tree cover gain**: change from either upland agriculture, lowland agriculture, bare rock, or shrub/grass to one of the tree cover types.
- **Open cover rotation**: Change between one of the non-tree land-covers including upland agriculture, lowland agriculture, bare rock, or shrub/grass. Excluding water.
- **Change involving water**: pixels changing to or from the water cover type.

Finally, patch metrics were calculated in each fokontany for each classification and date to better portray different land-cover trajectories, including the number and average area of patches of each land-cover class. This was completed using the landscapemetrics library in RStudio (Hesselbarth et al 2019). Land tenure security and dominant agricultural practices were applied categorically to the fokontany based on the Land Tenure Center's report (Leisz et al 1995) to observe any potential relationship between tenure and land-cover change.

RESULTS

Random forest classification

The nine random forest land-cover classifications achieve overall accuracies from 89.9% to 94.5%. Accuracy varies slightly depending on Landsat scene availability and classification scheme. The lowest accuracy, 89.9 percent, occurs in the classification of the Zahamena area for the 1990 timestamp, where only a single Landsat scene was available, whereas the most accurate is the 1995 timestamp for the Andohahela region, where there were seven cloud-free scenes. Confusion matrices for these results are shown in Table 5. Accuracies for all classifications can be seen in appendix 1.

Table 5: Select accuracy matrixes from the lowest and highest overall accuracy classifications.

Zahamena, 1990

		Truth Data							
		Dense Tree Cover	Sparse Tree Cover	Shrub/Pasture	Water	Irrigated Agriculture	Upland Agriculture	Sum	User's Accuracy
Classification	Dense Tree Cover	135	4	4	2	0	0	145	0.93103
	Sparse Tree Cover	0	79	7	0	3	0	89	0.88764
	Shrub/Pasture	1	9	110	4	13	4	141	0.78014
	Water	1	0	0	62	0	0	63	0.98413
	Irrigated Agriculture	0	4	7	0	107	0	118	0.90678
	Upland Agriculture	0	0	2	0	0	88	90	0.97778
Sum		137	96	130	68	123	92	Overall Accuracy:	
Producer's Accuracy		0.98540146	0.822916667	0.846153846	0.91176	0.869918699	0.956521739	0.899380805	

Andohahela, 2000

		Truth Data								
		Dense Tree Cover	Sparse Tree Cover	Shrub/Pasture	Water	Irrigated Agriculture	Upland Agriculture	Spiny Forest	Sum	User's Accuracy
Classification	Dense Tree Cover	78	0	0	0	0	0	0	78	1
	Sparse Tree Cover	0	91	9	0	2	5	3	110	0.82727
	Shrub/Pasture	0	1	99	0	2	0	3	105	0.94286
	Water	0	0	0	92	1	0	1	94	0.97872
	Irrigated Agriculture	0	1	0	1	106	0	0	108	0.98148
	Upland Agriculture	0	0	4	0	1	84	0	89	0.94382
	Spiny Forest	0	1	3	0	0	1	123	128	0.96094
Sum		78	94	115	93	112	90	130	Overall Accuracy:	
Producer's Accuracy		1	0.968085106	0.860869565	0.98924731	0.946428571	0.933333333	0.946153846	0.945224719	

Although accuracies are quite high for all the land-cover classes present, the classifier had the most confusion between the open land-cover classes. Sparse tree cover consistently has the lowest user and producer accuracies averaging 87.6 and 87.4 percent respectively. When incorrectly classified, sparse tree cover is most often classified as shrub/pasture, upland agriculture, or spiny forest in the case of the Andohahela region. Aside from this class, average accuracies are above 90% for every other land-cover class.

The random forest classifier draws more consistently from some layers than others in the study. For almost all the classifications, elevation data has one of the highest Gini values. The most important wavelengths for the models are thermal infrared (Landsat TM and ETM+ band 6), followed by the near infrared (Landsat TM and ETM+ band 4). Finally, the spectral index with the highest importance according to Gini values is the NDVI.

Broad change trends

High land-cover classification accuracies allowed for post-classification change detection between the three classification dates for each analysis extent. Of the three analysis extents, the Montagne D'Ambre region with the fokontany of Ambondrona and Andonakaomby has the highest proportion of cover change, with around 30 percent of the cover changing over both periods (1985 – 1995, 1995 – 2000). The proportion of land-cover that experienced change for each of the three sites can be seen in Table 6. After lumping the different types of land-cover change, net tree cover conversion to open land-cover classes is observed in all three scenes, although the degree to which this takes place varies. Change between open land-cover types is common, particularly in the sites associated with Montagne D'Ambre and Zahamena national parks. Although water should theoretically be relatively stable on the landscape, there is significant change involving pixels changing to or from water. This change is most prevalent in the Andohahela study area, ranging from 20.4 to 23.3 percent of all pixels that changed across the analysis extent. Table 7 shows a summary of lumped land-cover change for the three classification extents for both change periods, and Table 8 shows the change for each of the classification extents with specific land-covers.

Table 6: The percent of total pixels in each study area that underwent land-cover change during each period

National Park/scene	% changing 1990 to 1995	% changing 1995 to 2000
Andohahela	14.7	13.3
Montagne D'Ambre	30.3	30.2
Zahamena	24.7	22.8

Table 7: Percent of observed change that belongs to each lumped change type for each classification region. This includes the national park and fokontany.

	Montagne d'Ambre classification extent		Zahamena classification extent		Andohahela classification extent	
	1985-->1995	1995-->2000	1990-->1995	1995-->2000	1990-->1995	1995-->2000
Tree cover loss	47.7	34.8	46.3	33.1	39.6	31.7
Tree cover gain	28.4	28.2	18.8	17.6	28.4	28.6
Open cover rotation	21.2	34.7	20.7	30.5	11.7	16.4
Change involving water	2.7	2.3	14.3	18.8	20.4	23.3

Table 8: Percentage of change pixels in each classification extent belonging to each specific type of change over the ten- or fifteen-year study period.

	Montagne d'Ambre classification extent
	1985-->2000
Sparse tree cover --> Upland agriculture	35.5
Shrub/grass --> Upland agriculture	15
Sparse tree cover --> Shrub/grass	14.1
Upland agriculture --> Sparse tree cover	13
Upland agriculture --> Shrub/grass	7.2
Shrub/grass --> Sparse tree cover	4.3
Dense tree cover --> Sparse tree cover	4
Sparse tree cover --> Dense tree cover	3.9

	Zahamena classification extent
	1990-->2000
Dense tree cover --> Shrub/grass	31.2
Sparse tree cover --> Shrub/grass	12.6
Dense tree cover --> Water	8.7
Shrub/grass --> Dense tree cover	5.9
Shrub/grass --> Water	5.5
Dense tree cover --> Sparse tree cover	5.5
Shrub/grass --> Sparse tree cover	5.4
Water --> Shrub/grass	4.5
Sparse tree cover --> Dense tree cover	3.7
Water --> Dense tree cover	3.4
Shrub/grass --> Upland agriculture	3.3
Upland agriculture --> Shrub/grass	3

	Andohahela classification extent
	1990-->2000
Sparse tree cover --> Shrub/grass	13.6
Dense tree cover --> Sparse tree cover	10.8
Spiny forest --> Shrub/grass	10.3
Spiny forest --> Sparse tree cover	9.9
Sparse tree cover --> Spiny forest	6.6
Shrub/grass --> Spiny forest	5.8
Shrub/grass --> Sparse tree cover	5.7
Upland agriculture --> Sparse tree cover	4.9
Shrub/grass --> Upland agriculture	4.9
Lowland agriculture --> Sparse tree cover	4.3
Upland agriculture --> Spiny forest	3.8

Fokontany and land-cover change

The land-cover change trajectory of the study sites primarily depend on the initial proportion of each cover type, land tenure system, and common agricultural practices. Land-cover percentages of the six fokontany, the protected areas in the scene, and the whole ten-kilometer national park buffer for each of the classified timestamps is shown in Table 9. In areas with more significant tree cover loss, there is a trend towards land-cover aggregation, with patch size increasing and the number of patches decreasing for most land-cover types. Table 10 shows a summary of mean patch size and the number of patches for each land-cover in each fokontany. In the following section, the primary change dynamics, patch metric trends for major cover types, and change maps are discussed for each fokontany.

Table 9: percent of land-cover at each timestamp for the national park, fokontany, and national park buffer

	Ambondrona-Andonakaomby area land-cover		
	% cover 1985	% cover 1995	% cover 2000
Montagne D'Ambre National Park			
Dense tree cover	52	54.6	50.3
Sparse tree cover	23.4	21.2	27.8
Shrub/grass	17.2	7.5	14.2
Water	0.4	0.6	0.2
Upland agriculture	7	16.1	7.4
Bare rock	0	0.006	0
Ambondrona			
Dense tree cover	0	0.2	1.1
Sparse tree cover	73.1	72.8	71
Shrub/grass	16	13.1	12.4
Water	0.1	0.1	0.01
Upland agriculture	10.7	13.7	15.6
Bare rock	0.02	0	0
Andonakaomby			
Dense tree cover	0.6	0.2	1.3
Sparse tree cover	64	51.7	54
Shrub/grass	29.6	39	21.7
Water	0.2	0.1	0.1
Upland agriculture	5.5	9	22.9
Bare rock	0.1	0	0
Entire national park buffer			
Dense tree cover	1.43	2.7	2.5
Sparse tree cover	57.1	47	45.7
Shrub/grass	13.9	12.3	18.9
Water	0.9	0.9	0.5
Upland agriculture	26.7	37	32.3
Bare rock	0.03	0.03	0.02

	Anosivola-Sahamalaza area land-cover		
	% cover 1990	% cover 1995	% cover 2000
Zahamena National Park			
Dense tree cover	95.2	96.1	97.6
Sparse tree cover	1.5	0.5	0.4
Shrub/grass	2	2.3	1.6
Water	1.3	0.8	0.4
Lowland agriculture	0.03	0.3	0.01
Upland agriculture	0.001	0.01	0
Anosivola			
Dense tree cover	16.3	14.1	13.1
Sparse tree cover	40.9	43.1	42.8
Shrub/grass	21.2	20.6	26.2
Water	0.3	0.1	0.1
Lowland agriculture	21.2	22	17.8
Upland agriculture	0.1	0.1	0
Sahamalaza			
Dense tree cover	55.3	44.8	42.7
Sparse tree cover	7.8	6.6	6.3
Shrub/grass	33.3	44.5	48.6
Water	3.5	2.1	1.4
Lowland agriculture	0.1	1.8	0.9
Upland agriculture	0.02	0.2	0.001
Entire national park buffer			
Dense tree cover	39	29.1	27.5
Sparse tree cover	10.6	10.4	8.8
Shrub/grass	40.5	44.9	50.3
Water	3.1	4	5.7
Lowland agriculture	0.8	3.5	1.7
Upland agriculture	5.9	7.9	6

	Marohotro-Montifeno area land-cover		
	% cover 1990	% cover 1995	% cover 2000
Andohahela national park			
Dense tree cover	73.9	72.7	74.1
Sparse tree cover	3.9	3.2	4.4
Shrub/grass	9	8.3	8.4
Water	0.01	0.03	0.03
Lowland agriculture	0.1	0.1	0.05
Upland agriculture	0.1	0.2	0.1
Spiny forest	12.9	15.5	12.8
Marohotro			
Dense tree cover	0	0	0
Sparse tree cover	12.2	11.8	10
Shrub/grass	59.7	63.6	67.3
Water	0.04	0.04	0.03
Lowland agriculture	7.1	5.3	3.6
Upland agriculture	0.04	1.7	0.6
Spiny forest	21	17.4	18.4
Montifeno			
Dense tree cover	3.6	2.6	2.6
Sparse tree cover	46.7	50.1	53.4
Shrub/grass	33.6	32.3	30.6
Water	1	0.8	0.7
Lowland agriculture	8.2	8.5	7.7
Upland agriculture	4	5.1	0.3
Spiny forest	2.8	0.6	4.7
Entire national park buffer			
Dense tree cover	18.4	16.6	16.6
Sparse tree cover	18.1	18.1	20.1
Shrub/grass	29.4	30.6	31
Water	0.2	0.3	0.3
Lowland agriculture	3.2	2.8	2.2
Upland agriculture	6.3	6.3	5.9
Spiny forest	24.3	25.2	23.9

Table 10: Mean area in hectares and number of patches for dense tree cover (DTC), sparse tree cover (STC), shrub/grass (SG), lowland agriculture (LA), upland agriculture (UA), and spiny forest (SF) land-cover classes grouped by fokontany

Ambondrona

Metric	1985	1995	2000
Mean area (DTC)	NA	0.32	0.657
Mean area (STC)	44.9	33.5	40.5
Mean area (SG)	2.56	3.58	2.01
Mean area (UA)	0.67	1.18	1.29
Number of patches (DTC)	NA	52	110
Number of patches (STC)	111	148	119
Number of patches (SG)	426	249	418
Number of patches (UA)	1085	794	822

Anosivola

Metric	1990	1995	2000
Mean area (DTC)	2.29	4.67	6.64
Mean area (STC)	3.35	7.27	7.83
Mean area (SG)	1.15	2.27	2.64
Mean area (LA)	4.06	2.71	2.59
Mean area (UA)	0.27	0.141	NA
Number of patches (DTC)	61	26	17
Number of patches (STC)	105	51	47
Number of patches (SG)	159	78	85
Number of patches (LA)	45	70	59
Number of patches (UA)	2	7	NA

Marohotro

Metric	1990	1995	2000
Mean area (DTC)	NA	NA	NA
Mean area (STC)	1.16	0.984	1.1
Mean area (SG)	14.5	24.3	27.6
Mean area (LA)	1.08	0.567	1.89
Mean area (UA)	0.24	0.355	0.2
Mean area (SF)	3.44	4.87	4.38
Number of patches (DTC)	NA	NA	NA
Number of patches (STC)	539	616	462
Number of patches (SG)	210	134	124
Number of patches (LA)	336	483	97
Number of patches (UA)	9	250	151
Number of patches (SF)	312	183	214

Andonakaomby

Metric	1985	1995	2000
Mean area (DTC)	0.975	0.334	0.65
Mean area (STC)	19.5	12.8	13.7
Mean area (SG)	4.13	10	2.39
Mean area (UA)	0.393	1.61	1.74
Number of patches (DTC)	31	34	107
Number of patches (STC)	175	215	210
Number of patches (SG)	383	208	483
Number of patches (UA)	753	297	699

Sahamalaza

Metric	1990	1995	2000
Mean area (DTC)	6.56	10.3	11.8
Mean area (STC)	0.5578	1.43	0.883
Mean area (SG)	3.46	11.3	23.5
Mean area (LA)	0.182	0.903	0.592
Mean area (UA)	0.135	0.265	0.09
Number of patches (DTC)	700	362	301
Number of patches (STC)	1181	382	594
Number of patches (SG)	799	326	172
Number of patches (LA)	42	165	133
Number of patches (UA)	14	59	1

Montifeno

Metric	1990	1995	2000
Mean area (DTC)	5.02	4.09	5.48
Mean area (STC)	5.59	7.32	9.42
Mean area (SG)	5	5.5	3.59
Mean area (LA)	0.891	0.871	1.55
Mean area (UA)	0.455	0.456	0.31
Mean area (SF)	0.306	0.191	0.441
Number of patches (DTC)	30	26	20
Number of patches (STC)	348	285	236
Number of patches (SG)	280	245	355
Number of patches (LA)	384	408	206
Number of patches (UA)	370	468	41
Number of patches (SF)	380	123	443

In Sahamalaza, there is a sharp decline in area of tree cover in the fokontany. Both dense and sparse tree covers decline from a combined 64.6 to 47.1 percent of total land-cover during the time period studied. Along with the steep decline in tree cover, the average patch size of dense tree cover and shrub/grass increases, while the total number of patches for both declines. Tree cover loss is greatest in the remaining primary forest in the south of the fokontany, whereas the region bordering the river in the northern portion of the community is already open at the beginning of the study period. The land-cover change map for Sahamalaza can be seen in Figure 5.

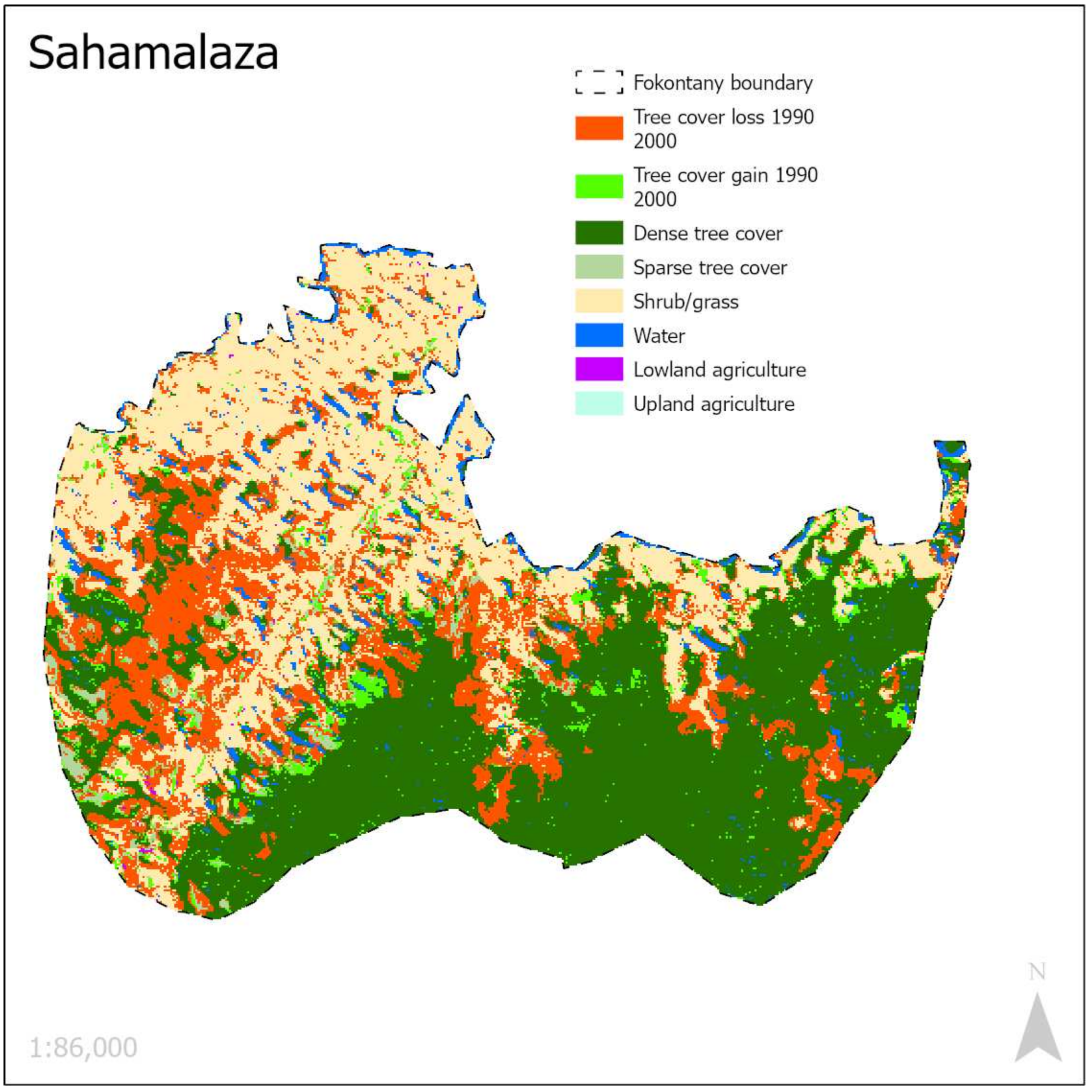

Figure 5: Land-cover change map of Sahamalaza

In Anosivola, results show consistent tree cover decline, but at a lower total proportion of area than Sahamalaza. Dense tree cover declines from 16.3 to 14.1 percent in the first half of the decade from 1990 to 1995, and then declines further to 13.1 percent in 2000. Sparse tree cover remains relatively stable, measuring 40.8 and 41.3 percent of total cover at the beginning and end of the period respectively. Patch size and number of patches in Anosivola follows the same trend as is seen in Sahamalaza, with tree cover and shrub/grass patches becoming fewer but larger. However, in Anosivola sparse tree cover also exhibited this trend. Figure 6 shows land-cover change in Anosivola. Both tree cover loss and tree cover gain seem to be concentrated on the northeast side of the fokontany, in the direction of Zahamena national park.

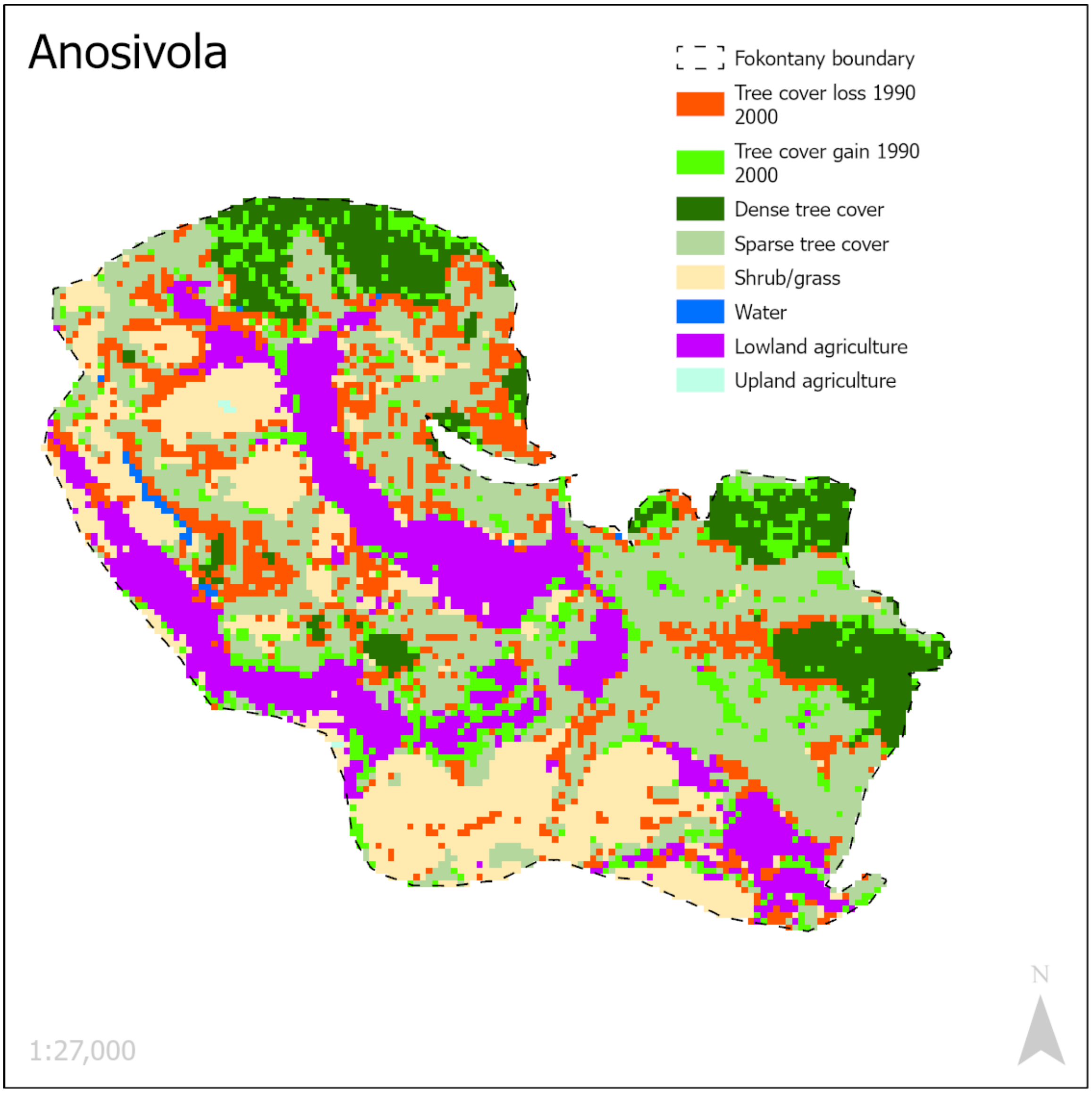

Figure 6: Land-cover change map of Anosivola

There is evidence of slow but consistent decline in remaining tree cover in Marohotro, with sparse tree cover declining from 12.2 to 10 percent and spiny forest from 21 to 18.4 percent of the area of the fokontany across the ten-year period. This loss is almost entirely accounted for by the increase in shrub/grass cover from 30.5 to 34.2 percent.. Spiny forest and shrub/grass cover types showed an increase in patch size and decrease in number of patches in the fokontany. In Figure 7, the change map for Marohotro shows the regeneration of sparse tree cover pixels, but almost none for spiny forest. It also shows that tree cover loss is focused around the spiny forest in the northern part of the fokontany.

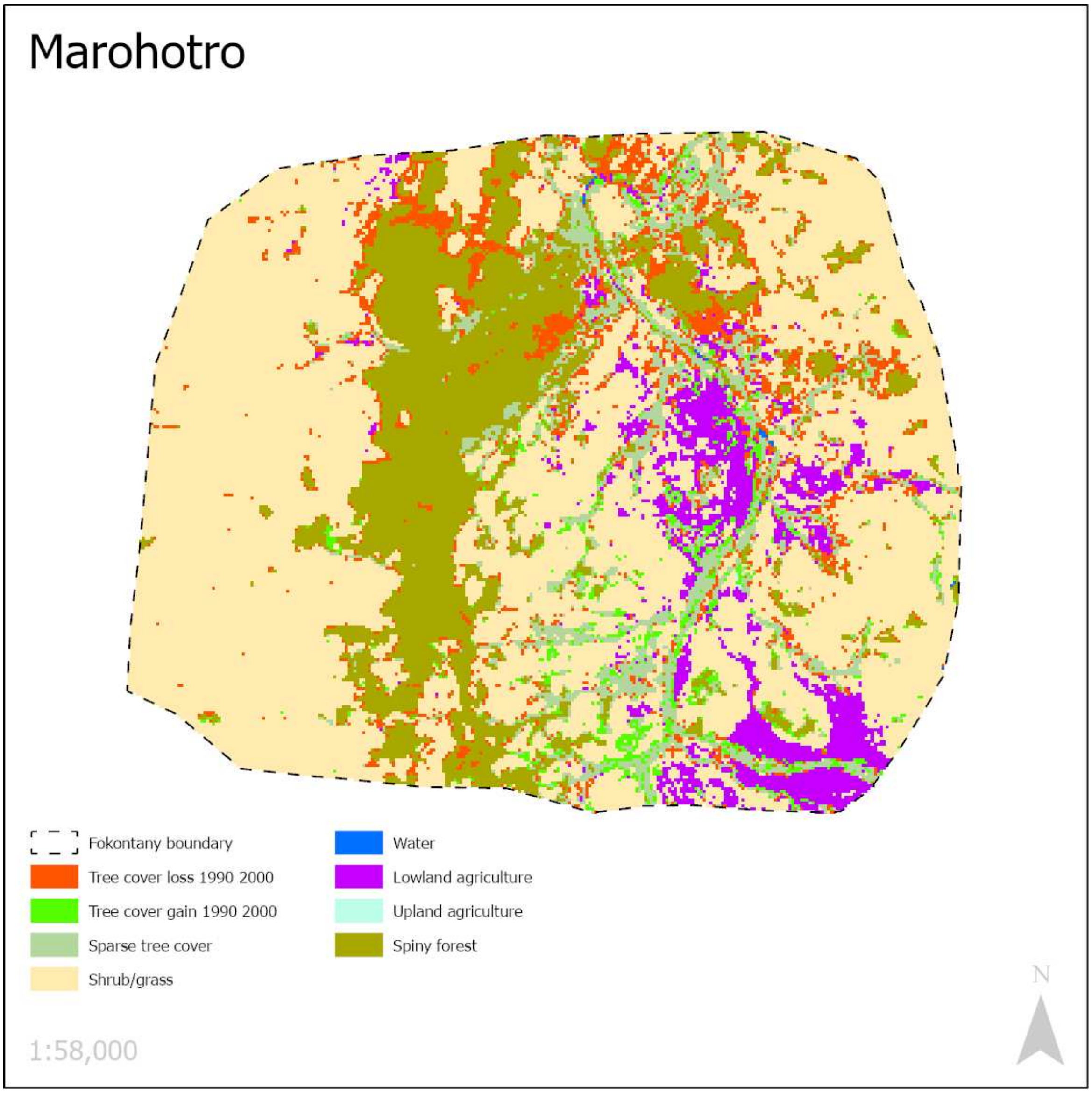

Figure 7: Land-cover change map of Marohotro

Tree cover in Montifeno is more stable, seeing a slight increase in sparse tree cover and a decline of only a single percent of total fokontany area for dense tree cover. Additionally, sparse tree cover patch size and number of patches increase and decrease respectively in the fokontany. The largest portion of tree cover loss seems to be located near the northwest portion of the community, where there is a large primary forest remnant, while tree cover regeneration seems to be scattered throughout the sparse tree cover of the fokontany. Land-cover change for Montifeno can be viewed in more detail in Figure 8.

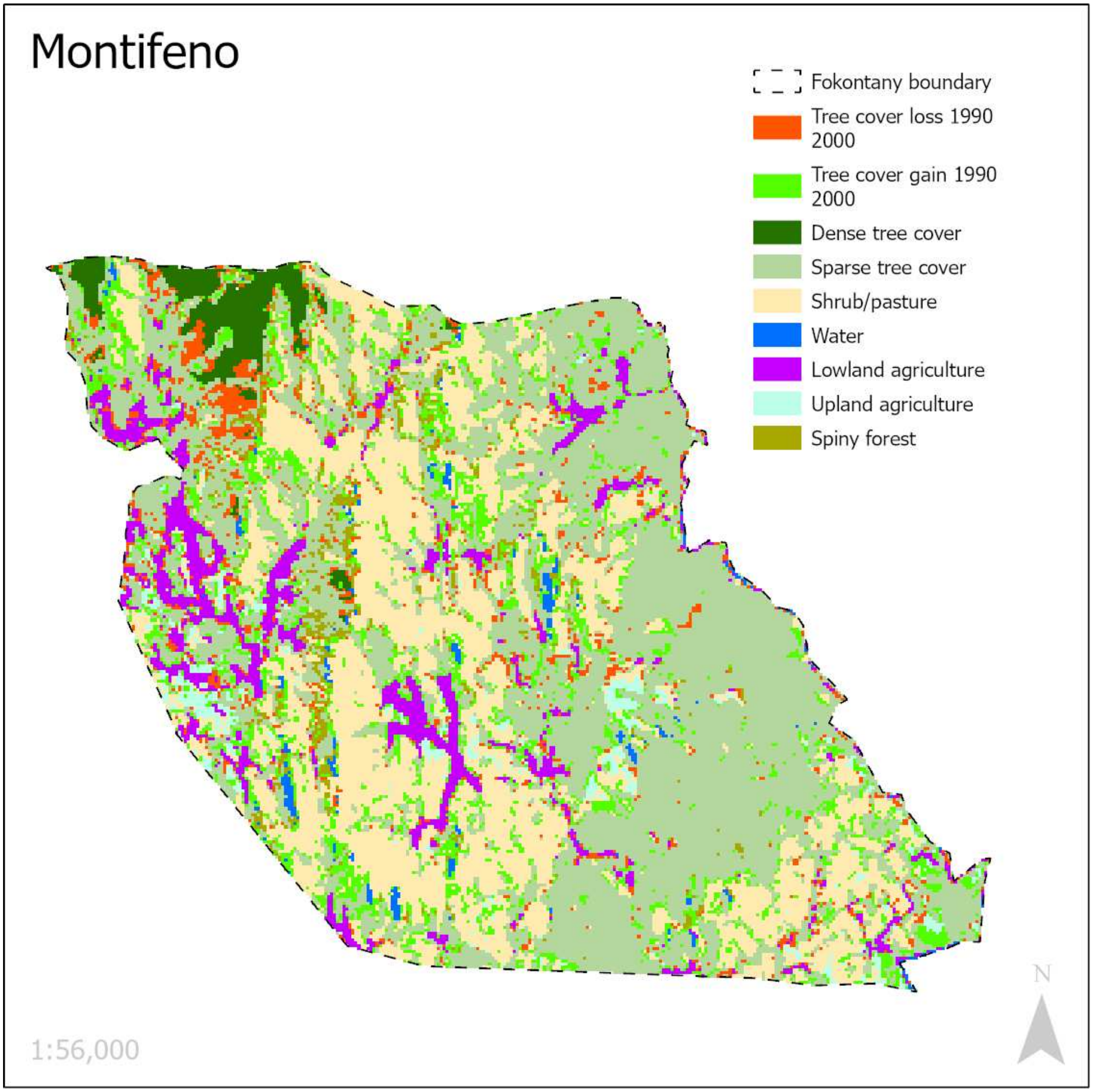

Figure 8: Land-cover change map of Montifeno

For both Ambondrona and Andonakaomby, results show slow declines in, or stability in tree cover over the extended 15-year period. In Ambondrona, sparse tree cover remains stable at around 71 to 72 percent of the land-cover of the fokontany, while this cover type declines from 64 percent to 51.7, and then stabilizes at 54 percent of cover across the three timestamps in Andonakaomby. Patch metrics indicate the fragmentation of remaining sparse tree cover in Andonakaomby, with a decrease in patch size and a slight increase in the number of patches. Trends for patch size or number of patches in Ambondrona are not consistent across the whole fifteen-year span for the most prominent land-cover classes.

Figures 9 and 10 show the land-cover change maps for Ambondrona and Andonakaomby, respectfully. Land-cover change of any type does not seem to be concentrated in any part of the fokontany. Upon visual inspection, the southernmost portion of Ambondrona, which lies within Ankarana special reserve, does not have a greater amount of land-cover change than the rest of the community.

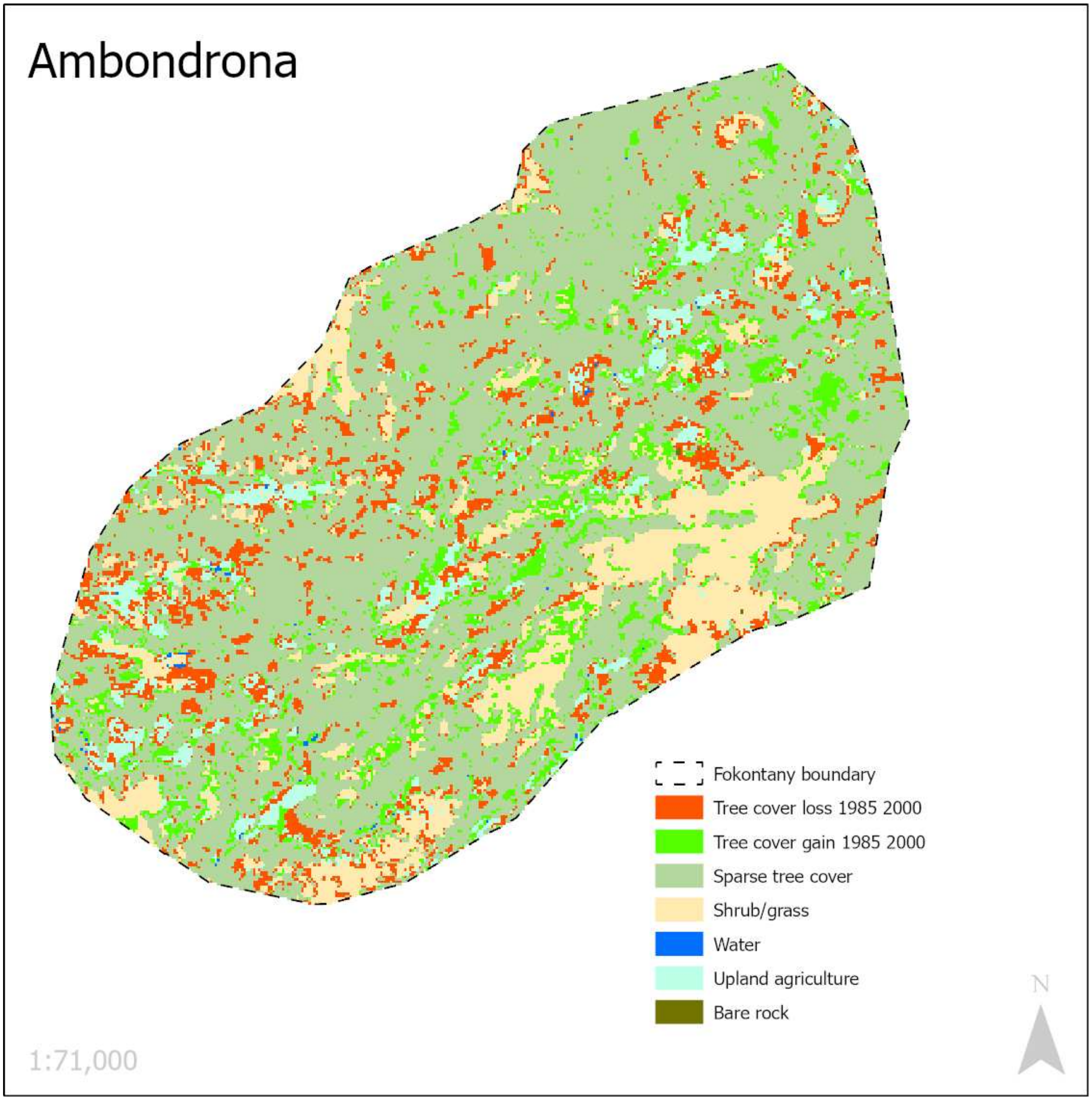

Figure 9: Land-cover change map of Ambondrona

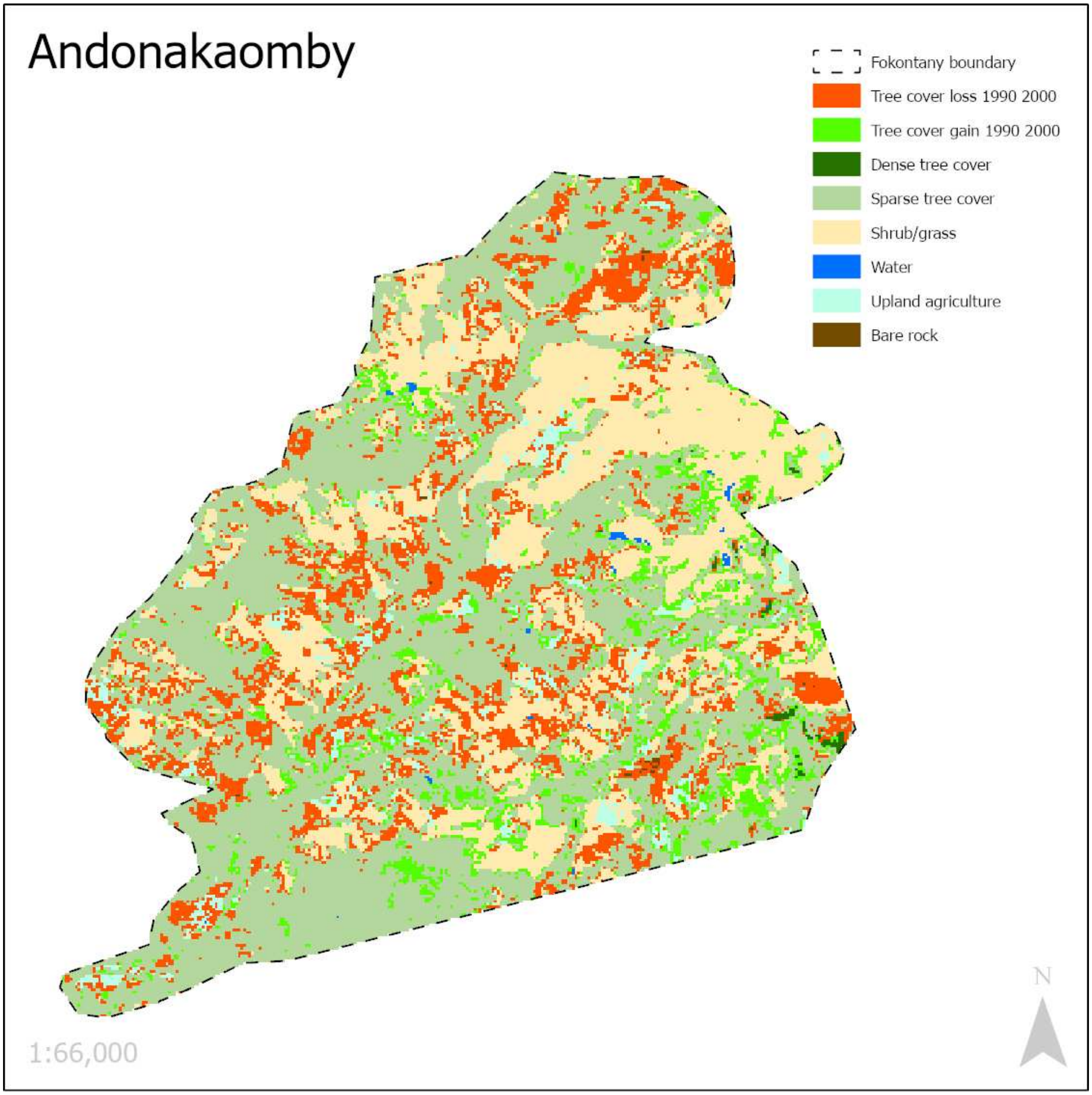

Figure 10: Land-cover change map of Andonakaomby

Protected areas and land-cover change

Tree cover within all three of the national park sites either remains stable or increases slightly. In Montagne D'Ambre national park, where the initial proportion of shrub/pasture cover was 15.4 percent, the highest of all three national parks in the study, dense and sparse tree covers remain within three percent of their initial proportion of land-cover by the end of the study. In Zahamena national park, there is evidence of a slow increase in dense tree cover. This class increases from 95.5 percent of cover in the park to 97.6 by the year 2000. Spiny forest cover in Andohahela national park remains relatively stable during the observation period, declining by only two tenths of one percent of the area of the park. There is no evidence to suggest that spiny forest cover regenerated in Andohahela national park or in the rest of the study area.

Parts of the national parks closest to each fokontany show stable or slightly increasing tree cover over the study period. In the intersects between each fokontany's five-kilometer buffer and the national park, there is either decline in tree cover of no greater than one percent of total cover or a slight increase. Ankarana special reserve shows a decline in total tree cover in the first half of the study from 73 to 60 percent of total cover, but then this cover stabilizes around 60.5 percent by the year 2000. Around five percent of the reserve is covered in bare rock, and there is significant area of upland agriculture and pasture within the boundary of the reserve.

DISCUSSION

Research questions

This study explores the following questions: how a community's land tenure and its relative security influence land-cover change within its own territory, and how the tenure security of a national park buffer zone community impacts land-cover change in parts of the park adjacent to the community.

The results of this study indicate that the type of land tenure has very little influence on land-cover change but rather that the security of tenure is more important. Table 10 shows each fokontany, it's land tenure system type, level of security, and change in each land-cover type. As is illustrated, the fokontany where land tenure security is reported to be high have the lowest levels of tree cover loss. Although tree cover loss is the largest type of change in all three analysis extents over the study (Table 7), whether that loss was from dense tree cover or sparse tree cover depended on the fokontany (Table 8). Greater loss of dense tree cover primarily took place in Anosivola and Sahamalaza, which started the study duration with the greatest proportion of that type of cover. In national parks, where the state land tenure system is considered secure, there was very minimal land-cover change of any type over the study period. Both customary land tenure (in a fokontany) and state land tenure (in national parks) systems, where land tenure is considered stable, are associated with relatively little change in forest and tree land-cover change during the study period. However, Table 11 also shows that in the two fokontany with land tenure insecurity, there are elevated rates of dense tree cover loss. However, regardless of tenure type or security, change between open land-cover classes is common, with change between shrub/grass and upland agriculture being a significant change type for all classification regions (Table 8).

Table 11: each fokontany, its land tenure system type, level of security, and change in percent of fokontany area for each land-cover type between the beginning and end of the study period. DTC is dense tree cover, STC is sparse tree cover, SG is shrub/grass, UA is upland agriculture, LA is lowland agriculture, BR is bare rock, and SF is spiny forest.

Fokontany	**Land tenure type**	**Land tenure security**	**Land-cover % change**
Ambondrona	Customary	High	DTC: +1.1 STC: -2.1 SG: -3.6 UA: +4.9 BR: -0.02
Andonakaomby	Customary	High	DTC: +0.7 STC: -10.0 SG:-7.9 UA: +17.4 BR: -0.01
Anosivola	Overlapping and conflicting	Medium	DTC: -3.2 STC: +1.9 SG: +5.0 UA: -0.1 LA: -3.4
Sahamalaza	Overlapping and conflicting	Low	DTC: -12.6 STC: -1.5 SG: +15.3 UA: -.002 LA: +0.8
Marohotro	Customary	High	DTC: 0 STC: -2.2 SG: +7.6 UA: +0.56 LA: -3.5 SF: -2.6
Montifeno	Customary	High	DTC: -1.0 STC: +6.7 SG: -3.0 UA: -3.7 LA: -0.5 SF: +1.9

The following sections explore our results in detail and offer additional insight into drivers of land tenure insecurity, study limitations, potential management implications, and potential areas of future research.

Land tenure security and land-cover change

Fokontany that have "overlapping and conflicting" land tenure scenarios and land tenure insecurity (Table 11) display higher rates of tree cover loss during the study period than ones with secure customary tenure systems. The rate of tree cover conversion to open land-cover types is highest in the two fokontany (Anosivola and Sahamalaza) that reported having insecure land tenure. In these communities, tree cover loss follows a pattern of aggregation, with the smallest patches being cleared before larger stands. In both communities it was reported that the overlapping rule systems of the customary tenure system and the newer national land laws have led to a situation where some of the households in the fokontany rely on the customary system's rules regarding access to and rights to use land, while others in the community now claim land under the national land laws. In both fokontany a result is that some households, mainly those who have relied on accessing land through the customary system, believe that their rights to land that they previously used are no longer secure and they had to clear additional forest land in order to continue to earn a living.

In Anosivola, where permanent cultivation techniques such as lowland rice cultivation are feasible and present, there is slower, but substantial, tree cover conversion over the ten-year study period and a significantly slower rate in the latter half. However, in Sahamalaza, reliance on the tavy agriculture systems, which make use of fallow land that was previously cleared for agriculture further compounds the insecurity caused by overlapping tenure systems, since tavy systems are specifically not recognized as a valid form of land use under the national land laws (Ralk 2007, Jarosz 1996). Where households lack confidence in their access to their fallowing swidden plots, they reported in the Land Tenure Center Study that they seek additional land to clear.

Fokontany where a customary rules system allowed for tenure security, and where the primary agricultural activities were cattle raising and lowland rice cultivation, exhibit more stable land-cover during the ten-year period. Marohotro and Montifeno exhibit lower tree cover loss than Anosivola or Sahamalaza.

In Andonakaomby, where land tenure is considered secure and upland rice cultivation is predominant, the tree cover seems to decline in the first half of the study and then stabilize in the second. Although swidden is uncommon in the region, there may still be demand for new land for upland rice and pasture for cattle that resulted in the initial decline. The earliest classification date for the Andonakaomby area also has the lowest overall accuracy of any in the study, so it is possible that the decline is not as pronounced as it appears.

In the case of Ambondrona, where the land tenure security derived from the customary system was reported in the Land Tenure Center Study to have come into question, but the conflict was resolved by the provincial government in a way that reinforced the customary rule system, this study's results show that the land-cover trajectory resembles that of customary tenure where security is reportedly strong; specifically, tree cover in the fokontany remained stable throughout the study period. This is an example of a case in which wider governmental policy can accommodate an existing customary land tenure system, resulting in little tree cover or forest cover loss over time.

Land-cover change between open classes is prevalent, but not predominant, in all three classification sites. Frequent rotation between shrub/grass, upland agriculture, and even sparse tree cover is common, demonstrating the complex and heterogeneous smallholder land-use patterns in rural Madagascar. Plots cultivated for several years identified as upland agriculture in one timestamp may be left to fallow and become shrub/grass land-cover in another, and the reverse is feasible when it is cleared again for cultivation. Additionally, it follows that upland agriculture or shrub/grasslands starts to resemble sparse tree cover as fast-growing tree species or remnant shade trees begin to grow in the fallow land over the ten or fifteen years of this study.

Evidence from the land-cover change analysis in this study indicates that the state tenure system (national land laws) that is enforced in national parks is effective in protecting tree cover within the park boundaries regardless of the type of land tenure system, status of land tenure security, or dominant agricultural practices of surrounding fokontany. The analysis of land-cover change during this study shows negligible loss or gain in tree cover in all three national parks. Furthermore, land-cover change in the intersecting area between the national park boundary and the five-kilometer buffer of fokontany is negligible, regardless of the land tenure system type or land tenure security in the fokontany. The special reserve of Ankarana experienced significant tree cover loss in the first ten years of the study but tree cover did not change in the latter five years. Because of the structure of special reserves, the state tenure system is not as restrictive on how rural communities can access and use natural resources within the protected area, which may explain the reason for the differences in tree cover change seen between the national parks in this study and this special reserve. The continuation of natural resource preservation in special reserves in the country may require continued monitoring, but this type of protected area may offer a more equitable alternative for local communities than national parks and still open the possibility of tourism development as a source of economic activity.

Study limitations

There are a few factors that challenge the generalizability of the findings of this study and limit the interpretation of the results. One consideration is the paucity of satellite imagery for this period in the humid tropics. Due to lower overall image availability and the prevalence of clouds in the scenes, classifications done for the initial time period of the study (e.g. 1985 and 1990) for Montagne d'Ambre and Zahamena analysis extents relied on relatively few images. This possibly explains much of the observed change to or from the water cover type, which should theoretically remain stable on the landscape. The classification of some cloud remnants as water, particularly in the first two timestamps of the Zahamena classification region is possibly causing this. However, no other images were available and cloud cover was primarily in the eastern portion of the image and national park. Because the fokontany studied are located in the west and southwest of the national park and the interpretation of land-cover change is limited mainly to the fokontany and the national park, this amount of cloud cover was deemed acceptable. In the Andohahela classification extent, the high proportion of the pixels in the 'change involving water' category was likely due to the following factor. Accuracy for the land-cover classification of this analysis extent was the highest amongst the three, which likely lead to lower change in tree cover loss, tree cover gain, or open cover rotation. This, in turn, lead to a higher proportion of the change pixels belonging to 'change involving water'. Another limitation of having limited imagery is that it lowers the temporal and seasonal variation on which the random forest classifier makes predictions, potentially making it more challenging to discern between specific vegetation classes. For this reason, this study did not attempt to classify fallow tavy plots versus grassland used as pasture for livestock. The land, particularly in Sahamalaza, that is part of a tavy cultivation system based on surveys in the fokontany is thus categorized as shrub/grassland in the classification results.

The low number of fokontany in this study also limits the strengths of the conclusions that can be drawn regarding the impact of the different land tenure systems across the whole island. Surveys from the Land Tenure Center team took a year to complete, and for this reason, it would not be feasible to categorize large portions of Madagascar in the same fashion. However, examining the land-cover of additional fokontany with insecure land tenure rights would provide more insight into the associated land-cover change patterns in communities with different compositions of land-cover.

Broader implications

This study is not unique in its examination of the land tenure land-cover change relationship, but it is the first of such to take place in Madagascar. Findings presented here concur with other studies suggesting a link between secure land tenure and lower rates of forest loss (Alemie and Amsalu 2020, Robinson et al 2014, Wannasai and Shrestha 2008). However, this study identifies an additional connection between swidden agriculture, land tenure insecurity, and tree cover loss. Swidden systems worldwide are threatened by government changes to land laws, migration, and global market pressures which may displace practitioners and limit the sustainability of the practice (Lawrence et al 2010, Meyfroidt et al 2013).

The difficulty of obtaining nearly cloud-free imagery is not unique to Madagascar and can be a consistent barrier to the remote sensing of tropical vegetation (Sano et al 2007, Shiraishi et al 2014), but by taking appropriate measures and carefully selecting imagery, the classifications in this study achieve high accuracies that are required for post-classification change detection (Lu et al 2004), allowing for an analysis of the relationship between land tenure systems, land tenure security, and land-cover change.

The land-cover maps show that tree cover is declining across the whole of the three classification extents. Other inventories of forest cover in Madagascar confirm this trend (Grinand et al 2013, Harper 2007, Nelson and Horning 1993). Furthermore, there is little to suggest in our results that there is net tree cover gain outside of the national park boundaries, which seems to confirm broader examinations of the country's forest cover that found little evidence of forest regeneration across the country (Harper et al 2007, Vieilledent 2018). In the context of the fokontany, the lack of dense tree cover regeneration could be for various reasons. Firstly, it is likely that community members are limiting tree cover around agricultural plots or planting smaller patches of fruit trees for personal use. A more underlying reason is that soils in Madagascar are quite poor, so after land has been cleared for cultivation or pasture, it is unlikely that soils are able to support native forest communities in the short-term. The expansion of sparse tree cover in both fokontany of both insecure and secure land tenure could be a result of the thinning of dense tree cover, or the planting of trees for personal use by community members.

Furthermore, this examination of land-cover trajectories for each fokontany supports findings from other countries that suggest tenure insecurity as an important factor driving land-cover change, specifically forest conversion to other land-covers (Robinson et al 2014, Wannasai and Shrestha 2008). It is important to note the association of land tenure insecurity with the practice of swidden rice cultivation in this study, but Leisz et al (1995) also found that a lack of confidence in land tenure security can be caused by interpersonal conflict from within or outside of a community. Where customary tenure systems overlaps with state tenure systems, local elites or powerful outsiders may try to use the newly implemented system to gain an advantage in access to land already regulated by the local system (Higgins et al 2018), and this was the main driver of land tenure insecurity according to survey respondents in Anosivola (Leisz et al. 1995).

The stability of tree cover found in the three national parks during the study period gives further credibility to more recent findings suggesting that protected areas across the country are effective in limiting forest loss (Eklund et al 2019). In the special reserve of Ankarana, a moderate loss of tree cover is observed when compared to fokontany with similar starting land-cover during the study period, but it experiences a greater amount than any of the national parks in the study, suggesting that the reserve is still somewhat successful at slowing forest conversion. Other studies confirm the importance of special reserves in achieving conservation goals in Madagascar (Waeber et al 2019, Eklund et al 2019), and the more flexible structure of this type of protected area may result in more equitable outcomes for communities that rely on forest resources, and thus less conflict with the governance of the protected area.

The results of this study confirm the effectiveness of protected area buffer zones at limiting impacts to national parks, since it appears that forest cover inside the national parks has not decreased and actually has increased in some of the parks. However, this appears to have come at the cost of there being very limited amounts of remaining forest cover surrounding both Montagne d'Ambre and Andohahela national parks, while the remaining forest cover to the south of Zahamena declined at substantial rates in Sahamalaza and in the adjacent corridor of tree cover to the south. Buffer zone status outside of the core protected area seems to have had limited success in the preservation of habitat and natural resources outside of the park boundaries. A recent examination of buffer zones in Brazil confirms this problem, and even shows that buffer zones are nearly as degraded as areas with no protection (Almeida-Rocha and Peres 2021). If buffer zones are to function as intended, they likely need greater enforcement of resource use restrictions so that national parks do not become 'forest and resource islands'.

Possible management implications

In the late 1990s and early 2000s, the Malagasy government created new legal frameworks to transfer forest and natural resource governance to local communities called *Géstion Local Sécurisée* (GELOSE) and Géstion Contractualisée des Forêts (GCF). One of the goals of these new policies was to limit land tenure conflicts, but there is a question regarding whether the framework's implementation has actually led to equitable community governance (Ralk 2007, Pollini 2011). Pollini and Lassoie (2011) contend that some problems associated with the framework were caused "by creating new institutions instead of strengthening existing ones…". For this reason, if federal or regional policy can be crafted to make space for highly variable customary tenure systems that have significant community confidence, it may go a long way to reinforce tenure security against future shocks or conflict.

Another possible path to resolve land tenure security is through the formalization of property rights, usually done through titling. Because customary tenure in Madagascar contains both private and communal access to different types of land, there could be a titling program that accommodates both types of property rights. Presently, no community titling system is in place in Madagascar, but allowing a fokontany to gain a collective title to land or natural resources within their borders could help to improve levels of security and increase the community's investment in land, by dejure, through the fokontany land title reinforcing the fokontany's customary land tenure system.

Although not novel, the link identified by this study between insecure land tenure security, expanding tavy cultivation, and forest conversion, have important implications for both Malagasy policymakers and the myriad of foreign development interests in Madagascar. Although tavy has been historically and presently discouraged in numerous ways, the practice will continue to take place due to its cultural importance (Raik 2007, Jarosz 1996). For this reason, the legitimization of swidden (tavy) rice cultivation through governmental codification could lead to securing the land tenure rights of its practitioners. This, in turn, could help limit the need to clear additional forests, allowing farmers to rely on existing fallows whose uncertain status is the cause of land conflict in some of the fokontany of this study.

Additionally, the link between insecure land tenure, swidden (tavy), and forest conversion identified here should provide incentive for development projects to be more targeted. Agricultural and technological innovations brought to a community that practices swidden in a way that provides an alternative/improvement, such as improved fallow, without discouraging it could offer a pathway to the adoption of more sustainable cultivation practices. In this study, Sahamalaza lies within an important ecological corridor connecting humid forest in Zahamena to other intact humid forest remnants further south that are known as the Ankeniheny-Zahamena corridor in the protected areas system (Rajaspera et al 2011, Rosimeiry et al 2012). This corridor represents a large portion of the remaining protected rainforests in the eastern part of the country and is under considerable pressure from timber extraction and agricultural expansion. Slowing tree cover loss in Sahamalaza would improve the connectivity between protected parcels of rainforest. Targeting communities where swidden is known to be prevalent in particularly sensitive ecological areas offers the best return on investment for conservation initiatives.

One such threatened ecosystem that is particularly concerning is the spiny forest in the south of Madagascar near Andohahela and the study fokontany of Marohotro. Due to the biology of plants and soils in arid habitats, the regeneration of spiny forest after being cleared takes place very slowly and does not regenerate as readily as humid forest in the country, leaving the land particularly vulnerable to degradation (Neudert et al 2018). For this reason, the spiny forest cover loss observed in and near Andohahela and the fokontany of Marohotro is particularly concerning. The conservation of spiny forest should be a priority for land managers and international NGOs, and to do this, one important step is to secure land tenure for fokontany in areas of encroachment.

Results showing significant deforestation outside of the national parks also raise the concern that national parks are becoming isolated islands of wildlife habitat that export deforestation that might've happened within their borders to the park buffer (Ford et al 2020, Fuller et al 2019). Although this study is not designed to identify potential spillover effects from the national parks on the buffer zone, the higher rate of tree cover loss in the buffer of Zahamena national park, where there was a much higher starting tree cover level than the other parks, seems to suggest that this is a distinct possibility. Following the Durban Vision in 2003, the government of Madagascar pledged to triple the area of protected areas in the country (Duffy 2008), so any new protected area implementation should be designed to better preserve buffer zone resources.

Future research

The relationship between land tenure security and land-cover change is likely one part of a complex group of factors that drove the observed dynamics. Further exploration would help clarify the results seen in this study.

Almost thirty years have passed since the survey of these fokontany by Leisz et al. (1995), so there may have been substantial change in the agricultural activities, property rights, or tenure security after the duration of this study. Follow-up surveys and corresponding land-cover observations would give a longer trajectory of change for each site, and it would yield insight into any significant deviation from the pattern observed here. This would allow a researcher to look at any potential impact of GELOSE or GCF implementation in these communities.

Because of the threat of national parks becoming isolated patches of natural resources, monitoring the health of the corridor between these spaces and other habitat or protected areas is crucial for the long-term health of wildlife. For this reason, it would be interesting to examine the effect of land tenure of the fokontany in the corridor on connectivity and land-cover change. This would aid in the prudent design of new protected area systems in Madagascar.

Land tenure systems could also be categorized differently. Leisz et al (1995) discretely classified both land tenure system type and security, but it would be useful in future studies to measure the degree of tenure security in each fokontany by having survey respondents measure the confidence of their access to land and resources on a scale. This would allow for useful correlations between security and different agricultural practices in addition to land-cover.

This study also does not offer insight into the land-cover change - land tenure security link outside of the context of protected area buffers. The long-term success of protected areas is important to ensure conservation goals, but as of 2016, only 12.1% of Madagascar is protected (Gardner et al 2018), so an examination of the land tenure security - land-cover change link outside of the context of a national park buffer zone could yield important insight for land management more widely.

Conclusion

The goal of this research was to explore two main questions. Firstly, how does a community's land tenure system and its security influence land-cover change? The results of this study show that land tenure insecurity is linked to higher tree cover loss, although there is considerable change involving other cover types regardless of land tenure security. Finally, for communities in the periphery of protected areas, how does the land tenure system and its land tenure security influence land-cover change in national parks? Stable land-cover in each of the national parks nearest the communities in this study indicates that land tenure security in each community has little impact on the protected area. Because of the potential for land tenure insecurity to drive forest loss in Madagascar, reinforcing local customary tenure systems should be a priority to protect the country's uniquely threatened biodiversity and to enable the community management of local land and natural resources. Additional effort to link land tenure systems, land tenure security, and land-cover change in the country should seek to increase the diversity of land-cover composition and agricultural activities of the surveyed communities to reinforce the results of this study. This will aid in the formation of prudent land management strategy and the promotion of just outcomes for communities that continue to rely on land to meet everyday needs.

Conflict of Interests

The author declares no conflict of interests.

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Appendix 1: Accuracy matrix for each of the nine classifications. Three for each of the analysis extents. They start in the northern part of the country with the Montagne d'Ambre classification extent, and continue with the Zahamena extent, and finally the Andohahela extent. Each extent starts with the earliest date and proceeds to the latest.

Montagne d'Ambre, 1985

		Truth Data							
		Dense Tree Cover	Sparse Tree Cover	Shrub/Grass	Water	Upland Agriculture	Bare Rock	Sum	User's Accuracy
Classification	Dense Tree Cover	59	1	0	2	0	0	62	0.951613
	Sparse Tree Cover	0	74	4	0	9	0	87	0.850575
	Shrub/Grass	0	4	91	1	4	0	100	0.91
	Water	0	0	0	89	0	0	89	1
	Upland Agriculture	0	11	2	1	107	0	121	0.884298
	Bare Rock	0	0	0	0	0	36	36	1
Sum		59	90	97	93	120	36	Overall Accuracy:	
Producer's Accuracy		1	0.822222222	0.93814433	0.956989	0.891666667	1	0.921212121	

Montagne d'Ambre, 1995

		Truth Data							
		Dense Tree Cover	Sparse Tree Cover	Shrub/Grass	Water	Upland Agriculture	Bare Rock	Sum	User's Accuracy
Classification	Dense Tree Cover	64	0	0	0	0	0	64	1
	Sparse Tree Cover	0	79	0	1	5	0	85	0.929412
	Shrub/Grass	0	7	95	1	3	0	106	0.896226
	Water	0	0	0	85	0	0	85	1
	Upland Agriculture	1	8	0	1	113	0	123	0.918699
	Bare Rock	0	0	0	0	0	32	32	1
Sum		65	94	95	88	121	32	Overall Accuracy:	
Producer's Accuracy		0.984615385	0.840425532	1	0.965909091	0.933884298	1	0.945454545	

Montagne d'Ambre, 2000

		Truth Data							
		Dense Tree Cover	Sparse Tree Cover	Shrub/Grass	Water	Upland Agriculture	Bare Rock	Sum	User's Accuracy
Classification	Dense Tree Cover	59	0	0	0	0	0	59	1
	Sparse Tree Cover	0	86	0	1	4	0	91	0.945055
	Shrub/Grass	0	2	81	1	2	0	86	0.94186
	Water	0	0	0	94	1	0	95	0.989474
	Upland Agriculture	0	8	1	0	115	0	124	0.927419
	Bare Rock	0	0	0	0	0	40	40	1
Sum		59	96	82	96	122	40	Overall Accuracy:	
Producer's Accuracy		1	0.895833333	0.98780488	0.979167	0.942622951	1	0.95959596	

Zahamena, 1990

		Truth Data							
		Dense Tree Cover	Sparse Tree Cover	Shrub/Pasture	Water	Irrigated Agriculture	Upland Agriculture	Sum	User's Accuracy
Classification	Dense Tree Cover	135	4	4	2	0	0	145	0.931034
	Sparse Tree Cover	0	79	7	0	3	0	89	0.88764
	Shrub/Grass	1	9	110	4	13	4	141	0.780142
	Water	1	0	0	62	0	0	63	0.984127
	Irrigated Agriculture	0	4	7	0	107	0	118	0.90678
	Upland Agriculture	0	0	2	0	0	88	90	0.977778
Sum		137	96	130	68	123	92	Overall Accuracy:	
Producer's Accuracy		0.98540146	0.822916667	0.846153846	0.911765	0.869918699	0.956521739	0.899380805	

Zahamena, 1995

		Truth Data							
		Dense Tree Cover	Sparse Tree Cover	Shrub/Pasture	Water	Irrigated Agriculture	Upland Agriculture	Sum	User's Accuracy
Classification	Dense Tree Cover	137	1	1	1	0	0	140	0.978571
	Sparse Tree Cover	0	81	10	0	6	0	97	0.835052
	Shrub/Grass	3	6	110	2	2	5	128	0.859375
	Water	0	0	0	74	0	0	74	1
	Irrigated Agriculture	2	3	3	0	96	0	104	0.923077
	Upland Agriculture	0	0	0	0	0	103	103	1
Sum		142	91	124	77	104	108	Overall Accuracy:	
Producer's Accuracy		0.964788732	0.89010989	0.887096774	0.961039	0.923076923	0.953703704	0.930340557	

Zahamena, 2000

		Truth Data							
		Dense Tree Cover	Sparse Tree Cover	Shrub/Pasture	Water	Irrigated Agriculture	Upland Agriculture	Sum	User's Accuracy
Classification	Dense Tree Cover	139	1	1	1	0	0	142	0.978873
	Sparse Tree Cover	0	84	5	0	3	0	92	0.913043
	Shrub/Grass	0	9	120	0	3	1	133	0.902256
	Water	0	0	0	78	1	0	79	0.987342
	Irrigated Agriculture	0	3	1	0	106	0	110	0.963636
	Upland Agriculture	0	0	2	0	0	88	90	0.977778
Sum		139	97	129	79	113	89	Overall Accuracy:	
Producer's Accuracy		1	0.865979381	0.930232558	0.987342	0.938053097	0.988764045	0.952012384	

Andohahela extent, 1990

		Truth Data								
		Dense Tree Cover	Sparse Tree Cover	Shrub/Pasture	Water	Irrigated Agriculture	Upland Agriculture	Spiny Forest	Sum	User's Accuracy
Classification	Dense Tree Cover	68	1	0	0	0	0	1	70	0.971429
	Sparse Tree Cover	0	86	4	0	2	3	9	104	0.826923
	Shrub/Grass	0	3	103	0	0	1	1	108	0.953704
	Water	0	0	0	93	0	0	0	93	1
	Irrigated Agriculture	0	1	2	3	109	1	0	116	0.939655
	Upland Agriculture	0	0	0	0	0	92	0	92	1
	Spiny Forest	0	7	1	0	0	0	122	130	0.938462
Sum		68	98	110	96	111	97	133	Overall Accuracy:	
Producer's Accuracy		1	0.87755102	0.936363636	0.96875	0.981981982	0.948453608	0.917293233	0.943899018	

Andohahela extent, 1995

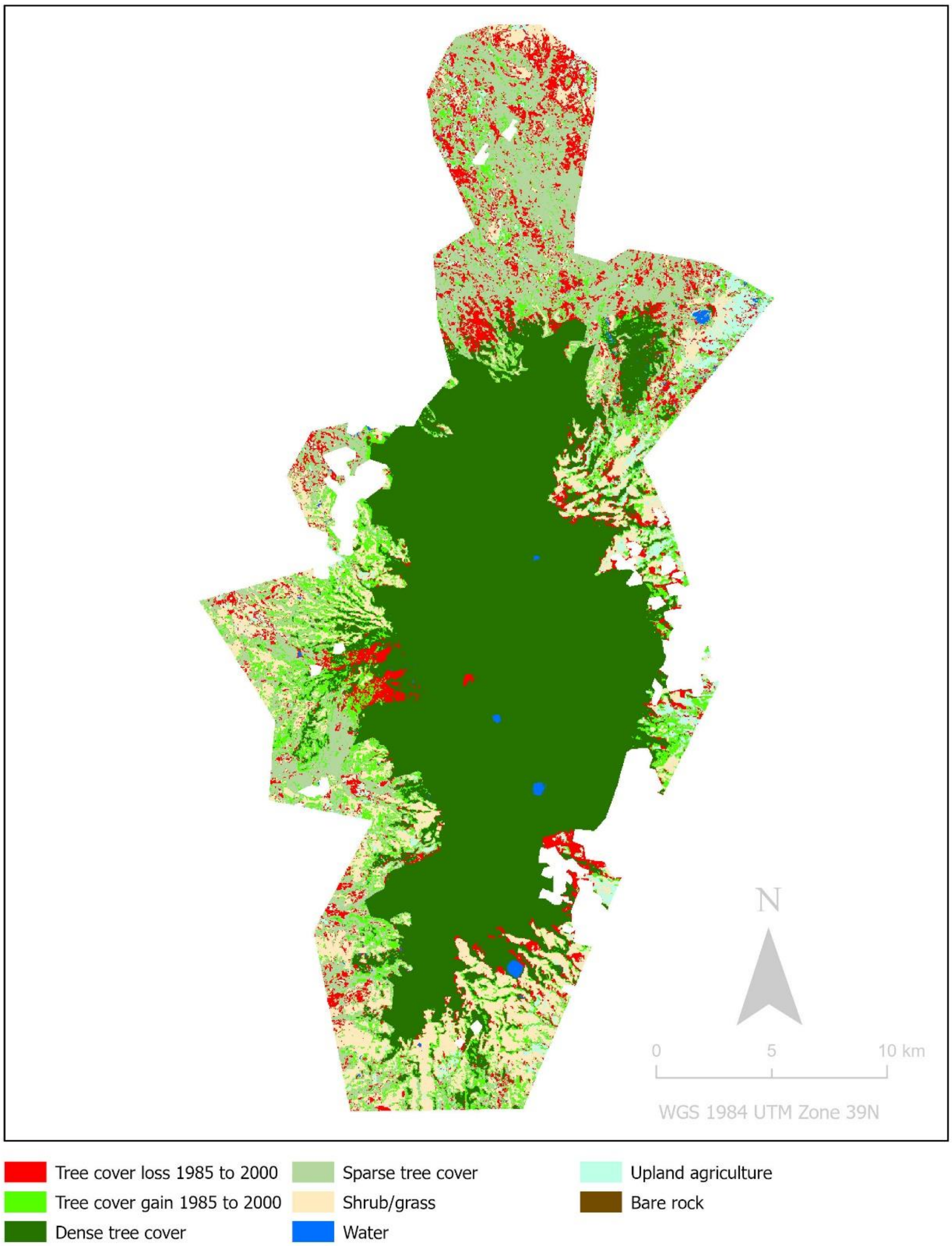
		Truth Data								
		Dense Tree Cover	Sparse Tree Cover	Shrub/Pasture	Water	Irrigated Agriculture	Upland Agriculture	Spiny Forest	Sum	User's Accuracy
Classification	Dense Tree Cover	81	0	0	0	0	0	0	81	1
	Sparse Tree Cover	2	87	5	0	4	1	1	100	0.87
	Shrub/Grass	0	1	95	0	1	1	1	99	0.959596
	Water	0	0	0	94	1	0	0	95	0.989474
	Irrigated Agriculture	0	3	1	6	81	0	0	91	0.89011
	Upland Agriculture	0	3	3	0	0	94	1	101	0.930693
	Spiny Forest	1	4	0	0	0	1	140	146	0.958904
Sum		84	98	104	100	87	97	143	Overall Accuracy:	
Producer's Accuracy		0.964285714	0.887755102	0.913461538	0.94	0.931034483	0.969072165	0.979020979	0.942496494	

Andohahela extent, 2000

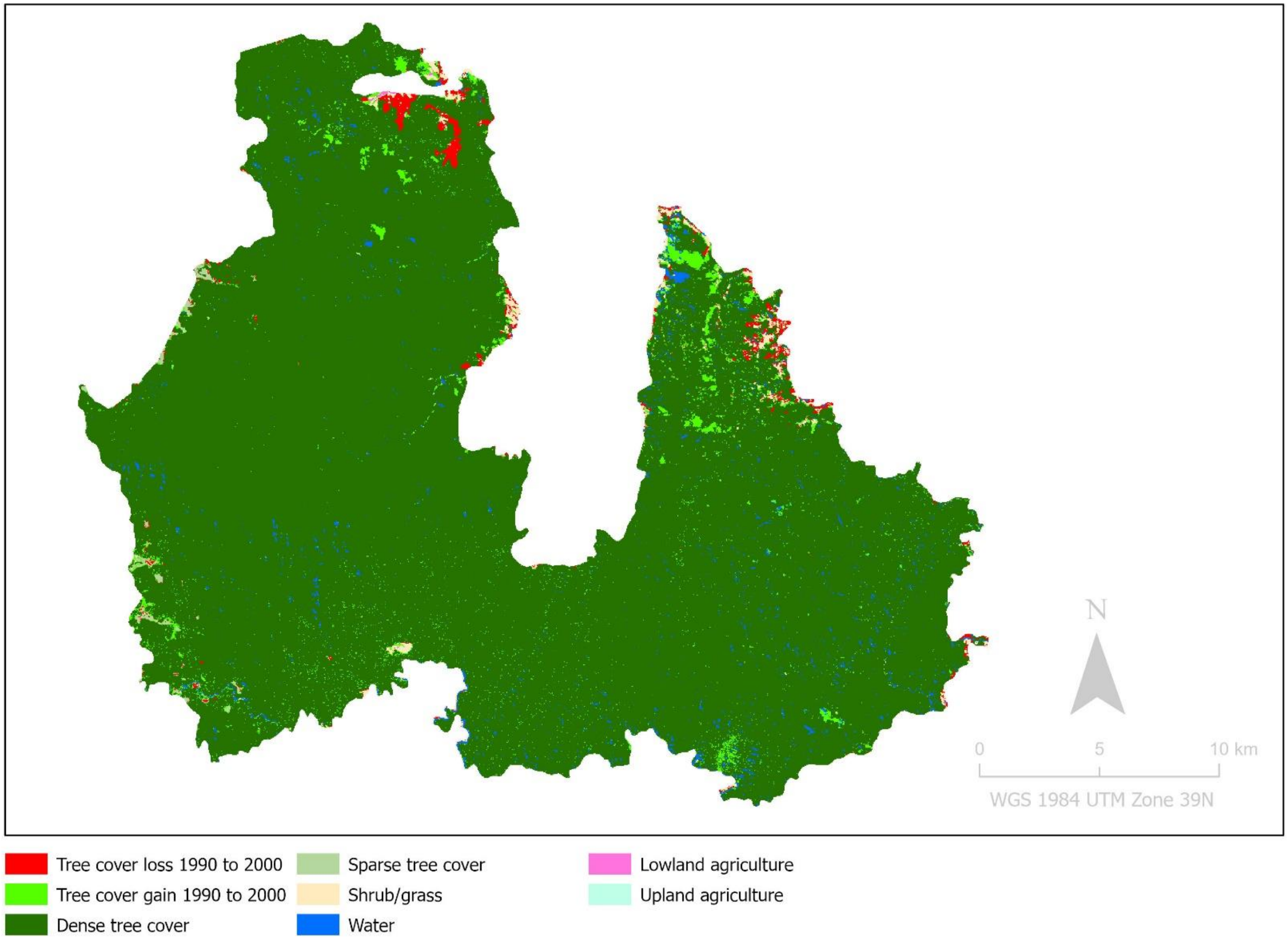
		Truth Data								
		Dense Tree Cover	Sparse Tree Cover	Shrub/Pasture	Water	Irrigated Agriculture	Upland Agriculture	Spiny Forest	Sum	User's Accuracy
Classification	Dense Tree Cover	78	0	0	0	0	0	0	78	1
	Sparse Tree Cover	0	91	9	0	2	5	3	110	0.827273
	Shrub/Grass	0	1	99	0	2	0	3	105	0.942857
	Water	0	0	0	92	1	0	1	94	0.978723
	Irrigated Agriculture	0	1	0	1	106	0	0	108	0.981481
	Upland Agriculture	0	0	4	0	1	84	0	89	0.94382
	Spiny Forest	0	1	3	0	0	1	123	128	0.960938
Sum		78	94	115	93	112	90	130	Overall Accuracy:	
Producer's Accuracy		1	0.968085106	0.860869565	0.989247312	0.946428571	0.933333333	0.946153846	0.945224719	

Appendix 2: Change maps for each of the national parks. Arranged in order from north to south starting with Montagne d'Ambre, then Zahamena, and finally Andohahela national park.

Montagne d'Ambre land-cover change 1985 to 2000



Zahamena land-cover change 1990 to 2000



Andohahela land-cover change 1990 to 2000