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# Forest Landscape Change Detection in the Meseta Purépecha, Michoacán, México

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THESIS APPROVAL

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ABSTRACT

An abstract of the thesis of John Malcolm Chase for the Master of Science in Geography presented April 29, 2002.

Title: Forest Landscape Change Detection in the Meseta Purépecha, Michoacán, México.

Social, political, economic, and environmental factors converge in developing countries to stimulate high rates of deforestation. Forest conversion reduces biodiversity, contributes to carbon loading of the atmosphere, alters the global water balance, and degrades the quality of life for rural people. México is the fifth most biologically diverse country in the world and temperate and tropical forests in México are rapidly disappearing with environmental and cultural repercussions for people and ecosystems.

This study examines changes in the forest landscape surrounding two *communidades indígenas* in Michoacán, México over a 15-year period. The research area includes communal forest, pasture, and agricultural land within the adjacent municipal boundaries of two Purépecha Indian communities: Sevina and San Francisco Pichátaro. The economies of both villages depend in part on wood products manufacturing with timber harvested in local mixed-pine forests. As a result, forest

landscapes surrounding the towns are at risk for potentially rapid land cover change and environmental degradation.

Remotely sensed digital satellite images (Landsat Thematic Mapper), government forest maps, air photos, and ecological sample data collected in the region were compiled, registered, and analyzed. Supervised classifications of the imagery were compared to detect changes in forest and non-forest land cover classes between 1986 and 2000. A change image shows the location and extent of landscape transformation during the period of interest.

Post-classification comparison of the imagery indicates Sevina converted more than 40% of its forest to non-forest land cover and Pichátaro, 7% of its forest. Pichátaro experienced more vegetation regeneration than Sevina. Distinct spatial patterns of deforestation and vegetation re-growth emerge from the image change map. Sevina exhibits large contiguous regions of deforestation while the pattern in Pichátaro is more evenly dispersed.

This research is useful for assessing the impact of current forest management practices in the study area. It contributes to planning future harvest strategies, replanting programs, and conservation measures by local stakeholders. The change detection process is transferable to a variety of cultural and environmental situations where forest landscapes and the people who depend on them are at risk.

FOREST LANDSCAPE CHANGE DETECTION IN THE

MESETA PURÉPECHA, MICHOACÁN, MÉXICO

by

JOHN MALCOLM CHASE

A thesis submitted in partial fulfillment of the
requirements for the degree of

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in
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| | |
|---|---|
| COFOM | *Comisión Forestal del Estado de Michoacán* (Forestry Commission of Michoacán, México) |
| CFE | Communal Forestry Enterprise |
| dbh | Diameter at breast height |
| DEM | Digital elevation model |
| EMR | Electromagnetic radiation |
| ERDAS | Earth Resource Data Analysis System |
| ETM | Enhanced Thematic Mapper |
| ETM+ | Enhanced Thematic Mapper plus |
| UTM | Universal Transverse Mercator |
| GATT | General Agreement on Trade and Tariffs |
| GCP | Ground control point |
| GIS | Geographic information system |
| GPS | Global positioning system |
| INEGI | *Instituto Nacionál Estadística Geografía y Informática* (National Institute of Geographic Statistics and Information) |
| Landsat | Land Observation Satellite |
| NAFTA | North American Free Trade Agreement |
| NAD 27 | North American Datum 1927 |
| RMS | Residual mean square |
| WRS | World Reference System |

# CHAPTER 1: INTRODUCTION

The global environment is undergoing rapid systemic transformation. The realization that humans are the main catalyst for that change is not new. Pre-historic and ancient human modifications of the environment have fluctuated with the rise and fall of civilizations, punctuated by periods of reversal and ecological regeneration (Marsh 1864; Deneven 1992). At present, the magnitude of human interference with the physical environment appears to have out-paced the transformational power of natural systems.

The historic human ability to alter landscapes at local and regional scales has become elevated to global proportions with the development of a fossil-fuel-based industrial society over the past 300 years (Kates et al. 1990). Forested landscapes are an important component of the global ecosystem and deforestation is an instrument of globally cumulative change (Meyer and Turner 1995). As the magnitude of human-induced change increases, so does the vulnerability of the world's forests.

The process of deforestation as an agent of global change is long established and accelerating (Kates et al. 1990). Forest removal results in biotic carbon emissions, creating a strong link to global change via the atmosphere (Houghton et al. 1991). Rates of tropical deforestation nearly doubled during the 1980's causing the global increase in biotic carbon emissions to exceed the growth in fossil fuel emissions

(Myers 1989). The removal of forest cover has negative effects on the availability of fuel wood for household heating and cooking, the integrity of soil and water resources, and the quality of rural life (Adger et al. 1995). Deforestation degrades genetic resources, reduces biological diversity, accelerates soil erosion, and adversely affects the global water budget (Allen and Barnes 1985).

Deforestation is a major concern for developing countries. The pace of deforestation in México, like other emerging nations that control forest resources, is accelerating. México is rapidly losing its remaining closed forests with rates of deforestation during the 1980's estimated between 365,000 ha to 1.5 million ha annually (Adger et al. 1995; Barbier and Burgess 1996). Rates vary by forest type, and tropical forests are believed to be under the greatest pressure. Masera (1992) estimates the rate for temperate coniferous forests at 0.64% and tropical evergreen at 2.0%. México ranks fourth globally behind Brazil, Indonesia, and Zaire for tropical deforestation (Cairns et al. 1995).

The most commonly cited anthropogenic causes of deforestation in developing countries are clearing for agriculture and pasture, logging, and fuel wood cutting (Allen and Barnes 1985; Barbier and Burgess 1996). The drivers behind these cultural practices are less easily defined social, economic, and political forces. Stimuli promoting deforestation in developing countries include population pressure, national debt, land tenure, private property rights, governmental natural resource policy, and political stability (Gibson et al. 2000).

México controls vast regions of forest suitable for commercial exploitation. México's 191 million hectare (ha) land area contains approximately 26% closed forest or 49.7 million ha (Masera et al. 1992). Of the total forest area, 25.5 million ha is classified as temperate forest located in the mountainous regions of the country, and 24.2 million ha is broadleaf humid forest located in the south and southeast (Adger et al. 1995, Barbier and Burgess 1996). Approximately 25% of the forests are privately held while 70% are controlled by *ejidos* and 5% by indigenous *communidades* (Silva 1997; Castillo and Toledo 2000).

México's forests have come under increasing pressure following the modification of Constitutional Article 27, passage of the 1992 Forestry Law, and the North American Free Trade Agreement (NAFTA) (Adger et al. 1995; Menotti 1998). These three events substantially expanded the private forestry sector by allowing the sale of communally held lands, encouraging *ejidos* and *communidades* to enter joint ventures with private industry, and privatizing governmental forestry engineering services (Bray and Wexler 1996; Silva 1997). The consequences of such market liberalizations and changes in land tenure systems may prove detrimental to the future sustainability and success of local forest production and management in México.

Michoacán ranks second in importance among Mexican states with extensive amounts of subhumid temperate vegetation. The forests of the Meseta Purépecha are among the most biologically diverse subhumid temperate mixed-pine and oak forests in the world. They thrive on the cool, moist slopes of eroded tertiary volcanoes surrounding flat-floored agricultural valleys inhabited by the Purépecha since Pre-

Columbian times. The forests contain several species of pine, many oaks, alder, and true fir. They provide habitat for high levels of biological diversity and endemism in flowering plants, mammals, amphibians, reptiles, and terrestrial vertebrates (Toledo and Ordóñez 1993).

The purpose of this investigation is to determine the extent of deforestation that occurred within two Purépecha Indian *communidades* in central México over a 15-year period. The study relies on remote sensing and GIS technology to analyze forest change within an ecological framework. The analysis consists of classifying two Landsat (Land Observation Satellite) Thematic Mapper (TM) satellite images for forest and non-forest land cover categories, then comparing the two land cover maps to determine the amount of deforestation that occurred between 1986 and 2000. GIS and remote sensing technology provide tools for the assessment and analysis of our rapidly changing environment. When used within a landscape and cultural ecological framework these tools improve our ability to evaluate the amount and direction of social and environmental change. A better understanding of how and why the natural world is changing presents the opportunity to plan for future sustainability of social and natural systems from local to global scales.

The villages of Sevina and San Francisco Pichátaro are located in the Meseta Purépecha, in the state of Michoacán, México (Figure 1.1). Both villages are indigenous Purépecha communities with federally sanctioned land rights. In both communities forest, pasture, and agricultural parcels are held privately and communally. The economies of both villages are bolstered by a combination of timber/lumber production and furniture/wood products manufacturing. The communities share a common municipal boundary and their town centers are located about 12 km apart (Figure 1.2).

Changes in trade and forestry policy and enhanced access to external markets created a recent boom in lumber and furniture production in the region. Sevina and Pichátaro were thrust into modern markets exposing their community forests to the consequences of profit driven resource extraction. Traditional, sustainable forest resource use is being traded away for short-term gain in a boom or bust cycle of commercial exploitation. Workers who migrated to find jobs elsewhere have returned to Pichátaro to participate in the growth and profits the local industry recently experienced. Sevina experienced this cycle when its forests were cleared in the 1990's to supply sawmills and can no longer participate in the boom because of a depleted resource base. Pressure on Pichátaro's forests is growing and the dominant activities in the forest in terms of altering the structure and function of the ecosystem are logging and grazing. Access to regional markets and modern consumer goods contributes to forest degradation in the region.

This thesis is part of a larger investigation of forest ecology and landscape change in the Meseta Purépecha focused on better understanding the political, economic, and cultural forces shaping forest resource use in the region (Works and Hadley forthcoming). The condition and composition of the Meseta's pine forests are linked to the socio-economic well being of local indigenous groups who manage them. A deeper understanding of vegetation dynamics in the region's forests contributes to informed decisions about how future resource use will affect the stability of local communities, and the forest environment they depend on. Additionally, an improved concept of how cultural activities affect forest ecology and the sustainability of timber harvest contributes to enhanced forest stewardship by local stakeholders.

Few studies have examined spatial landscape change and vegetation dynamics in temperate subhumid forest ecosystems (Mladenoff et al. 1993; Velázquez et al. 2000). This research aids future assessment of forest change and serves as an historical snapshot in time for comparison purposes. Research plots established on the ground in 2000 can be revisited in the future with the digital mapping, GIS, and GPS technology used by the study.

The results of my change detection study can also contribute to more thoughtful programs of harvest, production, and conservation for local people who rely on the forests culturally and economically. Whereas tropical and temperate forests have been studied extensively with remotely sensed imagery, few studies have examined satellite data from temperate subhumid forests to estimate deforestation and temporal-spatial landscape change. Such results are useful for resource managers who make decisions about land use policies, harvest practices, reforestation activities, and conservation measures.

Currently no study of forest landscape dynamics for the communities of Sevina and Pichátaro exists. This research offers a benchmark for additional evaluations of natural resource use and sustainability in the region. The study provides local resource managers with a baseline against which to compare their forest landscape in the future. The land cover maps produced by classifying and comparing satellite images from 1986 and 2000 allow extended appraisals of deforestation and forest regeneration.

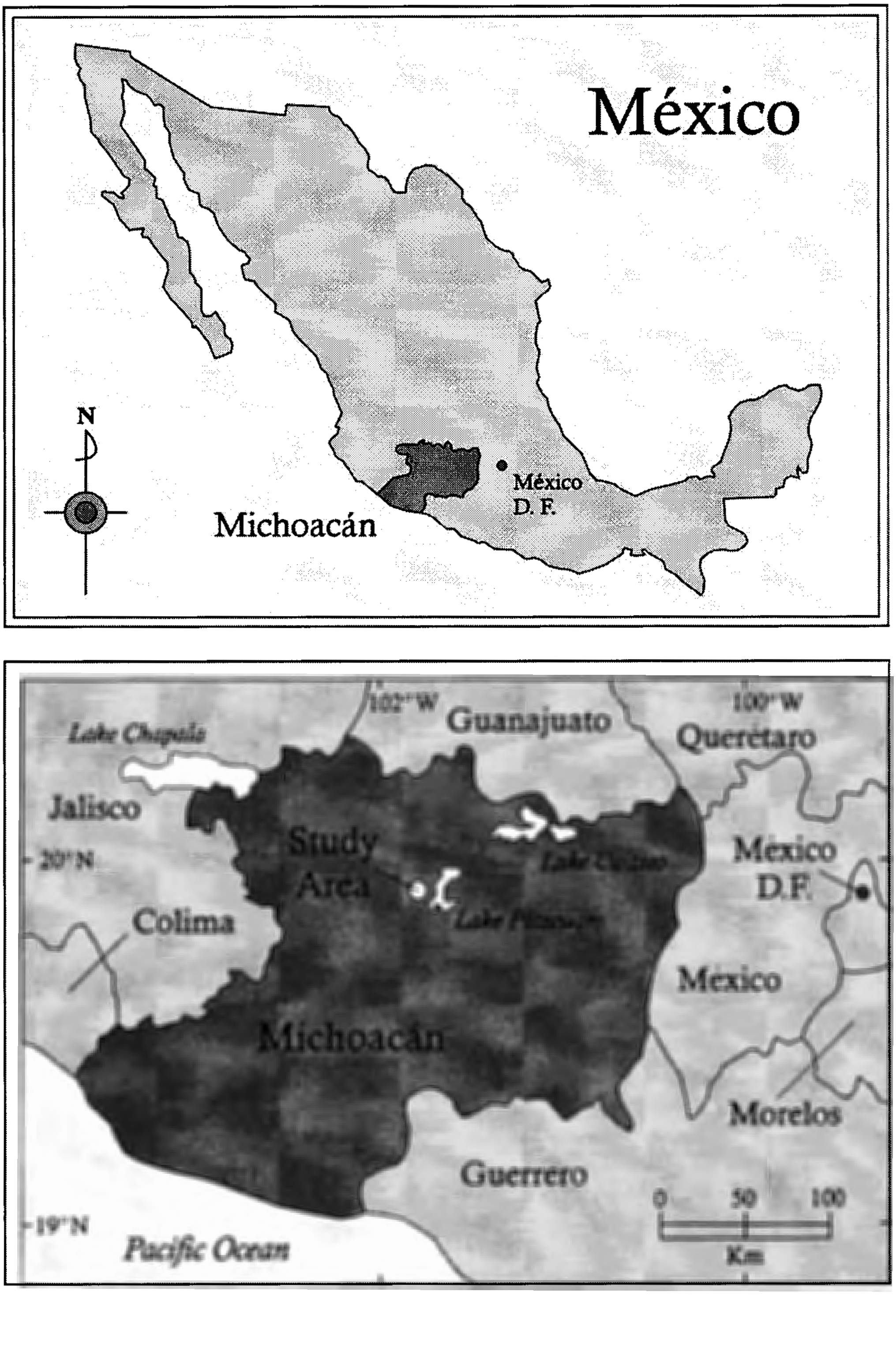


**Figure 1.1.** Relative location of the study area.

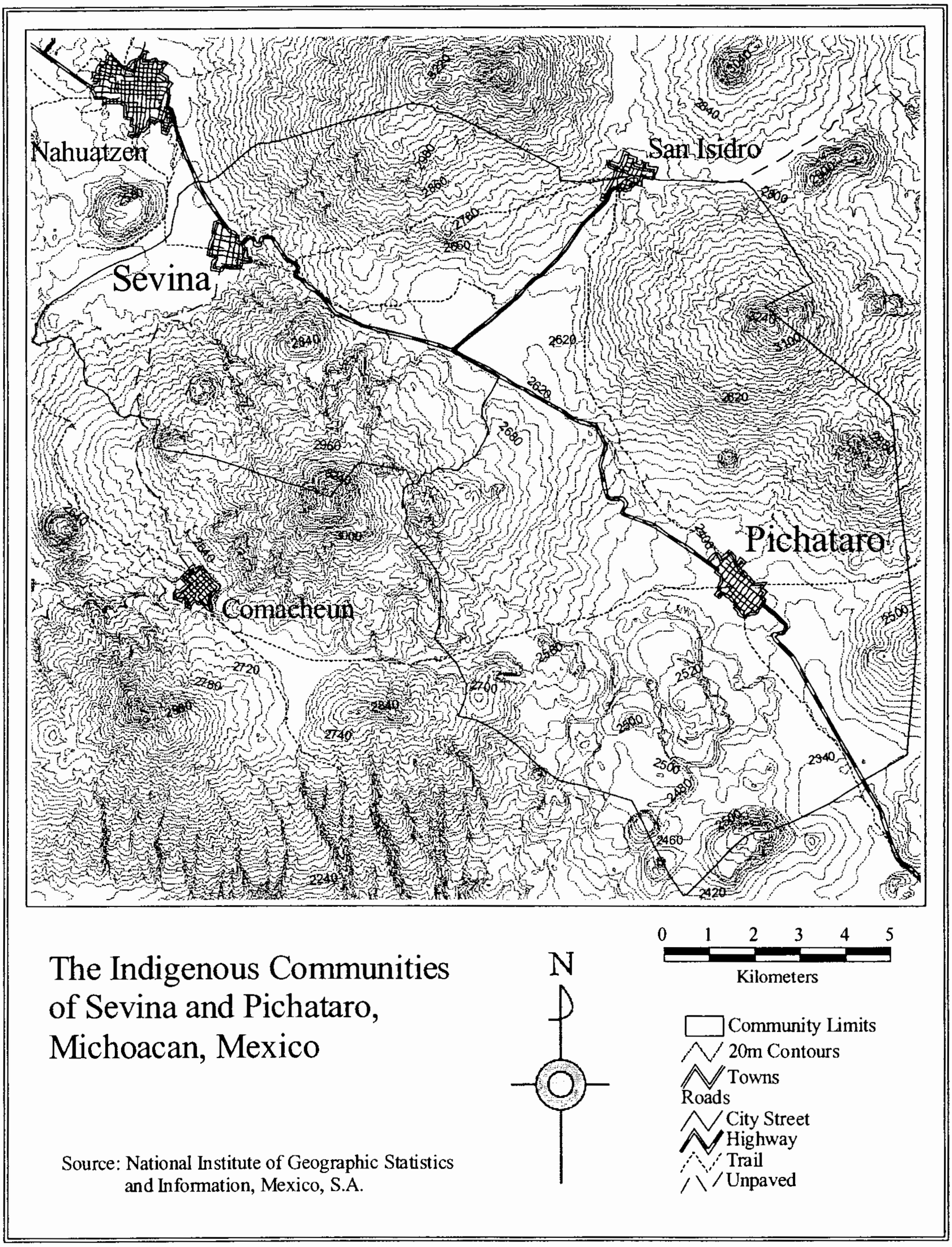


**Figure 1.2**. Absolute location of the study area.

# CHAPTER 2: RESEARCH CONTEXT

Community forestry, biodiversity, diminishing forest resources, and land degradation in the region have stimulated interest in the Meseta Purépecha's temperate mixed-pine forests and the indigenous culture that has survived there since pre-conquest times. Multiple social, economic, and political layers of influence and conflict color the landscape adding to the region's complexity.

## People and Forests of the Meseta Purépecha

Globalization and liberalization of markets and trade in México have profoundly affected previously isolated *ejidos* and *communidades* with forest reserves. The repeal of constitutional article 27, the Forestry Law of 1992, and the passing of trade agreements like the General Agreement on Tariffs and Trade (GATT) and NAFTA have changed the face of land tenure, forestry, agriculture, migration, trade, and transport in the region. Opportunities for small villages in the Meseta to participate in the global economy provide economic prospects, but often lead to mismanagement of the forests, timber theft, and environmental degradation of communal lands (Bray and Wexler 1996; Silva 1997).

Several investigations in the Meseta have contributed to a body of literature concerning deforestation, communally managed forests, and land degradation. The economic success and sustainability of community forestry enterprises (CFEs) in Michoacán and nearby states provides a model for timber-reliant communities like Sevina and Pichátaro. Although Sevina and Pichátaro are not truly CFEs with a formal governing body whose duty it is to regulate communal forests and control a centralized milling and woodworking enterprise, there are some important similarities. Both communities have a quasi-communal forest management and timber distribution hierarchy and regulations regarding logging practices. Unfortunately the regulations are often ignored, leading to over cutting, clandestine logging, and environmental degradation.

The recent liberalization of the forestry sector and land tenure regulations has seen outside interests take advantage of local naivety concerning prices and markets for timber, lumber, and value added wood products. Like most of México, indigenous people are often marginalized by the dominant mestizo culture and excluded from direct participation in national and international markets, capital lending, and improvements in rural technology (Klooster 1999). Because Sevina and Pichátaro face many of the same problems addressed by the following research, the work merits review.

Rees (1971) studied the increasing prevalence of timber resource use for milled wood products in response to the diminishing returns from traditional agricultural production. He observed that although illegal at that time, harvesting logs and milling timber was increasingly attractive for Purépecha villagers experiencing rapid population growth, low agricultural productivity, and increased connectivity to the amenities and opportunities of markets outside their communities. Rees (1971) noted that several species of broadleaf trees had already been eliminated from the region because of over cutting. He concluded that accelerated levels of timber extraction would likely deplete resources near the villages of San Lorenzo and Capacuaro (Rees 1971).

Bray (1991) studied CFEs in the Sierra Juarez in the central México state of Oaxaca prior to the trade agreements, land tenure changes, and neo-liberal market reforms that would take place in the early-mid 1990's. With NAFTA yet on the horizon he was optimistic about the outlook for communally managed forests. He observed that community forestry was a breakthrough for grassroots development because local people retained the real value of production. Bray (1991) concluded that sustainability was a possibility where local people controlled the fate of their own forest resources without external pressure from giant timber concerns.

Klooster (1997, 1999, 2000a) conducted research in Oaxaca concerning community property rights, CFEs, deforestation, and land degradation resulting from a tragedy of the commons scenario perpetrated by alienated members of excluded communities. He discovered that corruption, kickbacks, under valuation of lumber, the creation of a forestry elite, smuggling, and clandestine cutting all threatened the sustainability of the resource and the equitable distribution of economic opportunity. The most successful communities had strong governing assemblies and citizen participation, open accounting and recording practices, effective control of timber smuggling, and a commitment to the future sustainability of their forests (Klooster

2000). Klooster concluded that an increase in democratic community control improved forest management practices because of the potential economic benefits from collective action. He further suggested that improved integration of capital, forestry skills, and administrative methods could elevate a community's ability to organize and improve access to markets, NGOs, and government agencies (Klooster 1999).

Jaffee (1996) studied two CFE's, Cheran and San Juan Parangaricutiro, and a *communidad*, Angahuan, similar in its economy to Pichátaro. All three are in the Meseta Purépecha in Michoacán. He concluded that the liberalization of the forest sector in the 1990's had threatened the ability of the villages to sustainably manage their forests because of the lure of short term profits, cheap imported wood products, and clandestine cutting (Jaffee 1996).

## Theoretical Context

The landscape of the Meseta has been modified by its human inhabitants for thousands of years. This research not only seeks to quantify the magnitude of forest change in the area, but also strives to illuminate why these transformations have taken place. The observational perspective and analytical tools provided by remote sensing and GIS technology form the core of the investigative framework for the study. The analysis is guided and informed by a cultural and political-ecological perspective for the appraisal of landscape-scale forest change.

## Cultural and Political Ecology

Cultural ecology examines the interconnected nature of culture groups and their natural world (Butzer 1989). It weighs the social and environmental forces that drive human activities to modify the biosphere (Turner 1989). The discipline integrates themes from geography and anthropology to understand the relationships between people, resources, and space (Butzer 1989). Cultural ecologists are concerned with 1) how energy and information transfers interact to create landscape pattern, 2) food and resource production in relation to demographics and the sustainability principle, and 3) the role of people and the manipulation of resources within ecosystems (Butzer 1989: 193). Cultural ecology attempts to bring human and natural science together by incorporating ecology, information theory, and systems theory with the cultural landscape overlay. For this multi-disciplinary study a cultural-ecological perspective integrates the linkages between land use and land cover change, and the social and environmental forces that drive them.

Another related sub-discipline, political ecology, compliments the investigation. According to Blaikie and Brookfield (1987), land degradation is the product of an equation including both human and natural forces: net degradation = (natural degrading processes + human interference) - (natural reproduction + restorative management). They recognize a need to include natural and social scientists in the debate over why land managers are unable or unwilling to prevent accelerated land degradation. Because nature-society relationships are reflexive and vary across time and space, the model combines physical and social theory to extract the nature of interactions between human and natural land degradation.

The issue of geographic scale is central to understanding land degradation and human-nature interactions because transfers of material, energy, and information take place at multiple spatial and temporal scales. Blaikie and Brookfield (1987) propose a "regional political ecology;" an integrative approach combining interactive effects, different geographical scales and hierarchies of socioeconomic organization, and the contradictions between social end environmental change through time. This model combines ecology and political economy, imposition of social structures and policy by the state, applied theories of state and core-periphery models, and the ecology of agricultural systems to assess the dynamic links between society and land-based resources. This framework incorporates the multiple layers of policy, local economies, internal power structures, and outside market forces that influence resource use, land degradation, and environmental restoration in the study area.

## Landscape Ecology and Land Use

A landscape ecology perspective allows the reader to holistically consider the study area in terms of its landscape scale patterns and processes. Landscape ecology examines the structure, function, and change experienced within and between ecosystems and the influence of human activity on that change (Forman and Godron 1986). It is a holistic tool for ecosystem-scale planning, environmental management, and the conservation of biological diversity within a system. Landscape ecology is a strategy for the organismic assessment of the health and management of ecosystems by human stewards. The focus of landscape ecology is on human land use and its effects, and how scientific discovery and theory can be applied to real-world problems in natural resource management and land use planning (Wiens 1999). The model dictates that management and conservation efforts should address entire landscape mosaics rather than simply isolated patches of habitat.

Forman (1995) states that the objective is to better understand the spatial processes that occur when land is modified, and to identify an ecologically optimum sequence for a particular change. Landscape ecology is presently used in Europe as the basis for holistic landscape planning, management, and conservation. It integrates traditional biological sciences and human centered fields of knowledge including the socio-psychological, economic, geographic, and cultural sciences associated with modern land use (Naveh and Lieberman 1994).

Risser (1987) defines the model as how processes functioning at different spatial and temporal scales operate as a system to create pattern. It synthesizes related disciplines that focus on pattern and process in the landscape as a field of scientific inquiry in both natural and managed ecosystems. It considers the development and maintenance of spatial heterogeneity, the influence of heterogeneity on biotic and abiotic processes, and the management of that heterogeneity (Risser 1987).

According to Forman and Godron (1986), landscape ecology focuses on the structure, function, and change of regions and landscapes. Structure consists of the spatial patterns of landscape elements and ecological objects like organisms, biomass, and mineral nutrients. Function is the flow of materials between landscape elements. Change is alteration in the mosaic through time. Landscape ecology can be applied to this case study to illuminate the cultural and physical interconnections that contribute to forest landscape change within the study area.

## Forest Dynamics

Natural and human disturbance maintain patchy mosaics of vegetation in a variety of different seral stages throughout the forested landscapes of the Meseta. Most researchers recognize fir forest as the mesic climax stage of México's temperate subhumid forest ecosystems. High elevation fir and pine forests, when clear-cut, revert to alpine bunchgrass land dominated by *Calmagrostis*, *Tristetum*, *Agrostis*, and *Festuca*. These bunchgrass lands may return to fir and pine forests in the absence of further disturbance, but fire and grazing activities often suppress natural forest regeneration (Velázquez and Toledo et al. 2000).

Few studies have been conducted in central México on the ecology of temperate subhumid mixed-pine and pine-oak forests. A large percentage of the area where these vegetation types occur have never been surveyed in detail. Therefore, knowledge about the development of vegetation assemblages and successional pathways in pine forests on the Meseta is limited (Velázquez et al. 2000).

Ecological research on similar pine and mixed-pine forests conducted elsewhere in México and North America provides comparative insight into the situation on the Meseta. Savage (1997) investigated the role of anthropogenic influences on tree mortality in montane mixed conifer forests in southern California, USA, and northern Baja California, México. Her study indicated that anthropogenic effects, especially fire suppression, might increase the impact of natural stresses on the dynamics of mixed conifer forests (Savage 1997).

Another study conducted by Savage (1991) in the Chuska Ponderosa pine forest of the American Southwest examined the influence of anthropogenic disturbance on structural shifts in forest composition. Her study indicated that structural shifts in ponderosa pine forests occurred throughout the region in the early decades of the twentieth century, but that anthropogenic disturbance alone could not account for the changes to younger, denser, more even-aged stands from the previously park-like, old-growth stands. Savage (1991) concluded that development of the Chuska ponderosa pine forest since early this century is the result of multiple agents of change operating on the landscape simultaneously, including grazing, fire suppression, and background climate change.

Segura and Snook (1992) examined the disturbance and regeneration patterns of a pinyon pine forest in east central México. Fire suppression, woodcutting, and grazing appear to have severely limited the forest's natural regenerative abilities. Mimicking the natural disturbance regime once found in the forest may improve regeneration success and prevent stand replacing fires (Segura and Snook 1992).

Research in disturbed pine-oak forests in the highlands of Chiapas, México, indicated that the regeneration of pines occurred only on exposed sites and may be favored by current land use patterns. Heavy grazing retarded the successional development of forested communities because of seedling removal and trampling, but selective logging of pines in mature stands may favor the regeneration of both pines and oaks by altering light and temperature conditions (Gonzalez-Espinosa et al. 1991).

The Meseta's forests exhibit similar possible outcomes. Fire, grazing, and selective logging all complicate the equation. Whether climatic variation influences forest dynamics appears likely but remains unproven. These forests have experienced extensive human modification historically, and especially during the last century. What a "natural" forested area looks like is also unknown. No comparative historical baseline exists. This study will provide baseline data for future examinations of succession and response to disturbance in the study area.

## Remote Sensing and GIS

Remote sensing and GIS contribute valuable tools and perspective for examining changes in landscape pattern in the Meseta. Remote sensing technology is useful for monitoring landscape pattern, process, and quality as it changes over time (Peterson and Running 1989; Luque 2000). Remote sensing and GIS provide the perspective and powerful analytical tools to map and measure the magnitude of cultural and ecological processes at the landscape scale (Naveh and Liberman 1995). Remote sensing, specifically satellite image classification and comparison, are useful for assessing forest landscape change in a variety of contexts (Singh 1989; Coppin and

Bauer 1996). Forests are amenable to structural and functional analysis at a variety of scales with satellite remote sensing data (Iverson *et al.*1989; Lunetta 1998).

The utility of integrating remote sensing technology and GIS for the study of forest landscape change and ecosystem management is well recognized (Allen 1994; Mladenoff and Host 1994; Sample 1994). Radiometers aboard satellites can collect multispectral biophysical information about forest landscapes at different scales because of their space borne perspective (Jensen 1983; Quattrochi and Pelletier 1991; Naveh and Lieberman 1994). GIS has become an analytical tool of major importance and future potential for modeling spatial and temporal landscape change in forest ecosystems (Flamm and Turner 1994; Franklin 1994; Bridgewater 1996; Haines-Young et al. 1996).

Numerous studies have used TM imagery and GIS to detect and model deforestation and forest dynamics in tropical forests (Gilruth et al. 1990; Stone et al 1991; Jusoff and Manaff 1995; Sader et al.1994; Sader 1995; Chatalain et al. 1996; Frohn et al. 1996; Gorge and Garcia 1997; McCracken et al. 1999; Shimabukuro et al. 1999; Peralta and Mather 2000; Tucker and Townshend 2000; Hayes and Sader 2001) and in temperate forests (Franklin 1986; Coppin and Bauer 1994; He et al. 1998; Ardö et al. 1997; Sachs et al. 1998; Luque 2000). Several studies have examined forest landscapes in subhumid temperate forests (Mas and Ramírez 1996; Keating 1997) but few assessments of subhumid temperate deforestation with TM imagery and GIS exist.

Mertens and Lambin (1997, 2000) conducted several studies using similar remote sensing techniques to assess land cover change in Cameroon, Africa. Their research produced a spatial model of deforestation by incorporating landscape attributes and human activity in a landscape experiencing substantial levels of forest clearing. The investigation resulted in a multivariate spatial model of land cover change trajectories associated with deforestation processes (Mertens and Lambin 1997, 2000). They relied on many of the same remote sensing and image processing techniques used here, including visual selection of training regions, application of the maximum-likelihood statistical algorithm for supervised classification, and post-classification comparison for change detection of multi-date Landsat imagery.

Klooster (2000b) analyzed the social context of deforestation in the nearby Lake Pátzcuaro region. Using air photos and interviews, his research indicated that woodcutting strategies and agricultural abandonment lead to an increase in forest cover and changes in forest composition that were not consistent with a unidirectionional deforestation scenario. He concluded that established methods of interpretation and forest classification in the area reinforced a "unilinear deforestation orthodoxy" that made no provision for other types of forest dynamics, particularly widespread regrowth initiated by agricultural abandonment (Klooster 2000b).

Rudel, et al. (2002), conducted supervised classification of multi-temporal TM imagery to assess land-use change in the Ecuadorian Amazon. The study extracted spectral signatures from training data to classify two Landsat TM images acquired ten years apart. The study found that contrary to forest transition theory, reforestation was more prevalent along roads and near communities rather than farther away from roads on less productive soils and in less favored locations.

Except for a comparison of image classification techniques by Mas and Ramírez (1996) using a single subscene from a TM image acquired in 1992 of the Meseta Purépecha, few similar studies have been conducted in the region. No published study of forest landscape dynamics incorporating the principles of landscape ecology with remote sensing and GIS technology is currently known for Sevina and Picháṫaro.

## Objectives of the Study

The primary objective for this study is to determine the extent of deforestation that occurred in two Purépecha Indian communities in central México. The research uses remote sensing and GIS technology to detect forest landscape change within an ecological framework between 1986 and 2000. My secondary objective is to compare land cover change between the two communities and assess the extent of forest recovery. More specifically, my objectives are to 1) produce land cover maps by classifying forest and non-forest land cover categories for the study region with two sequential Landsat TM satellite images, and 2) compare the maps to create a new land cover map depicting regions of change (deforestation and regeneration) and no change during the period of interest.

Sevina (19° 34' 17" N, 101° 48' 21" W, 2400 m elevation) and San Francisco Picháṫaro (19° 37' 47" N, 101° 54' 04" W, 2390 m elevation) are adjacent communities in a mountainous region west of the colonial town of Pátzcuaro. Their village centers are located approximately 12 km apart. The combined study area covers 133.9 $km^2$. Picháturo is the larger of the two villages with an area of 86.4 $km^2$. Sevina covers 47.5 $km^2$. Both communities are situated on near level benches in broad, gently sloping valleys surrounded by agricultural fields and pasture, with forest and hillside milpa plots above. Old eroded volcanoes rise up on either side of the valleys, towering to more than 2800m above the villages.

The study region is divided into two distinct communities along a shared boundary allowing comparison of forest landscape dynamics between the two villages. The results of the comparison shed light on the differences in local economies, timber extraction, and wood products manufacturing in each village. The ability to assess the pattern and extent of forest conversion and vegetation re-growth provides insight into the prevalence and trajectory of lumbering, reforestation, agriculture, and pastoral activities linked to the socio-economic fortunes of the communities.

The land cover change maps provide spatial statistics about the extent and location of forest conversion and vegetation re-growth in the study region. A comparison of the outcomes contributes to an enhanced understanding of the differences and similarities in forest landscape dynamics between the two communities.

Finally, the results contribute to an improved understanding of the linkages between forest resource use and landscape change in the area. An estimate of the amount and location of forest change allows speculation about how social, political, economic, and environmental structures affected forest resource use and landscape dynamics from 1986 to 2000. The results may be extended forward to predict possible outcomes and plan for sustainable forest stewardship in the future.

# CHAPTER 3: REGIONAL GEOGRAPHY

Toledo and Ordóñez (1993) estimate at least five million species inhabit the earth, and México contains more than 12 percent of the species known to exist. Because of its topographic and climatic variation, México is comparable only to India and Peru for the total number of vegetation types it contains (Velázquez et al. 2000). At the biome scale, the distribution of México's main vegetation types can be divided into categories according to two climatic variables: precipitation and temperature. México's geography allows the distribution of ecosystems along a transitional gradient between two major bioregions, Nearctic and Neotropical (Velázquez et al. 2000). Six ecological zones and their principal characteristics have been identified in México. These include humid tropic, subhumid tropic, humid temperate, subhumid temperate, arid and semiarid, and alpine environments (Toledo and Ordóñez 1993).

The Meseta Purépecha lies within the Mesa Central adjacent to the Central Valley of México along the Transverse Neovolanic Axis. The archeological record suggests the region has supported large human populations since the formative or Preclassic times (West 1971). In *The Handbook of Middle American Indians* West (1971) made an observation about the region's forests that would become the subject of research and discussion in years to come. While describing the physiography of the Meseta, West stated, "Although now largely destroyed by human action, pine-oak forests and open woods originally covered the more humid central and western portion of the Mesa Central" (1971: 372). As forest resources in the region shrink, the debate over how remaining forests should be managed widens. The question of whether local people and their traditional technology is better suited to manage forests than modern science and the policies of dominant culture divides the discussion.

This study is concerned with some of the subhumid temperate mixed-pine forests growing along the volcanic axis bisecting central México from Cape Corrientes on the west coast southeast to Jalapa and Veracruz on the east coast. In 1989 Toledo et al. (1993) estimated that Michoacán contained 3,436,172 ha of subhumid temperate forest. Little information is available on the biogeography and vegetation dynamics of these pine forests. Few studies have been conducted to better understand the fire chronologies, successional strategies, community relationships, resiliency to disturbance, and compositional structure of mixed-pine and pine-oak forests in the region.

## Landforms

Several large, flat-floored valleys of aeolian and alluvially deposited sediment characterize the region. The valleys are surrounded by and interspersed with volcanic peaks and smaller, more recent, crater-topped cinder cones (West 1971). Elevations range from 2,400 to over 3,800 meters within the study area. The dominant landforms in the Meseta were produced by Tertiary and Quaternary volcanism. The oldest composite cones, likely dating from the Eocene, are most prominent. These old eroded volcanoes are conical with radial drainages, but no longer exhibit craters.

Composed mainly of andesite, they sometimes contain deposits of mineral-bearing quartz and pinkish rhyolite near their summits (West 1948). Younger cinder cones and lava flows, dating from the Pleistocene to present, are situated throughout the Meseta with no regular spatial pattern.

Depositional processes created the other major landforms. Broad, flattened valleys accumulated from ash and cinder fall, then aeolian and alluvial deposition from surrounding slopes. The valley soils are composed of reworked volcanic material from adjacent cinder cones, lava flows, and ash deposits (Rees 1971). The valleys have been cleared for agricultural production and livestock grazing, and the peaks and cinder cones are often covered with temperate subhumid mixed-pine, and pine-oak, and occasionally at higher elevations, fir forests. Forest vegetation grows where sufficient soil development has taken place on mountains, cinder cones, and lava flows, depending on their age.

## Hydrology

Few perennial streams or lakes occur on the Meseta. Most villages are located near springs emanating from the porous flanks of the old composite volcanoes. Water percolates down through the slopes of the composite cones and then seeps out at the surface where older, impenetrable layers of bedrock are exposed. Spring water is collected in cisterns and tanks and piped to villages. Stock tanks carved from tree boles and made from cast cement collect surface seep and spring water for humans and stock in remote areas. Shallow lake basins formed by internal drainage patterns are the only bodies of surface water in the area. The closest are Lake Zirahuén to the south and Lake Pátzcuaro to the east. Limited seeps from springs and several small catchment ponds designed to trap and store rainwater are the only surface water in the study area.

## Climate

The *tierra fría* climate of the region corresponds to the Cwb designation of the Köppen climate classification system. This is a mesothermal climate with at least one month greater than 10°C (50°F) and the coldest month between 18°C (64.4°F) and 0°C (32°F), a marked seasonality of precipitation, dry in winter and wet in summer. The warmest month is below 22°C (71.6°F) but 4 months are above 10°C (50°F).

Rainfall is seasonal and occurs mainly during the summer months as convectional thunderstorms from June to September. During this time thunderstorms occur nearly every afternoon when solar heating of the land surface throughout the morning causes convectional uplift of moisture-laden air masses. Light winter rains and snow occasionally fall at higher elevations during December and January. Frosts and overnight freezing occur during the winter months. The warmest temperatures precede summer rains during April and May.

## Soils

Soils in the region belong exclusively to the order Andisol. The edaphic map developed by INEGI (1982) identifies two suborders in the study area; *humico* and *ocrico*. These Andisols developed on volcanic parent material composed of andesitic ash and rock produced by durable stratovolcanoes.

West (1948) reported two dominant soil types in the region identified by local people. The first is a yellowish-brown leached soil that develops at higher altitudes under seasonally moist conditions. This soil is associated with pine-fir forest vegetation, and has a fine sandy A horizon in which crops can be planted several months prior to the summer rains because it retains moisture. This *tierra de humidad* is infertile and acidic, and will only support crops for 4-5 years before it must be left fallow. This soil is most often used for hillside milpa agriculture.

The second soil type, *T'upurí*, is the more fertile, dark sandy loam of the lower slopes and valleys between 2,000 and 2,500 meters (West 1948). The surface dries to a powder and prevents moisture evaporation from lower layers. *T'upurí* is more heavily cultivated for row crop agriculture because of its higher productivity and accessible location on valley floors.

## Vegetation

México is a mountainous country with over half of its terrestrial area greater than 1000m in elevation. Temperate vegetation covers more than 22% of the land area, with subhumid temperate environments and vegetation dominating the largest part of the mountainous regions in México (Toledo and Ordóñez 1993; Velázquez et al. 2000). The subhumid temperate zone in México with pine, oak, and mixed forests, occupies more than 33 million ha in 20 states. The four states with the most significant quantities of subhumid temperate vegetation are Chihuahua, Michoacán, Durango, and Oaxaca respectively.

This ecological zone is significant biologically and biogeographically because of its distribution along the main mountain ranges in México. It contains high levels of endemism and biodiversity for flowering plants, conifers, terrestrial vertebrates, mammals, amphibians, and reptiles. The subhumid temperate zone along the Trans-volcanic axis is especially critical because it is believed to support to some of the highest rates of species-diversity and endemism among mammals anywhere (Toledo and Ordóñez 1993).

## Subhumid Temperate Pine Forests

The genus *Pinus* (Pinaceae-Coniferales) comprises a natural plant group including from 90-120 species. México may have a greater concentration of pines than any other country in the world with possibly more than 45% of the known species (Styles 1993). Pines are the most well distributed genus of all woody plants in México. Of the 30 million ha of forested or wooded land in México, 21 million ha contain coniferous forest, with the dominant species being pine. Some states in México, including Michoacán, support more than twenty distinct species of pines, exclusive of hybrids (Styles 1993).

Pines often grow in concentrated stands and form extensive forests because they are wind pollinated. They can be monospecific, growing in forests containing a single species, or coexist in a multispecies community with up to seven species in a single forest. Some pines in México exhibit clinal variation associated with environmental conditions along elevation and microclimate gradients. Pairs of the same species may appear different morphologically at the extremes of their ranges, and exhibit variations in form between the extremes (Styles 1993).

The principal pines in the area are *Pinus leiophylla* (*pino chino*), extensively tapped by the Purépecha Indians for turpentine producing resin, *P. pseudostrobus* (*pino cantzimbo*), preferred by woodworkers because it is easiest to work, and *P. michoacana* var. *cornuta* (*pino lacio*), highly prized for lumber because of its tall, straight growth form. *P. pseudostrobus* is no longer as abundant as it once was (Works and Hadley 2001). *P. michoacana* and *P. leiophylla* are the primary pines found in the region. Minor species include *P. teocote*, *P. montezumae*, *P. rudis*, *P. oocarpa*, and *P. hartwegii*. Remnant fir forests occasionally remain at higher elevations. *Abies religiosa* is the only fir species found in the study area.

A pine and mixed pine-oak vegetation type dominates the forested mountains of the Meseta, and correlates to the higher and colder range of the Cwb climatic zone (Figure 3.1). Pines are usually interspersed with oak, depending on elevation. More than twenty-five species of oak occur in the Meseta and are dominant at lower elevation, while pines dominate at higher altitudes. Alder is found in association with most forest assemblages.

Often no single species pine dominates a large forested area of mixed-pine. According to Velázquez and Toledo et al. (2000), this complex seral stage is the result of disturbance, promoted by intensive logging and fire. This occurs in heterogeneous landscapes with flats and slopes providing a variety of habitat. Stands of true fir occasionally remain in the forests.

Pine forests in the Meseta occur mainly on the flanks, ridges, and tops of peaks and cinder cones. They grow above the cleared valleys where agricultural production and livestock grazing dominate (Figure 3.2). They often exhibit somewhat park-like characteristics with a semi-closed canopy, partial under story, and low herbaceous layer.

## Origin of Pines

Florin (1963) suggests the genus *Pinus* originated in the Northern Hemisphere during the Jurassic Period of the Mesozoic era. It appears that pines migrated southward from North America along the mountain ranges of México and Central America (Perry 1991; Styles 1993). These pines were more widespread than they are presently, and did not form extensive forests. They migrated southward because of changes in climate and physical barriers during glacial advance and retreat. At times migration reversed and pines spread northward to occupy land previously covered by the great glaciers, but overall there was a general movement of pines southward into México and Central America (Perry 1991).

Several hypotheses about the timing of pine migration and arrival in México from North America have been suggested. Miller (1977) posits that they reached México during the Mid-Tertiary and no later than Mid-Cenozoic. Mirov (1967) concludes they arrived during the late Crustaceous or at the beginning of the Tertiary along the Sierra-Madre Occidental from the North American Cordillera. Martin and Harrell (1957) advocate a later invasion during the Middle Tertiary from the Appalachian uplands along the Sierra Madre Oriental. Most botanists and taxonomists presently believe that the western range of the Sierra Madre Occidental was the main route for the migration of western pines into México (Perry 1991).

## Purépecha Culture

The Purépecha Indians of the Meseta resisted conquest by the Aztecs, survived domination by the Spanish, and retain their cultural identity and native language despite marginalization by the dominant mestizo culture of modern México. They have lived for thousands of years by managing the natural resources found in the Meseta and nearby Lake Pátzcuaro Basin. The capital of the ancient Purépecha world lies on the edge of Lake Pátzcuaro at Tzintzúntzan. Several excavated *Yácatas*, large stone pyramid-like structures, sit atop the highest point in the village facing the lake. Tzintzúntzan was the cultural and economic hub of an agricultural society that thrived around the lake and in the nearby mountains. It was the seat of power and home to the dominant Purépecha ruling clan.

A unique set of geographical, environmental, and cultural circumstances gave rise to a distinct society in the Meseta. A combination of climate, landforms, flora, and fauna converged in the region to provide the necessary materials for the development of a rich and complex civilization. Purépecha culture flourishes today as an amalgam of customs, belief systems, and life ways incorporating ancient Indian, Hispano-Catholic, and contemporary Mexican cultures.

When West (1948) published *Cultural Geography of the Modern Tarascan Area* in 1948, the area where Purépecha language was still spoken occupied less than one-fifteenth its pre-Conquest extent. The pre-Columbian linguistic area encompassed most of the present state of Michoacán except for a portion of the Pacific slope of the *Sierra Madre del Sur* (Brand 1944). The political influence of the Purépecha Empire extended well beyond its language boundary into Jalisco to the west, south to the Pacific, and north to the Bajio de Guanajuato. The Purépecha cultural capital was situated in the north-central part of the region including the Lake Pátzcuaro-Cuitzeo area, the forest region of the Meseta highlands, and the upper escarpment zone (Brand 1944; Stanislawski 1947; West 1948).

Several factors led to the recession of Purépecha culture during the Spanish colonial and postcolonial periods. In some settlements, epidemics of contagious European diseases decimated native populations. The remaining population further declined when local people migrated to distant farming and mining areas to provide labor for the Spanish. In addition, wherever Spanish or Mestizo haciendas and estancias were established within the Purépecha culture area, the influence of Hispanicization slowly diluted and assimilated native speech and customs (West 1948).

Today, Purépecha culture and language survives, mainly in rural villages not yet fully incorporated into the national and global economies. Historically, small

Purépecha settlements were located on forested slopes conducive to both maize agriculture and defense from invaders. Modern settlements usually occupy level surfaces on lakeshores, or slopes and benches near a spring adjacent to valley basins suitable for agriculture and grazing.

Agriculture has long been the primary economic activity practiced in the region. The native trilogy of maize, beans, and squash provided enough surplus food to support population increase and an elaboration of cultural complexity. Fishing was a significant occupation along the shores of Lake Pátzcuaro, and continues to be important in some lake communities. Handicrafts, including woodworking and carving, and regional trade were also important traditional occupations and still provide income to Meseta communities. Medicinal plants, herbs, grasses, greens, mushrooms, and fruits are still gathered for household consumption and sale in local markets.

Agriculture was central to the Purépecha economy, but a recent diversification into specialized community industry has eclipsed the economic dominance of farming. NAFTA has further reduced the ability of local farmers to compete in expanding and increasingly competitive international and global markets. A reduction in the profitability of agriculture led to expansion of the local population's historic ability as woodworkers and craftspeople (Rees 1971; Bray and Wexler 1996; Klooster 1999).

## Traditional and Modern Forest Use

Purépechans modify their diverse forest landscape to provide a multitude of foods, medicines, and materials. They are pastoralists and agriculturalists who incorporate the ancient knowledge of their ancestors, Hispanic influences, and modern technology to manipulate the natural environment for their benefit. Local people know and name over 400 plant species (Alcorn and Toledo 1998). They gather or cultivate over two hundred species of plants and mushrooms for food and medicine. They practice 14 distinct land management and sivicultural strategies (Alcorn and Toledo 1998).

## Timber Harvest

The dominant timber harvest strategy observed in the region is high grading. High grading is a form of selective logging where the oldest trees, hence largest, with the straightest growth form are chosen for harvest. These trees contain the most board feet of lumber when milled into rough planks with either a chainsaw or band saw mill. Ideally, a pine tree will be selected for harvest and cut down after it serves multiple purposes as a resin, firewood, and *ocote* (highly resinous heartwood used as fire starting material) producer. This is the typical sequence of traditional Purépecha use for pines. The cycle may be accelerating as the demand for wood outweighs the value of traditional non-timber materials a tree can provide during its life.

Purépecha loggers in Sevina and Pichátaro operate in small crews of two or more men. They enter the forest with an axe for each man and at least one chainsaw between them. Virtually no access to the forest by motor vehicle exists, partly to prevent poaching. The loggers bring a team of draft animals, usually oxen, with a drag cart. The cart is made of two stout wood beams that act as a tongue harnessed to the oxen. The other ends of the beams are attached to a wheeled automobile axel to form a simple and effective drag rig.

After selecting a tree, the feller cuts it down with a chain saw. The team then limbs the bole with axe and chainsaw, and bucks it into manageable lengths (Figure 3.3). A large diameter tree would probably be cut into a square blank by a skilled sawyer and removed one section at a time. A smaller tree might be removed as several bucked logs at once. The operation depends on the skill of the loggers, the size of the tree, and the resources at hand. When the log or logs are ready for removal, the ox cart is positioned next to the load and one end of the section or sections are lifted onto the axel crossbar of the cart. The load is then lashed to the cart and the oxen driven down the trail effectively dragging the logs out of the woods to a waiting truck at the edge of the forest, or back to the village (Figure 3.4). Drag trails criss-cross the forest where logs have been skidded out of the woods in this manner for years. Soil compaction and erosion usually accompany the skid trails, especially where cattle repeatedly pass.

Purépecha logging practices appear less destructive to forest ecosystems than the degradation associated with heavy machinery and logging roads. However, the systematic removal of genetically superior trees, grazing, and burning may have negative impacts on the forest's resiliency to disturbance (Styles 1993) (Figure 3.5).

Removing the fittest trees may reduce a forest's ability to survive fires, pathogens, and insect outbreaks.

## Land Management and Resource Allocation

Human activities are now the major agent of disturbance operating in the pine forests of the Meseta Purépecha. Subhumid temperate ecosystems cover 33 million ha in México and are home to 1.55 million indigenous people (Alcorn and Toledo 1998, p. 236). Rural indigenous communities of Purépecha Indians now manage most of the pine forests in the region.

The Méxican Government recognizes community land tenure and allows the *ejidos* and *communidades* to operate somewhat autonomously within the larger framework of the national government. Until recently, land within the communal boundaries of indigenous *communidades* and *ejidos* could not be sold or privately owned. President Salinas lifted this restriction when he modified Article 27 of the Méxican Constitution in preparation for NAFTA. Land ownership and timber rights can now be transferred by sale and concession, although few such transfers have occurred in the Meseta.

The production of forest products and the condition of the forests differs dramatically between Sevina and Pichátaro. Sevina cut, milled, and sold much of its commercially valuable timber as lumber and logs over the past 20 years. Sevina is about 50 percent smaller than Pichátaro, and had less forest to begin with. The local timber industry is in the throes of a bust cycle and many people have migrated to urban centers and the United States in search of work. There are only a few local woodworking shops in Sevina and most of their lumber comes from local sawmills or other communities (Figure 3.6) (Works and Hadley 2001).

Pichátaro has a well-developed furniture and woodcraft production industry. Local forests are divided between eight subdivisions of the community providing each of over 500 households with access for resource extraction (Alcorn and Toledo 1998). Most of the timber used for local production comes from communal property or individual family parcels (Works and Hadley 2001). Pichátaro has numerous small workshops producing tables, chairs, entertainment centers, bookshelves, cabinets, armoires, ornamental doors, carved pillars, bars, planter boxes, bed frames, headboards, and numerous other handmade craft items. Elaborate relief carving is a local specialty and might adorn chairs, tables, picture frames, headboards, or trunks.

Buyers from outside the village purchase truckloads of woodcrafts and transport them to regional, national, and international markets. The hotels, stores, bars, and restaurants in nearby Pátzcuaro, a colonial town with major tourism from Guadalajara and México D. F., are full of pine furniture from the area. Local shops sell traditional wooden items and ornaments, and merchandise made especially for the tourist trade like coat racks, planter boxes, and carved mirror frames. Whether this boom remains sustainable for the people of Pichátaro has yet to play out.

**Figure 3.1.** Subhumid temperate mixed-pine forest.

**Figure 3.2.** The landscape of the Meseta Purepécha.

**Figure 3.3.** Purépechan loggers.

**Figure 3.4.** Transporting timber (Hadley 2000).

**Figure 3.5.** Landscape degradation.

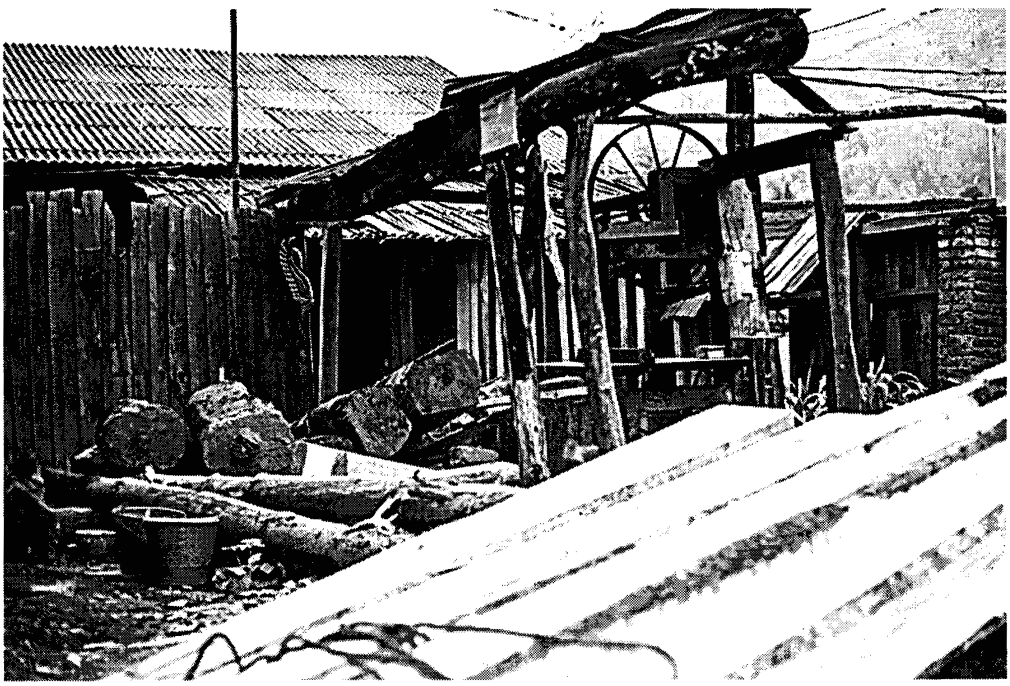

**Figure 3.6.** Band saw mill.

# CHAPTER 4: METHODS

Biotic sampling of large areas can be problematic. The forests in the study area are remote and difficult to access. Remotely sensed imagery provides the most efficient means for assessing the nature of change occurring in isolated forests. Anniversary dates were chosen to minimize seasonal differences in vegetation growth form and to correspond with geospatial information acquired during field investigations in the region.

## Remote Sensing and Cartographic Data

The multi-temporal satellite data used in this study consists of two digital satellite images. The first was acquired by the TM multi-spectral radiometer aboard the Landsat 5 platform on April 6, 1986 at 4:37 pm. The second was acquired April 20, 2000 at 5:04 pm by the latest version of the TM called the Enhanced Thematic Mapper Plus (ETM+) aboard the Landsat 7 platform. Both images record similar band widths at the same resolution.

Paper and digital map products obtained from The Forestry Commission of the State of Michoacán (COFOM) included forest stand classification maps for the community of Sevina, dated 1984 and 1992. The 1984 stand map provided visual verification of forest stand types believed to exist during the mid to late eighties and therefore proved useful as a secondary source of land cover verification during the training site delineation process. The maps also served as an aid for locating potential sample sites on the ground with GPS in Sevina during August 2000.

COFOM also supplied a digital version of the National Institute of Geographic Statistics and Information (INEGI) 1:50,000 scale Cheran topographic quadrangle map. The fifteen-degree latitude by twenty-degree longitude digital map layers were projected with the Universal Transverse Mercator (UTM) zone 14 north grid location system and North American Datum 1927 (NAD 27). The digital vector map layers were used for preliminary visual assessment and interpretation of the other digital layers during registration and rectification procedures. The most useful layers included urban area boundaries, 20-meter elevation contours, vegetation polygons, and transportation routes. The roads layer was used during the compilation process for comparison to the visible roads on the Landsat images.

Two flight lines of aerial photography were obtained from the archives at COFOM. The photos were acquired in 1974 and 1990. They proved useful during training site delineation as ancillary data for the identification of training area land cover classes.

INEGI provided the digital elevation model (DEM) used to produce the contours for the 1:50,000 scale Cheran quadrangle. The DEM was crucial for terrain correction, georeferencing, and registration of the satellite imagery and digitized map layers. The INEGI 1:50,000 scale topographic sheet of Cheran appears in the same format as the digital version because the paper edition was created with the digital vector layers (2000). The only notable difference is that the paper version was projected with the ITRF92 graticule. This discrepancy in cartographic projections was corrected during registration after the map was digitized with a raster scan.

## Field Data

Ecological data from forest stands was sampled for 10 plots in each of the communities during a field visit to the region in August 2000, for a total of twenty plots. Sites were chosen to represent the range of different stand composition types and environmental conditions found in the study region. Stand types varied along a gradient of tree species make-up and stand age. Ages ranged from young regeneration patches (approximately 10 years old) to mid-successional pine-dominated (approximately 70-80 years old) with only one mature oak-dominated stand (age unknown). Species composition of stand types ranged from oak dominated to mixed pine-oak to pine dominated to fir dominated.

Ecological and environmental measures recorded for each site were intended to provide details about the physical and cultural characteristics of the forest stand structure represented by the sample plot. Sample sites ranged from 125 $m^2$ to 1000 $m^2$ circular plots. Smaller plots were used where distinctly higher tree densities occurred. Each plot included a minimum combination of twenty live pine, oak, or fir trees greater than 4 cm diameter at breast height (dbh) (Hadley 2000). Plot centers were chosen subjectively within each forest stand to represent typical stand conditions and geo-referenced with a portable GPS satellite receiver.

GPS locational data was converted into digital data layers for use with a GIS. In addition to recording plot center point locations, GPS allowed the placement of forest stand and non-forest boundary polygons and features of particular interest into a database for subsequent use with GIS. This GPS application assists ground truthing and delineating training data for the classification of remotely sensed satellite imagery.

Forest stand outlines were recorded for use with digital map layers by walking the perimeter of the larger stand that contained each individual sample plot with a GPS receiver while recording positional waypoints at preset temporal increments. Non-forest polygons containing crops, fallow re-growth, and various stages of shrub, burn, and regeneration were delineated and later downloaded and incorporated into the digital dataset.

Georeferenced digital photographs were taken. These photo points allowed specific features of interest like agricultural fields, notable stand types, burn areas, and cultural features not linked to specific sample plots to be mapped. All stationary waypoints were averaged for at least ten minutes to improve locational accuracy (Jensen 1996).

## Data Processing

The objective for the preprocessing procedures was to compile and register all of the geographic information data so it could be visually and digitally integrated with a GIS (Figure 4.1). All layers were projected in or converted to NAD 27 and the UTM 14n grid system. Once the data layers were registered, they could be overlaid for the delineation of training sites. The training sites facilitated classification of the two images, and ultimately post-classification comparison to detect regions of change from between 1986 and 2000.

Four GIS software packages were instrumental in the pre-processing and analysis tasks performed for this project. ArcView and ARC/INFO were used to develop, edit, and display vector data layers. Idrisi and ERDAS Imagine were used to edit, display, and process raster data layers and satellite image files. Though the systems have some overlapping capabilities, each one has a unique functionality to perform certain tasks the others cannot, and was used according to specific needs.

The first processing task required digitization of several paper maps. Vegetation maps were manually digitized for the study area, one for Sevina and two for Pichátaro. The new vector files were attributed with forest stand information. The community boundaries for Sevina and Pichátaro were digitized from maps and built into the coverages.

The digital Cheran topographic quadrangle vector files were important reference layers for visual assessment, geo-referencing, and registration of other geographic information layers. The roads, vegetation, and contour layers were useful for providing visual identification of ground control points (GCP's) during the registration and ortho-rectification of the satellite images.

The satellite images were then ortho-rectified and registered. Terrain correction reduces geometric distortion caused by topographic variation. Both images required cropping to a smaller size before terrain correction and registration.

Proper registration of multi-date imagery data sets is crucial to the accuracy of image processing for change detection (Coppin and Bauer 1994). The satellite sub-scenes were compared visually with overlay to the INEGI digital roads layer by manually matching corresponding GCP's on both images. First, the higher resolution panchromatic band from the 2000 image was overlayed visually on the INEGI roads layer to locate useful GCP's. The resulting model was used to register and rectify all 2000 bands to the proper UTM grid with a second-order polynomial warp function and nearest neighbor resampling. The resampling technique met the requirement that the rectified image must be within 1/4 to 1/2 pixel of the reference map (Coppin and Bauer 1994, Jensen 1996). The resulting residual mean square (RMS) error fell within the acceptable limits (Table 4.1).

The same procedure was used for the 1986 image but the reference image was the corrected and registered 2000 ETM+ image. Again, acceptable RMS error results were achieved (Table 4.1). The registration of the two images was inspected visually and appeared to be within one pixel. This margin of error was deemed acceptable based on the RMS error, and visual overlay of the results. According to Coppin and Bauer (1994) a slight within pixel shift cannot be corrected for and must be accepted as a limitation inherent to change detection methodology using digital imagery. Next, the satellite images were windowed to the extent of the study area boundary.

Additive false color composites produced from various sets of bands were useful for registration, visual assessment, and correction tasks during the project. The combination of bands 2, 3, and 4 resulted in a false color infrared composite in which healthy vegetation appears in shades of red (Figure 4.2 and 4.3). This band combination afforded the best visual display image during processing operations.

The last image correction was the removal of pixels obscured by clouds. The 2000 study area image contained no cloud cover, however the 1986 image included two small clusters of clouds in the northeast portion of the community of Pichátaro. Clouds in an image may skew the distribution of reflectance values decreasing classification accuracy and should be removed (Yuan et al. 1998). Cloud regions were masked out of all bands in both the 1986 and 2000 images to maintain registration and a consistent number of pixels in both images.

The Cheran 1:50,000 scale topographic quadrangle was digitized and the resulting geo-Tiff (georeferenced Tiff image) was projected with NAD 27 and UTM 14n. Air photos were digitized and geo-referenced in the same manner. Low-resolution photocopies of the panchromatic air photos were scanned and converted to Tiff images. The images were geo-referenced with GCP's through visual overlay with the transportation layer from the INEGI digital quad map.

Two GIS projects were produced to help delineate training regions with the digital map and photo layers. The first focused on using 1990 air photos for the 1986 training region delineation. The second project compiled all digital geographic information gathered for the study except the air photos and was used to select the 2000 training sites. The projects allowed me to overlay and toggle between false color composites, the graphic INEGI topographic quad map, the INEGI digital quadrangle map layers, the GPS training layers and plot centers, the sample plots with all trees and stumps mapped and attributed, and the digital landscape and canopy photography. Photos and the plots were added to the view window by clicking on georeferenced hot-links. This allowed me to view photos of the landscape to assess the vegetation type and density at specific locations.

## Training Region Selection

The accuracy of post-classification comparison change detection is highly dependent on the quality of the training sites used for the initial image classifications (Campbell 1996; Coppin and Bauer 1996; Mather 1999). Training site selection required *a priori* knowledge of the study region, historical information, *in situ* environmental information, and on-screen polygonal selection of sites. Classification of the 1986 TM classification relied most heavily on the 1990 air photos and 1985 vegetation map. Classification of the 2000 image depended more on ecological field data collected during August of that year.

Training regions were interactively digitized on-screen using visual overlay of the data layers. For both images, my previous experience on the ground, knowledge of local conditions, and familiararity with the satellite images contributed to the selection of quality sites. Visual clues indicating the type and density of vegetation, or its lack thereof, were discernable with the eye. Knowledge of image characteristics including tone, color, texture, and pattern associated with ground features helped identify significant image components (Mas and Ramírez 1996). These visual indicators were then cross referenced against the air photos, GPS data, stand data, and digital photos to validate the classification of training regions.

## Signature Extraction

Supervised classification requires the extraction of spectral signatures based on training region classifications. After the training sites were digitized, signature extraction produced statistical characterizations of the forest and non-forest information classes for each image. The signature files contain the names of the bands from which the information was extracted, the minimum, maximum, and mean values for each band, and the variance/covariance matrix for the multispectral image band set for each class (Eastman 1999a). The file can be viewed graphically to assess the separation or overlap between each informational class for all bands.

Jensen (1996) and Eastman (1999a) suggest at least a 10:1 ratio of pixels per training class to the number of bands in the image. Campbell (1981) indicates that selecting a large number of small training fields rather a few large contiguous areas reduces high levels of similarity and better represents variation within classes, increasing classification accuracy. He also recommends at least 100 pixels per training class (Campbell 1981). The training regions for this study represented many smaller areas for the forest and non-forest classes, and exceeded both requirements for the minimum number of pixels necessary for each class (Tables 4.2 and 4.3).

For the supervised classifications in this study, signatures were extracted from bands 1 through 7 excluding 6 and the panchromatic. The 2000 panchromatic band does not contain digital reflectance values appropriate for classification based on vegetation types. Thermal band 6 was omitted because it is not readily associated with the reflective region of the electromagnetic radiation (EMR) spectrum and may degrade classification accuracy (Coppin and Bauer 1994).

## Initial Classification

The maximum likelihood classification algorithm was chosen to process the Landsat images. Maximum likelihood is generally regarded as the most powerful hard classifier when applied with high quality training data exhibiting unimodal (Gaussian) or near normal distributions (Campbell 1996; Jensen 1996; Mather 1999). The maximum likelihood equation uses Bayesian probability theory to calculate the prior probability that a pixel belongs to one class or another based on the signature files extracted from a set of training regions. Maximum-likelihood uses not only the means, but also the variance/covariance matrices from the signatures to estimate the prior probability that a pixel belongs to each class (Eastman 1999a).

When the natural spectral variability of brightness values from separate land cover classes causes their frequency distributions to overlap, maximum likelihood uses *a priori* knowledge to assign pixels to the appropriate class (Campbell 1996). The equation produces what can be described as a multidimensional elliptical characterization of the signature where the prior probability of belonging to each class is highest at the mean position, and decreases in an elliptical pattern away from the mean (Eastman 1999a). The set of signature files that defines the proportion of the area to be classified covered by each class is characterized as a vector of prior probabilities. The probabilities are proportional to the area covered by the classes, similar to weights (Mather 1999). The weights are incorporated into the algorithm by weighting each class according to its appropriate *a priori* probability (Jensen 1996).

## Post-classification Comparison

The classified images were compared to determine the extent of forest cover change that occurred for deforestation and forest re-growth. An image was produced that assigned a unique class to every new combination of original values, in effect a cross-tabulation of the time 1 (1986) and time 2 (2000) images. The new image displays coded regions of change and no change in the form of a land cover map.

The change map was then generalized with a 3 by 3 median filter to reduce isolated pixels and strings of single pixels. These strings occurred mainly along patch boundaries and were likely caused by the slight misregistration inherent to the post-classification comparison of multi-temporal imagery. The median filter preserves detail while removing random noise in qualitative images (Eastman 1999b). The median value of the 9 pixel values in the "mask", or filter window, is output in the case of the 3 by 3 filter.

## Accuracy Assessment

Accuracy assessment was conducted to evaluate the correctness of the initial classifications. An accuracy assessment determines the quality of the information derived from remotely sensed digital imagery and is a prudent part of the classification procedure if the results will influence decision making (Congalton and Green 1999). The error matrix is a basic tool for evaluating classification results (Congalton 1991). Ideally, the matrix results from the comparison of ground truth data to the interpreted land cover map created by the classification operation. If no additional reference data exists, as was the case with this study, the alternative is to use the training data to conduct a basic assessment of classification accuracy. The vector training area layers were converted to raster images and compared with the classified images to produce an error matrix that tabulated errors of commission and omission from which an overall Kappa Index of Agreement (KIA) measure (also known as Coen's Kappa, KHAT, or simply Kappa) was output for each image.

Kappa measures association or agreement and is used in accuracy assessment to determine if one error matrix is significantly different from another (Congalton and Green 1999). Kappa corrects the observed percent agreement for chance and normalizes the resulting value so that the coefficient ranges from 0.0 indicating no correlation, to 1.0 indicating perfect agreement (Norusis 1998). The Kappa measure rates correctness based on agreement in the error matrix indicated by the major diagonal and chance agreement represented by the row and column totals.

**Table 4.1.** RMS error.

| | X coordinate | Y coordinate | Total RMS error |
|---|---|---|---|
| **1986 TM** | 7.8701 | 5.8369 | 9.7984 |
| **2000 ETM+** | 6.5814 | 4.0605 | 7.7332 |

**Table 4.2.** Number of polygons per training region class per image.

| | 1986 TM | 2000 ETM+ |
|---|---|---|
| **Forest** | 23 | 19 |
| **Non-forest** | 11 | 19 |

**Table 4.3.** Number of pixels per training region class per image.

| | 1986 TM | 2000 ETM+ | Image Total |
|---|---|---|---|
| **Forest** | 4327 | 2706 | 148648 |
| **% of Total** | 2.9 | 1.8 | 100 |
| | | | |
| **Non-forest** | 7198 | 12096 | 148648 |
| **% of Total** | 4.8 | 8.1 | 100 |

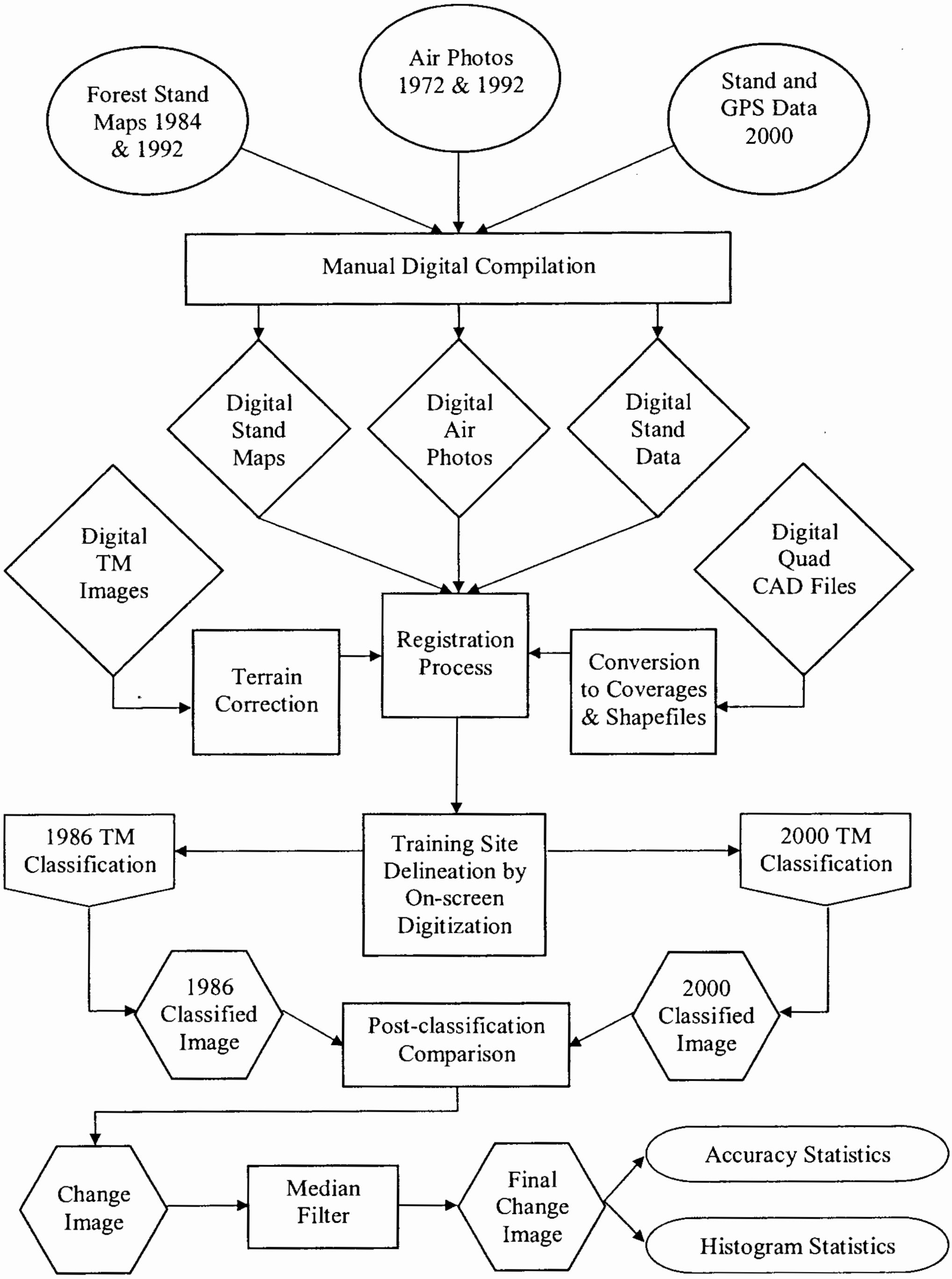


**Figure 4.1.** Post classification comparison process.

April 1986 False Color Infrared Composite

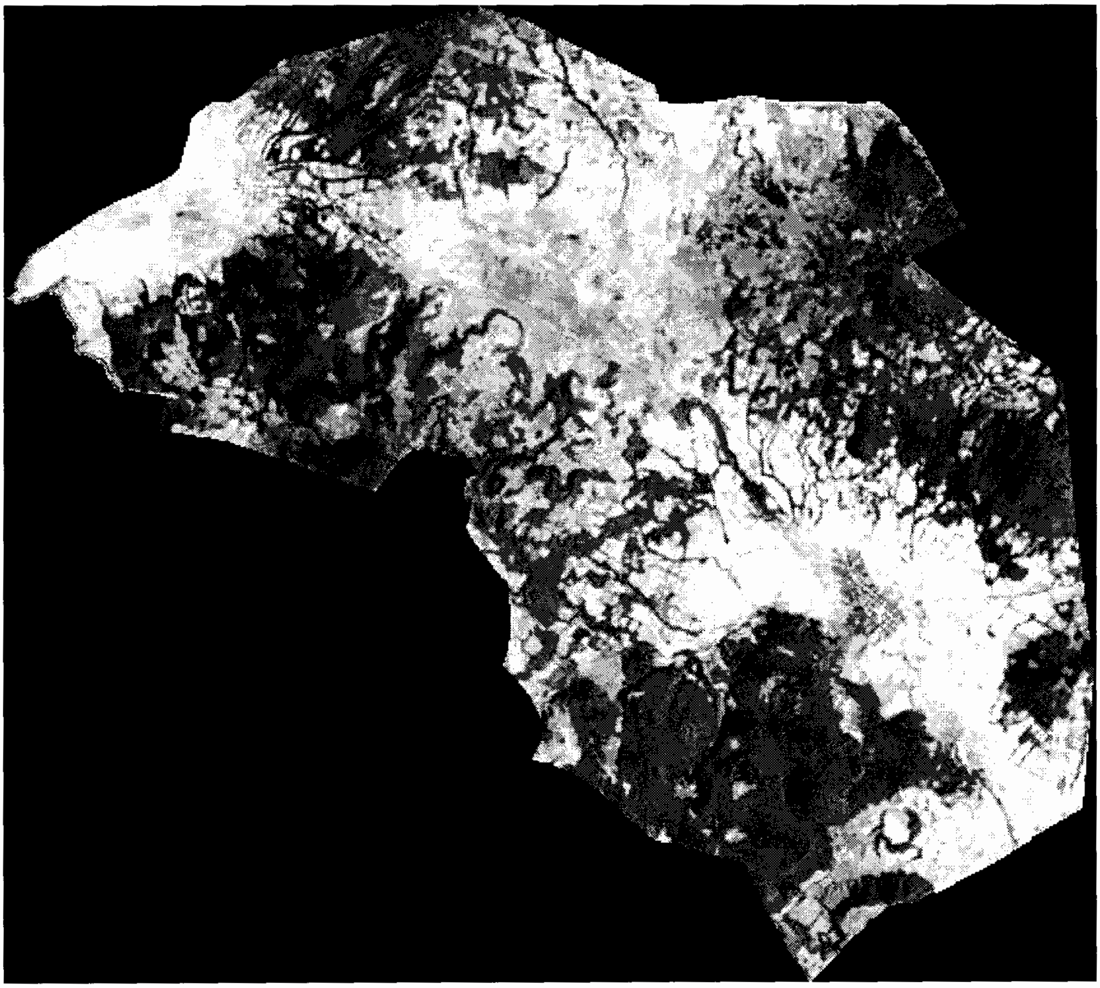

**Figure 4.2.** 1986 false color infrared composite.

April 2000 False Color Infrared Composite

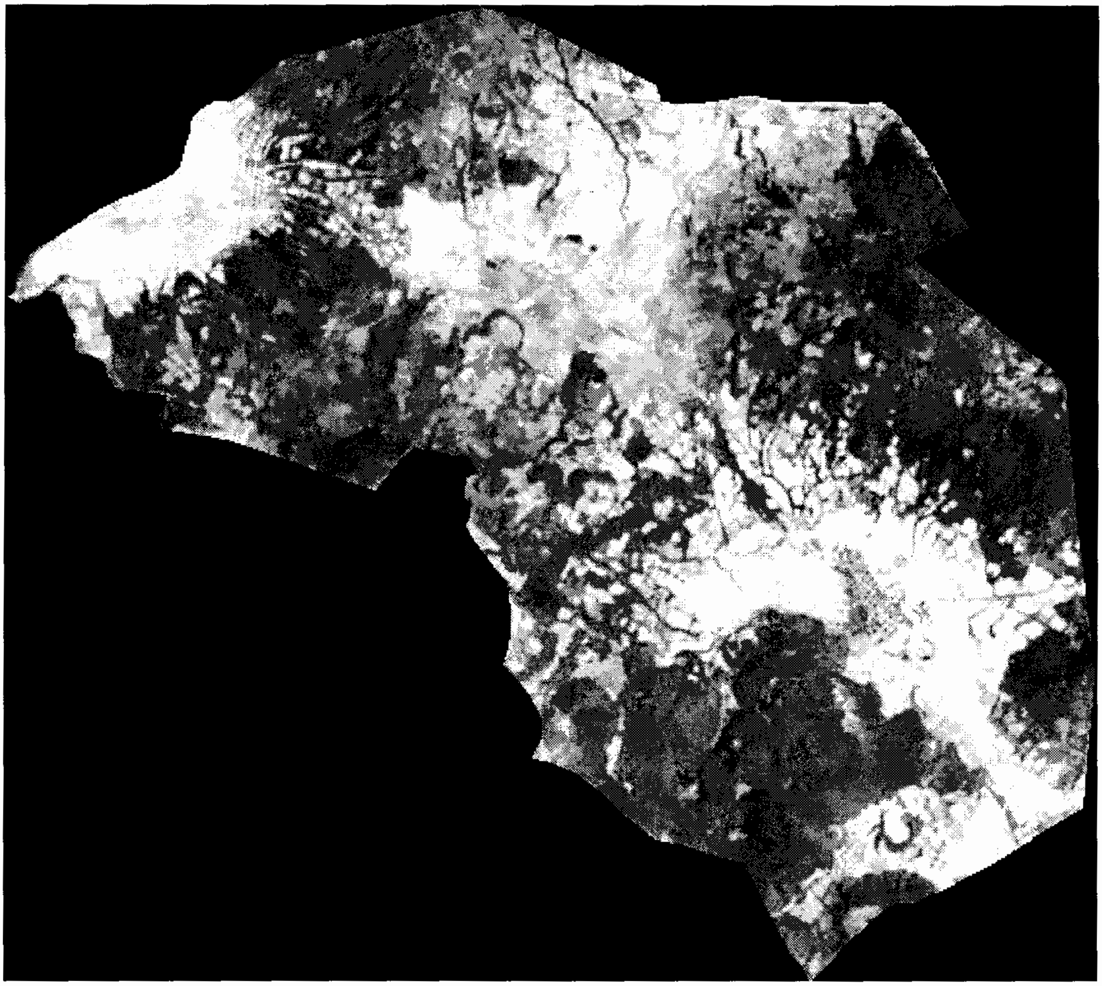

**Figure 4.3.** 2000 false color infrared composite.

# CHAPTER 5: RESULTS AND DISCUSSION

The results from the change detection analysis consist of two kinds of information; 1) land cover maps depicting land cover classes and the amount and location of landscape change, and 2) histograms summarizing the amount of landscape change in terms of pixels per land cover class. Land cover change totals from the histograms were then converted from pixels to hectares, and $km^2$.

## Supervised Classification

The Landsat images were classified for two land cover classes; forest and non-forest. According to Congalton (1999), a classification scheme should be mutually exclusive and totally exhaustive. A scheme is mutually exclusive when each mapped area falls into only one category or class. In order to be totally exhaustive, every part of the mapped landscape must receive a map label. The scheme for this study met the preceding criteria and was chosen based on the poor results obtained from several unsupervised cluster classifications of the study area.

Separating different forest types produced poor results because of the mixed-species nature of the pine-oak forest stand-types in the study area. The lack of contiguous separable training regions definable as a particular homogeneous stand-type made classification at the stand level problematic. For the purposes of this study, because mixed classes with similar spectral signatures were difficult to separate even with TM imagery, the two classes provide the highest likelihood for reliable results (Jusoff and Manaf 1995).

I produced two classified maps of the study area, one each for 1986 and 2000, with the Idrisi image processing module (Figs. 5.1 and 5.2). Numeric histograms extracted from the classified images represent the land cover classification tabulation for every pixel, and the descriptive statistics for the distributions (Table 5.1). I verified the classifications with visual inspection of the false color infrared and true color composites for the respective years.

**Post-classification Comparison**

I compared the classified images to determine the location and extent of forest landscape change from 1986 to 2000. Using Idrisi's cross-tabulation operator I compared the original classified images and produced a change map, land cover classification statistics, and a cross-tabulation matrix with several measures of association between the images (Tables 5.2 and 5.3, Figure 5.3). The change image shows the location and extent of all new combinations of land cover classes from the original input images. I then smoothed the initial change image with a 3 by 3 median filter to remove isolated pixels producing a final change image (Figure 5.4).

The new image map contains four land cover categories; 1) forest (no change), 2) deforestation, 3) non-forest (no change), and 4) regeneration (re-growth). In other words, the new land cover classes depict forest that remained forest, forest that became non-forest, non-forest that remained non-forest, and non-forest that regenerated enough to appear forested (but likely includes shrubby vegetation regeneration). Each new mapped class graphically renders the extent and location of forest loss, regeneration, and no change in land cover class.

The cross-tabulation (comparison) produced two contingency tables (Table 5.3). The first is a cross-tabulation matrix listing the frequency with which each possible combination of the categories from the original images occurred, or frequency of sameness and difference between 1996 and 2000. The matrix assigns a unique identifier to every combination of original values and includes the number of pixels in each combination. The table shows the frequency with which the classes remained the same (frequencies along the diagonal) or changed (off-diagonal) (Eastman 1999b). The second table tabulates the proportional values for the number of pixels that fell into each possible category relative to the total number of pixels in the sample.

I calculated two measures of association between the images based on the proportional values and frequencies output by the cross-tabulation operation (Table 5.3). First, the chi-square ($\chi^2$) test of homogeneity of proportions is used when two or more random samples are compared and each response is classified as belonging to two or more categories (Schweigert 1994). The Chi-square computed for the classified images was $\chi^2$ (1, 148.647) = 77381.22, $\underline{p} < .001$.

Because the two images contained an identical number of categories, a second measure of association, the Kappa Index of Agreement (KIA) was output. Kappa measures correlation between the two images, corrects the observed percent agreement for chance, and normalizes the resulting value (Norusis 1998). Kappa is a meaningful measure of association because the two maps represent the same type of data with identical classes (Eastman 1999b). The overall KIA for the two images is K = .7211.

## Change Statistics

I calculated land area totals for each community and for the entire study area using the classified images (Table 5.4). Next, I calculated the total area of forest and non-forest land cover for the individual communities (Table 5.5) and the entire study area for 1986 and 2000 (Table 5.6). Finally, I extracted land cover change statistics for the individual communities (Table 5.7) and the entire study area (Table 5.8). The statistics show that Sevina contains nearly one half the total land area (47.5 $km^2$) compared to Pichátaro (86.4 $km^2$).

The total forested area for Sevina and Pichátaro in 1986 was 16.8 $km^2$ and 33.2 $km^2$ respectively. Total area forested in 2000 was 11.8 $km^2$ and 36.6 $km^2$ respectively. Pichátaro actually experienced a net increase in its forested area according to the classifications, while Sevina experienced an overall decrease.

The total land area deforested for each community was 7.3 $km^2$ for Sevina and 2.3 $km^2$ for Pichátaro. The percentage of original forest deforested by 2000 was 43.5% and 6.9% for Sevina and Pichátaro respectively equating to 19.1% of the total original forest area for the study region. The percentage of total land area for each community deforested was 15.4% and 2.6% for Sevina and Pichátaro respectively and 7.2% for the entire study area.

Vegetation regeneration totals indicated that Pichátaro experienced a greater degree of re-growth than Sevina. Non-forest land cover encompassed 30.7 $km^2$ and 53.2 $km^2$ for Sevina and Pichátaro respectively in 1986. The total non-forest area in 2000 for Sevina and for Pichátaro was 35.7 $km^2$ and 49.8 $km^2$. The total land area that experienced regeneration for each community was 2.2 $km^2$ and 6.0 $km^2$ for Sevina and for Pichátaro. The percentage of the original non-forest area that experienced regeneration was 7.1% for Sevina and 11.3% for Pichátaro or 9.8% of the total original non-forest area. The percentage of total land area that experienced regeneration was 4.6% and 6.9% for Sevina and Pichátaro respectively, and 6.1% for the entire study region.

I used differential equations to statistically determine an average deforestation percentage per year for the fourteen years within the period of interest. Sevina lost an average of 3.99% of its original forest per year or 52.21 ha. Pichátaro converted an average of 0.51% or 16.34 ha per year.

## Accuracy Assessment

Congalton (1991) suggests adopting an error matrix to assess the accuracy of classified images. I conducted a cursory accuracy assessment using error matrices for both images. The procedure used ground reference information to create a contingency table indicating correctly classified pixels, those pixels incorrectly classified as errors of commission, known as "user's accuracy", and errors of omission, known as "producer's accuracy" (Congalton 1991).

Congalton and Green (1999) state that existing data is only useful as a qualitative assessment tool and should not be used for accuracy considerations unless additional reference data is not obtainable. In this case, the only reference information available was pre-existing data. Raster training region images converted from polygon data layers during the training site delineation process were compared to the classified results.

The raster training images for 1986 and 2000 were correlated with the appropriate classified image for each year. The Idrisi system's ERRMAT module produced two error matrices, one for each classified image (Table 5.9). The matrices tabulated each land cover class to which ground truth cells were assigned correctly or incorrectly. The procedure also output column and row totals, errors of commission and omission, an overall error figure, confidence intervals for that figure, and a Kappa Index of Agreement for all classes and on a per category basis. Kappa measures association based on the difference between the actual agreement in the error matrix (the difference between the interpreted land cover classification map and the reference image depicted by the major diagonal) and the chance agreement represented by the marginals (row and column totals)(Congalton 1999). The 1986 image resulted in an overall Kappa of .9917 while the 2000 image resulted in an overall Kappa of .9785.

Since the post-classification comparison land cover change map relies on the accuracy of the initial classifications, errors in the initial classifications were compounded by the comparison (Coppin and Bauer 1996; Singh 1989). The overall accuracy figure for the post classification comparison was calculated by combining the figures obtained for each individual classification; .9917 x .9785 x 100 = 97% correct joint classification rate.

## Deforestation

For the purposes of this study deforestation is defined as the conversion of forest land cover to some other category. Land cover classifications reveal how much forest each village had in 1986 and in 2000. Sevina lost 43.5% (731 ha) of forested area during that time compared to 6.9% (228.7 ha) for Pichátaro. This finding is consistent with the large number of sawmills that operated in Sevina during the 1990's stimulating substantially more cutting than Pichátaro experienced.

A change image representing the extent of deforestation provides a dramatic visualization of the disparity in deforestation patterns between the two community forests. Distinctly different land management strategies were applied to the landscape, clear cutting (Sevina) versus high grading (Pichátaro), during the period resulting in the obvious contrast in pattern between the northeast and southwest portions of the study area. The boundary between communities is visible in the pattern of deforestation (Figure 5.5).

Sevina lost extensive patches of contiguous forest indicative of clear-cutting and concentrated harvest. This pattern of intensive harvest is usually associated with logging stimulated by the demands of organized sawmill operations. Historically, sawmills move into an area, operate until they exhaust all the large dimension timber they can extract and mill at a significant profit, then close down and move on in search of more trees. Deforestation took place throughout Sevina's forests but was mostly concentrated at higher elevations, further from the urban center, where the largest remaining and most valuable trees were located.

Pichátaro experienced a more evenly dispersed pattern of forest conversion with only a few areas of concentrated change. This finding is consistent with the recent history of forest use in the community. Selective logging was the dominant extraction strategy in Pichátaro, in response to the demands of a developing furniture-making industry. A value added industry based in carpentry, cabinetmaking, and finished wood products consumed less wood than one based on intensive extraction for lumber production by sawmills. At least during the period of interest, Pichátaro's forests appear to have undergone significantly less conversion.

## Vegetation Regeneration

Image comparison reveals significant areas of vegetation regeneration in the region (Figure 5.6). Re-growth in the context of the study area is considered natural shrub regeneration, the re-establishment of seedlings and saplings naturally or through replanting, or a combination of the two processes (Figure 5.2). Tree regeneration occurs in areas cleared by logging, burning, or where agricultural fields and pasture have been abandoned. Although natural and culturally influenced regeneration may eventually result in the return of forest cover, most of the areas classified as re-growth are not forest. This conclusion is based on field observations of land use in the region, an expansion in the wood products sector, and a decline in the profitability of agriculture leading to abandonment of marginal parcels.

While the major process of landscape change for Sevina between 1986 and 2000 was deforestation, for Pichátaro it was regeneration. My results indicate Pichátaro experienced more re-growth than Sevina. This is a consequence of the disparity in size between the communities and forest conversion in Sevina where significant areas of deforested land have not yet had time to recover enough to appear as re-growth in the change image. Re-growth in Sevina (220.3 ha) was approximately 35% of that identified for Pichátaro (600.7 ha).

The greater re-growth in Pichátaro reflects its larger land area, 8,644 ha opposed to Sevina's 4751.9 ha, but there are likely other factors that caused the discrepancy. A different pattern of re-growth for each village is evident in the change image indicating that each management strategy influenced landscape pattern and process in different ways. The northern forest area of Sevina exhibits larger contiguous areas of re-growth than are found anywhere else in the image. This is one of the most difficult places to reach in the forests of Sevina and is an area the change image indicates was most heavily deforested during the period of interest. These large patches of re-growth may be the result of logging that predates the forest conversion detected by this study and are now experiencing a return of shrubby vegetation and young forest.

The pattern of re-growth in Pichátaro is more consistent with the return of vegetation in areas cleared for agriculture and pasture. The pattern is more random and dispersed than the concentrated pattern found in Sevina. Visual feature analysis indicates that most of the re-growth took place in and around the margins of forested areas and hillside agricultural plots. This distribution suggests that re-growth was associated with the abandonment of more marginal milpa plots and the selective removal of forest cover at higher altitudes. This is consistent with an increase in selective timber harvest in response to expanding markets for wood products in the area.

As markets change, so do land use practices. The abandonment of marginal agricultural lands is indicative of the trade reforms that went into effect during the 1990's limiting the ability of small-scale farmers to compete against foreign imports. This disparity probably also reflects the abandonment of milpa agriculture on marginal hillside plots by many townspeople who in one way or another became involved in the woodworking industry.

## No Change

Little change took place in the broad valleys. This area contains the most productive soil, is easiest to plow and plant, and produces the highest returns on planting investments. Visual feature analysis indicates that most of the valley floors experienced a degree of cultivation and/or grazing sufficient to maintain their classification as non-forest, no change regions between 1986 and 2000. Also notable is that most of Pichátaro's forest canopy remained intact, although it was likely somewhat degraded by selective harvesting. Pichátaro retained over 90% of the forest it had in 1986.

## Conclusion

My results indicate that both community forests in the study area underwent rapid change between 1984 and 2000. The land cover change map shows large differences in the in the area of deforestation between the communities and abrupt changes adjacent to their shared boundary. These differences are associated with concurrent ecological and social change but along different trajectories.

Political, economic, and social forces shaped the character of forest landscape change. Shifts in policy governing land-tenure and property rights contributed to these changes by allowing the sale of communal lands and timber concessions. The liberalization of markets by NAFTA and the GATT altered the smallholder farmer's ability to subsist on maize cultivation. Migration responded to boom and bust cycles in village economies. Sevina experienced population loss when its timber supply diminished and workers migrated in search of work. Pichátaro's population grew after members of the community returned to participate in the current boom in value-added woodworking. The decision to seek short-term profits from the extraction of timber became a destabilizing force for one village while the other has thus far retained its historical identity by resisting the pressure to sell its timber off quickly.

The neighboring villages experienced dramatically different trajectories of landscape change as a result of economic, political, and social determinants.

Migration, community structure, access to markets, local traditions, geographical location, the spatial distribution of natural resources, and government policy all played a role in how events unfolded for each community.

Exactly what sent each village down its particular path is beyond the scope of this study. However, recognizing the importance of these vectors for social, environmental, and economic change contributes to a better theoretical understanding of how the villages could experience radically different patterns of landscape change. This understanding provides insight into how patterns of landscape change occur, lending evidence in support of the validity of the land cover classifications.

The boundary between Sevina and Pichátaro is not merely political: It is also ecological and social. Visual feature analysis of the forest change maps indicate that two distinct regions exist within the study area based on the pattern of deforestation and regeneration. This example of how culture influences landscape pattern supports the effectiveness of an ecologically framed remote sensing perspective for analyzing human-environment interactions. This approach provides a holistic context in which to examine landscape change and a better causal understanding of emergent spatial patterns in the landscape.

Initial investigations in the region hinted there was a significant amount of deforestation and degradation taking place, and that it had occurred to a greater extent in Sevina. When the problem is assessed with satellite imagery the magnitude of this change becomes obvious. Over 15 years Sevina lost close to 2.5 times the amount of forest Pichátaro did, from an original area of forest nearly half the size.

GIS analysis of remotely sensed imagery proved to be an effective means to approach the problem. Comparison of the satellite imagery elicited a graphic map of the extent and location of deforestation and regeneration in the study area. The logistics of conventional biotic field sampling on the ground limit the ability to conduct large scale analysis of landscape change. Digital imagery, GIS analysis, and limited ground truthing are an inexpensive compromise to the enormous cost required for extensive field work in remote locations.

This approach to landscape change detection allows transferability to similar situations where landscapes and people face potential environmental crisis. The basic strategy used to understand forest change with satellite imagery in this study can be fine tuned and applied in a multitude of different but related scenarios. Images of change, especially dramatic change sensed remotely from the air or space, are potent tools for education and persuasion. When they illustrate impending or transpiring environmental degradation and resource depletion they become even more powerful.

**Table 5.1.** Land cover classification image pixel totals.

**1986 Landsat TM Image Classified with Maximum Likelihood Algorithm**

| Class | Freq. | Prop | Cum. Freq. | Cum. Prop. |
|---|---|---|---|---|
| Forest | 55542 | 0.1988 | 55542 | 0.1988 |
| Non-forest | 93106 | 0.3333 | 148648 | 0.5321 |
| No Data | 130730 | 0.4679 | 279378 | 1.0000 |

| | |
|---|---|
| Class width | 1.0000 |
| Display minimum | 1.0000 |
| Display maximum | 3.0000 |
| Actual minimum | 1.0000 |
| Actual maximum | 3.0000 |
| Mean | 2.2691 |
| Standard Deviation | 0.7709 |
| df | 279377 |

**2000 Landsat ETM+ Image Classified with Maximum Likelihood Algorithm**

| Class | Freq. | Prop | Cum. Freq. | Cum. Prop. |
|---|---|---|---|---|
| Forest | 53792 | 0.1925 | 53792 | 0.1925 |
| Non-forest | 94856 | 0.3395 | 148648 | 0.5321 |
| No Data | 130730 | 0.4679 | 279378 | 1.0000 |

| | |
|---|---|
| Class width | 1.0000 |
| Display minimum | 1.0000 |
| Display maximum | 3.0000 |
| Actual minimum | 1.0000 |
| Actual maximum | 3.0000 |
| Mean | 2.2754 |
| Standard Deviation | 0.7646 |
| df | 279377 |

**Table 5.2.** Change comparison pixel totals.

**Initial Change Image**
(cross-tabulation of 1986 maxlike against 2000 maxlike)

| Class | Freq. | Prop | Cum. Freq. | Cum. Prop. |
|---|---|---|---|---|
| Forest | 45032 | 0.1612 | 45032 | 0.1612 |
| Regen | 8760 | 0.0314 | 53792 | 0.1925 |
| Deforest | 10510 | 0.0376 | 64302 | 0.2302 |
| Non-Forest | 84346 | 0.3019 | 148648 | 0.5321 |
| No Data | 130730 | 0.4679 | 279378 | 1.0000 |

| | |
|---|---|
| Class width | 1.0000 |
| Display minimum | 1.0000 |
| Display maximum | 5.0000 |
| Actual minimum | 0.0000 |
| Actual maximum | 5.0000 |
| Mean | 3.8840 |
| Standard Deviation | 1.4381 |
| df | 279377 |

**Final Change Image with 3x3 Median Filter**
(cross-tabulation of 1986 maxlike against 2000 maxlike)

| Class | Freq. | Prop | Cum. Freq. | Cum. Prop. |
|---|---|---|---|---|
| Forest | 44181 | 0.1581 | 44181 | 0.1581 |
| Regen | 9123 | 0.0327 | 53304 | 0.1908 |
| Deforest | 10634 | 0.0381 | 63938 | 0.2289 |
| Non-Forest | 84721 | 0.3032 | 148659 | 0.5321 |
| No Data | 130719 | 0.4679 | 279378 | 1.0000 |

| | |
|---|---|
| Class width | 1.0000 |
| Display minimum | 1.0000 |
| Display maximum | 5.0000 |
| Actual minimum | 1.0000 |
| Actual maximum | 5.0000 |
| Mean | 3.8901 |
| Standard Deviation | 1.4310 |
| df | 279377 |

**Table 5.3.** Cross-tabulation matrices.

**Cross-tabulation of 1986 and 2000 classified images**

| | | 1986 | | |
|---|---|---|---|---|
| | | **Forest** | **Non-forest** | **Total** |
| **2000** | **Forest** | 45032 | 8760 | 53792 |
| | **Non-forest** | 10510 | 84346 | 94856 |
| | **Total** | 55542 | 93106 | 148648 |

**Proportional Cross-tabulation**

| | | 1986 | | |
|---|---|---|---|---|
| | | **Forest** | **Non-forest** | **Total** |
| **2000** | **Forest** | 0.30 | 0.06 | 0.36 |
| | **Non-forest** | 0.07 | 0.57 | 0.64 |
| | **Total** | 0.37 | 0.63 | 1.00 |

**Chi-square** = $\chi^2$ (1, 148647) = 77381.22, $p < .001$

**Overall Kappa** = .7211

**Table 5.4.** Total land area statistics by community.

**Land Area Totals**

| | | **Sevina** | **Pichátaro** | **Entire Area** |
|---|---|---|---|---|
| **Total Area** | **pixels** | 52746.0 | 95955.0 | 148648.0 |
| | **ha** | 4751.9 | 8644.0 | 13391.7 |
| **% Total Area** | | 35.5 | 64.5 | 100.0 |

**Table 5.5.** Forest/non-forest land area statistics by community.

**Forest/Non-forest Area Statistics by Community**

| | | Sevina | | Pichátaro | |
|---|---|---|---|---|---|
| | | **1986** | **2000** | **1986** | **2000** |
| **Forest** | **% total area**[a] | 35.0 | 25.0 | 38.0 | 42.0 |
| | **pixels** | 18658.0 | 13080.0 | 36876.0 | 40666.0 |
| | **ha** | 1680.9 | 1174.8 | 3322.2 | 3663.6 |
| **Non-forest** | **% total area**[a] | 65.0 | 75.0 | 62.0 | 58.0 |
| | **pixels** | 34088.0 | 39666.0 | 59079.0 | 55289.0 |
| | **ha** | 3071.0 | 3573.5 | 5322.4 | 4981.0 |

[a] = percentage of the total community land area.

**Table 5.6.** Forest/non-forest land area statistics for the entire study area.

**Forest/Non-forest Area Statistics for the Study Region**

| | | Total 1986 | Total 2000 |
|---|---|---|---|
| **Forest** | **% total area**[a] | 37.0 | 36.0 |
| | **pixels** | 55542.0 | 53792.0 |
| | **ha** | 5003.1 | 4846.1 |
| **Non-forest** | **% total area**[a] | 63.0 | 64.0 |
| | **pixels** | 93106.0 | 94856.0 |
| | **ha** | 8393.4 | 8545.6 |

[a] = percentage of the total combined study region.

**Table 5.7.** Change statistics by community.

**Change Statistics by Individual Community**

| | | Sevina | Pichátaro |
|---|---|---|---|
| **Deforestation** | **% total area**[a] | 15.4 | 2.6 |
| | **% original area**[b] | 43.5 | 6.9 |
| | **pixels** | 8114.0 | 2539.0 |
| | **ha** | 731.0 | 228.7 |
| **Regeneration** | **% total area**[a] | 4.6 | 6.9 |
| | **% original area**[c] | 7.1 | 11.3 |
| | **pixels** | 2445.0 | 6668.0 |
| | **ha** | 220.3 | 600.7 |

[a] = percentage of the community's land area.
[b] = percentage of the community's original forest area (1986).
[c] = percentage of the community's original non-forest area (1986).

**Table 5.8.** Change statistics for the entire study area.

**Change Statistics for the Entire Study Region**

| | | Entire Area |
|---|---|---|
| **Deforestation** | **% total area**[a] | 7.2 |
| | **% original area**[b] | 19.1 |
| | **pixels** | 10634.0 |
| | **ha** | 958.0 |
| **Regeneration** | **% total area**[a] | 6.1 |
| | **% original area**[c] | 9.8 |
| | **pixels** | 9123.0 |
| | **ha** | 821.0 |

[a] = percentage of the total land area.
[b] = percentage of the total original forest area (1986).
[c] = percentage of the total original non-forest area (1986).

**Table 5.9.** Accuracy assessment of the image classifications.

**Error Matrix Analysis** of 86TRAIN_LAYER (columns:truth)
against 86MAXLIKE_EQUALPROB (rows:mapped)

| | 1 | 2 | Total | ErrorC |
|---|---|---|---|---|
| 1 | 4304 | 22 | 4326 | 0.0051 |
| 2 | 23 | 7176 | 7199 | 0.0032 |
| Total | 4327 | 7198 | 11525 | |
| ErrorO | 0.0053 | 0.0031 | | 0.0039 |

1=Forest 2=Non-forest

Using 86MAXLIKE_EQUALPROB as the reference image:

| Category | KIA |
|---|---|
| 1 | 0.9919 |
| 2 | 0.9915 |

86TRAIN_LAYER

| Category | KIA |
|---|---|
| 1 | 0.9915 |
| 2 | 0.9919 |

Overall Kappa = 0.9917

**Error Matrix Analysis** of 00TRAIN_LAYER (columns:truth)
against 00MAXLIKE_EQUALPROB(rows:mapped)

| | 1 | 2 | Total | ErrorC |
|---|---|---|---|---|
| 1 | 2695 | 85 | 2780 | 0.0306 |
| 2 | 11 | 12011 | 12022 | 0.0009 |
| Total | 2706 | 12096 | 14802 | |
| ErrorO | 0.0041 | 0.0070 | | 0.0065 |

1=Forest 2=Non-forest

Using 00MAXLIKE_EQUALPROB as the reference image:

| Category | KIA |
|---|---|
| 1 | 0.9626 |
| 2 | 0.9950 |

00TRAIN_LAYER

| Category | KIA |
|---|---|
| 1 | 0.9950 |
| 2 | 0.962 |

Overall Kappa = 0.9785

1986 Maximum Likelihood Classification

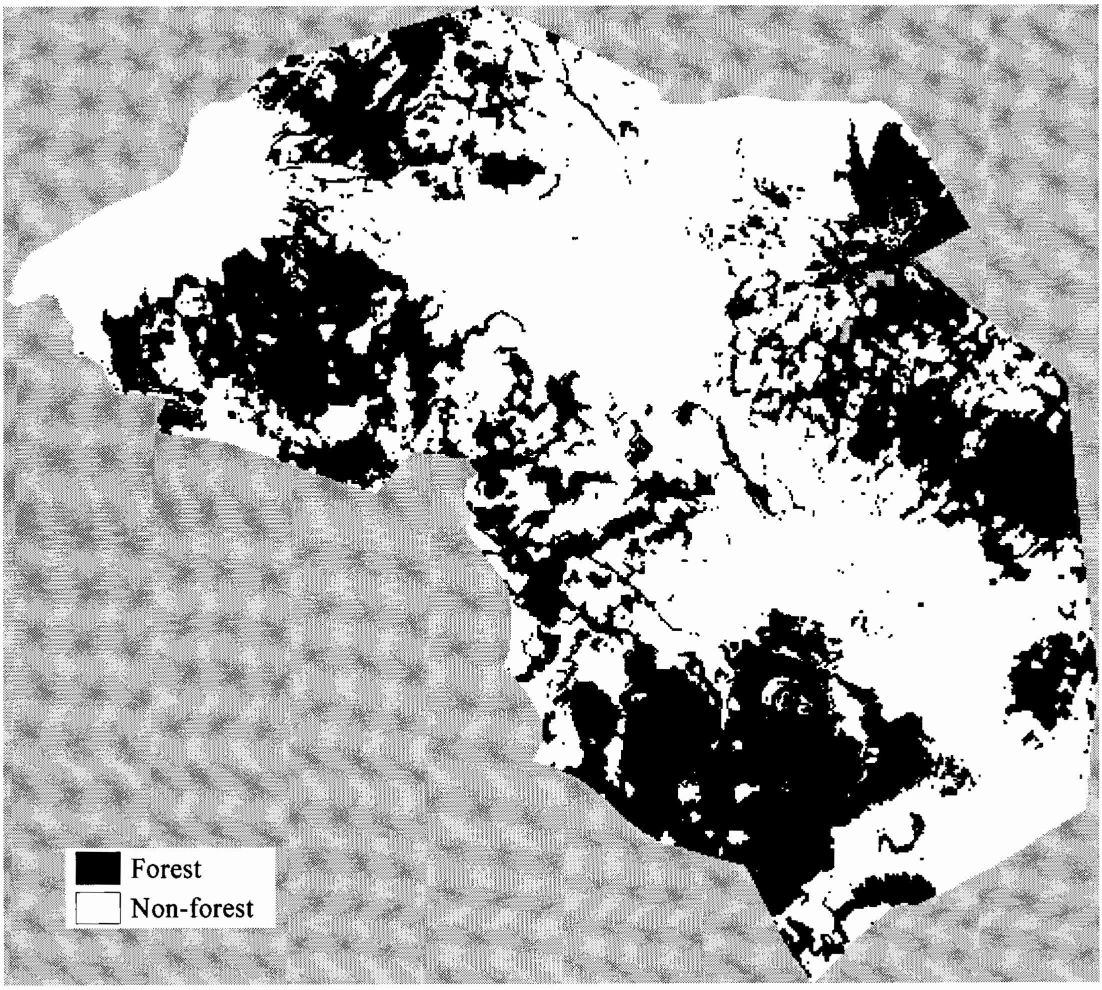


**Figure 5.1.** 1986 maximum-likelihood classification image.

2000 Maximum Likelihood Classification

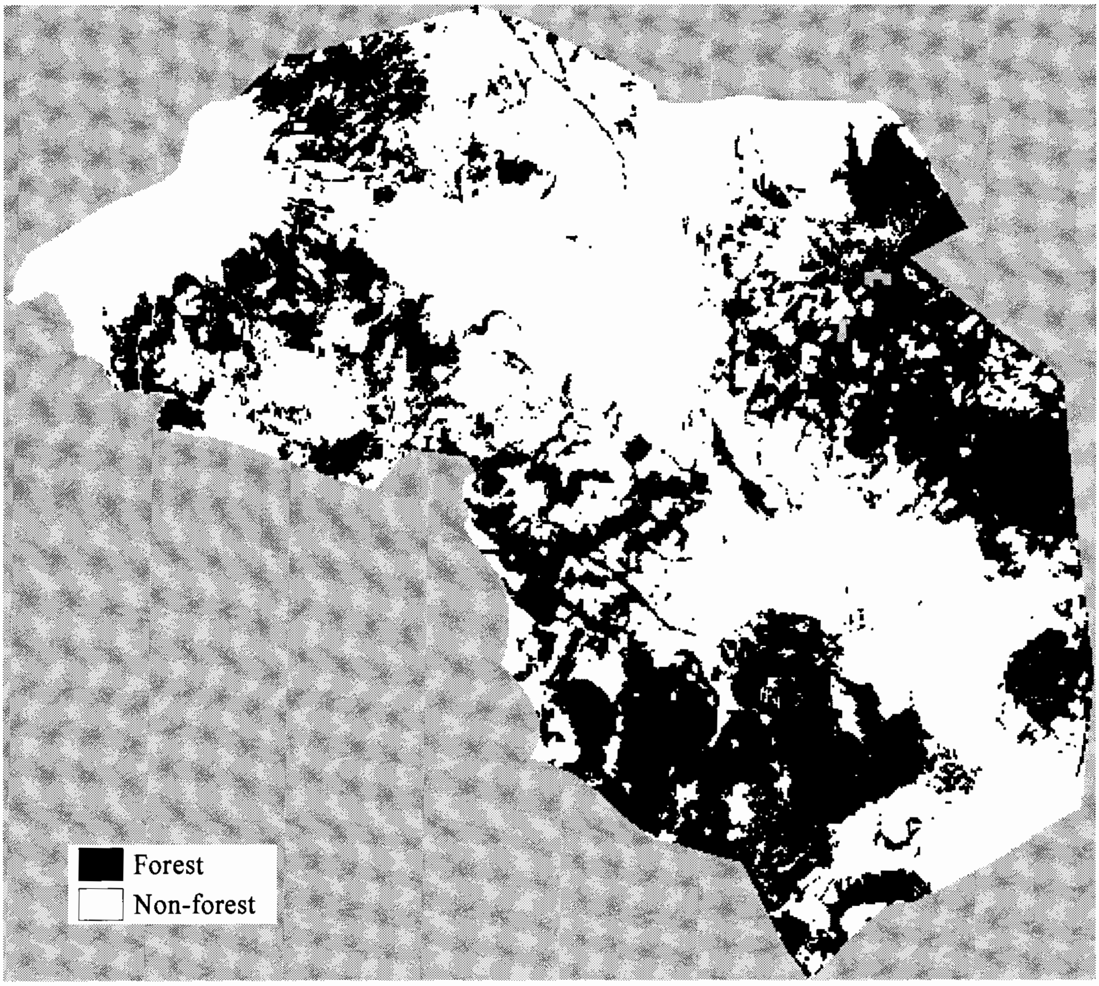


**Figure 5.2.** 2000 maximum-likelihood classification image.

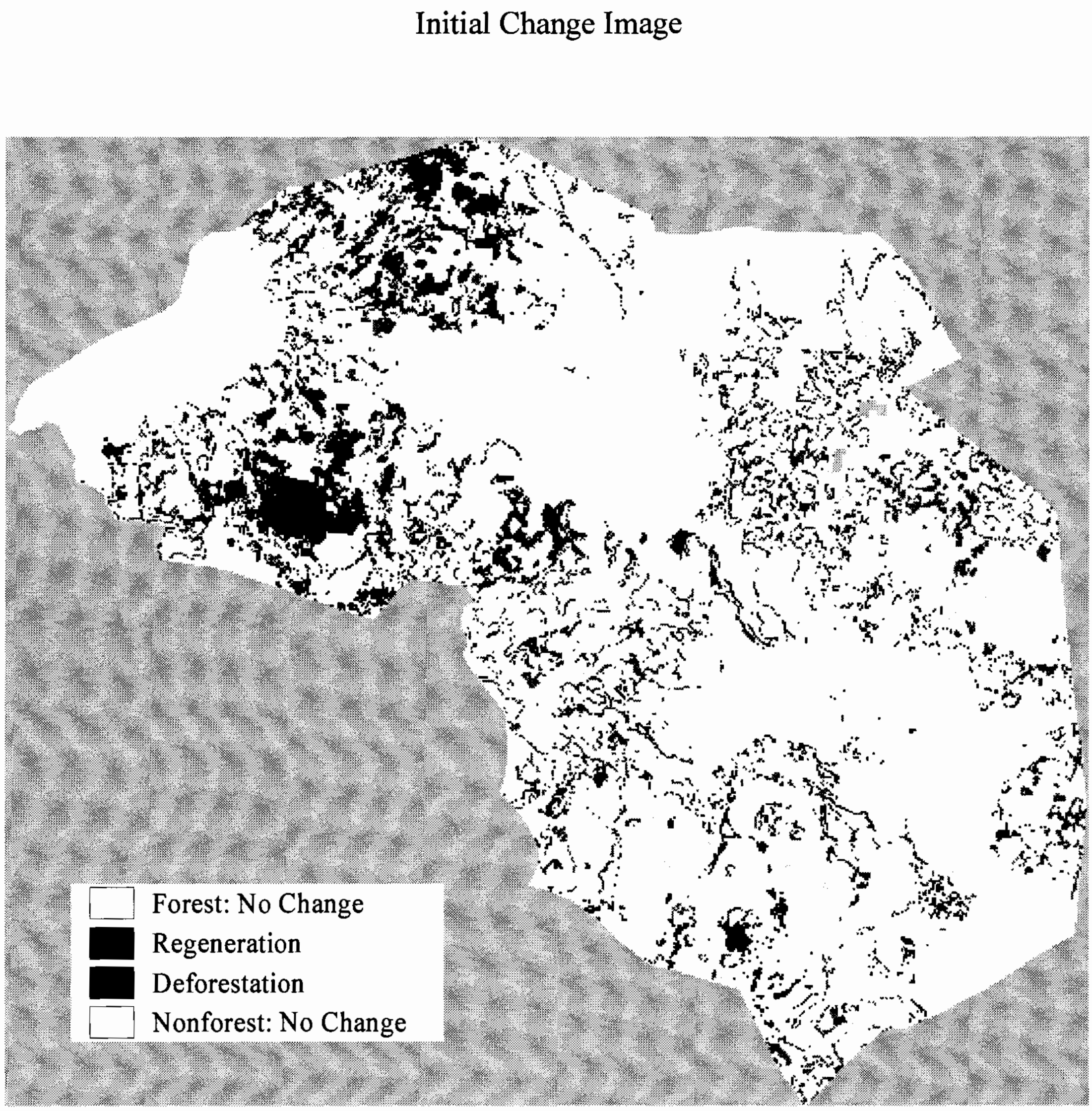


**Figure 5.3.** Initial change image.

Final Change Image

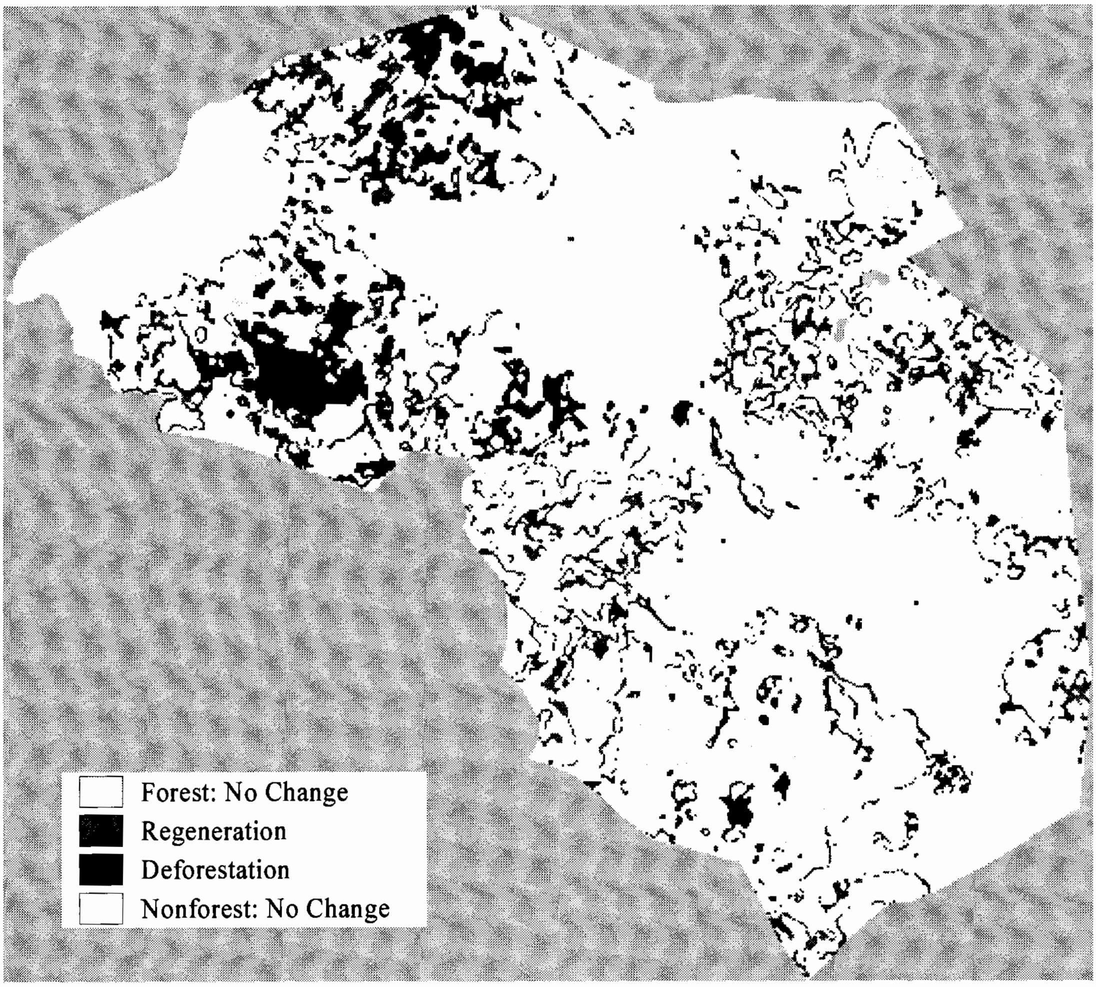


**Figure 5.4.** Final change image.

1986-2000 Deforestation Regions

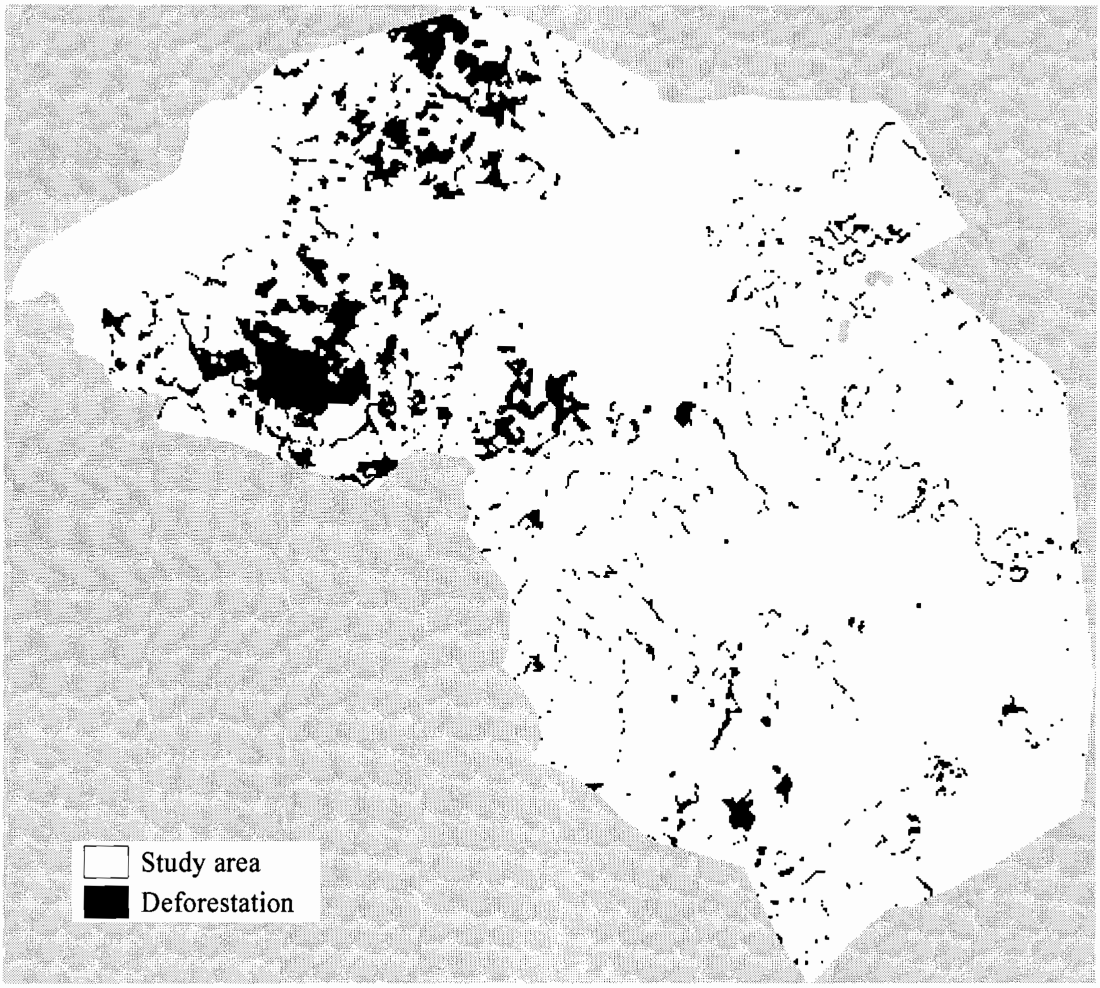


**Figure 5.5.** Deforestation regions.

1986-2000 Regeneration Regions

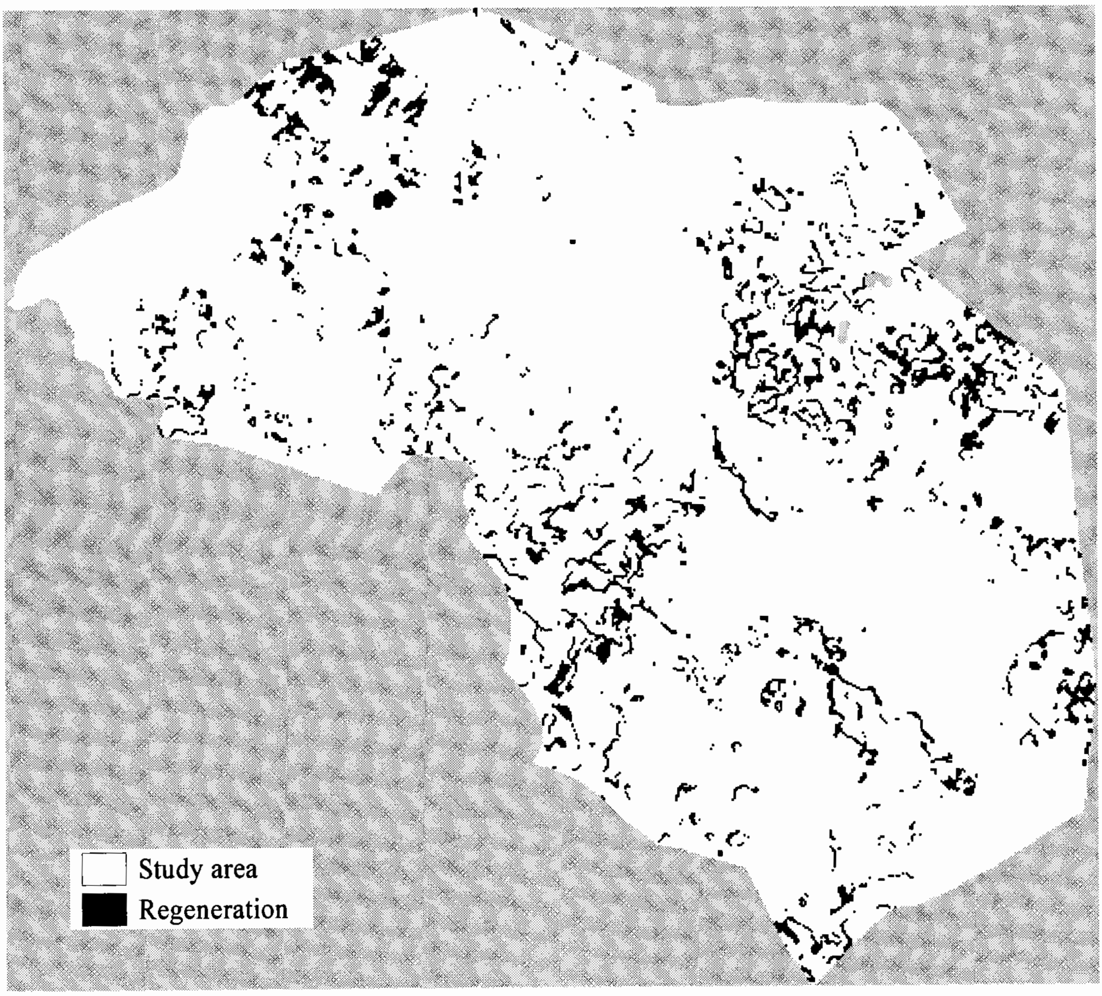


**Figure 5.6.** Regeneration regions.

# CHAPTER 6: SUMMARY

Developing nations are vulnerable to the factors that stimulate deforestation at multiple geographic scales. Natural resource management policies that change with each new administration contribute to a history of ineffective forest management in México. During the 20$^{th}$ century forest policy oscillated between the redistribution of land and communal tenure for rural peasants, logging bans, huge concessions to timber parastatals, and consolidation of government control over the forestry sector.

México is susceptible to a diverse set of forces that drive landscape change and degradation. Government policy designed to improve México's access to the global economy allows timber concessions and the sale of communal lands. Kick-backs and national debt lead to the liquidation of forests for short-term profit and loan repayment to outside lenders at the national level. Clandestine logging and timber smuggling occurs to the extent that theft is profitable and supported by a black market regionally. Ineffective forest resource management, poor community organization, and a tragedy of the commons scenario all contribute to forest degradation at local and regional scales.

The situation in Sevina and Pichátaro is directly affected by the micro and macro-scale changes taking place within and outside México. Each village appears to have reacted in its own way to external and internal pressures to cut down its remaining forests. These pressures stimulated different resource management strategies. The difference in strategies unevenly influenced pattern and process in the natural landscape.

Sevina is clearly in a predicament and although Pichátaro is currently not experiencing a timber shortage, one may be on the horizon. A forest resource management plan based on sustainable harvest, increased efficiency, and value added production in the region may or may not prolong the viability of local forests. Market forces might not even allow such an experiment. Intense pressure to liquidate forests for the short-term production of marketable commodities may preclude any attempt to manage pine forests in the region for sustainable timber production and the conservation of biological diversity. The purpose of this study is not to suggest ways to avoid a crisis, but simply to assess the dimensions of the current situation and attempt to better understand its causes.

Local people in the Meseta do not have the luxury to consider concepts like sustainability, biodiversity, ecosystem connections, or carbon sequestration. They face more immediate concerns like growing and gathering food, accessing the electrical power grid, and obtaining potable water and wastewater management systems for their villages and homes. After that, needs more tangible than forest health take precedence. Access to the modern amenities and consumer goods associated with emerging regional and local currency based markets supercede most other matters, including thoughtful forest management.

The desire to participate in this new marketplace is a potent and seductive agent of change in the region. Locals want satellite television, modern clothing, and telephones. They desire electricity, gas heat, and plumbing. They want pick-up trucks and chainsaws so they can participate in the industry that puts pesos in their hands. Pesos are the tickets that buy seats in the theater of the global marketplace. Trees are the resource that provides the opportunity to earn pesos. The marketplace, therefore, is the main agent of change that drives the entire system, and is the premier catalyst for deforestation and land degradation in the region.

The ability to regulate the environmental and social impact of market forces from within the community by organizing and managing local resources and production methods may improve the situation in the Meseta. Sevina appears to be attempting to do so with a program of community education, replanting, erosion prevention, and water resource conservation. A collapse of the forest industry in Sevina already caused economic depression and out-migration. Whether attempts to mitigate environmental degradation in there can succeed will not be knowable for perhaps 20-40 years.

If Pichátaro's forests and economic stability can endure also remains to be seen. As the local woodworking industry expands, so does the opportunity for mismanagement of the forests. At present, villagers appear to have some understanding of the potential problems they face if harvest levels increase unchecked. They seem either unwilling or unable to organize at the community level to seize control of their own natural resource based economy at this time. Perhaps they will recognize the potential economic disaster that awaits them and take steps to promote the future viability of their forests. On the other hand, they may not be able to resist the strength of the classic boom and bust cycles that challenge an economy reliant on primary resource extraction for survival. Only time will tell.

México and Latin America face difficult challenges concerning their rapidly disappearing forest resources. Rural and marginalized people look to the diversity of temperate and tropical forests for their livelihood and cultural identity throughout much of the region. The abandonment of subsistence agriculture for the production of furniture and other forest products is an attractive proposition for rural people with access to timber.

As forests disappear, so do traditional ways of life and ethnic identity. The destruction of forest landscapes produces a homogenizing effect that not only absorbs ancient cultures, but adversely affects the quality of human life at regional and global scales. Deforestation diminishes water quality, enhances soil erosion, degrades soil fertility, and generally reduces the quality of rural life. The global destruction of forests may influence climate change and accelerate global warming of the atmosphere. Ultimately, large-scale forest conversion renders landscapes uninhabitable because it degrades the biological diversity required by terrestrial life forms, especially human life. Unproductive land invites migration and abandonment. The social structures that bind culture groups to each other and their land dissolve when people drift away.

The future of Mexican temperate forests is a complex situation with multiple potential outcomes. Communal forest resource use may contribute to the sustainability of temperate forests if rural people are willing and able to organize and plan for the future. This requires cooperation and consensus from stakeholders, access to capital and administrative resources, replanting, conservation, and a genuine effort to reinvest in forests. Increased efficiency and adding value during the manufacturing process softens negative impacts on forest ecosystems and improves revenue for producers. An organized community can also reduce losses from timber theft and smuggling by policing its own land.

Communal forest management may, on the other hand, lead to runaway logging and the depletion of commercially useful timber for rural people in México. Recent liberalization of land tenure policy and improved access to outside markets might induce widespread forest conversion in favor of quick profits. This scenario usually ends in the depression or collapse of local and regional economies and a renewed cycle of out-migration.

The environmental consequences can be far reaching as well. Forests are self-regulating systems that maintain ecological and biophysical stability over time. Extensive forest cover removal destroys the microclimate that regulates an environment in which forests can regenerate. Forest fragmentation and declining biodiversity further reduce the landscape's ability to rebound causing long-term degradation. Severe degradation prolongs the period in which the landscape remains unproductive and uninhabitable. The magnitude of change happening in the forests is increasing exponentially because modern forest use is not as sustainable as traditional use. The lure of quick profits excludes provisions for the forest in terms of sustainable harvest or biological conservation.

There can be a balance between profit driven forest destruction and total preservation that includes the participation of local people who steward forest resources. A sustainable strategy for the long-term viability of timber harvest and conservation for non-timber forest benefits may be possible through a convergence of ancient and modern technologies. By blending traditional knowledge with low impact harvesting and the sustainability principle, forests may continue to provide multiple amenities indefinitely. The challenge is to find and implement an equitable strategy for the maintenance of biodiversity and continued resource extraction before the global forest becomes irreparably degraded.

## Future Research

My thesis leaves many questions untouched and provides opportunities for future studies. The results present the potential for additional forest change detection preceding, following, and within the time period of interest. GPS technology was used to georeference 20 sample plots, forest stands, farm fields, and pasture in a variety of conditions. These locations can be revisited and assessed in the future for comparison to the baseline ecological conditions established by this study. Landscape photography and stand composition data can be analyzed to assess harvest levels, vegetation dynamics, replanting success, and response to disturbance.

A logical continuation of this study is to pursue more image classification and accuracy assessment for landscape change detection. This requires additional field surveys of local forests to collect training and ground truth information. Only after further sampling is conducted on the ground, or new geospatial information becomes available for the study area can a more robust accuracy assessment be conducted. Additional ground sampling will lead to improved assessments of land cover maps and image classification. Such research builds toward a better understanding of landscape dynamics in the region.

Future research should address questions central to the structure and function of forest ecosystems. If forest removal continues at rates similar to those in Sevina what might the consequences be for processes like carbon sequestration and biotic carbon emissions to the atmosphere? How will an increase in carbon release affect climate and the continued viability of forest ecosystems at local and regional scales? How will deforestation affect the integrity of water and soil resources in the area? Ecological modeling of historic and current information provides the opportunity to build predictive models of possible trajectories for future landscape change. The unique cultural and physical geography of the study area presents great potential for additional research into the relationship between people and their forest environment.

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# APPENDIX: MAP DATA AND LANDSAT IMAGERY

Cheran, Michoacán, México. 1982. 1:50,000 Scale Edaphic Topographic Quadrangle. Projection: UTM zone 14n. Source: *Instituto Nacionál Estadística Geografía y Informática* (INEGI).

Cheran, Michoacán, México. 1980. 1:50,000 Scale Digital Topographic Quadrangle: Projection: UTM zone 14n. Ellipsoid: GRS80. Datum: NAD 27/ITRF 92. Vector data in digital CAD file format on CD-ROM. Source: *Instituto Nacionál Estadística Geografía y Informática* (INEGI).

Cheran, Michoacán, México. 2000. 1:50,000 Scale Topographic Quadrangle. Projection: UTM zone 14n. Ellipsoid: GRS80. Datum: NAD 27/ITRF 92. Digital Vector Data in CAD file format on CD-ROM. Source: *Instituto Nacionál Estadística Geografía y Informática* (INEGI).

Forest Vegetation Inventory Map of the Meseta Purépecha, Michoacán, México. 1994. 1:50,000 Scale. Basemap: 1:50,000 scale Cheran Topographic Quadrangle (INEGI). Source: *Comisión Forestal del Estado de Michoacán, México* (COFOM).

Landsat 5 Thematic Mapper Scene. April 6, 1986. WRS Path 28, Row 46 Capture Direction: Descending. Time 16:37. Reference System: UTM zone14n. Resolution 30m, Thermal 120m. USGS EROS Data Center.

Landsat 7 Enhanced Thematic Mapper Plus Scene. April 20, 2000. WRS Path 28, Row 46. Capture Direction: Descending, Time 17:04. Reference System: UTM zone 14n. Resolution 30m, Pan. 15m, Thermal 60m. USGS EROS Data Center.

Map of Forestry Plan for the Indigenous Community of Sevina, Municipality of Nauhatzen, Michoacán, México. 1985. 1:25,000 Scale, Base map: 1:25,000 Scale Aerial Photographs1969, complimented by 1:50,000 scale aerial photographs, 1973. Source: *Comisión Forestal del Estado de Michoacán, México* (COFOM).