Evaluating Land Use Dynamics and Forest Cover Change in Nepal's Bara District (1973–2003)

Keshav Bhattarai · Dennis Conway

Abstract This research uses Landsat Multi-Spectral Scanner of 1973, Thematic Mapper of 1989, Advance Earth Observing Satellite of 1996, and Enhanced Thematic Mapper of 2003 imagery to examine the effects of socioeconomic and demographic factors on land use and forest cover dynamics in the Bara district of the Central Tarai Region of Nepal for 1973–2003. These satellite images are used to generate three transition matrices for 1973–1989, 1989–1996, and 1996–2003; and the outcomes of the final transition matrix are compared with the land use and cover patterns seen on the IKONOS (1×1 m) 2003 images. This paper contributes to our understanding of how land use and cover dynamics correspond to national-level socioeconomic developments, demographic changes, and environmental awareness as envisioned by Ecological Modernization Theory. It also demonstrates how such a set of transition matrices generated from different resolution images helps assess these explanatory relationships at different temporal and spatial scales.

Keywords Ecological modernization theory · Nepal · Land use and land cover change · Remote sensing · Change matrix

K. Bhattarai (✉)
University of Central Missouri,
Warrensburg, MO 64093, USA
e-mail: bhattarai@ucmo.edu

D. Conway
Indiana University,
Bloomington, IN 47405, USA

Introduction

Rapid population growth and its demand for agricultural land and forest products such as firewood, fodder, timber, and lumber have accelerated deforestation processes in many developing tropical countries. Scientific interest in tropical deforestation and its impacts on livelihood have focused largely on high profile (international research focus) countries like Brazil (Brondizio *et al.* 1996; McCracken *et al.* 1999). Similar research has also been done in low profile (internationally low research focus) countries like Nepal (Tokola *et al.* 2001; Zomer *et al.* 2002) to explore the causes of deforestation. A study on deforestation in a low profile country such as Nepal is needed to understand how agrarian rural population, which depends on limited natural resources, responds to increasing resource scarcity with technological advancement as envisioned by Ecological Modernization Theory (Ehrhardt-Martinez 1998, 1999; Ehrhardt-Martinez *et al.* 2002).

Ecological Modernization Theory (EMT) is based on the assumption that capitalist development is able to reform and promote environmental goals through technologically innovative processes. As development proceeds, environmental damage, including deforestation, will eventually cease (Mather *et al.* 1999). However, the theory also warns that not all types of development help reduce deforestation and alleviate environmental problems due to changes in consumptive patterns (Carolan 2004) because in extractive farming systems, deforestation often becomes a 'casualty' of development (Rostow 1960; Rudel and Roper 1997). For example, increasing road access leads to deforestation due to increasing commodity prices (Rudel 1995) and increasing consumption of forest products (Bhattarai *et al.* 2002; Gautam 2003). Some authors (Anderssen and Massa 2000) consider ecological modernization theory only

makes sense for a reference to more radical structural changes that promote ecological consistence rather than ordinary efficiency. However, Ehrhardt-Martinez et al. (2002) argue that EMT might help to design a specific type of forward-looking and preventive environmental policy based on the long-term structural change of patterns of production and consumption. EMT assumes that deforestation and environmental problems initially accelerate with population growth because of the use of rudimentary 'development technology' and subsistence farming, but that problems are later alleviated as technology advances (Tole 1998) and public awareness increases (Fox 1993). This is because the growing population tends to adjust to limited resources by increasing land productivity (Boserup 1965; Fox 1993).

This paper examines whether or not EMT addresses the issues of deforestation and reforestation in the Nepalese context for the 1973–2003 period. Such research is essential because it addresses the issues of a developing agrarian economy with a high population density (>165 people km^{-1}) that faces many resource management problems, one of which is sustaining farm–forestry linkages. Farm–forestry linkage in Nepal is essential because the government-owned forests are receding at the rate of 1.3–1.7% per year (NPC 2003), in part due to encroachments by subsistence farmers, and in large part because of vacillating government policies (Bhattarai et al. 2002). Additionally, this research is important because past research approaches, such as community forestry (Gilmour and Fisher 1991), migration, settlement, and private land ownership (Shrestha 1990; Ghimire 1992; Bhattarai 2001), and farm–forestry linkage (Kanel 1995) have been unable to relate environmental problems to technological and economic developments. To evaluate contemporary relationships in agrarian Nepal between environmental management and economic development through technological change, this research uses remotely sensed data. The use of remote sensing to examine anthropogenic effects on land use dynamics over time has become a common practice (Aspinall 2004; Boyd et al. 2002; Schweik and Thomas 2002; Tokola et al. 2001; Zomer et al. 2002). However, this research differs from previous studies because it analyzes remote sensing data in the framework of EMT.

This paper utilizes imagery generated from the Multispectral Scanner (MSS) of 1973, Thematic Mapper (TM) of 1989, Advanced Earth Observing Satellite (ADEOS) of 1996, and Enhanced Thematic Mapper (ETM) of 2003, to create transition matrices of land use and land cover change in the Bara district of Nepal. These changing patterns are then compared with IKONOS images of 2003 to further investigate the effects of economic development and demographic change on the land use and forest cover dynamics of this region.

After an introduction to the study site, this paper first presents the post classification-based change detection method used in this evaluation. Second, it identifies the salient factors that have brought about permanent and temporary land use and land cover changes in the Bara district, both temporally and spatially from 1973 to 2003. Third, it highlights the main findings and possible contributions, summarizes the results, and offers some methodological recommendations.

Study Area

The Bara district is located in Nepal's Central Tarai region, which borders India in the south (Fig. 1a–b). It occupies 0.87% of the 14.5 million hectares (ha) area of Nepal's land surface, includes 1.8% of the country's farmland, and supports 1.9% of Nepal's 24 million people with an average population density of 7.5 per ha (CBS 2001). Government-published estimates of the total area of the district are not consistent, however. This study utilizes a shape-file obtained from the National Planning Commission (NPC) of Nepal to delineate the area of the district, which shows its area as 128,057 ha.

Of the 128,057 ha area, 6.3% is undulated gravelly hills called the Siwalik which are located in the north, while the other 93.7% lies in the south Tarai plain (MDM 1971), which constitutes 5% of Nepal's plain land area. Most of the region's forests are located in the north, with more extensive farmland in the southern plain. Bara district is an exemplary site to examine the effects of economic development and demographic changes on land use and land cover dynamics in Nepal's Tarai plain, because the region is representative of Nepal's settlement history. Additionally, this area's settlement trajectory is also similar to that of farming communities in the rapidly deforesting areas of Brazil, Ecuador, Jamaica, and Indonesia, as well as stratified South Asian communities.

Before the abolition of slavery in Nepal in 1924 and the relocation of emancipated slaves from the hills to the forested frontier of Amlekhganj (trans. "settlement of slaves") most of Bara's northern landscape was densely forested. In similar fashion to other developing countries where land cover has been rapidly changing due to anthropogenic activities (Boyd et al. 2002; Sader 1995), the Bara district has been experiencing rapid land use and land cover dynamics after the development of roads in the 1960s. Two highways—east–west and north–south—and the district-level roads, passing north–south through forests and farmlands (Fig. 1b), have been both 'blessings' and 'curses' on land use dynamics. In addition, the government-sponsored resettlements of the 1950s significantly affected this district's population growth rate and land use dynam-

Fig. 1 a Nepal showing the
location of Bara district, and b
Bara's ecological regions, Vil-
lage Development Committees'
(VDCs) boundaries, and road
network
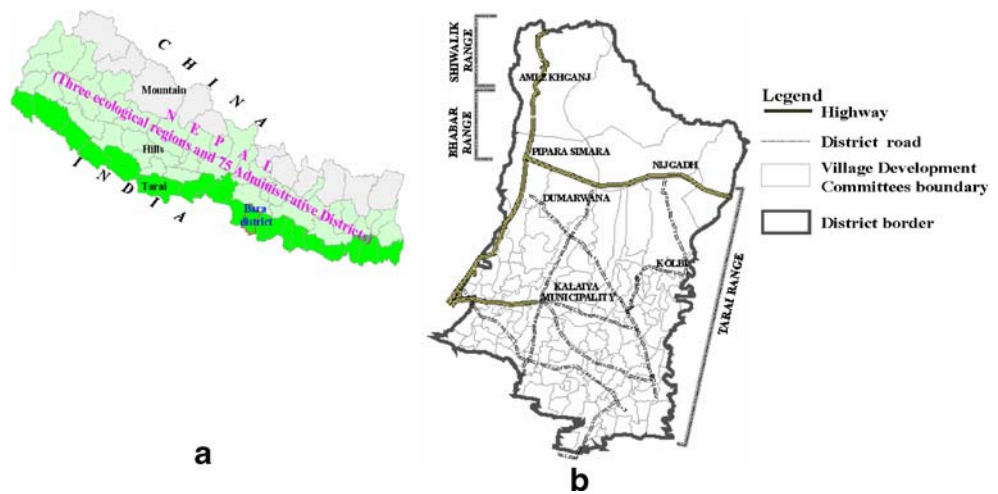
ics. The population increased from 0.25 million in 1971 (MDM 1971) to 0.55 million in 2000 (CBS 2001), with increasing landholding disparities ranging from 0.5 to over 5 ha per family. Though in the minority, the new migrant populations living in the north, mostly along the forest fringes located near highways and commercial centers (Bhattarai 2001; CBS 2001), strongly influences local and regional economics and forest use practices of this district.

The Bara district has national, community, and privately owned forests, each with different management practices (Bhattarai 2001). National forests include government-managed, protected, leasehold, religious, and community forests. The government controls the national forests, communities manage community forests for a certain period with an agreement between the government and communities, although the actual ownership titles stay in government hands. The government forests are rapidly diminishing. With the decline of these government forests and increasing environmental awareness among people, many individuals in the south have brought their farmlands under tree cultivation. Since the 1980s, tree cover on private farms increased due to government incentives to private individuals for farm plantations. In the north, many among the new migrant communities started working in new, urban-located industries. A shift in occupation from extractive economies to off-farm activities probably reduced these settlers' over-dependence on forest resources

(CBS 2001; NPC 2004), helping many forests to come back, or at least ameliorating local deforestation rates.

Data and Methods

This research utilizes multitemporal and multiresolution images (Table 1). Images taken at the same time and day over certain time intervals would have been appropriate for analyzing land use and cover dynamics including vegetation differentiation. However, due to cloud cover problems and the timing of satellites passing over the area under investigation, it was only possible to acquire images for different days and months in an uneven, periodic set of years (Table 1).

The TM 1989 image is geo-registered in Erdas Imagine 8.7 with keyboard digitizing options utilizing 25 ground control points (GCP) collected in latitude and longitude (datum WGS 84) by using Garmin IV plus global positioning system (GPS) unit. These GCPs covered most of the manmade features such as road cross-sections, buildings, and forest clearance seen on the areas covered by the images. Topographic maps (1:24,000) obtained from the Topographic Survey Branch of Nepal were utilized to locate edges of forest clearings, additional road intersections, and other infrastructural features of the built-in environment. These topographic maps are available both

Table 1 Images Used in the Research

Date	Sensor	Path	Row	Number of bands	Resolution (m)
02-28-1973	Landsat 2	51	41	4	80×80
10-31-1989	Landsat 5	141	41	8	30×30
10-31-1996	ADEOS	–	–	5	16×16
02-16-2003	Landsat 7 ETM	141	41	8	30×30
2003 October	IKONOS	–	–	4	1×1

in geographic coordinates and modified Universal Transverse Mercator (UTM, 44.5 zone). Only the latitude and longitude values are used for the geo-registration of images because the GPS datum WGS84 does not match Nepal's modified datum (UTM Zone 44.5).

The MSS 1973 image is geo-referenced using the image-to-image registration against the TM 1989 image. While resampling, errors were minimized to 15 m. All images were resampled using the nearest neighbor sampling method. These images were later reprojected into Universal Transverse Mercator (UTM), Zone 45 N, using WGS 84 for both datum and spheroid to match the projection of the ETM 2003 image that was available from the University of Maryland web site ftp://ftp.glcf.umiacs.umd.edu/glcf/Landsat/WRS2/). The ADEOS image came with geo-registration in latitude and longitude from the Department of Forest, Government of Nepal, which was later reprojected. With the reprojection, MSS, TM, and ADEOS all matched very well with ETM 2003. Since most of the maps of Nepal are projected in modified UTM (Zone 44.5 N), the projected images are reprojected into modified UTM, Zone 44.5 by using specific correction measurements. These include Spheroid-Everest, Quadrant NE, XSHIFT (–) 400000, YSHIFT 0, PARAMETERS—Longitude 84 00 00 E and Latitude 26 15 00 N. Projection and reprojection were needed to compare the alignments of some of the features with topographic (1:24,000) and land use maps of 1978, which are projected in UTM 44.5 N. Such projections into UTM Zone 45 N, modified UTM Zone 44.5 N, and latitude and longitude, and vice-versa made it possible to compare and integrate land use and cover information from different records.

Radiometric Calibration

Radiometric calibration was conducted to correct the possible spectral variance that might exist due to intra- and interinstrumental differences, instrumental drift, variations in earth–sun distances (d_{sun}), and different solar zenith angles (θ_{sun}). Since this research uses MSS, TM, ETM and ADEOS sensors, radiometric calibration is essential for sensor standardization. For example, MSS employs six detectors for each band and TM uses 16 detectors for each non-thermal band. ADEOS carried eight sensors. The relevant sensor to this research in ADEOS is Advanced Visible and Near Infrared Radiometer because it captures chlorophyll concentration segments with higher precision. Though a radiometrically calibrated ADEOS image taken in 1996 was obtained from the Department of Forest of Nepal's Government for this research, the MSS, TM, and ETM images had to be radiometrically calibrated using NLAPS and CPF calibration equations.

In theory, image calibration corrects any linear differences due to instrumentation (Lillesand *et al.* 2004). For

example, Landsat instruments are engineered for linear responses to incoming radiance from the earth–atmosphere system. These linear responses are described by slope and intercept values for each band or by using the engineering names gains and biases (Lillesand *et al.* 2004). By using the header file information (amount of light, instrument's gain–slope, bias–intercept, bandpass values, d_{sun}, and θ_{sun} for each specific date) of each images, the MSS, TM, and ETM images are radiometrically calibrated to convert images' digital numbers (DNs) into radiance values in order to make all the bands comparable at the satellite apparent at-sensor radiance.

Each band was calibrated using the Modeler Maker in Erdas Imagine 8.7 and the narrower green and red bands of the TM and ETM were made comparable with their MSS counterparts. In theory, this calibration made it possible to compare the narrower near band (4) of TM (and ETM) with the combined bands of the MSS that detect the plant vigor (Lillesand *et al.* 2004). In the calibration process, visible and near infrared Landsat MSS bands (1, 2, 3, and 4) and visible, near and mid infrared Landsat TM and ETM bands (1, 2, 3, 4, 5, and 7) are converted into DNs to a quantitative physical surface reflectance values. For each band, slope and intercept values are used to adjust DN values by multiplicative and additive terms, and all DN values are converted into radiance values to make them comparable at the satellite apparent at-sensor radiance for each band. However, TM 6 band has not been calibrated because it was not used in the analysis.

Though this radiometric rectification was done carefully, a comparison of results suggests that radiometric calibration has very little or almost no impact on classification results. This is probably because, with most classifiers, the algorithm was designed to assess relative differences among pixel values, so misclassification has little or no impact upon classification. Regarding our post classification-based change detection method, we argue that proper identification of different signatures based on ground circumstances most likely would improve classification accuracy rather than merely depending upon the radiometric calibration, though much of the literature has focused on this process. For example, secondary forest growth located in a dry area behaves much as mature forest due to water stress, compared to the secondary growth located near riparian or swampy areas. Such an understanding of the plant physiology and ground features might improve classification accuracy in remote sensing.

Classification Process

All images were classified using a supervised classification method following the maximum likelihood decision rules (Erdas Imagine 2001; Lillesand *et al.* 2004). Originally,

spectral signatures were collected for 30 different classes from each image. Several factors compelled us to collect 30 different classes. First, the area is distributed in three geographic divisions, *Siwalik*, *Bhabar*, and *Tarai* (Fig. 1b). Our original plan was to collect equal training samples from each of the three major geographic regions, but the disproportionate distribution of different land uses and covers forced us to gather unequal numbers of samples for various land use and cover classes. In the *Siwalik* range, plants exhibit water stress conditions. These conditions also vary from southern and northern exposures. Northern exposures retain more moisture than do southern ones. Samples were taken from various aspects. The *Bhabar* region has both high and low water tables with boulder geology. Representative samples were needed from different areas. The Tarai region generally has a high water table except for a few areas, and trees planted alongside terraces of irrigated farmland behave differently in spectral reflectance than those planted in low water table areas. Irrigated and non-irrigated farmlands show different spectral signatures. These factors led us to select many land use classes at the beginning. These training samples were collected from both ground collection and from different images including high-resolution 2003 IKONOS images, to train the satellite images. For MSS, most of the training samples were from aerial photos taken between 1971 and 1976, land use maps of 1976–1978, and TM images of 1989. The logic was that a mixed forest seen between 1971 and 1989 must be a mixed forest in 1973. For water, we collected training samples even at the pixel level in some cases because we observed different spectral characteristics among fishponds, streams, and irrigation pond waters. Many woodlots representing fruit trees, timber trees, and shelterbelts behave differently in spectral signatures. Some training samples were based on one of the authors' "a priori" knowledge, having worked in the area for over ten years. All these factors led us to select a large number of training samples for accuracy. However, different training samples belonging to similar classes such as mixed forest, secondary growth, dry sand/soils, and water exhibited overlapping separability indices. These overlapping separability values in the transfer divergence matrix were merged together to make four land use and cover classes (Table 2; Figs. 2 and 3a–d). The reason for retaining only four land use and cover classes was to maintain consistency with the distinct land use and cover classes that were clearly identifiable from the MSS 1973 image.

The MSS image taken in February did not show any shade or cloud cover. However, TM 1989 and ADEOS 1996 had some areas under shade that were unclassified. Likewise, ETM 2003 has some areas under cloud cover that are also unclassified (Table 2). Since this research uses multiresolution images, it was essential to match the resolution of each image to minimize the errors that might occur due to the aggregation and disaggregation of data in the change detection processes. The MSS image was accordingly resampled at 30×30 m and 60×60 m resolutions, so that the output areas obtained from differently resampled images for different land use and cover classes can be compared. Similarly, the ADEOS image (16×16 m) was resampled to 30×30 m to match the resolution of the TM and ETM (excluding the panchromatic band, which has 15 m resolution) images. The resultant products from these resampled images were compared (Table 3). The resampled outputs (30×30 m) of the MSS and ADEOS images showed no significant differences in land use and land cover areas from their original pixel-sized images (Table 3). Therefore, the MSS image was up-graded from 80×80 m to 30×30 m, while ADEOS was down-scaled from 16×16 m to 30×30 m to make all the images comparable.

Classification accuracies were examined using the maximum likelihood method. In accuracy assessment, parameters such as 1,024 search count and 300 number of points were chosen in the "Add Random Points" dialog to examine the accuracy of land use classes of all the

Table 2 Results of Land Use Classes from Classified Images (1973–2003)

Land use classes	Land areas (ha) recorded under various sensors			
	MSS 1973	TM 1989	ADEOS 1996	TM 2003
Mixed forest	44,049.03	41,476.60	40,950.00	34,357.50
Secondary growth	28,108.20	35,390.00	41,800.80	57,272.50
Farmland	52,782.70	45,830.40	40,967.70	31,210.90
Dry soil/sand	3,116.8	4,500.81	3,763.40	4,659.12
Unclassified	0	858.92	574.83	556.71
Total area	128,057	128,057	128,057	128,057
Accuracy percentages				
Overall	91.3	97.03	85.09	86
Kappa	80.34	95.69	77.83	80.45

Accuracy: Overall refers to overall classification accuracy
Kappa refers to overall kappa statistics ($\acute{K}$)

Fig. 2 Land use and cover (1973–2003) based on Table 2
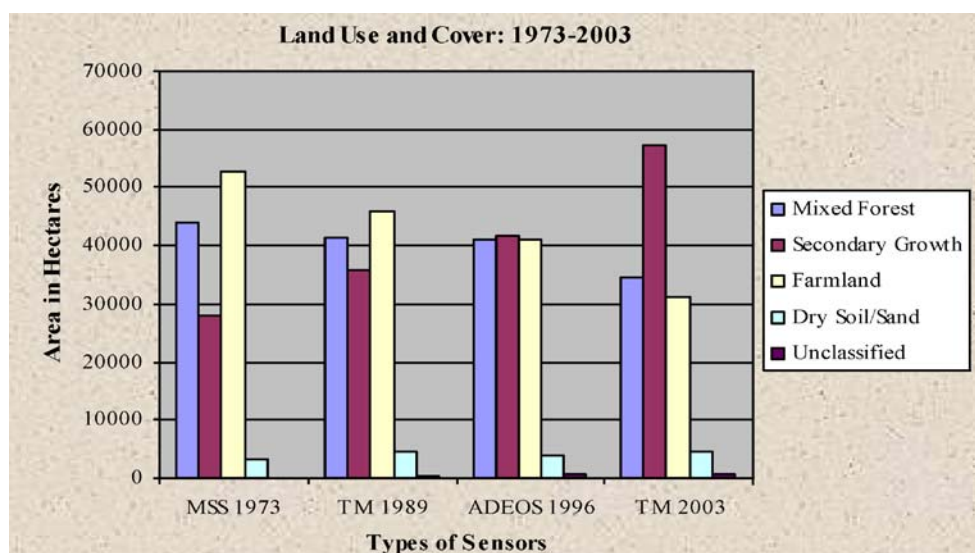
geographic areas. All four land use classes are involved in the classification accuracy assessment.

In all the classification accuracy assessments, thematic raster layers were used to identify pixels in a classified image that are most likely to be classified incorrectly. Contingency matrices were generated to examine the overall accuracy, Kappa statistics, and the procedural and use accuracies for each class, following the standard classification processes (Lillesand *et al.* 2004). Kappa quantifies how much better a particular classification is when compared to a random classification, making it possible to calculate a confidence interval for comparing two or more classifications. Two types of accuracies—procedural and user (Guerschman 2003)—were generated for each class. Procedure accuracy was generated to measure the percentage of pixels of a given land cover type that are correctly classified. User accuracy was generated to measure the commission errors that are useful to examine whether or not a pixel classified into a given class actually represents that class on the ground. While evaluating classification accuracy, Monserud and Leemans (1992) suggested the use of a subjective scale, where Kappa values >80% were considered excellent. As per their logic, this research's classification results are excellent except for the ADEOS 1996 (Table 2). Using these classified images, three transition matrices were generated to identify spatial and temporal land use and land cover dynamics that occurred in each discrete period.

Transition Matrices

Using the intersection method in Erdas Imagine 8.7, four classified images (Fig. 3a–d) were utilized to generate three

transition matrices (Fig. 4a–c). During the intersection processes, all corresponding pixels of both images matched with their spatial references (Erdas Imagine 2001).

However, while generating the second matrix (Fig. 4b; Matrix "A" and ADEOS 1996 image), information approximating 27.2 ha in area is lost. Similarly, information on 125 ha area is lost while generating a transition matrix between the matrix "B" and TM 2003 image (Fig. 4c). These losses of information warned us to further check if our approach was justifiable.

To verify our results from transition matrix (1973–2003), we utilized IKONOS images (1×1 m) taken in 2003 for Dumarwana and Kalaiya areas because these areas have most complex land use and cover situation. Dumarwana area (Fig. 5a–b) represented the most complex land use and cover scenarios due to high population density (6.7 per ha, CBS 2002), while Kalaiya, a Municipality area (Fig. 5c–d), represented much more complex human settlements, district headquarters, and the highest population density (15.7 per ha) in the district (CBS 2002).

Since the transition matrix represented a time series of images, and the IKONOS image represented only one time, the following assumptions were made to compare the results obtained from transition matrix and IKONOS images.

1. Any areas planted on or before 1989 are grouped under mixed forests as the study area has subtropical climate zone and plants can develop into forest, by definition and growth, within 15 years. Such an aggregation of data helped to compare forest land cover classes seen in the IKONOS 2003 images with the forest areas seen from the transition matrices (1973–2003).
2. All plantations done after 1996 were grouped under secondary growth in the transition matrix. These areas

Fig. 3 Supervised Classification: **a** MSS 1973, **b** TM 1989, **c** ADEOS 1996, and **d** ETM 2003

Legend

Mixed Forest
Secondary Growth
Farmland
Dry Soil/Sand
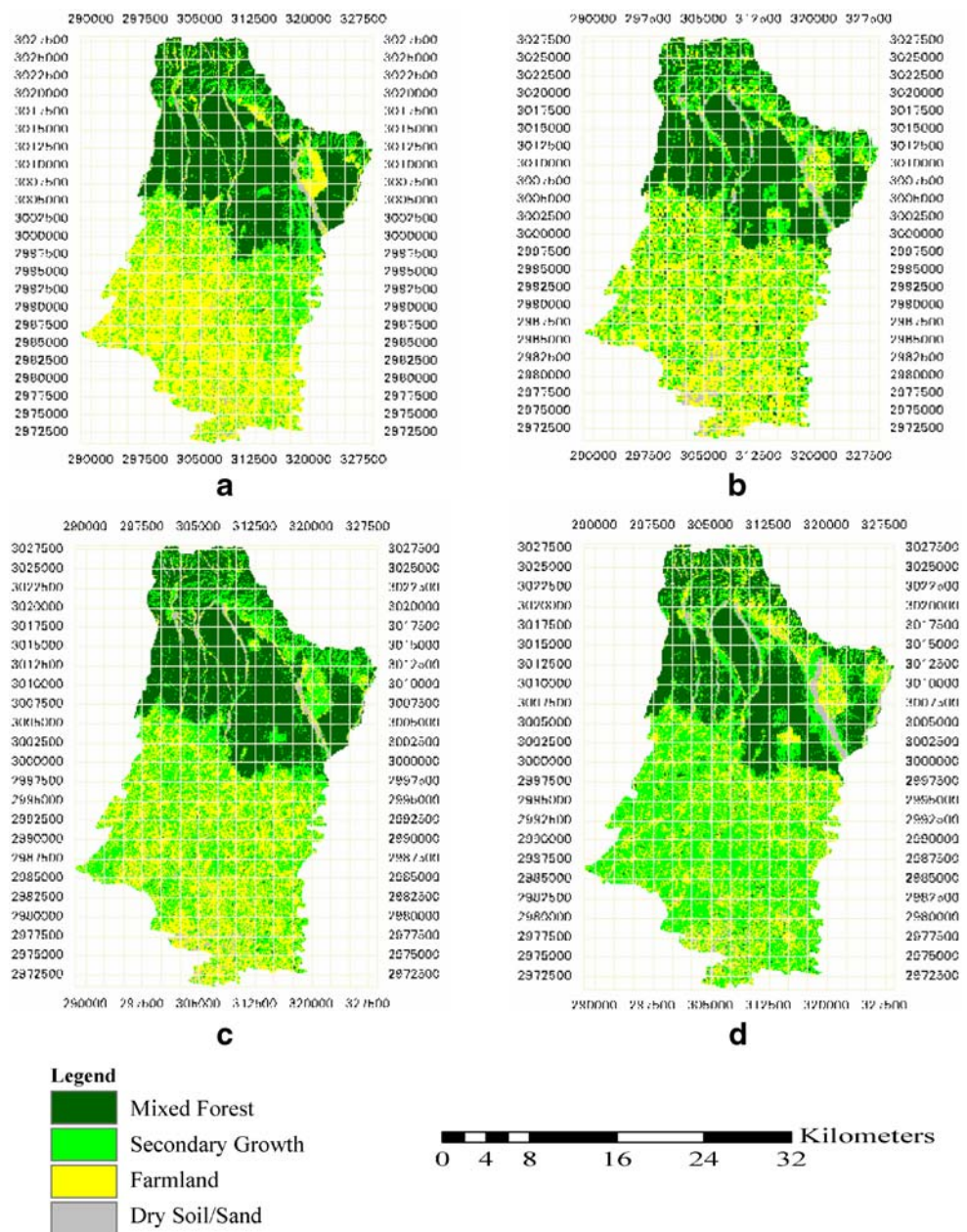
were then compared with the secondary growth land cover classes seen in the IKONOS 2003 images.

3. Areas under all types of croplands and grasslands seen in the IKONOS images were grouped under farmlands to be consistent with the transition matrices.

The land use and cover results obtained from transition matrix (1973–2003) and IKONOS images were compared (Fig. 6). Similarities between these outcomes suggested that our transition matrix approach was an improvement in the methodology of change detection processes. Having seen

Table 3 Results in Hectares from Re-sampled MSS and ADEOS Images

Land use classes	MSS $(80\times80)m^2$	MSS $(60\times60)m^2$	MSS $(30\times30)m^2$	ADEOS $(16\times16)m^2$	ADEOS$(30\times30)m^2$
Mixed forest	44,049.30	44064.40	44044.70	40950.00	40930.90
Secondary growth	28,108.20	28105.90	28102.90	41800.80	41801.40
Farmland	52,782.70	52,755.10	52,784.50	40,967.70	40,995.40
Dry soil/sand	3,116.80	3,126.60	3,126.06	3,763.40	3,758.49
Unclassified	0	5	0	575.10	570.81
Total area	128,057	128,057	128,057	128,057	128,057

Fig. 4 a Transition Matrix: "A" (MSS 1973 and TM 1989), and **b** Transition Matrix "B" (Matrix "A" and ADEOS 1996) **c** Transition Matrix (Matrix "B" and ETM 2003)
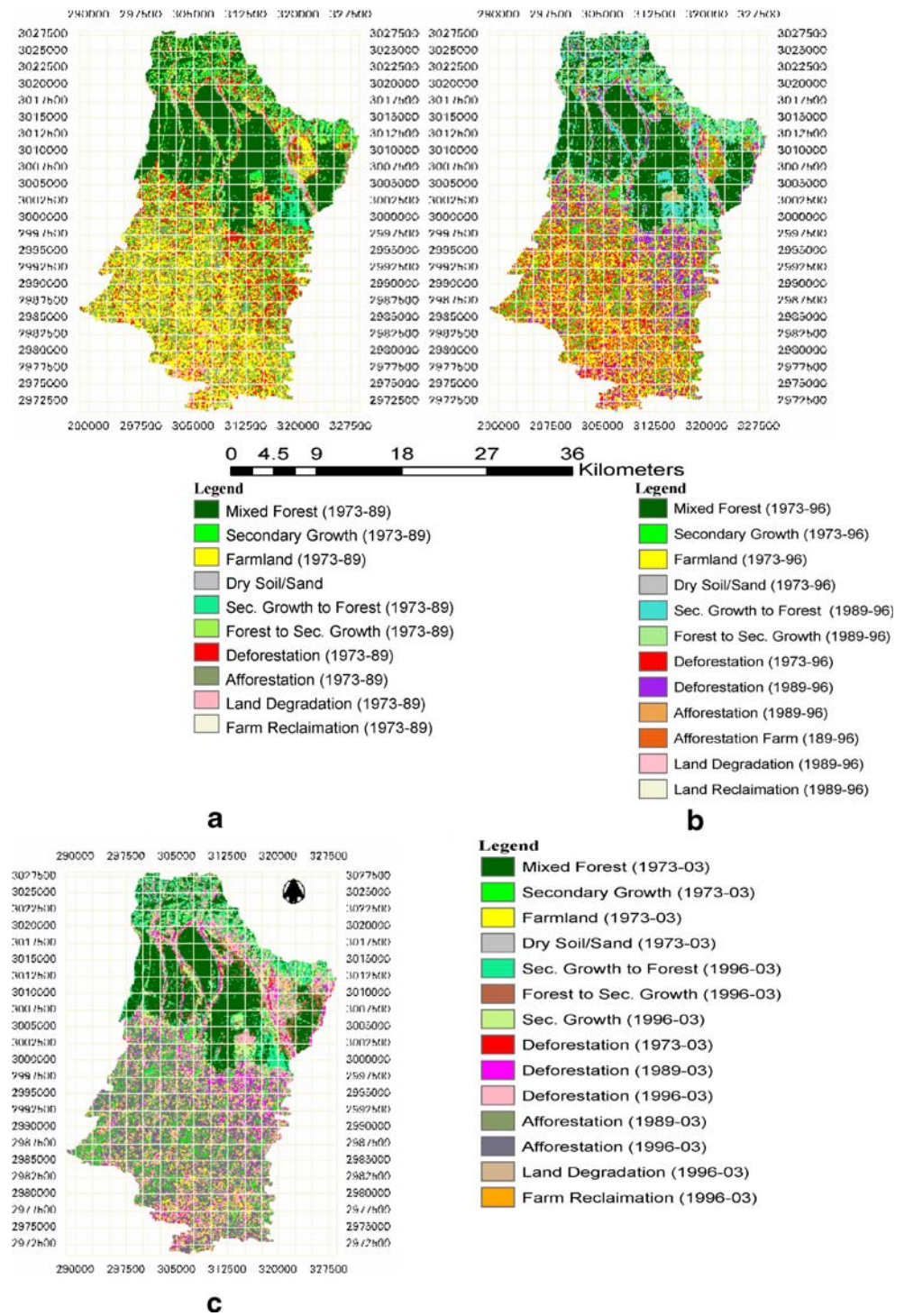

these improvements in change detection, we analyzed the driving forces of land use and land cover changes in the Bara district from 1973–2003.

Transition Period (1973–1989)

Analysis of this transition period (Fig. 4a) revealed that over 15,000 ha of mixed forest had changed and degraded,

either due to the opening of canopies or by conversion into secondary growth areas due to repeated tree felling. Within this period, over 12,000 ha were deforested, mainly by removal of tree stands from farmland, farm fringes, and nearby settlements. During the same period, 9,810 ha of secondary growth failed to progress into mature forest. This part of Nepal lies in the tropical and subtropical regions where most of the vegetation, except for Sal (*Shores*

Fig. 5 **a** Dumarwana Transition Matrix (1973–2003), **b** land use and cover from IKONOS 2003; **c** Kalaiya Transition Matrix (1973–2003), and **d** land use and cover from IKONOS 2003
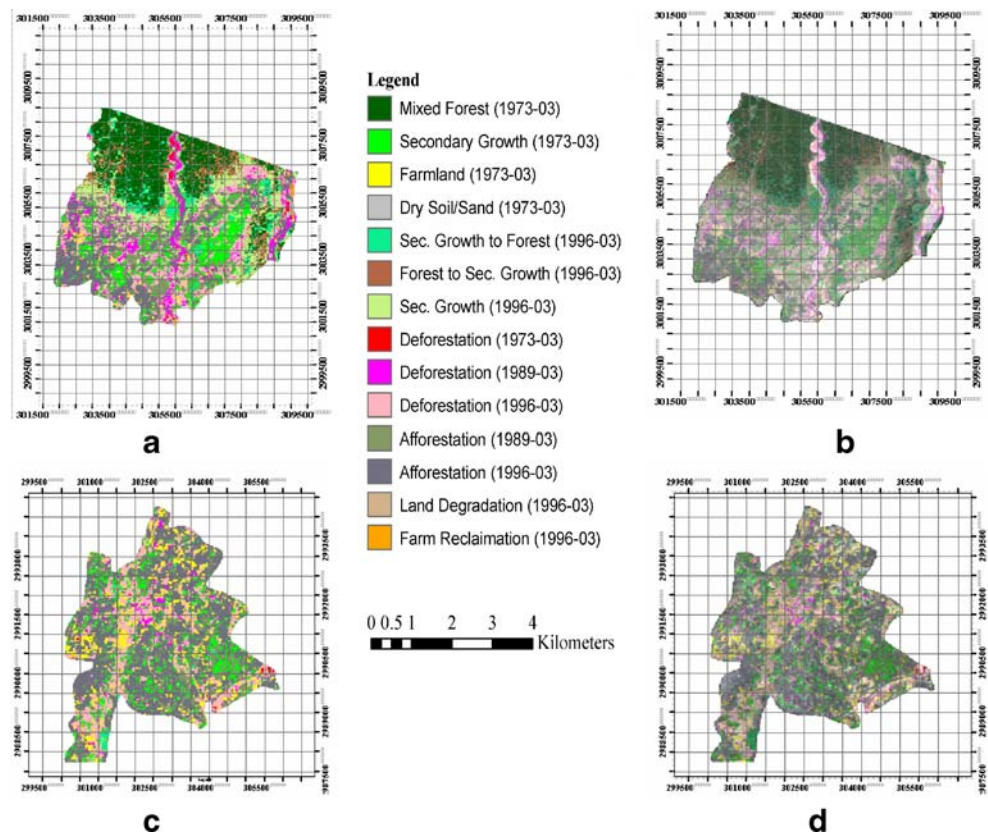
robusta), normally exhibits an annual growth increment of as high as 7–10 m^3 per ha. However, such growth depends upon the site quality and management. For example, many areas close to rivers, roads, and settlements surprisingly remained as secondary growth regimes due to government mismanagement. Likewise, many secondary growths on the *taungya* plantations (Fig. 7a–b), where trees and agricultural crops are grown together, did not develop into mature forests. Within this period, over 1,000 ha of vegetated areas were brought under cultivation to meet the growing demands of the increasing population, which grew from 0.255 million in 1973 to 0.412 million in 1990 (CBS 1995, 2002).

Until the early 1980s, the Nepal government exported timber to India by clear-cutting many Tarai forests (Bhattarai *et al.* 2002). Land-hungry, hill migrant families settled on these clear-cut areas, either with government sponsorship or voluntarily. However, the 1980s brought some environmental awareness to Nepal and the World Bank implemented a Tarai Community Forestry Project in 1985. This project helped in the management of many Tarai forests and some secondary growths (>5,000 ha) turned into mature forests, while many farmlands (>20,000 ha) in the south also were converted into tree stands (afforestation). Afforestation was stimulated by government incentives in the form of free seedlings and the consequent reduction in annual land revenue per hectare of farmland brought under

tree plantation. The southern part of Bara district "turned green" over time (Figs. 3a–d and 4a–c), because of the increasing environmental awareness and financial incentives provided to farmers to plant trees on their farmlands. Owners with large farmlands planted about 275–400 trees per ha with spacing of 6×6 m, or 5×5 m with agricultural intercropping. These activities increased the areas under secondary growth. Such secondary growth after a period of deforestation (Fig. 8) clearly supports the hypothesis of Ecological Modernization Theory, which envisages forest recovery accompanying growth in environmental awareness locally, nationally, and internationally.

Transition Period (1989–1996)

This period is marked by several political upheavals including the countrywide revolution in 1989–1990, which overthrew Nepal's 30 year-long dictatorial kingship and ushered in 'democracy' in the form of a British (West-minster-model) bicameral, legislative system with a constitutional monarchy. During this tumultuous political turnaround, many forest areas were encroached upon and converted into farmlands and settlements. Image analysis (Fig. 4b) shows that during this period not only were >4,000 ha of mixed forest areas lost, but also about 14,000 ha area remained as secondary growth, especially

Fig. 6 Land use and cover classes obtained from Transition Matrix (1973–2003) and IKONOS image 2003
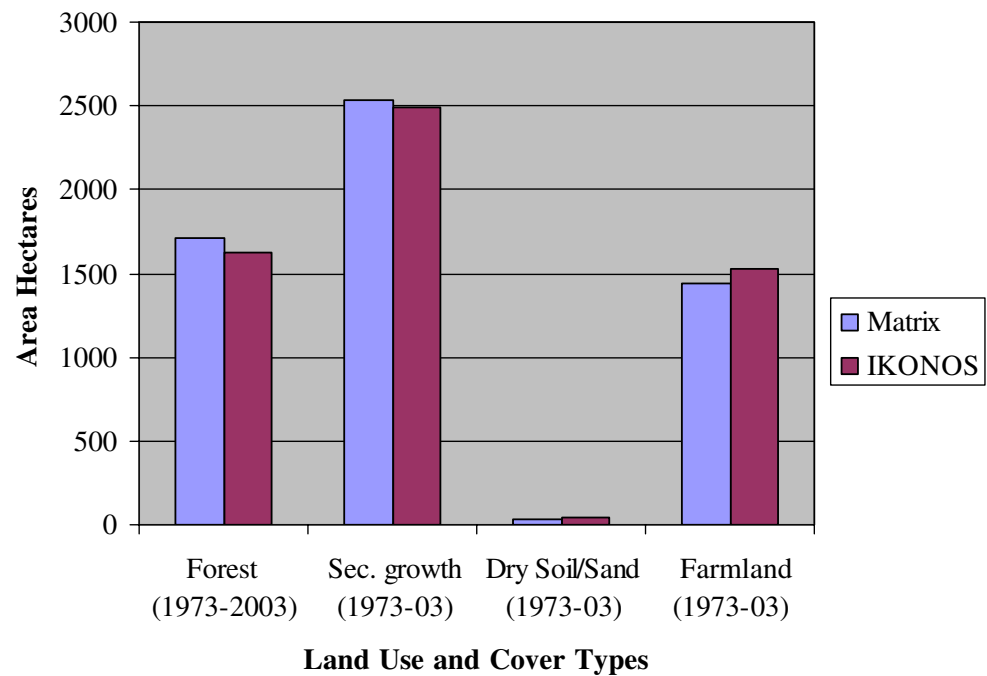
near settlements. Likewise, in remote areas where government officials were less vigilant, areas of secondary growth could not develop into mature forests. However, due to increasing environmental awareness and potential financial incomes from private tree planting, many farmers planted trees on private farmlands. Attracted by high market prices, farmers not only removed trees from 14,700 ha of farm areas, but also converted over 13,000 ha of farmland into tree stands (Figs. 4b and 8). Farm plantations became necessary as the national forests rapidly decreased, leading to increased scarcity of forest products and commodities.

Transition Period (1996–2003)

During this transition period, over 4,585 ha of mixed forests were converted into secondary growth. Image analysis (Fig. 4c) reveals the deforestation of 28,215 ha during this period, of which 16,488 ha is assumed to be due to the removal of trees from farmlands as a response to market demand for timber products. Many areas became deforested due either to the removal of trees from mixed forest or due to the failure of efforts to establish plantations. Increasing biotic interference has led to the failure of 8,000 ha of secondary growth to develop into mature forests, although almost the same amount, located away from settlements, developed into mature forests. Within this period, 37,679 ha were converted to plantations including 27,000 farm plantations. Although over 43% of the total land surface in this district used to be under farmland, most of the farmlands of the south are intercropped with trees making them greener than the natural forests of the north (Figs. 3a–d and 4c).

Fig. 7 a Effects of early settlements (*1, 3*), climatic effects (*2*), effects of road (*4*), effect of Taungya plantation and replacement of natural forest (*5*), and edge effects due to farm expansion (*6*); **b** effects of river (*1, 2*), effects of river, extensive farming, and commercialization of tree crops (*3*), and; **c** effects of commercialization of farm forestry (*1*)
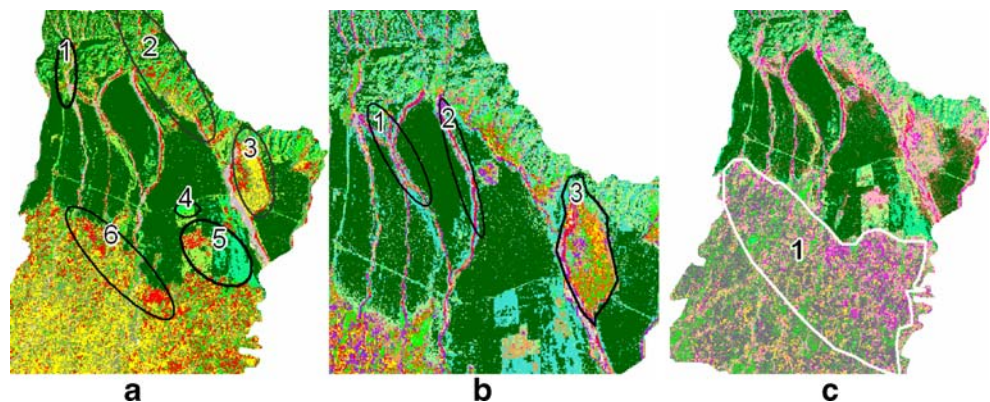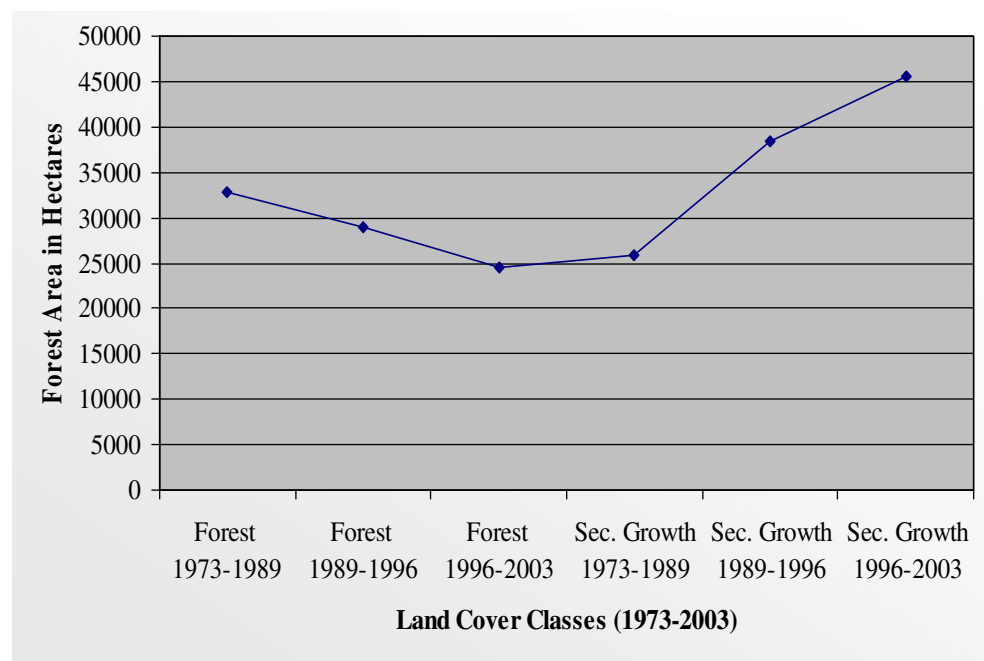
Fig. 8 Forest loss vs. forest growth: Nature of Kuznets Curve (1973–2003) showing U-shaped structure

Factor Influencing Land Use and Cover Changes (1973–2003)

Results generated from the three transition matrices reveal that areas of mixed forest decreased in successive periods, while areas of secondary growth increased (Fig. 8), mostly due to the conversion of farmlands into tree stands. Areas under farmland and dry soil/sand also decreased.

Classified images (Fig. 3a and b), transition matrix (Fig. 4a), and our "a priori" knowledge, including government publications, illustrate the major deforestation along the Siwalik belts during the early 1973–1989 period (Fig. 7a). This deforestation probably occurred because the hill migrants preferred settling in the subtropical belt of the Siwaliks located in the north (elevation above 700 m) to avoid malarial problems in the south. However, the Tarai indigenous people settled in the south because of its proximity to the Indian bazaars, fertile farmlands, accessible water tables, and possible on-farm employment with large landowners. Slowly, after the successful eradication of malaria in the Tarai in the 1960s, cultural synergism and mixed settlement occurred between the indigenous people and hill migrants. Following this, the more extensive farmland areas of the south spread into, and encroached upon, the forestlands located in the north (Bhattarai *et al.* 2002), so much so that deforestation accelerated (Figs. 3a–d and 7a–c).

Impacts of Roads and Rivers on Forests

In settlements close to or alongside roads such as Amlekhganj, Pathlaiya, Simara, Dumarwana, and Nijgadh

(Figs. 1b and 7a–c), the natural forests under the direct control of the government have rapidly shrunk. Amlekhganj was densely forested until 1924 before "emancipated people" were settled to help reclaim these dense forests, and expand the frontier settlement of the Tarai region so as to better utilize (exploit) this region's agricultural and forestry resources. Similar to the Brazilian Amazon, where 50–74% deforestation in the frontier reclamation process occurred during 1991–1997 (Alves 2002), Amlekhganj's settlement (Fig. 1b) and infrastructure development (Fig. 9) became one of the forerunners of Tarai deforestation (Fig. 7a–c).

Two highways (east–west and north–south) and several district roads (Fig. 9) have had major impacts on Bara's forests. Similar to the Brazilian Amazon, where Alves (2002) observed 90% of deforestation within 100 km from the major highways established under federal development programs, several deforestation patches along the Tarai's east–west highways, within a 2-km buffer zone and within a 1-km buffer along the river, can be observed (Fig. 9).

Population Growth and Forest Product Needs

Nepal's Tarai has been experiencing rapid population growth due to continuing high rural fertility rates and rural-to-rural (hill to Tarai) migration. These large-scale inter- and intra-regional migrations of young people, together with existing high fertility rates, have brought rapid changes in land use and land cover dynamics in this forested frontier region (NPC 2003). Although the current fertility rate has gone down to less than 4% from the 5.5 rate of the 1980s (CBS 1995, 2002), the relative population pressure generated at the bottom of the class hierarchy in
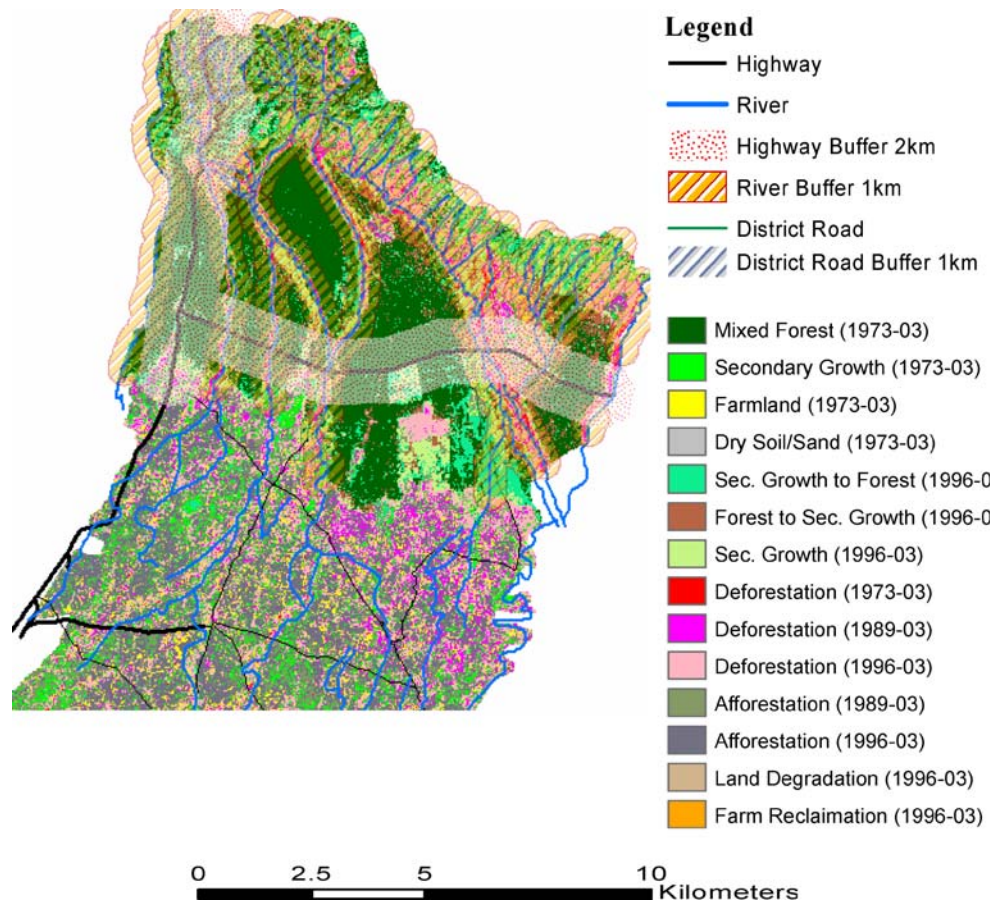
the Tarai region is still higher than in the hill region of
Nepal (Shrestha *et al.* 1999). Overdependence of this
increasing and impoverished population on forest resources
for energy, construction materials, and fodder (Fig. 10) will
continue to endanger forest resource stocks, and the
"luxury" of embracing greater environmental awareness is
probably beyond most of these peoples' means.

When Gautam and Thacker (1994) analyzed firewood,
timber, and fodder needs in the Bara district, they observed
a higher per capita consumption of firewood near the forest:
751 kg north of the highway, 674 kg in the southern fringe
of forest, and 370 kg in the far south of the district. Similar
trends exist for timber/logging consumption: 0.38 m^3 near
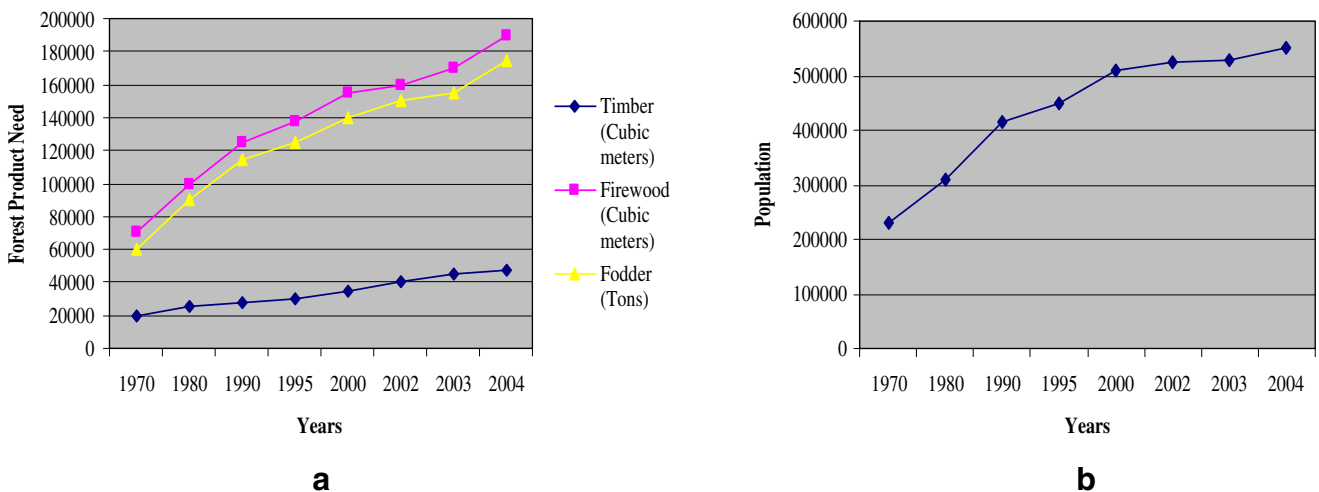the forest, 0.11 m^3 in the southern fringes of forest, and

Fig. 10 **a** Forest products needs, and **b** population growth

0.001 m^3 in the far south (FMUDP 1995:12). Earlier Unni et al. (1992) research found accelerated deforestation within a 5-km radius of settlements in rural India because of firewood needs. Similar to their findings, our analyses revealed forest destruction within a 2 km radius from settlements, 2 km distance from the highway, 1 km distance from the district road, 1 km distance from rivers, and decreasing trends further away (Fig. 9).

Environmental Awareness and Economic Incentives from Farm Forestry

Geospatial data derived from the transition matrices (Fig. 4a–c) supports the proposition of Ecological Modernization Theory (EMT) that where forests were lost rapidly at the initial phase of settlement, later deforestation occurs at a slower pace because of socioeconomic and demographic changes. For example, during the 1973–1989 period, 7,119 ha of forest were brought under farmland; 2,215 ha during 1989–1996, and 3,828 ha during the 1996–2003 period (Figs. 3a–d and 4a–c). Image analyses reveal that although the government forests receded rapidly during the last 30 years, in many places forests have come back (Figs. 4a–c and 7b–c). Many areas of secondary growth have turned into mature forests; for example, 6,106 ha of secondary growth turned into mature forest between 1989 and 1996, and 8,766 ha between 1996 and 2003 (Fig. 4b–c). In this area of Nepal, except for Sal (Shorea robusta), other species generally experience an annual growth increment between 7 and 10 m^3 per ha, depending upon the site quality (FMUDP 1995), and many secondary growths turned into mature forests over an interval of 15–20 years. Increasing environmental awareness, rising prices of forest products, and incentives provided by the government all positively impacted farmland plantations, apparently. Accordingly, 37,677 ha of farmland were intercropped with trees between 1989 and 2003, as opposed to the removal of trees from 28,214 ha within the same period.

Rural-to-urban migration, increasing trends of taking off-farm jobs and the consequent lack of farm labor have positively influenced farm plantations in the Bara district. Government incentives have also influenced farm tree plantations (Figs. 3a–c and 4a–c). Likewise, the ability of tree crops to grow with minimum attention as compared to agricultural crops, and the monetary incentives obtained from farm forestry, such as timber, firewood, and various types of fruits (Kanel 1995) and user-rights guarantees, could be additional reasons for the increasing hectares of farm forest plantations.

Bara experienced several economic changes between the 1970s and 2000s. Off-farm activities increased from 5% in the 1970s (MDM 1971) to 21% in the 2000s (CBS 2001). Recent activities include manufacturing (4%), trade and business (28%), transportation (3.27%), services (35%), and others (28%). Involvement of women in off-farm activities increased from less than 1% in the 1970s to 27% in 2001 (MDM 1971; CBS 2001). Likewise, 42% of females are attending schools today (CBS 2001), as compared to less than 2% in the 1970s (MDM 1971). All these developments probably have indirect and direct effects on farm plantations.

Within the Bara district, major industrial activities, located in Amlekhganj, Simara/Dumrawana, Nijgadh, and Kaliaya, have become centers for rural farm labor forces. Over the period of 30 years (1973–2003), the population of Amlekhganj increased by 211%; in Nijgadh by 163%, in Pipara Simara by 554%; and in Kalaiya by 1,091% (MDM 1971; CBS 1995, 1999, 2001). Some of this population growth may very well have been caused by shifts in workforce regimes from rural area agricultural dependency to areas having potential for off-farm employment.

Because households receive monetary incentives from farm forestry (Kanel 1995), it is common to replace matured trees with new ones from farmlands. Image analyses reveal the removal of trees from 12,775 ha between 1973 and 1989, from 14,700 ha between 1989 and 1996, and 16,488 ha between 1996 and 2003. Assuming 275–400 tree-stands per ha of farmland, it is estimated that on average each year 0.25 million mature tree-stands are removed from the Bara district. Generally, farmers grow Sissoo (Dalberia sissoo) species for timber and firewood because of the ability of this species to synthesize atmospheric nitrogen in the soil. However, because of a recent epidemic affecting Sissoo stands, farmers are diversifying their tree plantations by planting fruit trees, including mango, guava, litchi, jackfruit, and other trees for fruits, timber, and firewood. Assuming that one tree stand could yield an average of 1.5–2.5 m^3 timber/firewood after 15–20 years, depending upon the site quality, Bara can produce approximately 0.5–0.6 million m^3 of timber/firewood a year from its farm plantations on a sustained basis, in addition to various types of fruits. These products, besides other environmental amenities, are major economic incentives for farm households.

Conclusion and Discussion

This research reviewed the literature, identified some problematic issues such as map projection rectification and errors associated with resolution-matching (Table 2), then generated transition matrices (Fig. 4a–c) using classified MSS 1973, TM 1989, ADEOS 1996, and ETM 2003 images (Fig. 3a–d and Table 2), and compared the

final outcomes of these transition matrices with high resolution IKONOS images (Fig. 5a–b and c–d). This research identified the factors influencing land use and cover dynamics by comparing the time series of events (Fig. 4a–c and 7c–d) and by overlaying transportation networks and rivers on the 1996–2003 transition matrix (Fig. 9). It also tested some of the claims of Ecological Modernization Theory to explain the impact of socioeconomic development and demographic changes on land use dynamics, and found the construct of some value (Fig. 8).

Image analyses for 1973–1989 revealed that the periods of the 1960s and 1970s were under the influences of the "frontier economic model" (Boulding 1966) in terms of the utilization of natural resources. In such conditions, a strong ecological correlation is evident between stagnant rural economic development and natural resource use. Similar to the Brazilian Amazon (Moran 1981), this research revealed rapid forest clearance at the beginning of frontier settlements (Fig. 4a–b) but a slower rate over time. Like Amazonia, increasing pressures of competing claims on these tropical forestlands by immigrants developed several land use complexities in the Bara district. Additionally, the growth of population from 0.25 million in the 1970s to 0.55 million in 2001 (Fig. 10) further increased land use pressures.

Rapid land use and cover dynamics seen on the images near Simara, Amlekhjanga, Pathlaiya, Dumarwana, and Nijgadh (Figs. 1b and 7b–c) suggest that there has been an attempt to convert hitherto non-agricultural land to agricultural land. Image analyses inferred a rapid increase in the number of farm plantations (Figs. 3a–d and 4a–c). Such an increase in farm plantation has probably occurred in response to the diversification of households' occupations from on-farm to off-farm. Tree plantations on farmland are a way to diversify households' activities to minimize financial risks in a monsoon dependent farming system. Farmers have probably brought farmlands under tree cover because of farm labor shortages, because of the ability of trees to grow with less attention, and because of the incentives provided by Government of Nepal for farm plantations. The increasing costs of forest products due to the shrinking of the government forests, increasing public environmental awareness, and opportunities available for off-farm jobs might all have positively influenced farm plantations. These findings suggest that land use dynamics and forest changes in the Bara district have been influenced by several factors, including economic incentives for farm plantations, shortages of farm labor, increasing trends toward off-farm occupations, rural-to-urban migration, and environmental awareness in response to the loss of government forests. These observations support one of the propositions of Ecological Modernization Theory that people respond to environmental degradation by changing their socioeconomic activities.

The transition methodology used in this research may be applicable in detecting land use and forest cover changes at temporal and spatial scales in other culturally complex, tropical forest regions having similar geographic, socioeconomic, and demographic conditions. However, it is essential to match the resolution of images by carefully analyzing the possible errors that might result in the resampling processes. In terms of methodological preciseness, radiometric calibration of different image systems should be critical in such analyses; however, its effects on our classification method's accuracy and interpretability turned out to be inconsequential. Finally, this study demonstrates the importance of remotely sensed, geospatial data for conceptualizing and analyzing a theoretical process that can be useful for improving forest resource management through a better understanding of local biophysical, cultural, and institutional conditions and their possible constraints.

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