

## Tropical deforestation in the Bolivian Amazon

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### Summary

The distributions of forest and deforestation throughout the tropics are poorly known despite their importance to regional biodiversity and global climate and biodiversity. Deforestation estimates based on surveys or sampling have large errors, and high-resolution, wall-to-wall mapping of tropical forests is necessary to assess the impacts of fragmentation. Landsat satellite images from the mid-1980s and early 1990s were thus used to map closed-canopy tropical forest extent and anthropogenic deforestation in an approximately 700 000 km<sup>2</sup> area of Amazonian Bolivia with precipitation >1000 mm yr<sup>-1</sup>. Total potential forest cover extent, including tropical deciduous forest, was 448 700 km<sup>2</sup>, while the area of natural non-forest formations was 245 100 km<sup>2</sup>. The area deforested was 15 500 km<sup>2</sup> in the mid-1980s and 24 700 km<sup>2</sup> by the early 1990s. The rate of tropical deforestation in the forest zone of Bolivia with >1000 mm yr<sup>-1</sup> precipitation below 1500 m elevation and north of 19° S, was 1529 km<sup>2</sup> yr<sup>-1</sup> from 1985–1986 to 1992–1994. Our estimates of deforestation are significantly lower than those reported by the Food and Agriculture Organization of the United Nations (FAO). We document a spatially-concentrated ‘deforestation zone’ in Santa Cruz where >60% of the Bolivian deforestation has occurred. These results indicate that the rate of deforestation in Bolivia has been rapid despite a relatively small human population, and, as in Brazil, clearance has concentrated in the more deciduous forests.

*Keywords:* deforestation, Bolivia, Amazon, tropical forest, Landsat

### Introduction

Deforestation has occurred in the tropics throughout history (Tucker & Richards 1983; Richards 1984; Hecht & Cockburn 1989; Williams 1989, 1990) and has accelerated recently, particularly in areas of seasonally-deciduous tropical forests

(Schmink & Wood 1984; Janzen 1986; Fearnside 1986, 1993; Houghton *et al.* 1991; Skole & Tucker 1993; Maas 1995). Accurate information on the extent of tropical forests and deforestation is essential for estimation of changes in surface energy balance and atmospheric greenhouse gas emissions (Cook *et al.* 1990; Gash & Shuttleworth 1991; Houghton 1991; Keller *et al.* 1991; Dixon *et al.* 1994; Gash & Nobre 1996; Fearnside 1996). Precise information about the spatial distribution of deforestation is also necessary to estimate the impacts of habitat destruction and fragmentation on biological diversity (Harris 1984; Skole & Tucker 1993; Pimm *et al.* 1995; Laurance & Bierregaard 1997; Laurance *et al.* 1997, 1998; Chiarello 1999).

Remote-sensing analyses of the Brazilian Amazon have demonstrated dynamic deforestation frontiers, particularly in areas near highways or industrial-scale agriculture (e.g. Fearnside 1993; Skole & Tucker 1993; Steininger 1996). The spatial pattern of land use in these areas demonstrates high levels of fragmentation of the remaining uncut forests. Fragmented forest patches and forest near clearance edges are susceptible to an array of human and bio-climatological impacts (Malcolm 1994; Laurance & Bierregaard 1997; Laurance *et al.* 1997, 1998; Cochrane & Schulze 1999; Nepstad *et al.* 1999), and the isolation of forest fragments also affects composition and diversity of local plant and animal communities (Miller & Harris 1977; Wilcox 1980; Karieva 1987).

Bolivia, a land-locked country with a total national territory of *c.* 1 098 000 km<sup>2</sup> in central South America, contains *c.* 500 000 km<sup>2</sup> of forest and woodland, including more than 400 000 km<sup>2</sup> of lowland tropical forest within the Amazon Basin. The Bolivian lowlands, the *Oriente*, maintain a high degree of biological diversity and have been identified among the top 10 conservation priorities in the world (Gentry 1995; Killeen & Schulenberg 1999; Myers *et al.* 2000). Part of the reason for the high biodiversity there is the large number of forest and savanna habitat types (Brockman 1978; Haase & Beck 1989; Killeen *et al.* 1993, 1998; Prado & Gibbs 1993; Hanagarth 1993).

Bolivia has only 6.5 million inhabitants, two-thirds of whom live in the Altiplano and Andean valleys (Montes de Oca 1997). Road construction, immigration from the highlands, low land prices, foreign investment, agricultural export demands, and structural adjustment have all

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contributed to the clearance of large areas of pristine and lightly-disturbed forest (Stearman 1985; Sanabria 1993; Barber 1995; Painter 1995; Thiele 1996; Pacheco 1998; Hecht 2000). Agricultural expansion has concentrated in south-eastern Santa Cruz, particularly in the Tierras Bajas, directly east of Santa Cruz de la Sierra, and on the Brazilian shield. The endemic vegetation in this area is known as *Chiquitano* forest (Killeen *et al.* 1993). This is believed to be the largest remaining area of contiguous, undisturbed tropical deciduous forest in the world (Killeen & Schulenberg 1999). The rapid changes which have occurred there and the virtual absence of intact tropical deciduous forests worldwide (Janzen 1986; Bullock *et al.* 1995; Myers *et al.* 2000) highlight the importance of its conservation.

Estimates of deforestation that are based on survey questionnaires or limited samples of satellite observations, such as those provided by the FAO (1981, 1993, 1996, 1997), have been subject to criticism and have failed to accurately document the distribution of deforested areas (Sanchez *et al.* 1997; Tucker & Townshend 2000). Tucker and Townshend (2000) have shown that in sampling Landsat scenes for mapping deforestation, over half of a region's coverage must be analysed in order to obtain an estimate within 50% of that from a wall-to-wall estimate.

Several types of satellite data have been used to map the precise locations and areas of deforestation (Fearnside 1986, 1993; Green & Sussman 1990; Skole & Tucker 1993; Malingreau *et al.* 1995). However, comparisons of deforestation estimates in Brazil have shown that visual interpretation of high-resolution (30–60 m) satellite images tends to over-estimate deforestation, largely because of positional inaccuracy and boundary generalization (Skole & Tucker 1993). Digital analysis of coarse-resolution (1–8 km) data can over-estimate deforestation by up to 50% (Malingreau & Tucker 1988; Cross *et al.* 1991; Downton 1995; Malingreau *et al.* 1995). Digital processing of high-resolution images provides the most accurate estimates of the area and distribution of cleared tropical forests, and previous studies have shown that forest and most types of deforested land can be distinguished with accuracies of over 90% (Sader *et al.* 1991; Moran *et al.* 1994; Steininger 1996). We document a study of the spatial distributions of forest cover and deforestation, using Landsat data from the mid-1980s and early 1990s, for the entire Amazon Basin of Bolivia (Townshend *et al.* 1995; Tucker & Townshend 2000).

## Methods

We constrained our study area by adopting the FAO (1993) ecofloristic stratification of Bolivia and mapped only forest in the zone with  $>1000 \text{ mm yr}^{-1}$  precipitation. In the Bolivian lowlands, this roughly corresponds to the transition from Chiquitano deciduous forest, closed canopy and over 10 metres tall, to Chacoan woodland, which is shorter, more completely deciduous and floristically distinct (Roche & Rocha 1985; Killeen *et al.* 1993; Cordecruz 1994). All

broadleaf forest in the Andes was mapped, thus including cloud forest but not including Andean grasslands or coniferous forests.

Digital Landsat Thematic Mapper (TM) and Multispectral Scanning System (MSS) data were acquired for the mid-1980s (1984–1987) and early 1990s (1992–1994); a total of 44 images per time period were used. Digital analysis was performed on the 1990s data, projected into an equal-area coordinate system, edge matched, and merged into a seamless data set for the six departments in lowland Bolivia. Each 1980s scene was processed and co-registered to the georeferenced 1990s TM mosaic. Of the 44 scenes for the 1980s, 12 were MSS. All digital analysis was resampled to a 60 m grid cell size.

Prior to classification, five of the authors had conducted aerial and field surveys from 1993 to 1998 over much of the study area. During these trips, Global Positioning System (GPS) data were collected and land cover types and other field notes were marked directly on colour composite prints of images. The classes identified were natural non-forest, deforestation, water, cloud and cloud shadow. Natural non-forest included savanna, cerrado, chaco woodland and sand banks; deforestation included areas of forest converted to urban, pasture agriculture and young fallow regrowth.

Prior to classification, each image was reviewed by the authors and training sites were marked throughout the image. Analysis entailed clustering of the multi-spectral data. Output clusters were labelled according to their distribution within training areas of known cover types. Sub-sections of images were classified independently in areas of extreme atmospheric haze. All classified images were reviewed by all of the authors. Because of classification difficulties, and the need for additional field surveys in mountainous areas, we only mapped forest cover in the 1990s above 1500 m altitude and south of 19° S latitude.

Using the results from both time periods, we produced and edited a map of anthropogenic deforestation between periods at 60 m resolution. In this product we mapped only forest loss associated with forest clearance and not selective logging, natural disturbances such as river migration or imperfect co-registration. In these areas, we accepted the class from the 1990s coverage, since these data were generally of better quality and fairer atmospheric condition. We next produced a potential historical closed-canopy forest and non-forest stratification for our entire study area using data from both periods. Areas which were cloud covered in the 1990s data but observed as forested in the 1980s were added to the potential forest stratum, as were any areas classified as deforested in either period. The final change product was reviewed by all of the authors.

The final product was a 60 m resolution map of forest, natural non-forest, water, deforested by the mid-1980s and deforestation from the mid-1980s to the early 1990s. The average deforestation rate between time periods for the entire study area was calculated as the area deforested divided by

the difference in the mean dates of the 1990s and 1980s images. We estimated the rate over a six-year time period from 1986, 80% of the 1980s data, to 1992, 50% of the 1990s data. The difference in the results in this study versus those in Tucker and Townshend (2000) is because we included here only deforestation that was below 1500 m altitude and had been identified as anthropogenic.

A set of independent field surveys from western Santa Cruz were compared to our product for an estimate of classification accuracy. These surveys were collected in areas of small-scale, highly-fragmented deforestation with much secondary regrowth (Steininger 2000). Accuracies reported for these areas are most likely to be larger than those expected for areas of large-scale deforestation. Of 680 ha of surveyed semi-deciduous forest, 97% was correctly classified, and of 950 ha of completely deciduous forest, 85% was correctly classified. Of 1000 ha of inundated forest, 99% was correctly classified. Most of the Bolivian oriente is semideciduous, strictly deciduous forest being found only on rocky slopes or

the southern-most areas of the Chiquitano forest. Of 600 ha of surveyed agricultural fields, 98% was correctly classified. Among 115 ha of secondary forest fallows, ranging from four to 25 years in age, 75% was correctly classified and less than 5% was mis-classified as forest.

## Results

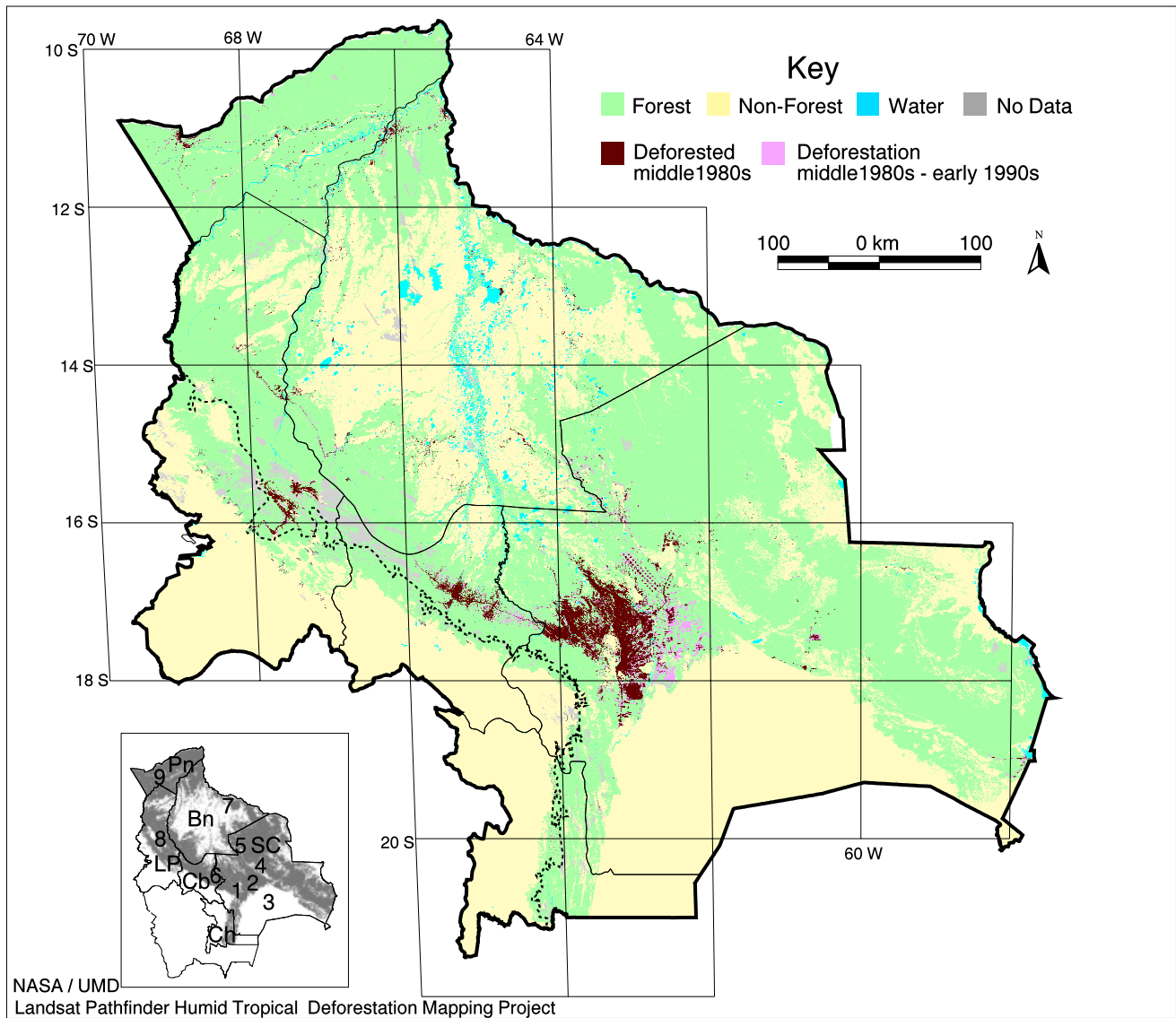
The total potential closed-canopy forest area was 448 700 km<sup>2</sup>, non-forest covered 245 140 km<sup>2</sup>, and water 133 900 km<sup>2</sup> (Table 1; Fig. 1). Cloud cover in both time periods obscured 10 580 km<sup>2</sup> of the surface. Approximately 52 000 km<sup>2</sup> of the potential forest was above 1500 m elevation or south of 19°S. The land area deforested was 15 530 km<sup>2</sup> by the mid-1980s and 24 700 km<sup>2</sup> by the early 1990s (Table 2). The average rate of anthropogenic deforestation between the middle 1980s and early 1990s for the entire area below 1500 m, north of 19°S and in the >1000 mm precipitation zone is estimated to be 1529 km<sup>2</sup> yr<sup>-1</sup>.

**Table 1** Summary of forest, non-forest and deforestation areas (km<sup>2</sup>) estimated for Bolivian forests in the >1000 mm precipitation zone. Deforestation was estimated only in areas below 1500 m altitude and north of 19°S. Data from the 1980s are from 1984 to 1987, the 1990s from 1992 to 1994. \*For one Landsat scene of montane forest in La Paz (WRS 002-71), only data from the 1990s were available, and thus no change was estimated for this area.

Department	Potential forest	Forest	Non-forest	Deforested by the 1980s	Deforested by the 1990s	Deforestation 1980s–1990s	Water	Cloud/No data	Total area
Beni	88 625	88 625	10 6 056	1220	2455	1235	9578	2706	209 419
Cochabamba	18 307	15 618	4152	1315	2264	950	447	2261	24 742
Chuquisaca	17 165	17 282	1672	0	0	0	51	651	19 657
La Paz	47 476	45 323	10 936	1195*	1694*	499*	488	3633	62 075
Pando	57 163	57 070	1918	615	1357	743	774	210	61 331
Santa Cruz	222 109	213 985	120 406	11 187	16 933	5745	2050	1119	354 494
Total	448 703	437 904	245 141	15 532	24 703	9171	13 388	10 582	731 717

**Table 2** Summary of forest cover (km<sup>2</sup>) and deforestation rates (km<sup>2</sup> yr<sup>-1</sup>) estimated for the >1000 mm precipitation zone in Bolivia. The deforestation estimate from this paper (UMD) is for the area below 1500 m altitude and north of 19°S. The UMD rate is estimated as the area of change divided by 6 yr (1986–1992). The FORIS data are from FAO (1976, 1981, 1990). The FAO data from satellite samples are from FAO (1996, 1997). Other data are from CUMAT (1992) and MDSMA (1995).

Source	Date of forest cover estimate	Forest cover (km <sup>2</sup> )	Time period of deforestation estimate	Deforestation rate (km <sup>2</sup> yr <sup>-1</sup> )	Total forest cleared (km <sup>2</sup> yr <sup>-1</sup> )
UMD	1984–1987	447 075			15 532
	1989–1994	437 904	1987–1993 (6)	1529	24 703
FAO – Foris	1941–1945	599 500			
	1966	592 000	1945–1966 (21)	1500	
	1970	582 000	1966–1970 (4)	2500	
	1975	570 000	1970–1975 (5)	2400	
	1980	440 100	1976–1980 (5)	6500	
				1981–1985 (5)	8700
	1990	493 170	1981–1990 (10)	6250	
FAO – Satellite Sample	1995	483 100	1991–1995 (5)	5810	
CUMAT	1990	402 500	1985–1990 (5)	3750	24 000
MDSMA	1995		1975–1993 (18)	3000	54 000



**Figure 1** Distribution of deforestation in the Bolivian lowlands estimated from digital analysis of Landsat images. Forest includes all closed-canopy tropical forest within the >1000 mm precipitation zone. Non-forest includes all areas of savanna, cerrado, chaco woodland and montane puna. Deforested mid-1980s includes all areas classified as deforested in the 1980s image data set (1984–1987); deforestation mid-1980s – early 1990s includes all areas of anthropogenic clearance between the 1980s and the 1990 image data set (1989–1994). Deforestation classes are not mapped south of 19°S latitude or above 1500 m elevation, indicated by a dashed line. Shaded area in inset map indicates the limits of the study area, defined by a potential forest mask based on the entire image set. Departments indicated in the inset are: Be = Beni, Cb = Cochabamba, Ch = Chuquisaca, LP = La Paz, Pa = Pando, and SC = Santa Cruz. Locations referred to in the text are: (1) Santa Cruz de la Sierra, (2) Tierras Bajas, (3) Chaco, (4) Brazilian shield, (5) Guayaros, (6) Chapare, (7) north-east Beni, (8) La Paz lowlands, and (9) western Pando. The deforestation and potential forest maps are available from the authors upon request.

## Discussion

### Comparison with previous estimates

Our estimates of deforestation are significantly lower than those of the FAO (1976, 1981, 1993, 1996, 1997) and Lanly (1982), which are based either on compilations of surveys, as in the FORIS data, or samples of satellite images in the most

recent estimates. Questions have been raised regarding the sampling strategy and accuracy of the FAO forest extent and deforestation data in Table 2 (Tucker & Townshend 2000). The FAO deforestation estimates for Brazil have been previously challenged by studies based on analyses of wall-to-wall satellite acquisitions by INPE (Tardin 1979; Tardin *et al.* 1979, 1980, 1990) and NASA (Skole & Tucker 1993).



Comparisons are difficult because some reports include forest and woodland, while others include only forest, and because methods have changed and raw data are not available for review.

The FAO (1981) reported a total Bolivian forest and woodland cover of 599 500 km<sup>2</sup> for 1941–1945 falling to 592 000 km<sup>2</sup> in 1966, 582 000 km<sup>2</sup> in 1970 and 570 000 km<sup>2</sup> in 1975 (Table 2). The original area of forest cover is larger than our estimate of potential forest cover, and more than can be accounted for by including Chacoan woodlands. The rates of deforestation between these periods range from 1500 km<sup>2</sup> yr<sup>-1</sup> to 2400 km<sup>2</sup> yr<sup>-1</sup>. The estimate of deforestation since 1975 ranges from 5800 km<sup>2</sup> yr<sup>-1</sup> to 8700 km<sup>2</sup> yr<sup>-1</sup> (FAO 1981), the lower rate from the most recent estimate based on a sample of four satellite images. These rates are three to five times greater than our estimates from analysis of complete Landsat coverage.

The estimate of 24 000 km<sup>2</sup> deforested by 1990 (CUMAT 1992) is close to our estimate; however, CUMAT (1992) estimated that only 3750 km<sup>2</sup> of this area were cleared between 1985 and 1990. The Bolivian National Secretary of Natural Resources reported that 3000 km<sup>2</sup> yr<sup>-1</sup> of lowland forest were cleared from 1975 to 1993, which is double our estimate (MDSMA 1995). We believe that the inconsistencies in these products, particularly in estimates of change, are caused by limitations in the visual interpretation approach to deforestation mapping, especially interpretation differences, data co-registration and boundary generalization.

### *Distribution of Bolivian deforestation*

Anthropogenic deforestation in Amazonia is prehistoric, but in Bolivia it began historically with the founding of Jesuit missions in *Chiquitos* (Santa Cruz) and *Moxos* (Beni; Denevan 1966; Block 1994). Some of these settlements remain as small villages, although the city of Santa Cruz de la Sierra, at the base of the Andes, became an agricultural centre in the 1950s. Most of the deforestation by the 1970s in Santa Cruz was in sugar, rice, corn, and citrus farms immediately surrounding the city (Stearman 1985; Thiele 1996; Pacheco 1998; Hecht 2000). Several planned colonies of highlanders were settled along the highways north and west of the city. Pastures are most common on the Brazilian shield, and Mennonite communities have settled east of the city.

By the 1980s, spontaneous colonization had increased around the city and along the new highway between Santa Cruz and Cochabamba. Also in the 1990s, industrial soybean farmers had arrived from outside Bolivia and rapidly cleared large areas of forest east of the city. The result was that the area deforested by the mid-1980s had increased 60% by the early 1990s. This part of the map in Fig. 1 is based on a TM image from 1992. Analysis of a 1998 TM image showed an additional 6000 km<sup>2</sup> deforested in this area alone (Steininger *et al.*, unpublished data), increasing the national total for deforested land in 1998 to at least 30 700 km<sup>2</sup>. By this time, soybean farming had further expanded into the drier Chaco

woodlands and clearance for pasture had become increasingly common on the Brazilian shield to the north (Pacheco 1998; Hecht 2000). The dynamics of deforestation in this frontier differs from many Amazonian frontiers in that soils are relatively fertile, access to land is inexpensive and export of soybean products is encouraged by Bolivia's favoured status in the Andean pact.

In areas of small-scale agriculture, especially along the roads north and west of Santa Cruz de la Sierra, deforestation has expanded in small patches adjacent to older farms. A similar phenomenon of concentrated deforestation along the base of the Andean crescent, facilitated by road construction, can be observed in Peru and Ecuador (Moran 1981; Rudel & Horowitz 1993). Newer frontiers are observed north of the Andes in Guayaros, La Paz and the Pando, and it is possible that the deforestation patterns along the Santa Cruz – Cochabamba highway will be repeated in these areas (Pacheco 1998). Roadside deforestation has expanded most quickly in the Chapare municipality of Cochabamba, where clearance for traditional crops and coca have reached from the highway to the Andean foothills. Continued expansion in this area threatens to completely isolate over 4000 km<sup>2</sup> of foothill and montane forest from all neighbouring lowland forest.

The clearance patterns of indigenous communities practising shifting cultivation can also be observed, particularly along rivers throughout Beni, Pando, La Paz and Guayaros, Santa Cruz. Similar patterns are observed in interior forests in north-east Beni and among communities of rubber tappers and Brazil-nut collectors in the Pando. While communities practising small-scale shifting cultivation were found in many areas, their contribution to total deforestation was small compared to that of the Tierras Bajas and around Santa Cruz de la Sierra. Thus, despite a national population of 6.5 million and lowland population of under 2 million, the rate of deforestation over this period was similar to rates reported for Brazilian states with much larger populations, such as Maranhão, Mato Grosso and Rondônia during the 1980s and 1990s (Skole & Tucker 1993; Houghton *et al.* 2000).

With continued immigration, road construction and globalization of the Bolivian agricultural economy, we expect high rates of deforestation to continue in the Bolivian Oriente. Of particular concern is the prospect of depleting the remaining Chiquitano forest. Unless necessary planning and resources are provided for its conservation, soybean farming and cattle ranching threaten to complete an arc of Amazonian deforestation extending from Pará, Brazil to the Bolivian Andes, with near-total destruction of Amazonian semi-deciduous forest.

### **Conclusions**

This study documents rapid deforestation at the national level, caused by several major economic and social trends during the past two decades in Bolivia. Because of a depressed economy and the closing of many mines in the

highlands, there has been large-scale migration from the cities of the Altiplano and inter-Andean valleys to the lowlands throughout the 1980s and 1990s. As a result, small-scale deforestation occurred along roads from the Andes to the lowlands, especially along the new Santa Cruz to Cochabamba highway. In this area, deforestation threatens to isolate over 4000 km<sup>2</sup> of montane tropical forest from all neighbouring lowland forests. Figure 1 shows that small-scale, roadside deforestation extends over 30 km from major roads. Much forest remains near major roads in lowland Bolivia, and this is the most likely forest to be cleared in the coming years.

Although widespread, the total area of shifting cultivation among indigenous communities and other settlements associated with rivers is relatively small. Likewise the contribution to deforestation by indigenous groups and rubber tappers in interior forest is relatively small. The greatest concentration of deforestation is in the Tierras Bajas, east of Santa Cruz de la Sierra, where half of the national deforestation has occurred. This area was the focus of a World Bank development project (Ledec 1989), and forest there was cleared almost exclusively for industrial-scale soybean production, largely by Mennonites, and Brazilian and other foreign land owners (Hecht 2000). For these reasons, Bolivia differs from the Brazilian Amazon by having a high deforestation rate despite a low population density.

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