Tropical Deforestation in the Bolivian Amazon

Compton J. Tucker[1], Marc K. Steininger[1], John R. G. Townshend[2], Timothy R. Killeen[3], and Arthur Desch[2]

[1]NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771 USA; [2]Department of Geography, University of Maryland, College Park, Maryland 20742 USA; [3]Missouri Botanical Garden, St. Louis, Missouri USA.

Abstract

Landsat satellite images from the mid-1980s and early 1990s were used to map tropical forest extent and deforestation in ~800,000 km^2 of Amazonian Bolivia. Forest cover extent, including tropical deciduous forest, totaled 472,000 km^2 while the area of natural non-forest formations totaled 298,000 km^2. The area deforested totaled 15,000 km^2 in the middle 1980s and 28,800 km^2 by the early 1990s. The rate of tropical deforestation in the >1,000 mm y^{-1} precipitation forest zone of Bolivia was 2,200 km^2 y^{-1} from 1985-1986 to 1992-1994. We document a spatially-concentrated "deforestation zone" in Santa Cruz Department where >60% of the Bolivian deforestation is occurring at an accelerating rate in areas of tropical deciduous dry forest.

Keywords: tropical forests, deforestation, habitat fragmentation, biological diversity, Landsat, GIS, Bolivia

Introduction

Deforestation has occurred in the tropics throughout history (Tucker and Richards, 1983; Richards, 1984; Hecht and Cockburn, 1989; Williams, 1989 and 1990) and has accelerated recently, particularly in areas of seasonally-deciduous tropical forests (Schmink and Wood, 1984; Janzen, 1986; Fearnside, 1986, 1993; Houghton et al. 1991; Myers, 1991; Skole and 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 and Shuttleworth, 1991; Houghton, 1991; Keller et al. 1991; Dixon et al. 1994; 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 and Tucker, 1993; Pimm, 1995; Laurence and Bierregaard, 1997; Laurence 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 (Fearnside, 1986; Skole and Tucker, 1993). The spatial composition from 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; Laurence, et al., 1997 and 1998; Cochrane and Schulze, 1999; Nepstad et al., 1999), and the isolation of forest fragments also affects local composition and diversity of both plants and mammals (Miller and Harris, 1977; Wilcox, 1980; Karieva, 1987; Laurence et al., 1999).

Bolivia, a land-locked country with a total national territory of ~1,098,000 km^2 in central South America, contains ~500,000 km^2 of forest and woodland, including more than 400,000 km^2 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 (Dinerstein et al. 1995; Gentry, 1995; Killeen and Schulenberg, 1999). Part of the reason for the high biodiversity there is the large number of forest and savanna habitat types (see Prance and Schaller, 1982; Haase and Beck, 1989; Killeen et al., 1993, 1998; Prado and Gibbs, 1993; Hanagarth, 1993; Killeen and Schulenberg, 1999).

In *Wavelet Applications VII*, Harold H. Szu, Martin Vetterli, William J. Campbell, James R. Buss, Editors, Proceedings of SPIE Vol. 4056 (2000) • 0277-786X/00/$15.00

Bolivia has only 6 million inhabitants, two-thirds which live in the Altiplano and Andean valleys. Road construction, immigration from the highlands, low land prices, foreign investment, agricultural export demands, and structural adjustment have all contributed to the clearance of large areas of pristine and lightly-disturbed forest (Stearman, 1985; Sanabria, 1993; Painter, 1995; Thiele, 1996; Pacheco, 1998; Hecht, 1999).

Estimates of deforestation based on survey questionnaires, such as those produced by the FAO, have been subject to criticism and fail to document the distribution of deforested areas (Tucker and Townshend, 2000). Several sources of satellite data have been used to map the precise locations and areas of deforestation (Fearnside, 1986, 1993; Green and Sussman, 1990; Skole and Tucker, 1993; Malingreau et al. 1995). However, comparisons of deforestation estimates in Brazil showed that visual interpretation of high-resolution (30-60 meters) satellite images tends to overestimate deforestation, largely because of positional accuracy and boundary generalization (Skole and Tucker 1993). Digital analysis of coarse resolution (1-8 kilometers) data can overestimate deforestation by up to 50 percent (Malingreau and Tucker, 1988; Cross et al., 1991; Downton, 1995; Malingreau et al., 1995). We believe that digital processing of high-resolution images provides the most accurate estimates of the area and distribution of cleared tropical forests. We document a study of forest cover and deforestation, using Landsat data from the middle 1980s and early 1990s, for the entire Amazon Basin of Bolivia (Townshend et al. 1995; Tucker and Townshend, 2000).

Deforestation in Bolivia

We applied the methodology reported by Skole and Tucker (1993) to Landsat images of Bolivia. Landsat thematic mapper (TM) and multispectral scanner (MSS) images were co-registered from the 1980s to a 1990s TM mosaic. We then produced and edited a map of deforestation between time periods at 60 meter resolution. Using data of forest cover from both time periods, we created a mask of potential forest cover to allow comparison with other studies.

We adopted the FAO (1993) ecofloristic stratification of Bolivia and mapped only forest in the >1000 mm precipitation zone (Roche and Rocha, 1985; Cordecruz, 1994). In the Bolivian lowlands, this roughly corresponds to the transition from Chiquitano deciduous forest, closed canopy and over 10 meters tall, to Chacoan woodland, which is shorter, more completely deciduous and floristically distinct. All broadleaf forest in the Andes were mapped, including cloud forest (Killeen et al., 1993).

Digital Landsat data were acquired for the middle 1980s (1984-1987), and early 1990s (1992-1994); a total of 44 images per time period. 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. 36 of the 44 1980s scenes were MSS, and all digital analysis was resampled to a 60 m grid cell size. The classes identified by spectral analysis and editing were natural non-forest, deforestation, water, cloud and cloud shadow. Natural non-forest includes savanna, cerrado, sandbanks and puña; deforestation includes areas of forest converted to urban, pasture agriculture and young fallow regrowth. These include all areas of closed-canopy forest clearance, including smaller forest clearings (>2 ha.) associated with rubber tappers, indiginous groups, roads, pipelines, power line rights-of-way, airfields, mining operations, and timber concessions.

We also produced a potential closed-canopy forest, water, and non-forest stratifications for our entire study area using the analysis of the 1990s TM data. 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 date.

Based on the co-registered 1980s and 1990s mosaics, we identified all areas of forest loss between the time periods. These areas were edited to exclude cases of non-anthropogenic deforestation, such as river migration, and imperfect co-registration. Editing was based primarily on field surveys and numerous low-altitude overflights conducted by Killeen, Tucker and Steininger over 3 years. These areas were incorporated into our GIS and only accepted as deforestation if they occurred within the potential forest stratum. Because of classification difficulties in mountainous areas, we only mapped areas of change between the time periods and did not map the areas deforested by the 1980s above 1000 m altitude.

Our final product was a 60 m resolution map of forest, natural non-forest, water, deforested by the middle 1980s and deforestation from the middle 1980s to the early 1990s (Figure 1). An additional mosaic of Landsat scene dates was created. The average deforestation rate between time periods for the entire country was calculated as the intersection of the scene years and deforestation map.

Our analysis of Bolivia determined a total potential closed-canopy forest area of 471,800 km^2, 322,000 km^2 of non-forest, and 13,700 km^2 of water (Table 1). Approximately 52,000 km^2 of the potential forest was above 1000 m elevation. The land area deforested was 15,000 km^2 by the middle 1980s and 28,800 km^2 by the early 1990s. Of the 13,800 km^2 of deforestation between time periods, 1,650 km^2 was above 1000 m. Cloud cover in both time periods obscured a combined total of 16,000 km^2 of the surface. The average rate of anthropogenic deforestation between the middle 1980s and early 1990s for the entire area was ~2,200 $km^2\ y^{-1}$.

Comparison with Previous Estimates of Forest Cover and Loss

Our estimates of deforestation are significantly lower than those of the FAO (FAO, 1981, 1990, 1993, 1996, 1997; Lanly, 1982) which have been based upon compellation of survey data from non-satellite sources. Questions have been raised regarding the sampling strategy and accuracy of the FAO forest extent and deforestation numbers in Table 2 (Tucker and Townshend, 2000. The FAO deforestation numbers for Brazil have been challenged using analyses of satellite data by INPE (Tardin et al. 1979, 1980, and 1990) and Skole and Tucker (1993).

The FAO Production Yearbook (FAO, 1976) reports a total Bolivian forest and woodland cover of 599,500 km^2 for 1941-1945 falling to 592,000 km^2 for 1966. This figure decreases to 582,000 km^2 in 1970 and to 570,000 in 1975. This is considerably higher than our estimate of potential forest cover of 460,000 km^2. However, the FAO reported an average rate of 5,100 $km^2\ yr^{-1}$ of deforestation for 1985 to 1995, a rate over twice ours (Table 2). Thus, their estimate of the area deforested in 1995 surpasses ours.

The estimate of 24,000 km^2 deforested by 1990 reported by CUMAT (1992) is close to ours; however, they estimated that only 375 km^2 of this area was cleared between 1985 and 1990. The Bolivian National Secretary of Natural Resources reported that 3,000 km^2 of lowland forest were cleared from 1975 to 1993 (MDSMA, 1995). This is lower than our estimate since we report 13,800 km^2 of change between the 1980s and 1990s alone. 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

Deforestation in Amazonia can be prehistoric but in Bolivia historically began with the founding of Jesuit missions in *Chiquitos* (Santa Cruz) and *Moxos* (Beni) (Metraux, 1948; Denevan, 1966; Block, 1994). Some of these settlements remain as small villages, although Santa Cruz de la Sierra, at the base of the Andes, became an agricultural center 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, 1999). Several planned colonies of highlanders were settled north and west of the city. Further north, pastures began to appear on the Brazilian shield, and several Mennonite communities have settled east of Santa Cruz de la Sierra.

By the 1980s, spontaneous colonization had increased around the city and along the new Santa Cruz – Cochabambe highway. Also in the 1990s, industrial soybean farmers had arrived and rapidly cleared large areas east of the city. The result was that the area deforested by the middle 1980s had nearly doubled by the early 1990s. Despite a national population of 6 million and lowland population of only 1.5 million, the rate of deforestation over this period was similar to rates reported for Maranhão, Mato Grosso and Rondônia, Brazil during the early 1980s (Skole and Tucker, 1993).

The spatial patterns of deforestation indicate several zones of agricultural growth in the Bolivian Amazon. The most dramatic case is the Tierras Bajas Project, east of Santa Cruz de la Sierra, where mechanized soybean agriculture has created many large regular-shaped clearances. This part of the map in Figure 1 is based on a TM image from 1992. Analysis of a 1998 TM image showed an additional 6,000 km^2 deforested in this area alone (Steininger et al. 2000), increasing the national total for deforested land in 1998 to at least 34,700 km^2. During the 1990s, soybean farming has further expanded into the drier Chaco woodlands and clearance for pasture is increasingly common on the Brazilian shield to the north (Pacheco, 1998; Hecht, 1999).

In areas of small-scale agriculture, along the roads north and west of Santa Cruz de la Sierra, deforestation has expanded in small patches adjacent to older farms. Roadside deforestation has expanded most quickly further west 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 4,000 km^2 of foothill and montane forest from all neighboring lowland forest.

The clearance patterns of indigenous communities practicing shifting cultivation can also observed, particularly along rivers throughout the Beni, Pando, La Paz, Guayaros, and Santa Cruz departments. Similar patterns are observed in interior forests in Baure and Siriono communities in northeast Beni, and among communities of rubber tappers and Brazil nut collectors in the Pando. While variations of small-scale shifting cultivation are found in many areas, their contribution to total deforestation is relatively small.

Conclusions

The data we report document a case of rapid deforestation at the national level, caused by several major economic and social trends during the past three 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 – Cochabamba highway. A similar phenomenon of concentrated deforestation along the base of the Andean crescent, facilitated by road construction, can be observed in Peru and Ecuador (Aramburú, 1985). In the Bolivian case, deforestation at the base of the Andes in Santa Cruz and Cochabamba threatens to isolate over 4,000 km^2 of montane tropical forest from all neighboring lowland forests.

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). Although widespread, the total area of shifting cultivation among indigenous communities and other settlements associated with rivers appears to be relatively small. Likewise the contribution to deforestation by indigenous groups and rubber tappers in interior forest is relatively small.

The most conspicuous form of deforestation is 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, Brazilian and other foreign land owners. 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 are encouraged by Bolivia's favored status in the Mercosur pact (Hecht, 1999).

The endemic vegetation in the Tierras Bajas and on the Brazilian shield is known as *Chiquitano* forest. This is believed to be the largest remaining area of contiguous, undisturbed tropical dry or deciduous forest (Killeen and Schulenberg, 1999). The rapid changes which have occurred there and the virtual absence of tropical deciduous forests worldwide (Janzen, 1988) highlight the importance of its conservation. With the construction of a new highway from Santa Cruz eastward to Brazil, and an associated oil pipeline by Shell and Enron, we expect deforestation to continue to deplete the remaining *Chiquitano* forest. Unless the necessary planning and resources are provided for its conservation, this will result in the completion of an arc of Amazonian deforestation extending from Pará, Brazil to the Bolivian Andes, with near-total destruction of tropical deciduous forest. Landsat data are crucial for studies such as ours, without which this would never could have been attempted.

References

Aramburú, C.E., 1984. Expansion of the agrarian and demographic frontier in the Peruvian Selva. In *Frontier Expansion in Amazonia.* Edited by M. Schmink and C.H. Wood, Gainesville: Univ. of Florida Press, pp. 153-179.

Block, D., 1994. *Mission Culture on the Upper Amazon.* Lincoln: Univ. of Nebraska Press. 240 pp.

Chiarello, A.G., 1999. Effects of fragmentation of the Atlantic forest on mammal communities in south-eastern Brazil. *Biological Conservation* 89:71-82.

Cochrane, M.A. and M.D. Schulze, 1999. Fire as a recurrent event in tropical forests of the eastern Amazon: effects on forest structure, biomass and species composition. *Biotropica* 31:2-16.

Cook, A.G., A.C. Janetos, and W.T. Hinds, 1990. Global effects of tropical deforestation: towards an integrated perspective. *Environmental Conservation* 17:201-212.

Cordecruz, 1994. *Plan del Uso del Suelo.* Santa Cruz de la Sierra, Bolivia, Proyecto de Protecion de los Recursos Naturales del Departmento de Santa Cruz, Bolivia.

Cross, A. M., J. J. Settle, N. A. Drake, and R. T. M. Paivinen. 1991. Subpixel measurement of tropical forest cover using AVHRR data. *Int. J. Remote Sensing* 12:1119-1129.

CUMAT, 1992. *Desbosque de la Amazonia Boliviana.* Vegetation Map. La Paz: Capacidad de Uso Mayor de la Tierra.

Denevan, W.M., 1966. *The Aboriginal Cultural Geography of the Llanos de Mojos of Bolivia.* Berkeley: Univ. of California Press.

Dinerstein, E. D. Olson, M. Graham, D. J. Webster, A. L. Rim, A. A. Bookbinder M. P. & Ledec, G. 1995. *A conservation assessment of the terrestrial ecoregions of Latin America and the Caribbean.* World Wildlife Fund - The World Bank, Washington DC. 135 pp.

Dixon, R. K., S. Brown, R. A. Houghton, S. M. Solomon, M. C. Trexler, and J. Wisniewski, 1994. Carbon pools and flux of global carbon forest ecosystems. *Science.* 263:185-190.

Downton, M.W., 1995. Measuring tropical deforestation: development of the methods. *Environmental Conservation* 22:229-240.

Fearnside, P. M., 1986. Spatial concentration of deforestation in the Brazilian Amazon. *Ambio* 15:74-81.

Fearnside, P. M., 1993. Deforestation in Brazilian Amazonia: The effect of population and land tenure. *Ambio 22*, 537-545.

Fearnside, P. M., 1996. Amazonian deforestation and global warming: carbon stocks in vegetation replacing Brazil's Amazon forest. *Forest Ecology and Management* 80:21-34.

FAO, 1976. FAO Production Yearbook. Food and Agricultural Organization of the United Nations, Rome.

FAO, 1981. *Tropical Forest Resources Assessment Project. Forest Resources of Tropical America.* Food and Agricultural Organization of the United Nations, Rome.

FAO. 1990. *Interim Report on Forest Resources Assessment 1990 Project.* Committee on Forestry, Tenth Session, Rome, Italy. Food and Agricultural Organization of the United Nations, Rome.

FAO, 1993. *Forest resources assessment 1990.* FAO Forestry Paper 112, Food and Agricultural Organization of the United Nations, Rome.

FAO, 1996. *Forest resources assessment 1990: Survey of tropical forest cover and study of change processes.* FAO Forestry Paper 130, Food and Agricultural Organization of the United Nations, Rome.

FAO, 1997. *State of the World's Forests: 1997.* Food and Agricultural Organization of the United Nations, Rome. 200 p.

Gash, J. H. C. and W. J. Shuttleworth, 1991. Tropical deforestation: albedo and the surface energy balance. *Climate Change* 19:123-133.

Gentry, A. 1995. Diversity and floristic composition of neotropical dry forests. Pp. 146-194 in Bullock, S. H. Mooney, H. A. & Medina E. (eds). *Seasonally dry tropical forests*, Cambridge University Press, Cambridge. 450 pp.

Green, G. M. and Sussman, R. W., 1990. Deforestation history of the eastern rain forests of Madagascar from satellite images. *Science* 212-215.

Haase, R. and S.G. Beck, 1989. Structure and composition of savanna vegetation in northern Bolivia: a preliminary report. *Brittonia* 41:80-100.

Hanagarth, W., 1993. *Acerca de la Geoecología de las Sabanas del Beni en el Noreste de Boliva.* La Paz: Instituto de Ecología, 186 pp.

Harris, L. D. (1984). *The Fragmented Forest.*

Hecht, S. B. and A. Cockburn (1989). *The Fate of the Forest.* London: Verso. 240 pp.

Hecht, S. B., 1999. Structural adjustment and land usage in lowland Bolivia. *World Development*, in press.

Houghton, R. A., 1991. Tropical deforestation and atmospheric carbon cycle. *Climate Change* 19:99-118.

Houghton, R. A., Skole, D. L., and Lefkowitz, D. S., 1991. Changes in the landscape of Latin America between 1850 and 1985, II: a net release of CO., into the atmosphere. *J. Forest Ecol. Mgm.* 38:133-199.

Janzen, D. H., 1986. Tropical dry forests: the most endangered major tropical ecosystem. In *Biodiversity.* Edited by E. O. Wilson, pp. 130-137. Washington: National Academy Press.

Karieva, P., 1987. Habitat fragmentation and the stability of predator-prey interactions. *Nature* 326:388-390.

Keller, M., D. J. Jacobs, S. C. Wofsy, and R. C. Harris. 1991. Effects of tropical deforestation on global and regional atmospheric chemistry. *Climate Change* 19: 139-158.

Killeen, T. J., S. G. Beck and E. Garcia, 1993. *Guía de Arboles de Bolivia*, Herbario Nacional de Bolivia and Missouri Botanical Garden, La Paz, Bolivia. 958 pages.

Killeen, T.J., A. Jardim, A., F. Mamani, N. Rojas, and P. Saravia, 1998. Diversity, composition, structure, and biomass estimates of a tropical semideciduous forest in the Chiquitanía region of Santa Cruz, Bolivia. Submitted to. *J. Tropical Ecology* 14: 803-827.

Killeen, T. J. and T. Schulenberg, 1999. *Conservation of Noel Kempff National Park.* Washingonton, D.C., Conservation International.

Lanly, J. P., 1982. *Tropical forest resources.* . FAO Forestry Paper 30, FAO. Rome.

Laurance, W. F. and R. O. Bierregaard, 1997. *Tropical Forest Remnants: Ecology, Management and Conservation of Fragmented Communities.* Chicago: University of Chicago Press. 409 pp.

Laurance, W. F., S. G. Laurance, L.V. Ferreira, J.M. Rankin-de Merona, C. Gascon and T.E. Lovejoy, 1997. Biomass collapse in Amazonian forest fragments. *Science* 278: 1117-1118.

Laurence, W., L., L.V. Ferreira, , J.M. Rankin-de Merona and S. G. Laurance, 1998. Rainforest fragmentation and the dynamics of Amazonian tree communities. *Ecology* 79: 2032-2040.

Ledec, G. (1989). *Bolivia Eastern Lowlands Development Project: Appraisal of Natural Resource Planning and Management Component*. Washington, D.C.: World Bank.

MDSMA, 1995. *Memoria Explicativa. Mapa Forestal.* Vegetation Map. La Paz: Sectretaría Nacional de Recursos Naturales.

Maass, J.M., 1995. Conversion of tropical dry forest to pasture and agriculture. In *Seasonally Dry Tropical Forests*. Edited by S.H. Bullock, H.A. Mooney and E. Medina, pp. 399-422. . Cambridge: Cambridge University Press.

Malcolm, J. R., 1994. Edge effects of Amazonian forest fragments. *Ecology* 75: 2438-2445.

Malingreau, J.P., F. Achard, G. D'Souza, H.J. Stibig, J. D'Souza, C. Estreguil and H. Eva, 1995. AVHRR for global tropical forest monitoring: the lessons of the TREES project. *Remote Sensing Reviews* 12:29-40.

Malingreau, J. P., and Tucker, C. J., 1988. Large-scale deforestation in the southeastern Amazon basin of Brazil. *Ambio* 17:49-55.

Metreaux, A. Tribes of eastern Bolivia and the Madeira headwaters. In *Handbook of South American Indians*. Edited by J. Steward. Vol. 3:351-454. Washington: U.S. Government Printing Office.

Miller, R. I. and L. D. Harris, 1977. Isolation and extirpations in wildlife reserves. *Biological Conservation* 12:311-315.

Myers, N. 1991. Tropical forests: present status and future outlook. *Climatic Change* 19 : 3-32.

Nepstad, D. C., Verissimo, A., Alencar, A., Nobre, C., Lima, E., Lefebvre, P., Schlesinger, P., Potter, C., Moutinho, P., Mendoza, E., Cochrane, M. and Brooks, V., 1999. Large-scale impoverishment of Amazonian forests by logging and fire. *Nature* 398:505-508.

Pacheco, P., 1998. *Estilos de Desarollo, Deforstación y Degradacióde los Bosques en las Tierras Bajas de Bolivia.* 389 pp. La Paz: CEDLA.

Painter, M., 1995. Upland-lowland production linkages and land degradation in Bolivia. In *The Social Causes of Environmental Destruction in Latin America*. Edited by Painter, M. and W.H. Durham, pp. 133-168. Ann Arbor: Univ. of Michigan Press.

Pimm, S. L., Russell, G. J., Gittleman, J. L., and Brooks, T. M., 1995. The future of biodiversity. *Science* 269:347-350.

Prado, D. E. & Gibbs, P. E. 1993. Patterns of species distributions in the dry seasonal forests of South America. *Ann. Missouri Bot. Garden* 80: 902-927.

Richards, J. F. 1984. Global patterns of land conversion. *Environment* 26 (9): 6-38.

Roche, M. A. & N. Rocha, 1985. Precipitacioes anuales. Programa Climatólogico e Hidrológico de la Cuenca Amazónica Boliviana (PHICAB): Servicio Nacional de Meteología e Hidrología (SENAHMHI) - ORSTROM, La Paz.

Sanabria, H., 1993. *The Coca Boom and Rural Social Change in Bolivia.* Ann Arbor: Univ. of Michigan Press.

Schmink, M. and C. H. Wood, eds. 1984. *Frontier Expansion in Amazonia.* Gainesville: Univ. of Florida Press. 502 pp.

Skole, D. L., and Tucker, C. J., 1993. Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. *Science* 260:1905-190.

Stearman, A. M., 1985. *Camba and Kolla, Migration and Development in Santa Cruz, Bolivia*. Orlando: Univ. of Florida Press, 227 pp.

Steininger, M. K., C. J. Tucker, T. Killeen, P. Ersts, A. Desch, and S. B. Hecht, 2000. Forest clearance and fragmentation in the Tierras Bajas, Santa Cruz, Bolivia: Satellite data from 1975 to 1998. Submitted to *Conservation Biology*.

Tardin, A. T., A. P. dos Santos, D. C. Lee, F. C. S. Maia, F. J. Mendoncza, G. V. Assunczio, J. E. Rodrigues, M. de Moura Abdon, R. A. Novacs, S. C. Chen, V. Duarte, and Y. E. Shimabukuro. 1979. *Levantamento de areas do desmatamento na Amazonia Lefal atraves de imagens do satellite Landsat.* 411-NTE/142, Instituto Nacional de Pesquisas Espaciais. San Jose dos Campos, Brazil

Tardin, A. T., D. C. L. Lee, R. J. R. Santos, O. R. Ossis, M. P. S. Barbosa, M. L. Moreira, M. T. Pereira, D. Silva, and C. P. Santos Filho. 1980. *Subprojecto Desmatamento*. IBDF/CNPq -INPE, Instituto de Pesquisas Espaciais, Sao Jose dos Campos, Brasil.

Tardin, A. T. and R. P. da Cunha, 1990. *Evaluation of deforestation in the Legal Amazon using Landsat TM images*. INPE-5015-RPE/609 (Instituto de Pesquisas Espaciais, Sao Jose dos Campos).

Thiele, G., 1996. The displacement of settlers in the Amazon: the case of Santa Cruz, Bolivia. *Human Organization* 54:273-282.

Townshend, J. R. G., V. Bell, A. C. Desch, C. Havlicek, C. O. Justice, W. E. Lawrence, D. Skole, W. W. Chomentowski, 1995. The NASA Landsat Pathfinder Humid Tropical Deforestation Project. *Land_Satellite Information in the Next Decade*, Tyson's Corner, Virginia, American Society of Photogrammetry and Remote Sensing. pp. IV76-IV87

Tucker, R. P. and J. F. Richards. 1983. *Global Deforestation and the Nineteenth Century World Economy.* Durham: Duke Univ. Press.

Tucker, C. J. and J. R. G. Townshend, 2000. Strategies for monitoring tropical deforestation using satellite data. Int. J. Remote Sens. (*in press*).

Wilcox, B. A., 1980. Insular ecology and conservation. In *Conservation Biology, an Evolutionary-Ecological Perspective,* pp. 95-117. Sunderland, MA: Sinauer.

Williams, M. 1989. Deforestation: past and present. *Progress in Human Geography* 13 : 176-208.

Williams, M. 1990. Forests. In *The Earth as Transformed by Human Action*. Edited by B. L. Turner, R. W. Clark, R. W. Kates, J. F. Richards, J. T. Mathews and W. B. Meyer, pp. 179-201. Cambridge: Cambridge University Press.

Table 1. Summary of deforestation estimated for Bolivian forests, based on digital analysis of Landsat Thematic Mapper (TM) and Multispectral Scanning System (MSS) images. All areas are in km^2 and rates are in $km^2\ y^{-1}$. Data from the 1980s are from 1984 to 1987, the 1990s are from 1992 – 1994. All forest in the >1000 meter precipitation zone were mapped. *Areas deforested by the middle 1980s were only mapped below 1000 m elevation; 1,645 km^2 of the total deforestation between the time periods were in areas over 1000 m above sea level. **For one scene of montane forest in La Paz (002-71), only data from the 1990s were available, and thus there is no change 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	92,277	87,712	105,699	816	2,909	2,093	9,564	3,030	2,646	211,560
Cochabamba	26,390	20,322	27,834	1,520	2,774	1,255	492	3,346	2,964	57,732
La Paz	64,351	56,318	37,422	1,238**	2,869**	1,627**	849	6,781	24,391	128,626
Pando	58,789	55,999	1,726	665	1,541	876	773	1,264	2,103	63,405
Santa Cruz	218,914	199,373	125,179	10,835	18,616	7,782	2,051	1,390	20,552	367,160
Chuquisaca	11,039	10,842	24,756	-	91	91	62	151	14,982	50,884
Sum	**471,760**	**430,566**	**322,615**	**15,073**	**28,801**	**13,724**	**13,791**	**15,961**	**67,638**	**879,367**

Table 2. Summary of Forest Cover and Deforestation Estimates for Bolivia. All areas are in km^2 and rates are in $km^2\ y^{-1}$. Estimates of total forest and woodland from all studies are for the >1000 mm y^{-1} precipitation zone. We find inconsistencies in the FAO figures for Bolivia that we cannot resolve and have greater confidence in our satellite-derived estimates. FAO data are from FAO 1981, 1993, 1996 and 1997; Cumat data are from CUMAT 1992; and MDSMA data are from MDSMA 1995.

Date	Forest cover	Deforestation Rate	Time period of Deforestation estimate	Total forest cleared
A. UMD				
1985-1986	443,700			15,000
1992-1994	430,600	~2,200	1987-1993	28,800
B. FAO				
1941-1945	526,500			
1966	519,000	360	1945-1966	7,500
1970	509,000	2,500	1966-1970	17,500
1975	497,000	650	1970-1975	29,500
1980	494,400	870	1975-1980	33,850
1990	439,000	5,300	1980-1990	86,850
1995	410,000	4,900	1990-1995	111,350
C. CUMAT				
1990	402,500	375	1985-1990	24,000
D. MDSMA				
1995	-	3,000	1975-1993	-

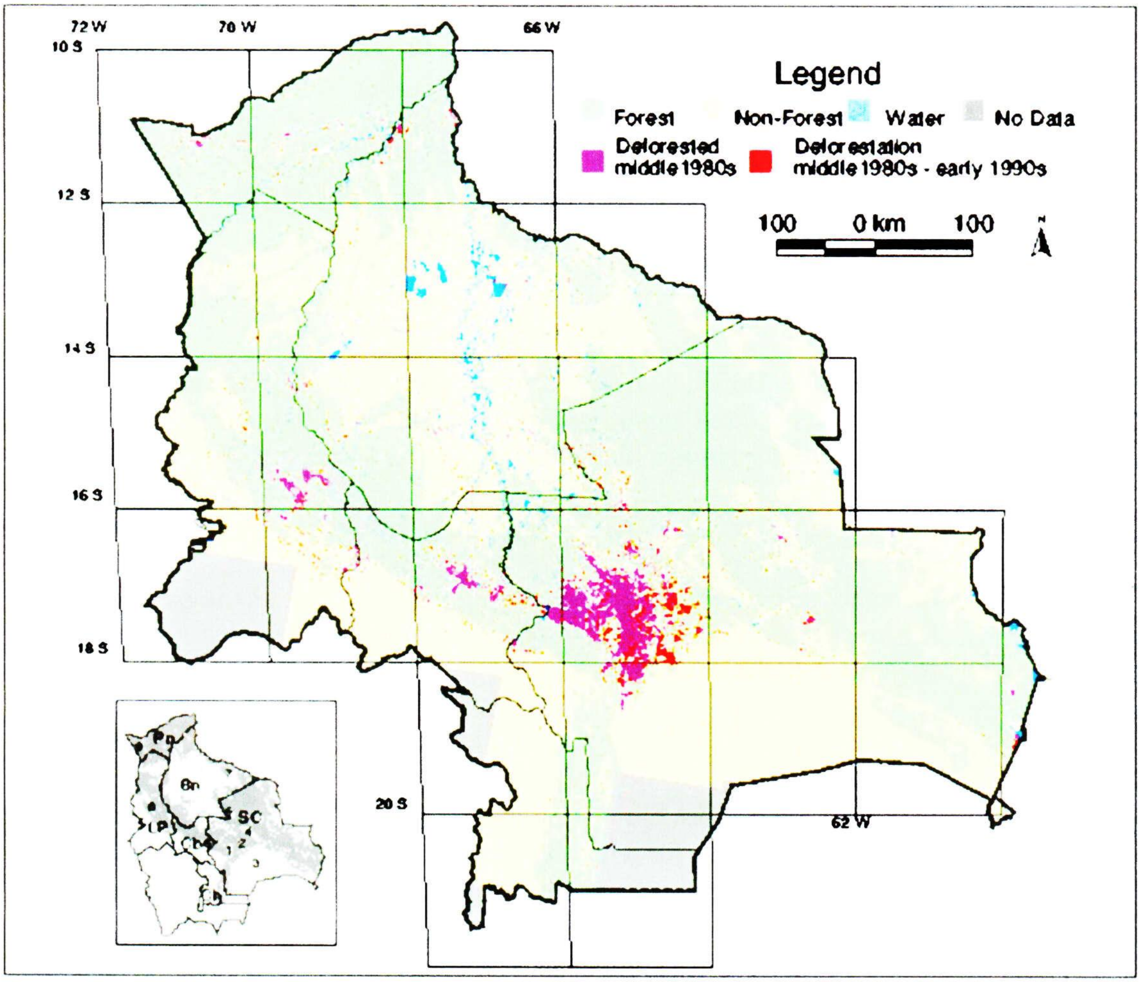

Figure 1. Distribution of deforestation in the Bolivian lowlands estimated from digital analysis of Landsatimages. Forest includes all closed-canopy tropical forest within the >1000 mm precipitation zone. Non-forest includes all areas of savanna, cerrado, chaco woodland and montane puña. Deforested middle 1980sincludes all areas classified as deforested in the 1980s image data set (1984-1987); deforestation middle 1980s – early 1990s includes all areas of anthropogenic clearance between the 1980s and the 1990 image data set (1992-1994). 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 = Cochebamba, 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 = northeast Beni, 8 = La Paz lowlands, 9 = western Pando.