Mapping Continental-Scale Biomass Burning and Smoke Palls over the Amazon Basin as Observed from the Space Shuttle

Michael R. Helfert and *Kamlesh P. Lulla*
Space Shuttle Earth Observations Office, NASA/Johnson Space Center, Houston, TX 77058

ABSTRACT: Space Shuttle and Skylab-3 photography has been used to map the areal extent of Amazonian smoke palls associated with biomass burning (1973-1988). Areas covered with smoke have increased from approximately 300,000 sp km in 1973 to continental-size smoke palls measuring approximately 3,000,000 sq km in 1985 and 1988. Mapping of these smoke palls has been accomplished using space photography mainly acquired during Space Shuttle missions. Astronaut observations of such dynamic and vital environmental phenomena indicate the possibility of integrating the Earth observation capabilities of all space platforms in future Global Change research.

INTRODUCTION

THE EARTH'S GLOBAL PHYSICAL and ecological environments are changing vigorously and rapidly (Botkin *et al.*, 1989). Major scientific concerns about global environmental changes are that these changes are occurring during man's period of planetary stewardship, that these changes are most likely the result of man-stimulated modifications of the Earth's environment, and that the extrapolated rate of present environmental change is more rapid than any known from the geological record, including the great waves of biological extinctions found at some major geological era boundaries (Alho *et al.*, 1988; Aubreville, 1947; Bruenig, 1987; Clark, 1989; Johns, 1985, 1988; Kapos, 1989; Lovejoy *et al.*, 1984; Morgan, 1987; Myers, 1986, 1985, 1982; Redclift, 1989; Reidel, 1988; Roberts, 1988; Sayer and Stuart, 1988; Smith, 1985; Uhl and Vieira, 1989; UN, 1987; Wilson, 1989).

Global biomass burning is an increasingly important agent of contemporary environmental change. Prior to the 19th-20th centuries, biomass burning in savannas, dry-wet tropical forests, and Asian lowland dipterocarp forest was a traditional practice with a relatively low-level biological impact (Albini, 1984; Clarke, 1976; Eden and Andrade, 1988; Janzen, 1973; Kellman, 1988; Mills, 1988; Russell, 1988; Stott, 1984, 1988; Wilkie and Finn, 1990) as well as a natural event of occasionally episodic proportions (Johns, 1986; Malingreau *et al.*, 1985; Sternberg, 1968; Woods, 1989). A scarcity of widespread historical charcoal lenses in lacustrine and riverine sediments in tropical moist forest areas now subjected to repetitious biomass burning indicates that man-stimulated biomass burning was less prevalent prior to the twentieth century (Liu and Colinvaux, 1988; Sanford *et al.*, 1985).

Biomass burning provides a significant input into the overall atmospheric budget of particulates and trace gases. Andrasko *et al.* (1990) report that global deforestation and biomass burning contribute perhaps 15 percent of the current anthropogenic emissions of greenhouse gases. There is increasing documentation on the scale of tropical biomass burning (Booth, 1989; Connors *et al.*, 1986; Helfert, 1983-90; Helfert and Lulla, 1989a, 1989b; Pereira and Setzer, 1986). Nevertheless, the geographical distribution and temporal frequency of biomass burning in traditional savanna management and in conversion of tropical moist forests to agricultural and grazing uses in South/Southeast Asia, Indonesia, Africa, and Latin America is not well understood. Confidence in modeling atmospheric, hydrologic, and ecological changes connected with large-scale, repetitive, biomass burning is inhibited by a lack of basic geographic, temporal, chemical, and physical data.

In order for global change models to be of predictive and real value, confirmatory data on areal extent of change processes are essential (Dickinson and Henderson-Sellers, 1988; Lulla, 1981, 1983). Our objective in this study is to delineate and map the continental-scale biomass burning and smoke palls observed over the Amazon Basin using the Earth-viewing photography from the Space Shuttle and Skylab missions. The determination of the spatial extent of biomass burning and associated smoke palls may help provide confident quantitative determinations of their environmental impact.

DOCUMENTATION OF SMOKE PALLS AND BIOMASS BURNING FROM THE SPACE SHUTTLE

The documentation of dynamic Earth phenomena observed during manned spaceflights remains the cornerstone of the Space Shuttle Earth Observations program (Helfert, 1989), as it was with the earlier Mercury, Gemini, Appollo, and Skylab Earth observations programs. Details on the camera systems and videographic systems used during these spaceflights have been addressed in Amsbury and Bremer (1989) and Lulla and Helfert (1989). Present Space Shuttle Earth observations are hampered by the less-than-adequate windows on the current Orbiters, and the lack of a payload bay position for sensors on all flights. The primary constraints at present are the windows' narrow and restrictive spectral transmissivity (approximately 400 to 800 nanometers) and the geometric distortion across and between the multiple-paned windows. Earth observing facilities of more exacting scientific standards have been proposed for the Space Station Freedom. At present, Orbiter window restrictions result in the use of two primary film bases in the 70-mm Hasselblad and 200-mm Aero-Technika Linhof camera systems. These two film bases are color visible (Kodak 5017/6017 Professional Ektachrome, ASA64) and color infrared (Kodak Aerochrome 2443) films. Additional films have been and will be flown, but the primary films remain the two above. Despite these restrictions, the data acquired by astronauts during their missions are of scientific value (Davis, 1986; Edelson, 1986; El-Baz, 1986; Gallegos *et al.*, 1984; Greer, 1988; Helfert and Holz, 1985; Muehlberger and Gordon, 1987).

Space Shuttle astronauts have documented global tropical moist forest areal and pattern changes over time with both photographic and videographic equipment. Within the context of this paper, large-scale biomass burning and forest clearing in South Asia, Africa and Madagascar, Indonesia, portions of Australia, and the Americas has been documented in both unmanned satellite imagery and NASA space photography seasonally and episodically, especially since the late 1970s (Booth, 1989; Connors *et al.*, 1986; Fearnside 1986b; Helfert and Lulla, 1989; Malingreau *et al.*, 1985, 1989; Malingreau and Tucker, 1988; Periera

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and Setzer, 1986; Rogers *et al.*, 1990; Sanford *et al.*, 1985; Whitehead *et al.*, 1990; Wood *et al.*, 1989). Photography from earlier spaceflights (Mercury, Gemini, Apollo) is less useful as the early photography is composed of more oblique views proportionally than is characteristic of the Space Shuttle (1982 to 1990) photography (Helfert *et al.*, 1990; Lulla *et al.*, 1989; Whitehead *et al.*, 1989, 1990; Wood, 1989).

Based on our review of all frames in the entire length-of-record (1961 to 1990) of the SSEOO global photography database, we recognize that the large-scale environmental changes in the global tropics of the 1960s were not as generally pronounced or as severe in degree as those observable from space in the 1980s. The 1960s data have, nevertheless, been reviewed as a temporal baseline, and to ascertain whether the Amazonian smoke pall phenomenon, in particular, was evident during equivalent Amazonian dry seasons in the 1960s.

DATABASE USED IN THIS STUDY

This study focuses on the geographical extent and seasonality of large regional-seasonal smoke palls associated with tropical moist forest clearing in the Amazon Basin of South America. Data used in this study are drawn from the more than 100,000 frames of NASA space photography taken of the Earth from 1961 through 1989. An additional geographic-sort, computer search of the archive's electronic database produced 520 photographs taken of large smoke palls associated with forest clearing activities in the Greater Amazon Basin. All 520 smoke pall photographs were individually plotted for evidence of biomass burning and smoke palls. All smoke pall photography above was acquired during the Amazonian "dry" seasons (July to October) of 1973, 1983, 1984, 1985, and 1988. Another 1,805 non-smoke photographs of the Amazon Basin from 1961 to 1989 were identified during the geographic-sort computer search and were individually reviewed.

It is recognized that the SSEOO database is temporally incomplete, and that manned spaceflights, except for the three Skylab missions, are of a short duration. Concerning mission coverage of the Amazon Basin during the annual "dry" seasons, there were no manned spaceflight *daylight* overpasses during the Amazonian dry seasons of 1974 through 1982. Specifically, there were no manned spaceflights from the last Skylab mission ending in February, 1974, through the initial Space Shuttle mission in April, 1981, other than the short Apollo-Soyuz cooperative mission of 1975. Additionally, no photography was obtained during the post-Challenger standdown of 1986-87. Additionally, unique mission parameters and non-repetitive Shuttle orbital paths allowed acquisition of only a few photographs of the easternmost Amazon Basin during Space Shuttle missions in 1989.

All 2,325 Amazon Basin photographs from the 1960s missions (Mercury, Gemini, and Apollo), the Skylab missions (1973 and 1974), and the Space Shuttle missions (1981 to present) were reviewed for this study. Occasional, very isolated smoke plumes along the southern periphery of the Amazonian biome were photographed during manned missions from 1965 through 1969 (105 frames), but no large regional smoke palls were photographed prior to that first photographed during Space Shuttle Mission 8 (1983).

Plates 1 and 2 are samples of oblique photography of the 1980's dry-season (July through October) smoke palls in the Amazon Basin. Nadir photography of these smoke palls has also been acquired, but for purposes of illustration of the size and location of the Amazon smoke pall phenomenon, the oblique photography is used here.

Plate 1 is a photograph taken during Space Shuttle Mission STS-14 (September, 1984). It is an oblique synoptic view of the large-scale Amazon smoke palls. The Orbiter nadir point was 8.3°S 60.3°W (Southern Amazonas State), with an altitude of about 163 nautical miles. The look direction is WSW (approximately 255°) across the fire plumes and smoke pall from forest slash clearing associated with the Polonoroeste Project along the spine of Brazilian Road 364 in Rondonia State. The smoke pall extends across Bolivia to the Andes Mountains on the horizon. The look distance to the horizon in this scene is approximately 15 degrees of longitude.

Plate 2 is an oblique photograph taken during Space Shuttle Mission STS-26 (August 1988). The Orbiter nadir position at the time of exposure was approximately 8°S 63°W over Northern Rondonia State. The altitude was 164 nautical miles. The view is to the WNW across Rondonia and Acre States of Brazil, Northern Bolivia, and ending in the Peruvian Amazon in the upper right. The Andes Mountains of Peru/Ecuador in the upper right are at approximately 2°S 78°W. The major forest fire plume in the center is approximately halfway between Porto Velho, Rondonia, and Rio Branco, Acre. The area within this view is trapezoidal, measuring some 10° of latitude by 15° of longitude.

Figure 1 was taken during STS-14 (September 1984). This photograph documents more isolated forest biomass burning in Eastern Mato Grosso State, Brazil, further to the southeast of the concentrated burning that has typified the forest clearing along BR-364. The centerpoint of this photograph is 21°S 52°W. The burning in Figure 1 is more typical of isolated biomass burning without large-scale smoke palls that was documented in the 1960s. This type of gradual forest erosion continues around established plantations, ranches, and farms in the eastern and southern Amazonian regions of Goias, Bahia, Mato Grosso, Para, and Maranhao States (Brazil) and the other major Amazonian biome nations (Colombia, Ecuador, Peru, and Bolivia), as contrasted with block-clearing documented in Rondonia and Acre States, and portions of Northern Mato Grosso, Para, and Amazonas States.

TECHNIQUES OF MAPPING SMOKE PALLS FROM EARTH-VIEWING SPACE PHOTOGRAPHY

Interpretation of the selected Earth-viewing photography was based on *a priori* knowledge of forest cover, agricultural areas, transportation networks, etc. This is essential in order to geolocate and measure with confidence the Amazonian smoke pall area. When seasonally present, the smoke palls of the 1980s commonly obscure ground features over much of the 5.67 million square kilometres comprising the "Legal" Amazon of South America (Landau, 1980). Photograph geo-location is assisted by on-orbit camera data recording modules and postflight ephemeris corrections which allow navigation within six km of Orbiter nadir points at the time of photograph exposure. The 520 Amazon smoke scenes were interpreted using standard photointerpretation and image analysis methods (Estes *et al.*, 1983), and all smoke edges and smoke features thereon were geo-located.

During conversion of the analog photography to digital images for computer processing, a set of parameters and an interpretation key (Figure 2) were developed for digital separation of smoke from clouds. The trained classifier was based on interpretation of the texture, tonal homogeneity, and associated morphology of smoke and clouds within each scene. For example, the tonal characteristics of clouds included very bright (saturated) irregularly shaped patches as seen on Plate 1 marked C. The individual smoke plumes appear as whitish/greyish cylindrical or elongated puffy masses. These smoke plumes are characterized by enlarging width at the top and narrow base, giving them a rough shape of an elongated funnel prior to their merging into the overall smoke pall. The arrows of plumes on Plate 1 show this pattern. Color and brightness were used to distinguish the land areas (see Plate 2, areas marked L) from the smoke-covered areas (in Plate 2, S1, S2, S3, S4 refer to smoke areas with a variety of tonal and textural properties, and C represent clouds).

PLATE 1. This west-southwest oblique view of the August-September 1984 Amazonian smoke pall [S] was acquired during Space Shuttle Mission STS-41D (STS-15) from an altitude of 163 nautical miles. The nadir point is at approximately 8.3°S 60.3°W. Distance to the Andes [L] on the horizon is approximately 13° of longitude. The view encompasses western Amazonas, northern Para and Mato Grosso, and all of Rondonia and Acre States as well as the majority of Bolivian and Peruvian Amazon. The individual smoke plumes [P] are visible in the middle foreground, and largely run along the axis of the Polonoroeste Project (Brazilian Road 364 from Cuiaba (Mato Grosso) to Porto Velho (Rondonia)). NASA Photograph S14-40-022. L = Land areas. C = clouds. S = Smoke. P = plumes

PLATE 2. This oblique photograph was taken during Space Shuttle Mission STS-26 (August 1988). The Orbiter nadir position at the time of exposure was approximately 8°S 63°W, over northern Rondonia State. The altitude was 164 nautical miles. The view is to the WNW across Rondonia and Acre States of Brazil, Northern Bolivia, and ending in the Peruvian Amazon in the upper right. The Andes Mountains of Peru/Ecuador in the upper right are at approximately 2°S 78°W. The major forest fire plume S1 in the center is approximately halfway between Porto Velho, Rondonia, and Rio Branco, Acre. The area within this view is trapezoidal, measuring some 10° of latitude by 15° of longitude. NASA Photograph S26-38-014T. L = Land areas. S(1,2,3,4) = smoke pall with various texture classes. C = clouds.

FIG. 1. This September 1984 photograph, also from Space Shuttle Mission 41-D, documents isolated forest burning (S), a heat plume (P), and cumulus (C) formation in an area of large farms and ranches in the more agriculturally developed areas to the south and southeast of Rondonia. This region of relict forests and extensive agricultural development is in the Brazilian Parana River Basin. The photograph centerpoint is at 21°S 52°W. NASA Photograph S14-44-075. S = Smoke pall. C = clouds. L = Land uses depicted

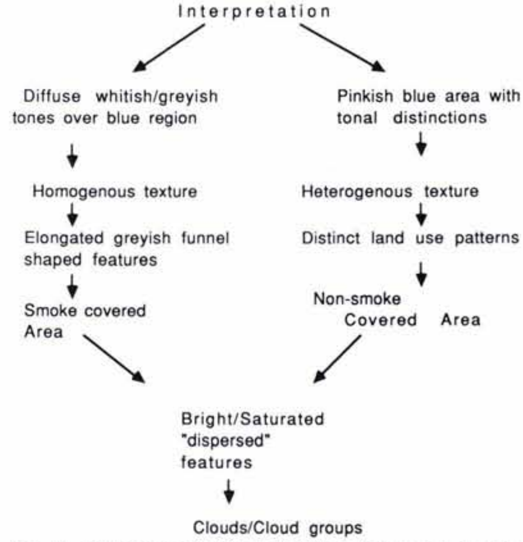


FIG. 2. Dichotomous interpretation key used in this analysis.

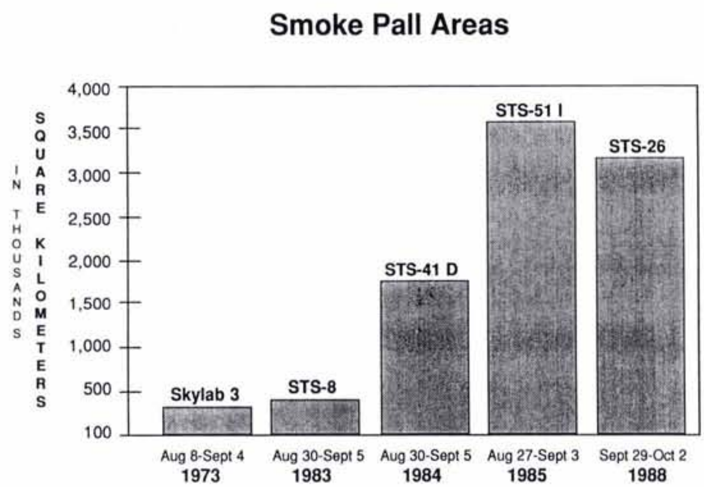


FIG. 3. A bar chart of the area of the major smoke palls photographed over the Amazon from 1973 through 1988. The major increase in the area of such palls came during the period 1984 to 1985. Smoke pall sizes were derived by plotting all mission smoke photography onto common base maps.

Landscape features (which remained relatively constant and were interpretable) such as mountain ridges and drainage patterns for visual matching of non-smoke areas were used to navigate adjacent and overlapping photographs to ensure the matching of boundaries. 1:1,000,000-scale Operational Navigation Charts (ONCs) were used to derive terrain elements and to measure the areal extent of the smoke palls. The Lambert Conformal Conic Projection was deemed appropriate for mapping as this projection does not pose serious distortions for large-area mapping. Scenes with smoke palls generally had sharp boundaries between non-smoke and smoke-covered areas. These interpretations were verified independently by an additional interpreter. Once the delineation on the ONCs was accomplished, the smoke pall edges for each set of photographs for each burn year were transferred to a commercially available base map of the same projection for representation.

RESULTS AND DISCUSSIONS: AREAL DIMENSIONS OF AMAZONIAN SMOKE PALLS

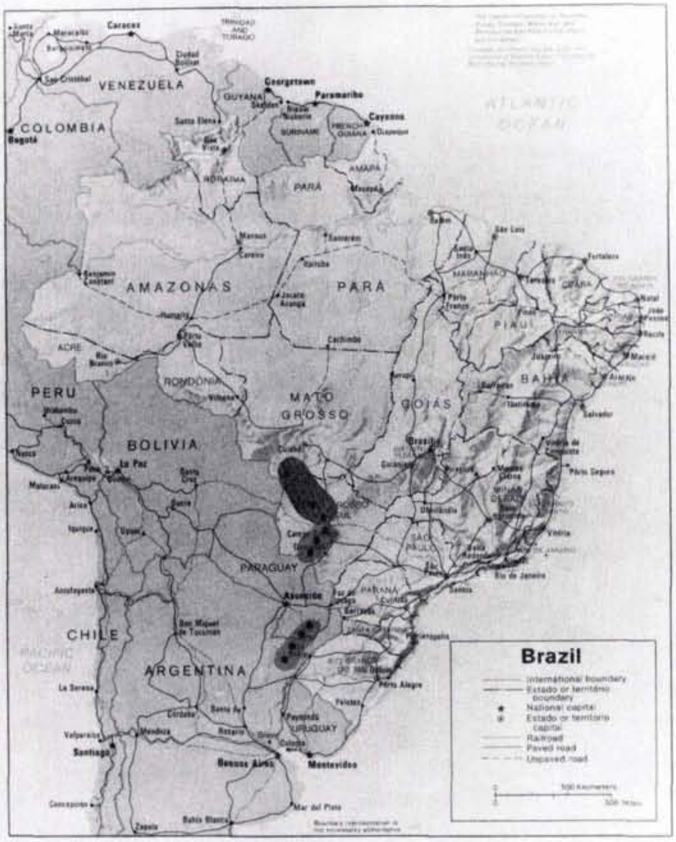
Figure 3 displays our estimations of the areal extent of Amazonian dry season smoke palls documented during Skylab-3 (1973) and four Space Shuttle flights from 1983 (STS-8) through 1988 (STS-26). The sharp increase in the size of Amazonian smoke palls becomes clearly established during 1984 and 1985. Data from the 1973 Skylab-3 mission was used to gain insight into the patterns existing prior to the Space Shuttle missions of the 1980's. These comparisons show a very slight increase in the areas covered by the smoke during the ten-year period, 1973 to 1983. Photography from earlier missions (to 1962) was also reviewed, but no coherent smoke palls were found during the Amazon dry seasons of the 1960s.

MAPPING THE SPATIAL PATTERNS OF THE SMOKE PALLS

In Figures 4, 5, and 6, the spatial locations and areal extent of the smoke palls were mapped from the interpretation of space photographs. These photographs allow mapping of the geographic extent fo tropical smoke palls. This Amazon Basin map series demonstrates changes in the geographic focus of these smoke palls from their first noted appearance in 1973 in southern Brazil, northern Argentina, and Paraguay to the very large palls associated with agro-industrial clearing of forests, large colonization projects, and roadbuilding schemes in the Brazilian "Legal" Amazonian regions during the 1980s. For details on the agro-industrial evolutionary trends underway in the Amazon Basin and similar tropical moist forest biomes, see Barrow (1988), Bunting (1988), Fearnside (1989a, 1989b, 1987, 1986a, 1986b), Hecht (1985, 1983, 1981), John (1988), and Malingreau *et al.* (1989).

Our analysis shows that there is gradual movement northward of smoke pall primary concentrations from 1973 to 1988 (see Figures 3, 4, and 5). In 1973 (Figure 3), the primary burning

CENTRAL SOUTH AMERICA SMOKE AREAS
AUG. - SEPT., 1973

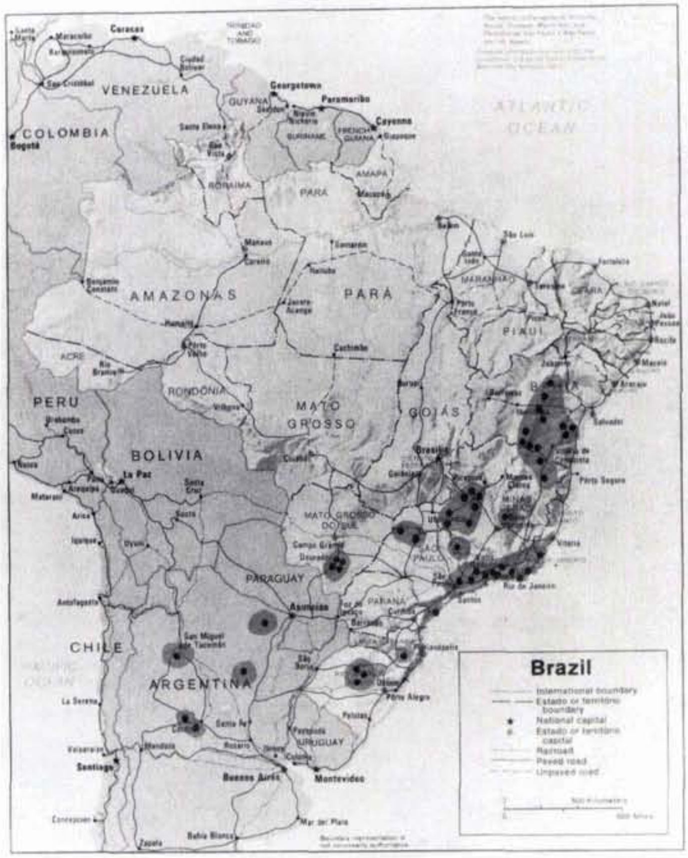


SKYLAB 3 MISSION SPACE PHOTOGRAPH LOCATIONS

• VERTICAL AND LOW OBLIQUE
AUGUST 8, 1973 SEPTEMBER 3 & 4, 1973

FIG. 4. The first major smoke palls noted over the Amazon were photographed during the Skylab-3 mission in August-September, 1973. These palls were most likely associated with agricultural field preparation, crop stubble burning, and some forest conversion. Note that most of the burn sources were concentrated in the developed open woodlands, savannas, and croplands of southern Brazil and northern Argentina.

CENTRAL SOUTH AMERICA SMOKE AREAS
AUG. 30 - SEPT. 5, 1983



STS 8 MISSION SPACE PHOTOGRAPH LOCATIONS

• VERTICAL AND LOW OBLIQUE

FIG. 5. During Space Shuttle Mission 8 (STS-8) in August-September, 1983, a number of disjunct, small-to-medium smoke pall were photographed over most of southern Brazil and northern Argentina. As with the 1973 smoke pall, most of the activity is probably associated with agricultural activity. The smoke palls in Bahia, Minas Gerais, and Sao Paulo States of Brazil, however, may also have been associated with sugarcane conversion to gasohol programs and to industrial fuelwood and backyard metallurgical operations receiveing priority incentives at this time.

was in the large farm/landholder regions of southern Brazil; the cerrados of Goias, Bahia, and Minas Gerais; and the forested areas of the wet-dry northeast areas (particularly, the Rio Sao Francisco region). In the 1980s (Figures 4 and 5), the core of the Amazonian burning shifted to middle and northern Para, northern Mato Grosso, extreme southwest Amazonas, and almost all of Rondonia State. This 1980s north and northwestward shift is related not only to establishment of agricultural areas of the Polonoroeste Project along highway BR-364 and its Acre State extension, but also to agricultural/ranching developments along the Cuiaba-Tapajos and Porto Velho-Manaus highways.

The clearing and agricultural activity along the axis of the original TransAmazon highway complex (Fortaleza-Teresina-Maraba-Porto Velho) during our period of observation has, on the other hand, remained at a moderately low level. It should be realized, however, that cloud cover and lack of nadir-looking overpasses over southcentral Amazonas State have resulted in incomplete observations between the Rios Tocantins and Madeira between 3° and 8°S.

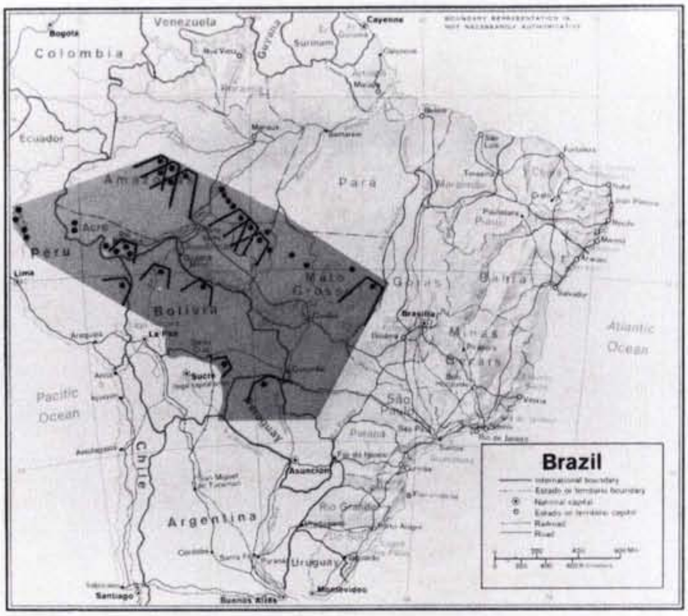
Our other analyses and interpretations concerning the north and northwest shift of forest clearing are, however, supported by other observers (Malingreau and Tucker, 1989; Molion, 1990; Myers, 1988).

CONCLUSION

We have reviewed each of the more than 100,000 photographs comprising the NASA manned spaceflight database of Earth photography in order to determine the frequency and areal extent of Amazonian smoke palls over the past 28 years. Our analysis and mapping of Amazonian smoke palls shows that there is a tenfold increase in smoke pall area since 1973. No major palls of any nature were seen during the 1960s dry seasons. In 1973 a 300,000 sq km dry-season smoke pall of a discontinuous nature was present. By 1985 and 1988, dry-season smoke palls increased to become contiguous units of approximately 3,000,000 sq km.

The interplay of forest clearing shifts, smoke pall areal extent, topographic influences, and the seasonal persistence and long-term opacity of these smoke palls with regional meteorological phenomena cannot be determined by using photography from short-duration Space Shuttle missions alone.

SW AMAZON BASIN SMOKE PALL
SEPT. 29 - OCT. 2, 1988



STS 26 MISSION SPACE PHOTOGRAPH LOCATIONS

HIGH OBLIQUE • **VERTICAL AND LOW OBLIQUE**

FIG. 6. By 1988, during the first reflight of the Space Shuttle (STS-26), the loci of burning in the Amazon had migrated north and west into large agricultural colonization and forest conversion areas of the western Amazon. Most of the activity was along the long axis of Brazilian Road 364 from Cuiaba, Mato Grosso, to Porto Velho, Rondonia, and Rio Branco, Acre, on the border with Peru and Bolivia.

We feel it useful to note that the Amazon dry-season smoke palls have gradually moved from the southern part of the basin to the north and northwest following the opening of the western Amazon road network. By 1985-88, these dry-season smoke palls had expanded to a continental scale, almost covering the entire north and west portions of the Brazilian-Bolivian-Peruvian Amazon Basin. Coverage over Amazonian portions of Ecuador, Colombia, Venezuela, and some portions of Brazil during these periods did not allow us to define with confidence whether smoke palls were present over the tributaries of the Amazon (Solimoes) north 0° to 2°S latitude, or east of approximately 55°W latitude.

In our view, this study also shows that an interactive melding of manned and unmanned Earth monitoring programs of global tropical environmental change, including assessment of tropical moist forest geographic changes, will be possible by integrating appropriate sensor suites, sensor development programs, and availability of Earth observations data and opportunities from both the forthcoming unmanned polar-orbiting Earth Observations System (EOS) and the 28.5° orbital inclination of the forthcoming manned platform, Space Station Freedom.

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REFERENCES

Albini, F. A., 1984. Wildland fires. *American Scientist*, 72: 590–597.

Alho, C. J. R., H. C. Goncalves, T.E. Lacher. 1988. Environmental degradation in the Pantanal ecosystem, *Bioscience*, 38(3): 164–171.

Amsbury, D., and J. Bremer, 1989. Medium-format Cameras Used by NASA Astronauts. *Geocarto Intntl*, 4(3): 59–63.

Andrasko, K., D. R. Ahuja, and D. A. Tirpak, 1990. Policy options for managing biomass burning to mitigate global climate change. *Abstr., Chapman Conf on Global Biomass Burning: Atmospheric, Climatic and Biospheric Implications*. 19-23 Mar 1990. Williamsburg, Virginia. No page numbers.

Aubreville, A. M. A., 1947. The disappearance of the tropical forests of Africa. *Unasylva*, 1(1): 5–11.

Barrow, C. J., 1988. The impact of hydroelectric development on the Amazonian environment: With particular reference to the Tucurui Project. *J Biogeography*, 15: 67–78.

Booth, W., 1989. Monitoring the fate of the forests from space. *Science*, 243: 1428–1429.

Botkin, D., M. Caswell, J. Estes, and A. Orio. 1989. *Changing The Global Environment-Perspectives on Human Involvement*. Academic Press, Inc., New York. 459 p.

Bruenig, E. F., 1987. The forest ecosystem: Tropical and boreal. *Ambio*, 16(2–3): 68–79.

Bunting, A. H., 1988. The humid tropics and the nature of development. *J Biogeography*, 15: 5–10.

Clark, W. C., 1989. Managing Planet Earth. *Sci Amer*, 261(3): 46–54.

Clarke, W. C., 1976. Maintenance of agriculture and human habitats within the tropical forest ecosystem. *Human Ecology*, 4(3): 247–259.

Connors, V. S., H. G. Reichle, K. D. Sullivan, and M. R. Helfert, 1986. Global observations of biomass burning from space. *Proc, American Geophysical Union Ann Mtg*, 8-12 Dec 1986, San Francisco, California.

Davis, B. E., 1986. Lava flow analysis from digitized Shuttle photography. *Proc 1986 ASPRS-ACSM Conv*, Anchorage, Alaska, pp. 121–131.

Dickinson, R. E., and A. Henderson-Sellers, 1988. Modeling tropical deforestation: A study of GCM land-surface parameterizations. *Quart J Roy Met Soc*, 114: 439–462.

Edelson, B. I., 1986. "Spiral Eddies" and "Strait of Gibraltar," in *Oceanography from Space*, NASA Hqs, Washington, D.C., n.p.

Eden, M. J., and A. Andrade, 1988. Colonos, agriculture and adaptation in the Colombian Amazon. *J Biogeography*, 15: 70–76.

El-Baz, F., 1986. Space photographs of drought in Africa, (abstr.), *Lunar Planetary Science*, 17: 200–201.

Estes, J., E. Hajic, and L. Tinney, 1983. Fundamentals of Image Analysis: Analysis of Visible and Thermal Infrared data. *Manual of Remote Sensing*. Vol 1 (R. Colwell ed.) American Society for Photogrammetry and Remote Sensing, Fall Church, Va., pp. 987–1124.

Fearnside, P. M. 1986a. Settlement in Rondonia and the token role of science and technology in Brazil's Amazonian development planning. *Interciencia*, 11(5): 229–236.

———, 1986b. Spatial concentration of deforestation in the Brazilian Amazon, *Ambio*, 15(2): 74–81.

———, 1987. Deforestation and international economic development projects in Brazilian Amazonia. *Conservation Biology*, 1: 214–221.

———, 1989a. The charcoal of Carajas: A threat to the forests of Brazil's Eastern Amazon region. *Ambio*, 18(2): 141–143.

———, 1989b. Brazil's Balbina Dam: Environment versus the legacy of the pharaohs in Amazonia. *Environmental Management*, 13(4): 401–423.

Gallegos, S. C., S. C. Nerem, and M. R. Helfert, 1984. Vegetative responses from Great Barrier Reef anomaly detected by Space Shuttle photography and NOAA Polar Orbiter AVHRR reflectance measurements. *Symp, Remote Sensing & GIS to Renewable Resources, Proc, Ann Mtg, ASP-ASCM*, San Antonio, Texas, Sept. 1984.

Greer, J. D., 1988. Space Shuttle handheld photography: A unique archive of imagery. *Field Enginrg Notes* (USDA), 20: 23–32.

Hecht, S. B., 1981. Deforestation in the Amazon Basin: Practice, theory, and soil resource effects. *Studies in Third World Societies*, 13: 61–108.

———, 1983. Cattle ranching in the Eastern Amazon: Environmental and social implications. *The Dilemna of Amazonian Development* (E.F. Moran, ed.), Westview Pr, Boulder, Colorado pp. 155–188.

———, 1985. Environment, development and politics: Capital accumulation and the livestock sector in Eastern Amazonia. *World Development*, 13(6): 663–684.

Helfert, M. R., 1983-90. Global Tropical Environmental Changes. Unpublished preflight lectures & briefings for astronauts of Space Shuttle Missions STS-09 through STS-41, NASA-JSC, Houston, Tx.

Helfert, M. R., 1989. NASA Human-directed observations of Earth from space. *Geocarto Intntl*, 4(1): 3–7.

Helfert, M. R., *et al.* (12). 1990. Earth Observations during Space Shuttle Mission STS-30, May 4-8, 1989. *Geocarto Intntl*, 5(1): 53–72.

Helfert, M. R., and R. K. Holz. 1985. Multi-source verification of the desiccation of Lake Chad, Africa. *Adv in Space Research*, 5(6): 379–384.

Helfert, M. R., and K. P. Lulla, 1989. Monitoring tropical environments with Space Shuttle photography. *Geocarto Intntl*, (4(1): 55–68.

Jacobs, M., 1988. *The Tropical Rain Forest - A First Encounter*. Springer Verlag, New York. 295 p.

Janzen, D. H., 1973. Tropical agroecosystems: Habitats misunderstood by the temperate zones, mismanaged by the tropics. *Science*, 182: 1212–19.

Johns, A. D., 1985. Selective logging and wildlife conservation in tropical rain-forest: Problems and recommendations. *Biological Conservation*, 31: 355–375.

———, 1988. Economic development and wildlife conservation in Brazilian Amazon. *Ambio*, 17(5): 302–306.

Johns, R. J., 1986. The instability of the tropical ecosystem in New Guinea. *Blumea*, 31: 341–371.

Kapos, V., 1989. Effects of isolation on the water status of forest patches in the Brazilian Amazon. *J Tropical Ecology*, 5: 173–185.

Kellman, M., 1988. Disturbance X Habitat Interactions: Fire regimes and the savanna/forest balance in the Neotropics. *Canadian Geographer*, 32(1): 81–83.

Landau, G. D., 1980. The Treaty for Amazonian Cooperation: A bold new instrument for development. *Georgia J of Intntl & Comparative Law*, 10(3): 463–489.

Liu, K-B., and P. A. Colinvaux, 1988. A 5200-year history of Amazon rain forest. *J Biogeography*, 15: 231–248.

Lovejoy, T. E., *et al.* (5). 1984. Ecosystem decay of Amazon forest remnants. *Extinctions* M. H. Nitecki, (ed.). Univ of Chicago Press, Chicago, pp. 295–325.

Lulla, K., 1981. Remote sensing in ecology. *Can J Rem Sensing*, 7(2): 97–107.

———, 1983. The Landsat satellites and selected aspects of physical geography. *Prog Phys Geography*, 7(1): 1–45.

Lulla, K., *et al.* (9), 1989. Earth Observations during Space Shuttle Flight STS-29: Discovery's Voyage to Earth, 13-18 March 1989. *Geocarto Intntl*, 4(4): 67–80.

Lulla, K., and M. Helfert, 1989a. Space Shuttle Earth Observations. *Geocarto Intntl*, 4(2): 59–62.

———, 1989b. Camcorders in Space. *Geocarto Intntl*, 4(4): 45–49.

Malingreau, J. P., G. Stephens, and L. Fellows, 1985. Remote sensing of forest fires: Kalimantan and North Borneo in 1982-83, *Ambio*, 6: 314–321.

Malingreau, J., and C. J. Tucker, 1988. Large-scale deforestation in the southeastern Amazon basin of Brazil. *Ambio*, 17(1): 49–55.

Malingreau, J. P., C. J. Tucker, and N. LaPorte, 1989. AVHRR for monitoring global tropical deforestation. *Intntl J Remote Sensing*, 10(4&5): 855–867.

Mills, K., 1988. The clearing of the Illawara rainforests: Problems in reconstructing pre-European vegetation patterns. *Australian Geographer*, 19(2): 230–240.

Molion, L. C. B., 1990. Amazonia, Burning and Global Climate. *Abstr., Chapman Conf on Global Biomass Burning: Atmospheric, Climatilc and Biospheric Implications*, 19-23 March 1990, Williamsburg, Virginia. No page numbers.

Morgan, C., 1987. A contemporary mass extinction: Deforestation of tropical rain forests and faunal effects. *Palaios*, 2: 165–171.

Muehlberger, W. R., and M. B. Gordon, 1987. Observations on the complexity of the East Anatolian Fault, Turkey. *J Structural Geol*, 9: 899–903.

Myers, N., 1982. Depletion of tropical moist forests: A comparative review of rates and causes in the three main regions. *Acta Amazonica*, 12(4): 745–758.

———, 1985. Tropical deforestation and species extinctions: The latest news. *Futures*, 17: 451–463.

———, 1986. Environmental reprecussions of deforestation in the Himalayas. *J World Forest Resouce Mgmt*, 2: 63–72.

———, 1988. Tropical deforestation and Climate change. *Environmental Conservation*, 15(4): 293–298.

Pereira, M. C., and A. W. Setzer, 1986. Detection of biomass burning and smoke plumes in the Amazon region through AVHRR imagery. *Proc, Latin American Symposium on Remote Sensing (4th Brazilian Remote Sensing Symposium)*, Sao Jose de Campos (Brasil), 1: 701–709.

Redclift, M., 1989. The environmental consequences of Latin America's agricultural development: Some thoughts on the Brundtland Commission Report. *World Development*, 17(3): 365–377.

Reidel, C., 1988. Natural resources and the environment: The challenge of economic and social development. Population and Environment: A *J Interdisciplinary Studies*, 10(1): 48–58.

Roberts, L., 1988. Hard choices ahead on biodiversity. *Science*, 241: 1759–1761.

Rogers, F., B. Zielinslka, R. Tanner, J. Hudson, and J. Watson, 1990. Potential effects of biomass smoke on cloud albedo. *Abstr, Chapman of Conf on Global Biomass Burning: Atmospheric, Climatic and Biospheric Implications*. 19-23 March 1990, Williamsburg, Virginia. No page numbers.

Russell, W. M. S., 1988. Population, swidden farming, and the tropical environment. *Population & Environment*, 10(2): 77–94.

Sanford, R. I., *et al.* (4). 1985. Amazon rainforest fires. *Science*, 227: 53–55.

Sayer, J. A., and S. Stuart, 1988. Biological deversity and tropical forests. *Environmental Conservation*, 15(3): 193–194.

Smith, N. J. H., 1985. The impact of cultural and ecological change on Amazonian fisheries. *Biological Conservation*, 32: 355–373.

Sternberg, H. O'R., 1968. Man & environmental change in South America, *Biogeography & Ecology in South America*, (E. J. Fittkau *et al.*, eds.) Junk Publ, The Hague, pp. 413–445.

Stott, P. A., 1984. The savanna forest of mainland southeast Asia: An ecological survey. *Progr in Physical Geography*, 8: 315–335.

———, 1988. The forest as pheonix: Towards a biogeography of fire in mainland South East Asia. *Geographical J*, 154(3): 337–350.

Uhl, C., and I. C. G. Vieira, 1989. Ecological impacts of selective logging in the Brazilian Amazon: A case study from the Paragominas region of the State of Para. *Biotropica*, 21(2): 98–106.

United Nations, 1987. *Our Common Future*. (World Commission on Environment and Development). Oxford Univ. Press, Oxford.

Whitehead, V. S., *et al.* (6), 1989. Earth Observations during Space Shuttle Flight STS-27: A high latitude observations opportunity, 2-6 December 1988. *Geocarto Intntl*, 4(3): 63–76.

Whitehead, V. S., *et al.* (12), 1990. Earth Observations during Space Shuttle Flight STS-28, August, 1989. *Geocarto Intntl*, 4(4): (In press).

Wilkie, D. S., and J. T. Finn, 1990. Slash-burn cultivation and mammal abundance in the Ituri Forest, Zaire. *BioTropica*, 22(1): 90–99.

Wilson, E. O., 1989. Threats to biodiversity. *Sci Amer*, 261(3): 108–116.

Wood, C. A., M. R. Helfert, K. P. Lulla, and R. O. Covey, 1989. Earth Observations during Space Shuttle Flight STS-26: Discovery's Mission to Earth, September 29-October 3, 1988. *Geocarto Intntl*, 4(2): 55–64.

Woods, P., 1989. Effects of logging, drought, and fire on structure and composition of tropical forests in Sabah, Malaysia. *BioTropica*, 21(4): 290–298.

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