Fire penetration in standing Amazon forests

BRUCE WALKER NELSON[1]
MARILANE NASCIMENTO IRMÃO[1]

[1]INPA--Instituto Nacional de Pesquisas da Amazônia
Caixa Postal 478, 69.011-970 Manaus, AM, Brazil
bnelson@internext.com.br

Abstract. Wall-to-wall Landsat images of the Brazilian Amazon from INPE, combined with interviews of local peoples and field checking of vegetation form and composition, are employed to show that infrequent fire has been an important abiotic determinant of forest type – even in central locations far from the climatic transition to savanna and open woodland (cerrado and cerradão). Evergreen Amazon forest types affected by fire over the last century include: "igapó" forest on seasonally inundated sandy soils; white-sand or "campinarana" forest on seasonally waterlogged and well-drained sandy soils; montane forest on well-drained rocky soils; and bamboo-dominated forest on low-permeability 2:1 clay soils. Vine forests may also be fire affected. Extensive fire scars are found even where average annual rainfall is 3600 mm/yr.

Keywords: Landsat, El Niño, bamboo, liana, white-sand, bracken fern, flooded forest.

1 Introduction

Prior to the conflagrations said to have consumed as much as 9,200 km^2 of forest in the state of Roraima in early 1998 (*A Crítica*, Manaus, 7 April 1998, p. C-3), few inhabitants of Amazonia would have given credit to the idea that mature standing Amazon forests, undisturbed by selective logging, are susceptible to fire penetration. In fact, previous studies of plant-available-water in deep soil profiles on the eastern fringe of the Amazon forest (Nepstad et al., 1995) had already shown that two consecutive drought years will cause leaf drop and consequent drying to the flammability threshold by fine fuels on the floor of mature undisturbed forest, while a normal dry season is sufficient to allow ground fires to penetrate secondary forests of that region. These experimental data by other workers imply that infrequent fires have affected some Amazonian forest types in the recent past. The hypothesis is here borne out by the detection of extensive, spectrally distinct vegetation types occupying recent fire scars throughout the Amazon basin. Evidence for extensive fire over the last century in standing forest is reported here for one type of white-sand forest of the upper Rio Negro, inundated forests of the middle Rio Negro and montane forests of the Serra Parima on the upper Orinoco. Additionally, two very extensive vegetation types are susceptible to fire and may be fire derived: 180,000 km^2 of bamboo-dominated forests in the southwest Amazon and liana forests covering 310,000 km^2, predominantly in southern and eastern Amazonia. The cumulative effects of these fires, possibly aggravated by three or more mega-droughts during the last 1500 years (Meggers, 1994), have had a profound effect on Amazonian phytogeography.

Only fire scars far from dry forest (cerradão) are discussed here. Babassu-palm dominated forests covering 6,700 km^2 between the Itacaiunas and Xingu rivers, detected in satellite images and in over-flights, are a regrowth type resulting from both past indigenous cutting and burning practices and fires in standing forest. They are not discussed further in this paper.

2 Methods

Features inferred to be fire scars were identified in images acquired between 1987 and 1992 by the orbital sensor Landsat Thematic Mapper (TM). These were examined for the entire forested portion of the Brazilian Amazon: 136 scenes or about 3.9 million km^2. The images, prepared by the Brazilian National Space Institute (INPE), are hard copy 1:250,000 scale, false-color composites of TM bands 3, 4 and 5, which are optimally located in the electromagnetic spectrum for detection of young secondary forest, primary rain forest, non-photosynthetic vegetation (including bare branches of trees deleafed by a ground fire) and black charred grassland. Secondary vegetation colonizing areas where fire penetrated standing forest, as opposed to regrowth in fallow swiddens, is recognized when boundaries form at natural fire breaks such as rivers, streams or damp gallery forests. Rounded fire scar boundaries unassociated with fire breaks also occur, given the low wind speeds of Amazonia, when a concentrically expanding fire is extinguished by a rain event (Nelson, 1994). Regrowth forests in these fire scars form much larger areas and are spectrally more homogeneous than the regrowth typically found in a collection of abandoned swiddens or in a large blowdown. Fire scars can be far from suitable Amerindian or peasant village sites, as they may be set by lightning, hunters or groups trekking long distances. Nonetheless, when combustibility is constant across a landscape, the greater availability of fire near agricultural swiddens makes fire penetration into standing forest much more frequent and extensive, as was the case for the recent fires in Roraima.

A small subset of the inferred fire scars was verified in low altitude aerial over-flights to determine vegetation structure and composition. Most vegetation types were also visited on the ground to obtain a more accurate characterization. Interviews with local people were conducted regarding past drought years and occurrence of fire in standing forests. Aerial verification was undertaken by the following means. Low altitude (300-1000 meter) flights were made with a single engine plane with the door removed. The observer was stationed on the side opposite the sun. A color video (VHS-C) was made viewing obliquely downward. Periodic photographs were made with 35 mm color film using a 28 mm wide-angle lens. The low spatial resolution video permitted identification of the time and position of each photograph along the flight line, while the wide-angle oblique photos provided good detail of the vegetation canopy in the foreground plus a broad view of the landscape in the background so that rivers, fields, and other features identified on the video would appear in the photos and the exact position of the photo on a digital Landsat image could be determined. Stereo vertical air photos made with black and white infrared film were located in government archives for some of the sites, the scales ranging from 1:40,000 to 1:90,000.

Digital TM images were purchased for the key areas selected for field verification. In some cases a time series of images was obtained that showed before and after effects of the most recent fires. After verification of test sites, additional fire scars were inferred from spectral and spatial patterns over much larger areas. These were either mapped or illustrated. Illustrations are from original satellite images or from 35 mm slide copies of false-color composite prints (original scale of 1:250,000) on file at INPE. Mapping was accomplished by projecting these same color slides onto a cartographic base at the scale of 1:1,000,000.

In addition to the inferred fire scars, field visits and interviews with local people were conducted to examine propensity of fire penetration into two geographically extensive "open" forest types: bamboo forests and vine forests. The bamboo forests were also mapped using 22 Landsat scenes. The phenomenon of synchronous bamboo dieback -- which increases their susceptibility to fire -- was also examined in a time series of Landsat images from 1975 to 1994.

Soil charcoal was not collected or carbon-dated nor were detailed descriptions of soil water, soil texture or vegetation profiles undertaken. Further systematic interviews of Amerindians, former rubber tappers and subsistence farmers regarding past fire penetration and fire setting practices are also desirable. The results presented here should be considered preliminary. They are reported in the hope of stimulating others to conduct more detailed field studies.

3 Results and Discussion

3.1 Fire scars in white-sand vegetation of the Uaupés, Içana and Tiquié basins

Distinct features inferred to be fire scars were found in a matrix of tall "campinarana" forest on flat interfluvial white sands in Landsat scenes 004/59 and 004/60 (**Figures 1 & 2**), which receive about 3,600 mm of rain in a normal year. Coveriing 5,000 km^2 in these two images, the scars are concentrated on the interfluves of the Içana, Aiari and Uaupés Rivers and along the lower Tiquié River. All the inferred fire scars have a spectral pattern similar to secondary forest. Many of these features abut natural fire breaks (**Figure 1A**). Others have very round, sharply defined edges indicating an abrupt transition to the surrounding matrix of tall white-sand forest, which is darker on the Landsat image. Isolated round scars imply concentric spread of different small fires extinguished by rain events. Well documented forest fires elsewhere in the Amazon are known to expand in a more or less circular fashion as prevailing wind speed is low (Nelson, 1994). In a comparison of two images from different years (Dec 1989 and Dec 1993) a portion of one inferred fire scar, located between the Uaupés and Aiari Rivers, changed from a spectral pattern of healthy secondary forest to a pattern typical of leafless vegetation. Within the boundaries of the old fire scar, the line between leafy and leafless vegetation was sharp, rounded and unrelated to topography (white box in **Figure 1**), suggesting that part of the area was deleafed by a ground fire expanding concentrically until extinguished by a rain event.

FIG. 1

FIG. 2

FIG. 1

In one portion of the area mapped in **Figure 2**, covered by stereo vertical air photos on file at CPRM in Manaus, the borders of second growth in fire scars remained unchanged from 1970 to 1993. Thus it is unclear whether the scars reburn in an isolated fashion and expand slightly after each burn, or whether they are the result of extensive conflagrations in one or more very dry years.

FIG. 2

The sandy interfluves of this region are largely uninhabited and uncultivated, but the clay soils which slope down to all local rivers and larger streams are clothed with a tall forest heavily exploited for swidden agriculture. The inferred fire scars are large and continuous on the uplands closest to the swiddens of the Aiari River, which are the probable fire source in this case. Further inland the scars are sparse and separate from one another. The more interior interfluves are traversed by numerous trails, frequently traveled for hunting and for material and cultural exchange between widely dispersed, linguistically exogamous indigenous groups.

The inferred fire scars of the upper Uaupés and Içana basins were seen in over-flight to include some open woody vegetation, but are mostly a low closed-canopy white sand forest with very even height and bright green leaves. A field visit on the upper Içana River showed the floristic composition to be typical of white-sand areas and lacking early pioneer secondary forest species known for clay soils. The canopy height was very even, averaging just 6-8 meters.

Tall, closed-canopy forest on white sand ("campinarana" forest) accumulates a thick fluffy leaf litter, but maintains a high relative humidity in the understory. This is the matrix forest which must have burned to form the fire scars described above. Despite the high load of fine fuel, this tall vegetation type could not be burned by Uhl et al. (1988) even after 41 days of rainfall exclusion using a small tarp. However, a standing charred trunk of the rot-resistant Massaranduba tree (*Manilkara* sp.) was found by a chicle tapper in a tall closed-canopy forest between the Negro and Branco rivers about 60 years after the 1926 fires reported there by Marchesi (1975), indicating that tall closed canopy forests probably did burn in that El Niño year south of the equator. Open-canopy woody vegetation on white sand also accumulates a thick loose layer of leaf litter which becomes dry and flammable. Uhl et al. (1988) were able to burn low open-canopy "bana" vegetation on white sand in the upper Rio Negro region after just two rainless days.

3.2 Seasonally inundated forest of the Rio Negro ("igapó")

Tall seasonally inundated forests on sandy alluvium along the middle and upper Rio Negro is burned intentionally at low water by local people. The fires are limited to tens of hectares in a normal dry season and can be detected in over-flight and in a time sequence of Landsat images (**Figure 3**). Several recently burned areas of this size were observed in over-flight in the normal dry season of 1995. All trees were dead and very few remained standing. The bleached trunks were lying over one another in a random fashion, very different from the oriented tree falls common in microburst blowdowns (Nelson, 1994). FIG. 3

Much more extensive fires on the alluvial islands of the middle Rio Negro were those of the 1925/26 El Niño year, witnessed and poetically described by Marchesi (1975): "Thunder and lightning appeared every day without rain. Then the great forest fires began. Flames crossed from one side of the river to the other.... Dense smoke covered the entire region, eclipsing the solar disk. It was night for us too on the upper Rio Negro where the fire had not yet arrived. We asked ourselves if it weren't the end of the world. Finally, in early April after 100 days of drought unlike any known before, a tempest struck."

Mono-dominant stands of the spiny Jauari Palm, *Astrocaryum jauary*, are visible today in over-flight of the large alluvial islands near to Barcelos and may be a result of those 1926 fires. The same species dominates a small floodplain across the Rio Negro from Manaus, where the understory burned in the low water season of 1990. Many palm species with thick trunks are resistant to fire damage due to the absence of a peripheral cambium and the presence of a single meristem tucked safely among thermally insulating leaf bases at the stipe apex. Extensive stands of Buriti Palm, *Mauritia flexuosa*, also a fire resistant species, occupy interfluvial, periodically waterlogged sandy savannas a few tens of kilometers inland from the south bank of the Rio Negro above Barcelos. According to Dr. M. Goulding, this latter vegetation is burned by local people during those infrequent years when it dries out completely. The fires are set for three reasons: (1) to facilitate locating turtle nests for their eggs; (2) to maintain open sandy habitat favorable for turtle nesting and (3) recreational burning. Inland from the town of Barcelos, on the middle Rio Negro, the terra firme landscape includes poorly drained interfluves dominated by Patauá Palm, *Oenocarpus bataua*. According to long-time Barcelos resident Francisco Demar, the extensive Patauá-dominated interfluvial forests, which are tall with a closed canopy, will also burn in exceptionally dry years.

Uhl et al. (1988) were able to set a controlled fire in low stature dense forest on black water alluvial floodplain in the upper Rio Negro after just nine rainless days. The low wicking rate of sand underlying black water flood forests probably allows the leaf litter to dry out more than is the case over the clay and silt rich alluvium of the Amazon River floodplain forest. An eye-witness to a fire in black water floodplain forest in the 1950's near to Barcelos described a weak ground fire which primed the landscape for a much more intense burn just two weeks later. The first fire killed some understory and deleafed some large trees, but this created dead fuel which dried quickly under the new canopy openings, setting the stage for a major fire later the same month. Simple rain exclusion experiments under a small tarp cannot detect or measure this important double burn phenomenon, which must also occur in other forest types.

3.3 Fern savannas of the Serra Parima

On shallow rocky soils of the Serra Parima drainage divide, between 2° 30' and 3° 00' N, where rainfall is 1750 mm/year, approximately 600 km^2 of montane forests have been converted to savanna by Yanoama Indians (**Figure 4**) Low altitude over-flight and ground verification showed these savannas to be dominated by the Southern Bracken Fern, *Pteridium aequilinum*. Fire-adapted woody species were absent. Several patches of very recently burned fern savanna, hundreds of hectares in size, were observed in the vicinity of a Yanoama trail. Occasional tall dead witness trees seen near the edges of remnant montane forest indicated that the fern savannas of the Parima have recently expanded at some points. FIG. 4

The leaves of *Pteridium aequilinum* are highly divided and wiry. They do not fall to the ground when they die, but rather dry out, creating a highly flammable fine fuel. Suspended dry leaves give bracken fern savannas a spectral pattern typical of non-photosynthetic vegetation in Landsat TM images. Underground rhizomes ensure that the species survives repeated fires which kill montane and pioneer trees.

The geographer William Smole (1976) dedicated a full chapter of his book to Yanoama landscape modification in this same region. He noted that the bracken ferns reach "heights of eight feet or more [and] are so thick that they must be cut or beaten down with poles before a barefoot Yanoama can walk through them. The Barafari [Yanoama] are accustomed to burning fern savannas ... and charred remnants of [standing] trees are not unusual." Otto Huber (Huber et al., 1984: 124-130), who spent five years studying the savannas of the Venezuelan Território Federal Amazonas, prefers to call the fern savannas of the Serra Parima "secondary non-forest vegetation", since the ones he observed were clearly derived from the burning of forest and were mixed to different degrees with woody elements characteristic of secondary regrowth (but not fire-adapted woody savanna elements). He notes that, once established, the secondary vegetation dominated by bracken fern is flammable and probably burned deliberately by the Yanoama to clear trails (p. 130). Huber also noted that standing uncut forest of the Serra Parima would burn in very dry years, giving rise to the fern-dominated secondary vegetation. Smole (1976) makes an interesting reference to sweeping fires which converted a forested ridge to fern savanna circa 1930. This imprecise data might, in fact, be the 1926 El Niño.

The absence of woody elements adapted to fire in the fern savannas visited and overflown indicates that the extensive non-forest landscape is relatively young. Together with the observations above, it is clear they were not created and maintained by lightning, but rather by some newer source of fire, namely nomadic Yanoama. This is in contrast, for example, to the much older Roraima savannas on the low lying Boa Vista Formation, or the savanna enclaves near to Humaitá where fire resistant woody species have established themselves.

3.4 Open or transition forest with climbing bamboo

In the southwest Amazon, basally erect and distally climbing spiny bamboos, *Guadua sarcocarpa* and *Guadua weberbaueri*, occupy and perhaps create large gaps extending over 20-50% of the forest as viewed in low over-flight. These bamboo-dominated forests on terra firme are spectrally distinct in Landsat images and have recently been shown to cover 180,000 km^2 (R. Kalliola, unpublished; Nelson, 1994), half of which is in Brazil and half in Peru (**Figure 5**). Bamboo forests are often associated with 2:1 clay soils of low permeability, found in valleys or on gently rolling regularly dissected topography. The northeasternmost bamboo-dominated forests terminate at higher landscape units with low drainage density and flatter surface (**Figure 6A**). These features indicate a well drained sandy or plinthitic soil with lower rates of surface runoff and superficial erosion than the corrugated topography on clay vertisols and cambisols of central and western Acre, where bamboo forests predominate. Within the heart of the bamboo-forest range are many boundaries between forests with and without bamboo that are not related to topography (**Figure 6B**). Such boundaries are often rounded, resembling the borders of a large fire scar extinguished by a rain event, though they rarely coincide with natural fire breaks. Smaller streams in the region dry out completely in the dry season, and *G. sarcocarpa* colonizes minor stream borders right down to the narrow channels, so that fire breaks would be ineffective.

FIG. 5

FIG. 6

There are three means by which dense *Guadua sarcocarpa* stands can increase the flammability of terra firme forests in the southwest Amazon: burning of living stands, burning of dead stands and burning of the secondary forest which occupies post-mortality sites. The leaves of this bamboo are papyraceous in texture, highly flammable and abundant on the forest floor under dense living stands. Agricultural fires were observed to have escaped into living *G. sarcocarpa* stands, killing large trees. Such fires usually stop less than 200 m from the forest edge, since the bamboo stands which sustain them are patchy. Though tall forests on deep clay soils of the Amazon are protected from wilting and leaf drop during a single prolonged dry season by their ability to tap water reserves as deep as eight meters (Nepstad et al., 1995), this does not appear to be the case with *G. scarcocarpa*, at least not in the first years of its life. A two meter tall three year old planted specimen studied in Manaus shows strong leaf curling after just three days without rain. Similar wilting is reported by local people in the ten year old *G. sarcocarpa* stands near the town of Sena Madureira in Acre. Thus, for this species, plant-available-water appears to be limited to the upper few decimeters of the soil and droughts of short duration should take living bamboo stands across the flammability threshold.

Culms of *G. sarcocarpa* have dense wood in a thin wall surrounding the hollow internode, features which facilitate a high intensity burn if the internodes are not filled with water. These culms are very flammable when a drought year occurs during a synchronous post-flowering/fruiting bamboo dieback event, a natural phenomenon which is part of the species' reproductive strategy. Synchronous massive dieback events for spiny arboresecent *Guadua* are documented as repeating after 16 years in Manu Park in Peru (Glenn Shepherd, pers. comm., 1997) and every 30 years in *G. sarcocarpa* stands along the Purus river between the towns of Manuel Urbano and Sena Madureira in the Brazilian state of Acre (based on interviews with local residents). Machiguenga Indians studied by anthropologist G. Shepherd, claim that a large fire killing many forest animals took place in a bamboo patch after a synchronous mortality event in 1980 in the Manu River Basin of Peru. A similar large conflagration raged for at least one month during the synchronous mortality year of 1988/1989 in the Seringal Oriental, about 15 km inland from the shore of the Purus river near the town of Manuel Urbano in Brazil.

Spiny Guaduas do not reoccupy a site very quickly after their self-inflicted disturbance of synchronous dieback. The *G. sarcocarpa* stands near Sena Madureira, Acre, are only now forming dense colonies, ten years after their last synchronous mortality. In the interim, the bamboo forest gaps have been occupied by a natural secondary vegetation of lianas, "taquari" grass and fast growing pioneer trees. Secondary forests studied at the eastern limit of Amazonia are know to cross the flammability threshold after just a few days without rain in a normal dry season (Nepstad, 1995). Central Amazonian secondary forests also suffered fire penetration during the dry El Niño months of July to October of 1997.

A time series of Landsat images examined from 1975 to 1994 shows that large patches of bamboo forest die synchronously and that these patches have sharp rounded borders with the normal forest. This can be explained by one of two mechanisms: (1) occupation of a large forest fire site or (2) vegetative expansion via rhizomes into the normal forest, without fire. Even more interesting is the fact that a very large area will be continuously covered with homogeneous bamboo-dominated forest in one year and then show only a part of this area dying in a later year. The newly formed borders between dead and living bamboo areas are again distinctly rounded and abrupt between the two internally synchronous populations. One such border examined in the field had occurred between populations of the same bamboo species, identified based on sterile morphological characteristics (**Figure 6C**). These borders remain visible for months, sometimes years, in a time series of images. Has the phenological clock of each stand been reset by separate fires in the past? In this case the alternative hypothesis of rhizomatous expansion is extremely unlikely. Each patch covers thousands of square kilometers and the plants do reproduce sexually FIG. 6

on a decadal time scale, so that vegetative expansion over such a large area is not feasible in a single life cycle.

3.5 Liana forests

Covering 310,000 km^2 of the Brazilian Amazon in southern Pará, northwestern Mato Grosso and parts of Rondônia and Roraima (IBGE, 1997), this evergreen forest type constitutes a geograpically broad ecotonal transition between dense evergreen rain forest and seasonally semideciduous forest. Structurally and floristically similar to old secondary regrowth, liana forest may be susceptible to fire penetration in very dry years, though this has not yet been demonstrated or observed. Light penetrates to the forest floor in many places, while mats of vines in large gaps provide close-set thin twigs and leaves for faster combustion as well as fuel ladders to the canopy in a double burn scenario. Some vine forests are, in fact, secondary forests. Regrowth dominated by thin woody vines presently occupies large portions of ~500 km^2 of tall forest sites which burned in 1983 El Niño, near to Santarém in the Curua River basin.

As noted above, fire and flammability have been documented in the structurally similar secondary forests elsewhere in the Amazon. Small fires were common in secondary forests near Manaus in the El Niño summer of 1997. Just four to six days of rainfall exclusion were sufficient to allow the spread of controlled set fires in a low-stature secondary forest and in an illuminated treefall gap in the upper Rio Negro (Uhl et al., 1988), which is a high rainfall region. Secondary forests of the eastern Amazon are now caught in a positive feedback loop with fire. Vine forest may owe its origin and maintenance to a similar feedback, but with a longer cycle.

An extreme example of liana forest dominates well-drained soils over hundreds of square kilometers of low flat interfluves in the western part of the Noel Kempff Mercado National Park in Bolivia, at the southwest limit of Amazonian forest. The heavy vine carpet is just 5-10 meters from the ground and held up by the crowns of low trees, predominantly secondary forest taxa: *Inga*, *Apeiba*, *Machaerium*, *Pourouma*, *Cecropia*, *Acacia*, among others (identifications by T. Killeen). The few very widely spaced emergent trees (*Erisma*, *Hymenaea*) are sometimes free of vines, which may have been eliminated by a fire. Most of the shorter trees which emerge free of vines are either *Euterpe* palms or *Cecropia*. *Euterpe* has a tall thin and smooth trunk which vines cannot easily climb once cleaned off by a killing ground fire. *Cecropia* can shed vines by very rapid vertical growth and self pruning of the lower branches. Fire resistant palms with textured or spiny trunks (*Astrocaryum* sp., *Scheelea principes*, *Maxmilliana inaja*) also occur in the Noel Kempf vine forest, but are heavily covered with vines.

At Noel Kempf Park, the lianas themselves are mostly thin and would be killed in a moderately intense ground fire. This would leave a large fuel load of thin dry stems, dry fallen leaves and dry fuel ladders, setting the stage for a sterilizing second burn in which only thick-trunked palms and a few large dicotyledonous trees with thick bark would likely survive. Most liana stumps will resprout after cutting (Putz, 1991) and may do the same after burning. If a fire opens large gaps in the forest, the high root/shoot biomass ratio should give vines an energetic advantage over trees when resprouting from the base.

4 Conclusions

Infrequent penetration of fire into standing forest – without prior selective logging – has been an important abiotic determinant of vegetation form and composition in three geographically extensive Amazonian vegetation types, far from the climatic transition to savanna. These are the interfluvial white-sand forests of the upper Rio Negro, seasonally inundated forests of the middle Rio Negro, and montane forests of the Serra Parima. Recent fire scars detected in Landsat images cover 5,000 km^2 of white-sand forest and 600 km^2 of montane forest. These two fire-susceptible vegetation types cover a significant area of the Amazon Basin: 152,000 km^2 and 29,000 km^2, respectively (IBGE, 1997). Historical accounts indicate that large areas of white-sand forest and inundated forest of the Rio Negro basin both burned extensively in the first half of this century. Only small scars from more recent fires are now evident in Landsat images. Two additional evergreen forest types which are fire prone and possibly fire derived are bamboo-dominated forest, covering 180,000 km^2 of the Brazilian and Peruvian Amazon (mapped here from Landsat images); and liana-dominated forest, covering 310,000 km^2 of the Brazilian Amazon (mapped by IBGE,1997).

5 References

Huber, O.; Steyermark, J.A.; Prance, G.T.; Alès, C. The vegetation of the Sierra Parima, Venezuela-Brazil: results of recent botanical exploration. *Brittonia* 36(2): 104-109, 1984.

IBGE. *Diagnóstico Ambiental da Amazônia Legal*. (CD-ROM using Vista-Map GIS, produced by IBGE/DGC/DERNA-DEGEO-DECAR), 1997.

Marchesi, G. *Tra Fiumi e Foreste: con le tribu del rio Negro d'Amazzonia* Publisher unknown, 1975.

Meggers, B.J. Archeological evidence for the impact of mega-Niño events of Amazonia during the past two millenia. *Climate Change* 28: 321-338, 1994.

Nepstad, D.C.; Jipp, P.; Moutinho, P.; Negreiros, G.; Vieira, S. Forest recovery following pasture abandonment in Amazonia: canopy seasonality, fire resistance and ants. In: D. Rapport (ed.). *Evaluating and Monitoring the Health of Large-Scale Ecosystems*. New York, Springer-Verlag, 1995.

Nelson, B.W. Natural forest disturbance and change in the Brazilian Amazon. *Remote Sensing Reviews* 10: 105-125, 1994.

Putz, F.E. Silvicultural effects of lianas. In: F.E. Putz and H.A. Mooney (eds.) *The Biology of Vines*. New York, Cambridge University Press, pp. 493-501, 1991.

Smole, W.J. *The Yanoama Indians, a Cultural Geography*. Austin,Univ. of Texas Press, 1976.

Uhl, C.; Kauffman, J.B.; Cummings, D.L. Fire in the Venezuelan Amazon 2: Environmental conditions necessary for forest fires in the evergreen rainforest of Venezuela.*Oikos* 53: 176-184, 1988.

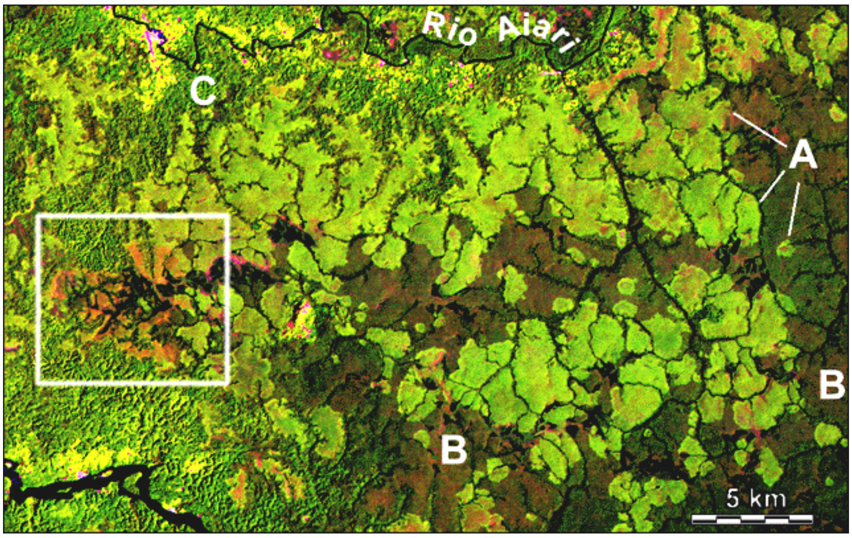

Figure 1. Burn scars on terra firme of upper Rio Negro: A) Low regrowth forest on sandy soil burn scars, some delimited by natural fire breaks; B) Tall unburned campinarana forest on sandy soil; C) Tall unburned dense forest on clay soil, light green areas along Aiari River are swidden fallows on same soil; White box: vegetation type "A" deleafed by recent ground fire. Landsat TM color composite of bands 3,4, & 5 (B,G,R), 29 Dec 1993, from INPE.

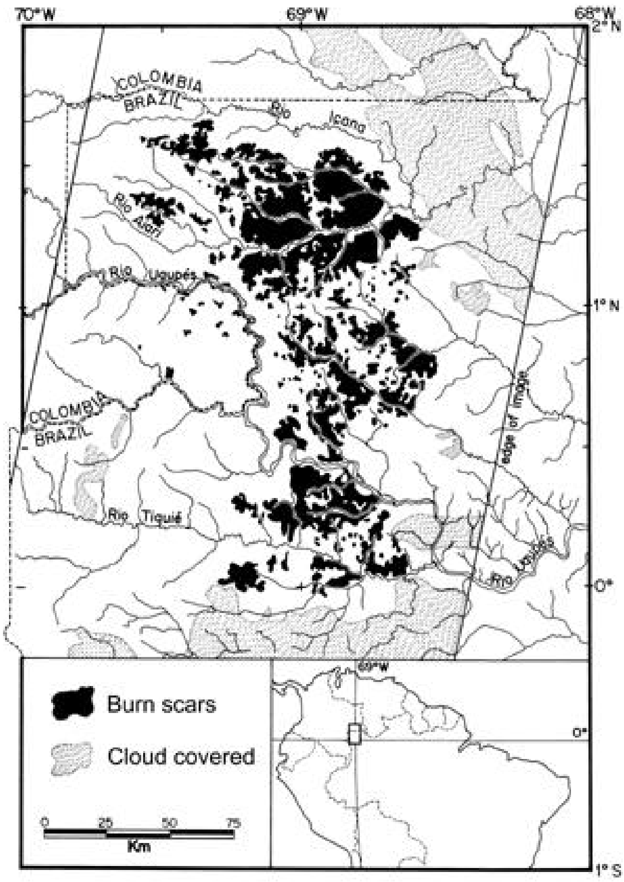

Figure 2. Burn scars covering 5,000 km^2 in two Landsat TM images of upper Rio Negro.

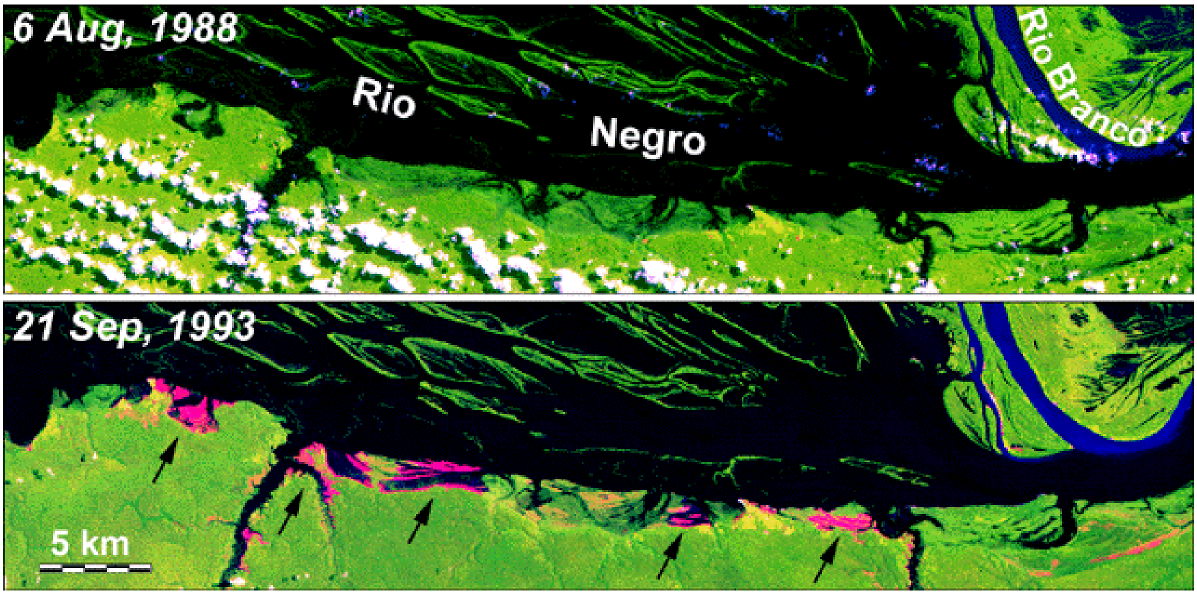

Figure 3. Temporal comparison of seasonally flooded "igapó" forest near confluence of Negro and Branco Rivers. Black arrows indicate recent burn scars in the igapó. Landsat TM color composites of bands 3, 4, & 5 (B,G,R), from INPE.

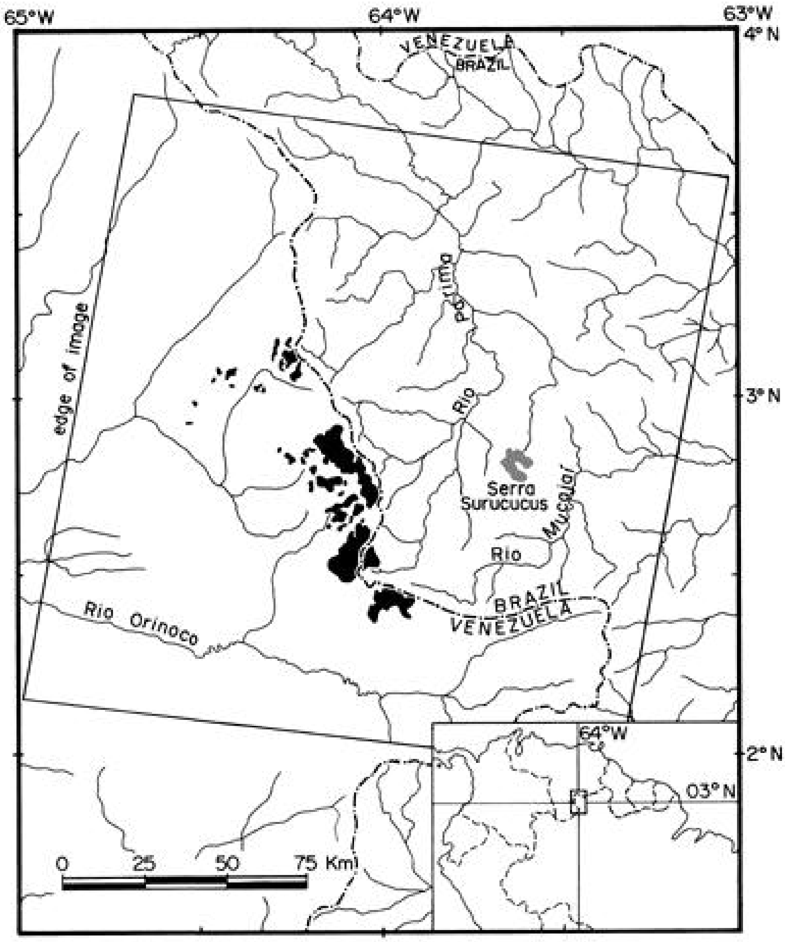

Figure 4. Fern savannas of the Serra Parima derived from burning of montane forest.

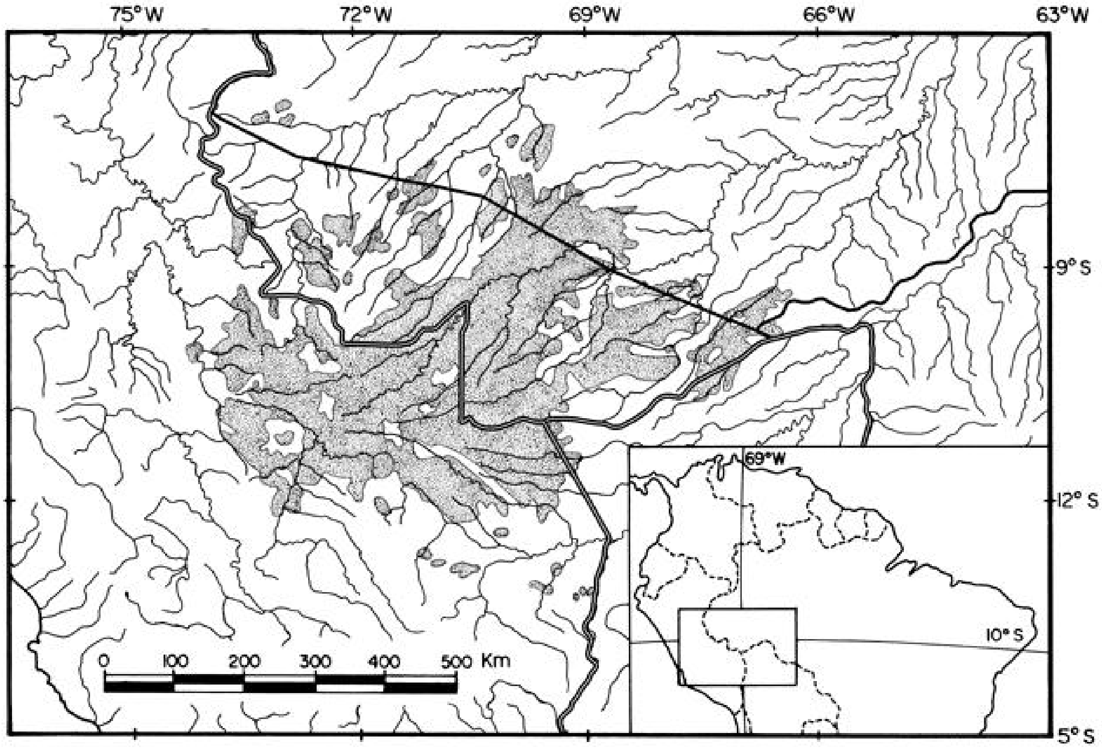

Figure 5. Bamboo-dominated forest covering 180,000 km^2 of the southwest Amazon, based on interpretation by B. Nelson and R. Kalliola of 22 Landsat TM images from INPE and INRENA.

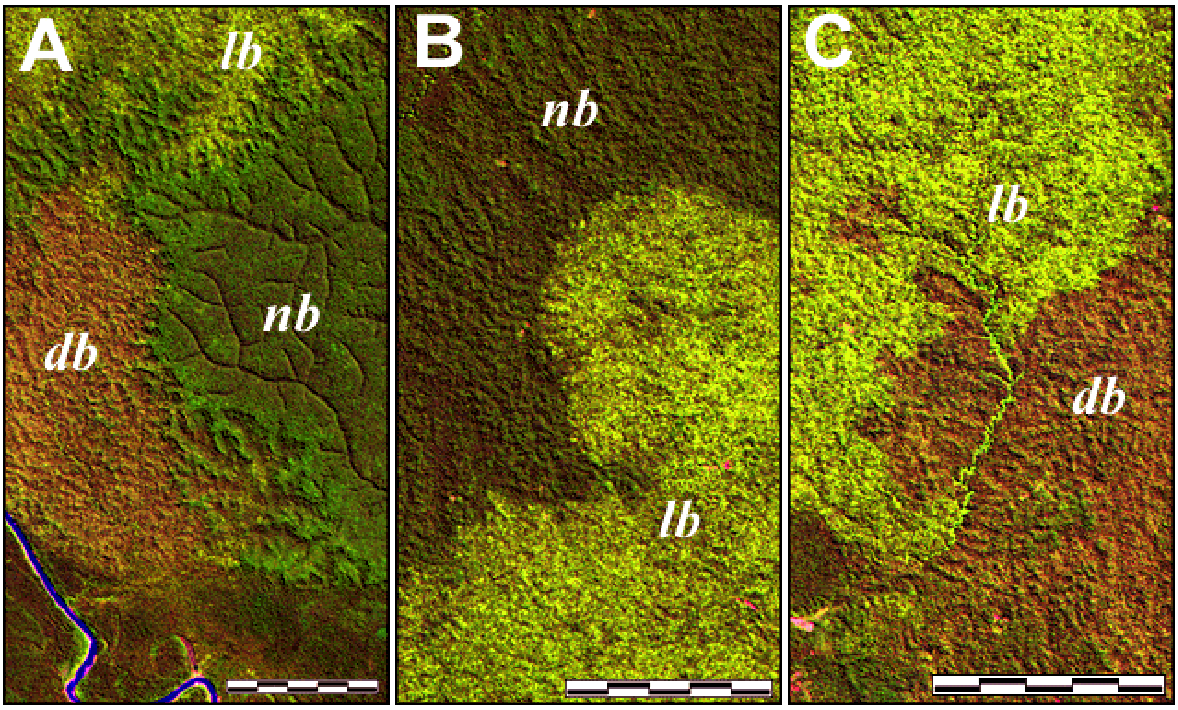

Figure 6: **A**): limit between bamboo and non-bamboo forests determined by soil/topography, **B**) rounded limit unrelated to topography; **C**) rounded limit between living and synchronously dying bamboo populations, partially coincident with natural fire break (stream). Scale bars are 5 km; *db*: forest with dead bamboo, *lb*: forest with living bamboo, *nb*: non-bamboo forest. Landsat TM color composites of bands 3, 4, & 5 (B,G,R), scene 002/066 of 04 August 1988, from INPE.