ing or gleaning) of bees on flowers of Myrtaceae depends on the morphology, pollen quantity and floral display, and also on the specific behavior of bees. ■

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Drought patterns in the Brazilian Amazon: Application to fire risk mapping

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The assessment of fire danger is critical to environmental management in the Amazon. Precipitation data were assembled from 212 climate stations spread throughout the Brazilian Amazon. Using a GIS, maps were constructed showing the spatial patterns of precipitation and drought. Then, these maps were crossed-referenced with vegetation cover to create fire risk categories. Using this approach, 38.1% of the Brazilian Amazon was classified in the low fire-risk category, either because of a wet, low-seasonal climate (10.0%) and/or because of the presence of closed-canopy evergreen forest with the longest droughts less than 75 continuous days (32.8%). Forty-one percent of the Brazilian Amazon was placed in the

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moderate fire risk category, owing to their more open vegetation cover (intermediate between closed-canopy evergreen forest and savanna) and association with anthropogenic activities in the region. Maximum drought disclosed by weather stations with over 10 years of data collection showed that 41.7% of the Brazilian Amazon has suffered drought for more than 75 days. Dense evergreen forest was classified as moderate risk in 13.5% of the area. The remaining 20.9% of the Brazilian Amazon was rated in the high fire-risk category. The vegetation in the latter areas is savanna or droughts are long and frequent. In the southern and northern borders of the basin rainfall may be as low as 1000 mm/year. An estimated 35.8% of the Brazilian Amazon receives < 2000 mm of rainfall each year. The driest regions receive an average < 1 mm/day of rain during the driest quarter of the year. Approximately 48% of the Brazilian Amazon falls into this category. In general, human presence increases fire susceptibility in the Amazon because man frequently replaces closed forest formations (low fire risk ecosystems) with low, open vegetation (fire prone vegetation).

Assessoramento ao risco de fogo é critico para o manejo ambiental da Amazônia. Dados de precipitação de 212 estações meteorológicas da Amazônia brasileira foram usados neste estudo. Mapas que mostram padrões espaciais de precipitação e de seca foram construídos usando técnicas de sistemas de informações geográficas. Então, estes mapas foram cruzados referencialmente com mapas de vegetação para criar categorias de risco ao fogo. Usando este procedimento, foi classificado 38,1% da Amazônia brasileira na categoria de baixo risco ao fogo pelo fato de ser úmida, ter clima pouco estacional (10,0%), e/ou pela presença de floresta com copa fechada com periodos máximos registrados de seca menores de 75 dias (32,8%). Cerca de 41,0% da Amazônia brasileira foi classificada como tendo risco moderado ao fogo, pela vegetação de copas mais abertas (vegetação intermediária entre floresta densa e savana) e atividades antropogênicas na região. Secas máximas ocorridas nas estações com mais de 10 anos de coleta indicaram que 41,7% da Amazônia brasileira já teve secas com mais de 75 dias. A floresta densa foi classificada como sendo de risco moderado ao fogo em 13,5% da área. O restante 20,9% da Amazônia brasileira foi classificada como sendo de alto risco ao fogo. Isto ocorre pelo fato do tipo de vegetação ser savana e/ou secas prolongadas serem muito freqüentes. Nos extremos sul e norte da bacia, as chuvas se reduzem a até 1000 mm/ano. Foi estimado que 35,8% da Amazônia brasileira recebe < 2000 mm/ano. As regiões de estiagem mais intensas recebem menos de 1 mm/dia durante o trimestre mais seco do ano. Cerca de 48% da Amazônia brasileira foi classificada nesta categoria. Em geral, a presença humana aumenta a suscetibilidade ao fogo na Amazônia pela freqüente transformação da floresta densa virgem para vegetação aberta e baixa (vegetação suscetível ao fogo).

Forest fires have been a constant concern in the temperate zone during recorded history (1). The humid tropics, and the Amazon, in particularly, have generally been regarded as a rainforest immune to fire. However, the Amazon basin encompasses an immense area with very variable rainfall patterns (from 1000 mm to 4100 mm/year) and a rich order of vegetation types (from tall, dense, evergreen forest to open savanna). Fires are common in savanna regions in the Amazon but fire events decrease as canopy cover thickens and rainfall increases. Thus, while humans reduce canopy cover and provide ignition sources, occurrence of fire is increasing throughout the Amazon (2,3).

A prerequisite for any fire is fuel. In general, Amazon ecosystems are rich in organic matter, fuel is rarely limiting. However, fuels will only burn if they are dry enough for combustion, and fuel drying depends on the microclimate. Canopy height and canopy denseness are critical to the fuel drying process. A high, closed canopy acts as a microclimate buffer – radiation is received and processed high above the ground and the fuel-rich forest floor frequently remains humid and fire resistant. When canopies are open and/or low, radiation processing occurs close to the fuel layer. As the ground layer warms, the drying power of the air increases (rise in vapor pressure deficit) and with the fire risk (3).

Time is necessary for the drying process. Therefore, the presence of rain-free periods (e.g., more than 10 days) (3) is a key determinant in the creation of fire conditions in the Amazon, as in temperate regions.

Data on climate, vegetation, and fuels have been used in the development of fire warning systems (4,5,6). This research from the temperate zone suggests that the length and characteristics of drought periods are much more important than absolute annual rainfall in predicting fire occurrence because of the dry season patterns (7).

Our study was undertaken to develop techniques to analyze drought distribution and duration in Amazon and to join this information with vegetation data to construct a fire risk map for the Brazilian Amazon.

The Amazon hydrologic basin covers around 6.1 million km^2 with the Brazilian portion occupying about 4.9 million km^2. This area includes the whole of the states of Acre, Amapá, Amazonas, Pará, Rondônia and Roraima; and part of Goiás, Maranhão, Mato Grosso and Tocantins states. We used data from 212 weather stations spread throughout the Brazilian portion of the basin: 135 of these weather stations were operated by DNAEE (Departamento Nacional de Águas e Energia Elétrica); 56 by INEMET (Instituto Nacional de Meteorologia); 8 by IDESP (Instituto de Desenvolvimento Econômico e Social do Pará); 6 by ELETRONORTE (Centrais Elétricas do Norte do Brasil); 5 by EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária) and 2 by DEPV (Diretoria de Eletrônica e Proteção ao Vôo do Ministério da Aeronáutica).

Obtaining reliable estimates is particularly difficult when the areal coverage provided by the surrounding stations is sparse or when precipitation characteristics vary greatly with location. Hevesi et al (8) analyzed rainfall distribution in southern Nevada and southeastern California, USA, and had to use the length of record ranging from 2 to 53 years of 62 gaging stations. In another study by Hevesi et al (9) in the same area, the length of record varied from 8 to 53 years for 42 precipitation stations.

Most of the Amazonian weather stations are in developed regions in the eastern and southern part of the basin. In the central portion of the basin, the weather stations are usually near the river margins, where human communities have developed because of the river transportation systems. The selection of the weather stations for this study was aimed at gaining even coverage of the Brazilian Amazon (Fig. 1). Some weather stations outside the basin were used to reduce error related to extrapolation. Initially, it was decided to only use stations with at least eight years of complete data (not necessarily in consecutive years). However, in the final phase of this study this requirement was relaxed to a minimum of four years to include data from underrepresented areas. Fifty-four of the 212 weather stations used had less than 8 years of data. Of these, 19 provided 7 years of data (stations with only 4-6 years of data are noted in Figure 1). The average number of years of data per station, considering all 212 stations, was 10.3 (sd = 6.3). Most of the data (87%) were from the period 1970-1987. All databases were meticulously checked for possible collection errors and any suspected different value was compared with results in the same year in the neighborhood stations. Abrupt changes in climate parameters are supported by more than one weather station in the neighborhood.

The following were determined for each station: *1)* Mean of annual precipitation; *2)* mean of percentage of days of each year that were part of droughts with a duration ≥ 10 days; *3)* mean of rainfall in the driest quarter yearly and *4)* the longest drought registered in the weather stations with at least 10 years of data (only 94 stations were used for this variable). Climate maps were produced using the inverse distance weighted interpolation routine (10). The map projection used was UTM.

Using data from Projeto RADAMBRASIL (1973-1984) it was possible to develop a simplified vegetation map with six main vegetation types. These six groupings were further reduced to the following three classes that have an important significance for fire mapping: *1)* Dense, closed-canopy evergreen forest; *2)* "intermediate" including open-canopy vegetation, deciduous and semi-deciduous forest, secondary forest, capinarana (humid scrub forest), ecological tension and anthropogenic areas and *3)* savanna (characterized by sparsely scattered trees in a grass matrix). Areas of savanna altered by man were not reported as anthropogenic areas by Projeto RADAMBRASIL. Vegetation maps were overlapped with climate maps using Idrisi (10) to demarcate areas showing its potential fire risk.

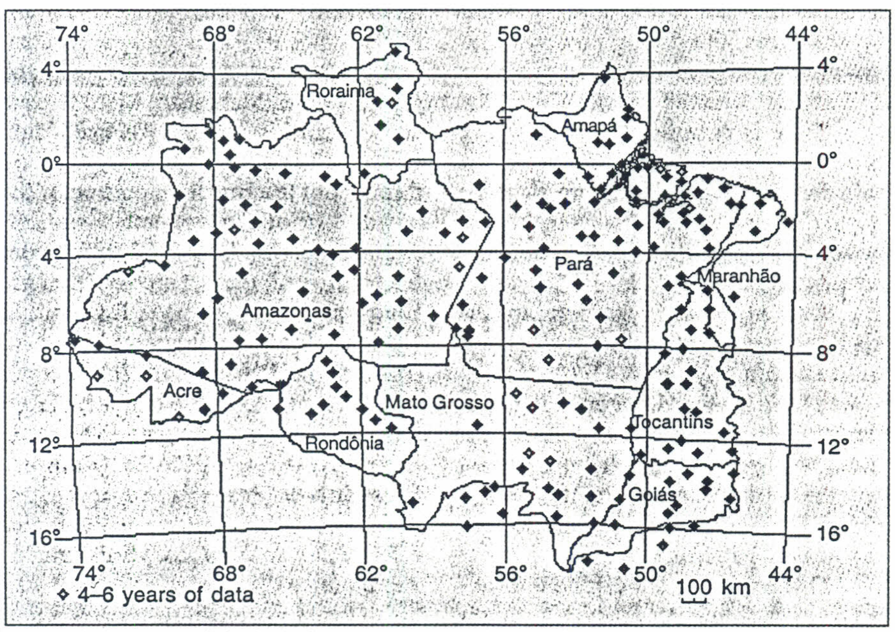

Figure 1. Location of the 212 climate stations in the Brazilian Amazon used in this study.

Rainfall and drought patterns

The vegetation cover types of Amazon are varied. Based on our grouping of Projeto RADAMBRASIL (11) vegetation data, it was estimated that 37.9% of the Brazilian Amazon is covered by closed-canopy forest, 41.2% is covered by "intermediate", open-canopy vegetation types, and 20.9% has savanna cover (Fig. 2). Closed canopy forest is most abundant in the central portion of the basin; open canopy forest, consisting of a variety of forest formations, is common to the south and north of this central core, and savanna is concentrated in the southern and eastern portions of the basin.

There are also great differences in the spatial distribution of rainfall in the Brazilian Amazon. In the wettest regions (e.g. Upper Rio Negro and mouth of the Amazon river) rainfall can approach 4000 mm/year. Nevertheless, in the southern and northern borders of the basin rainfall may be as low as 1000 mm/year. An estimated 35.8% of the Brazilian Amazon receives ≤ 2000 mm of rainfall yearly (Fig. 3) and 2.4% receives ≤ 1500 mm yearly.

Essential to fire mapping is a knowledge of spatial patterns of dryness. An average rainfall/day during the driest quarter of the year was used as a first measure of dryness (Fig. 4). The driest regions of the Brazilian Amazon receive < 1 mm/day of rainfall, and/or < 20% of total rainfall, during the driest quarter of the year. Some 48% of the Brazilian Amazon fits in this category. By contrast, in the wetter areas of the basin, average daily rainfall during the driest quarter of the year is > 3 mm. These re-

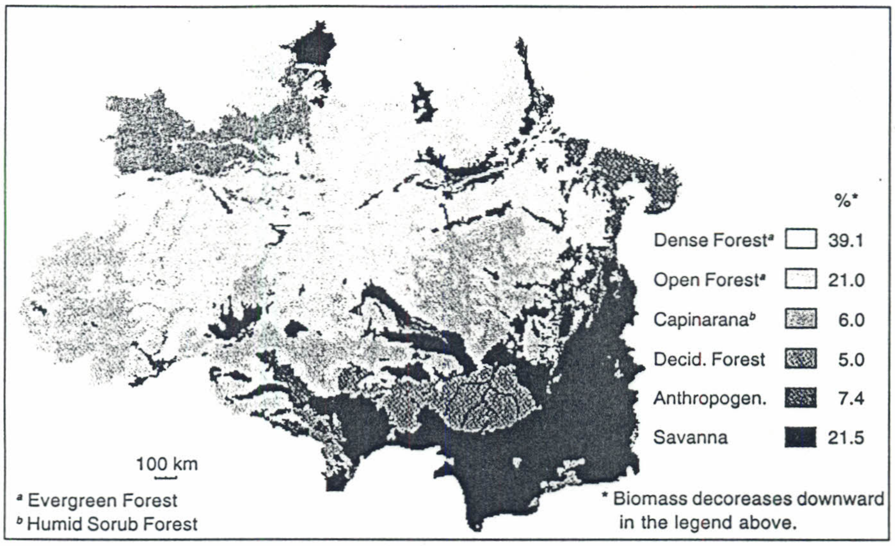

Figure 2. Vegetation types and distribution in the Brazilian Amazon.

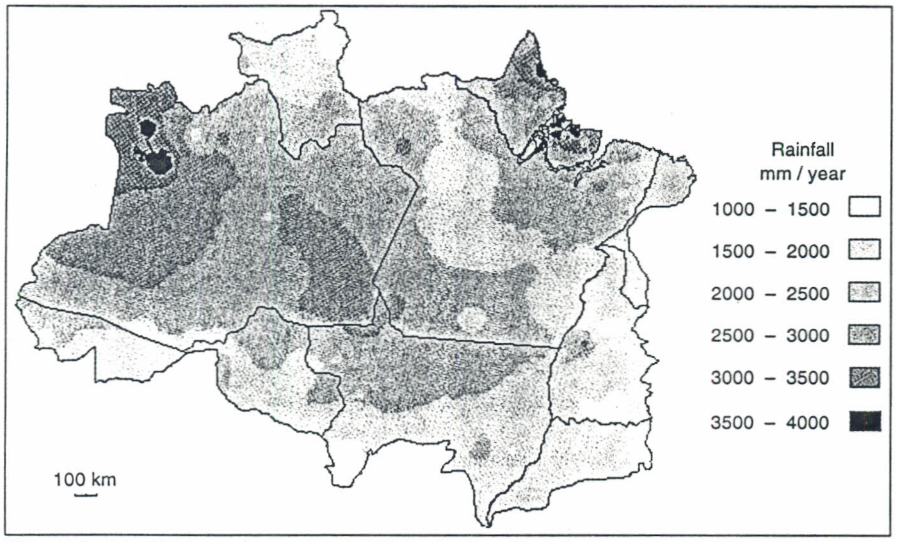

Figure 3. Distribution of annual rainfall in the Brazilian Amazon.

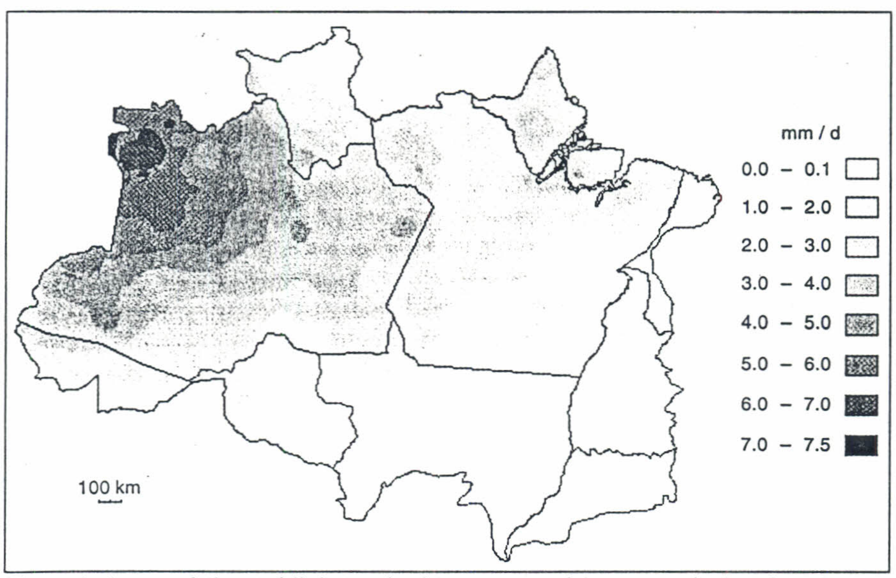

Figure 4. Average daily rainfall during the driest quarter of the year in the Brazilian Amazon.

gions of relatively even rainfall distribution throughout the year represent 14% of the Brazilian Amazon.

The second measure of dryness used is the percentage of days in the years that are part of droughts exceeding 10 days in length. Using this measure, it was found that weather stations varied from having 1.2 to 58.0% of their days assigned to drought periods (Fig. 5). On an aerial basis it was calculated that 66.7% of the Brazilian Amazon has at least 20% of the days (73 days) being part of drought periods yearly (≥ 10 consecutive rainless days) and 61.2% of this portion has already experienced a single drought period of more than 75 days.

The third measure of dryness that helped in the screening process was the maximum drought experienced by the weather stations reporting at least 10 years of data. The range of the data varied from 13 days to 242 days. It was calculated that 41.7% of the Brazilian Amazon has undergone > 75 days of drought and only 2.4% of this area did not have more than 20% of the days (73 days) yearly totalling rainless periods > 10 days. In addition there was some void of weather stations, therefore the surface interpolation used the 8 nearest stations to cover these areas (Fig. 6). This happened because some weather stations did not have data enough to fulfill the requirements in this analysis. It is expected that the accuracy of fire potential is higher in the more developed regions that also have more weather stations collecting data. Analysis of correlation between maximum droughts and the percentage of days in the year that are part of droughts exceeding 10 days in length showed a correlation coefficient of $r = 0.84$ ($t = 468.9$), maximum drought and rainfall in the driest quarter yearly showed a correlation coefficient of $r = -0.82$ ($t = -431.2$).

Fire map

Of the Brazilian Amazon 38,1% was classified in the low fire risk category, 41.0% in the moderate fire risk category, and the remaining 20.9% in the high fire risk category (Fig. 7). Regions in the low risk category initially met one

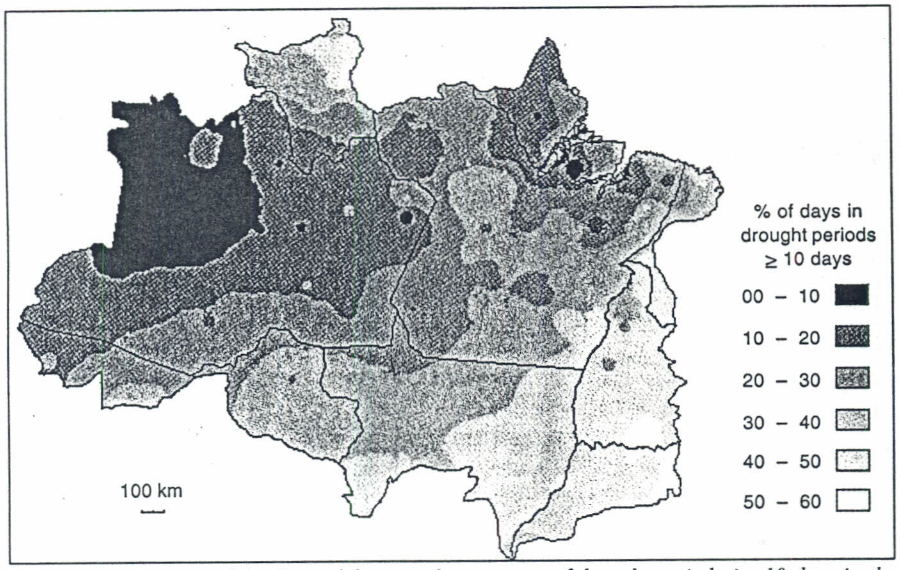

Figure 5. Percentage of the days of the year that are part of drought periods ≥ 10 days in the Brazilian Amazon.

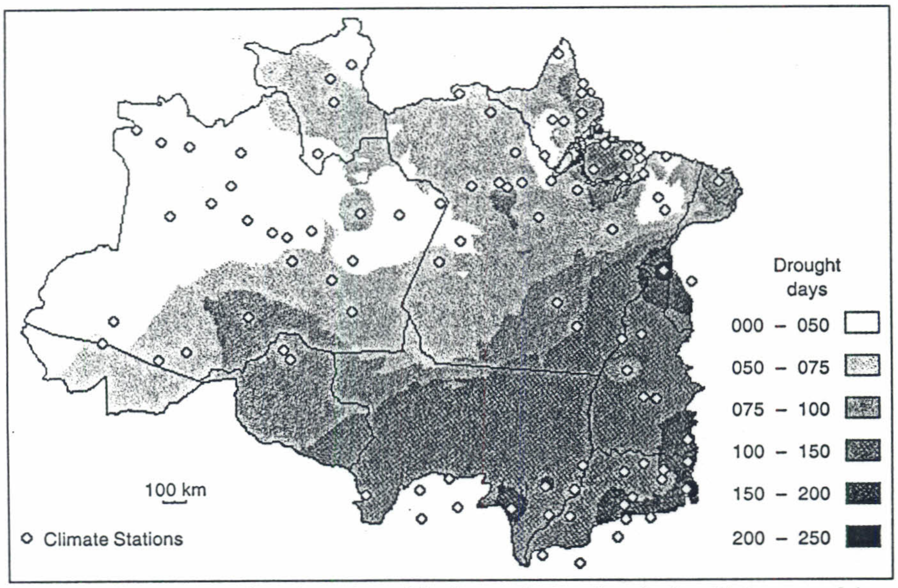

Figure 6. The maximum drought registered in the weather stations having 10 ≥ years of data.

or more of the following conditions: *1)* An average daily rainfall in the driest quarter of the year greater than 4 mm/day (the evaporation rate is around 4 mm/day) (12); *2)* less than 10% of the days of the year being part of droughts that exceed 10 days (approximate time necessary for fuels to dry to combustion level in open canopy ecosystems of Amazon) (3). Regions of low fire risk, based exclusively on these climatic considerations, occupy 10.0% of the Brazilian Amazon (4.9% in closed-canopy forest and 5.1% in areas of "intermediate", more open canopy vegetation).

Areas of closed canopy, evergreen forest (37.9%) were considered to be almost immune to fire (low fire risk) because closed canopies maintain a moist microclimate in the understory preventing fuel drying (3). Even for closed canopy under long drought, the underground water reservoir can be limiting in supplying water, so this closed canopy forest under more than 75 days of drought was considered as moderate risk. It was found that 13.5% of this area of dense forest has experienced more than 75 days of drought. The joining of climate and vegetation criteria suggests that 38.1% of the Brazilian Amazon can be classified in the low fire risk category at present (Fig. 8).

The remainder of the Brazilian Amazon (61.9%) was placed at moderate or high fire risk (Fig. 8). Areas that were not protected by climatic conditions and have a vegetation intermediate between dense forest and savanna (41.2% of the Brazilian Amazon) were placed in the moderate fire risk category, 41.0% and 12.4% of this area having closed canopy forest. Areas with savanna, 20.9%, were classified as high fire risk. This map should stress fire susceptibility of existing vegetation. A low fire risk area can become a moderate or high fire risk area through conversion to pasture or agriculture.

In characterizations of the Amazonian climate, the spatial arrangement of dryness in the region is emphasized. It might be the first study of the Amazonian climate that specifically focuses on spatial patterns of dryness and distribution of rain-free periods. Droughts of ten days or more are common: 90% of the Brazilian Amazon experiences at least two such droughts, on the average, each year. And 41.7% of the Brazilian Amazon has already registered at least one drought exceeding 50 days. Even prolonged droughts, more than 100 days, are likely to occur in 14.7% of the area considering as the maximum occurrence of each weather station reporting more than 10 years of data. Drought events of long duration are most common in the eastern and southern portions of the Brazilian Amazon and, therefore, coincide with the regions where development pressure is the greatest (see Fig. 6).

The vegetation of the Amazon responds to these drought events by reducing leaf surfaces: Litter fall frequently increases during drier periods of the year in the Amazonian evergreen rainforest (13). A second response to prolonged dry periods is to extend root systems deep into the soil. Working at Paragominas in the eastern Amazon, Nepstad et al (13) have found that the forest root system extends beyond 10 m. Then, at this soil depth water would be available to plants year round. Paragominas in our data reports the an-

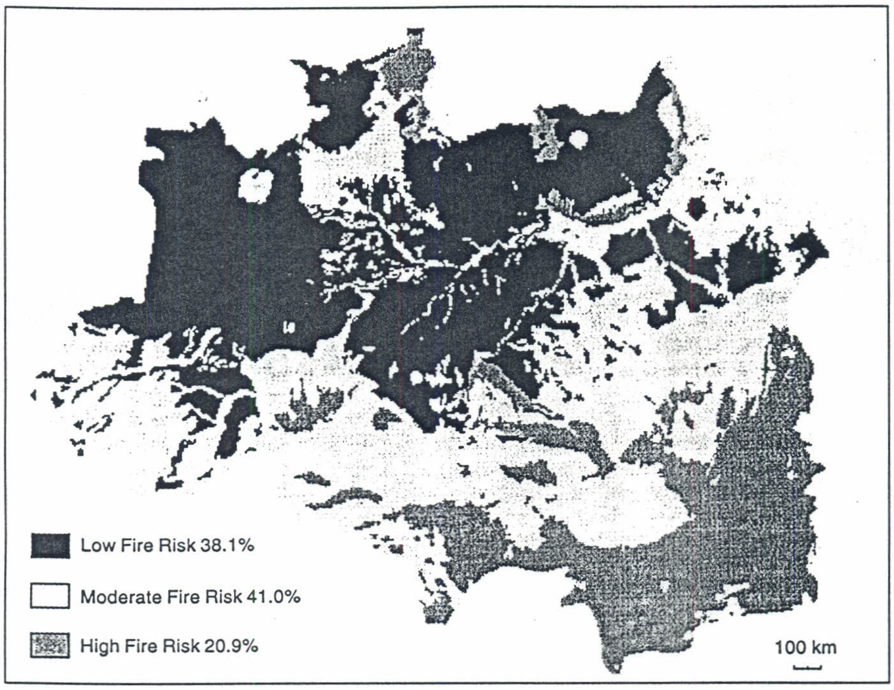

Figure 7. A fire map of the Brazilian Amazon showing areas that are at low, moderate or high fire risk.

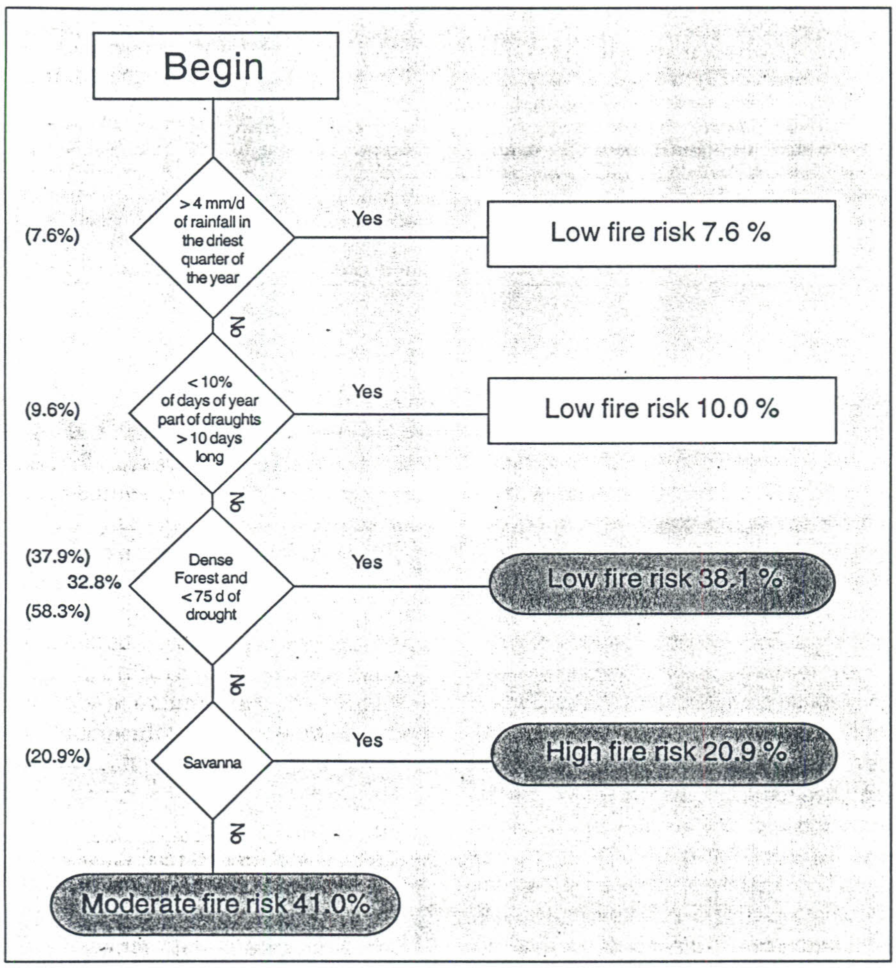

Figure 8. The model used to develop the fire rating map for the Brazilian Amazon.

nual rainfall of 1802 mm/year, 0.84 mm/day in the driest quarter, and has already experienced maximum droughts > 75 days.

While the Amazon flora of evergreen forest is effective in avoiding drought, it is not resistant to fire. Through an examination of bark tissues and the application of simulated fires, Uhl and Kauffman (3) estimated that 98% of all stems 1 cm dbh (diameter at breast height) would be killed in surface fires in the eastern Amazon. Thick bark insulation for fire resistance was not developed genetically. Mortality is projected to be high because most Amazonian tree species have only a thin layer of bark protecting their cambial tissues.

The area considered as generally immune to fire (low fire risk) in this study represents 1.9 million km^2 or 38.1% of the Brazilian Amazon. The remainder of the Amazon is susceptible to fire. It is likely that fire will become more common in the Amazon as human occupations both transform fire-resistant vegetation (closed forest) to fire-prone vegetation (open fields) and provide more ignition sources. Indeed, if the Brazilian Amazon were totally deforested and the distribution of rainfall did not change, only around 10.0% of this region would continue immune to fire (based just on climatic considerations) (Fig. 8). Since it is likely that the deforestation of the Amazon rainforest would produce more intense dry seasons because water from evapotranspiration is diverted to streams (14,15,16,17), the area immune to fire would probably be even smaller than 10.0%.

This is a very modest first step in beginning to think about the climatic and vegetation components necessary to develop fire risk maps for Amazon. The fire map (Fig. 8) is based on at least two untested assumptions. First, based on the work of Uhl and Kauffman (3) in the eastern Amazon, it is assumed that all closed forest areas will be immune to fire. But, their work was done on deep soils with good water holding properties, allowing the stands under study to maintain dense canopy cover during the occasional (ten-year maximum) severe drought event. Further studies may reveal that such closed forest areas are, in fact, at fire risk. Second, it is assumed that open canopy (intermediate) forests are more fire prone than closed forests. While this seems reasonable, there are no studies evaluating the fire sensitivity of open canopy forests in the Amazon. I hope that others will use this work as a starting point to understand the complexity of fire potential in the Amazon basin, mainly because of high concern for climate change related to deforestation.

Disclaim notice: The views expressed in this article are the author's and do not necessarily represent the official policy or interpretations of the Brazilian Enterprise for Agricultural Research (EMBRAPA). ■

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