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Deforestation and hydrology dynamic in Ji-Paraná river basin, Brazil

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Abstract. Land-use and land-cover conversion processes can induce significant changes in surface hydrology, particularly in the case of the large-scale loss of rain forests in the Amazon. The hydrological properties in two regional scale river basins in Western Brazilian Amazon – one subjected to large-scale deforestation and one almost undisturbed - were evaluated for a 23-year period. Annual land cover maps for both basins were generated and analyzed with hydrological data time series. No long-term hydrological trends were observed between 1978 and 2001, despite a deforestation rate of 55% in Ji-Paraná river basin at 2001. Nevertheless, annual variations on hydrological data appeared to be associated with annual deforestation rates in the largely deforested basin. The forest clearing produce a short-term response on hydrological data, probably because of changes in interception, infiltration, and evapotranspiration after forest removal. Human occupation patterns in Rondônia may contributed to smooth deforestation effects and to preserve hydrological and energy balances.

Palavras-chave: Rondônia, deforestation, land use, hydrological response, dynamic, desflorestamento, uso da terra, resposta hidrológica, dinâmica.

1. Introduction

Human-induced land cover and use changes constitute a major source of anthropogenic influence that can cause significant hydrological, physical and climatic changes. Among the various effects of climate change, an increase in global mean temperature and changes in rainfall is likely to be the most hydrologically important. Several studies have shown strong coupling between vegetation and the hydrological cycle. Vegetation has a direct influence on controlling erosion, water quality, nutrients, watershed protection, and water production. Vegetation removal leads to several changes, including a decrease in photosynthetic rates and evapotranspiration. At large scales, a decrease in evapotranspiration can impact precipitation, thus impacting streamflow and hydrological response. Many experimental small basins have been used to study the relationship between vegetation and hydrology. These experiments have often studied the hydrological impacts of different land-cover change events (like clear-cutting, thinning or reforestation) or changes in land cover (Cheng, 1989; Wright et al., 1990; Cornish, 1993; Gustard e Wesselink, 1993; Hornbeck et al., 1993; Jayasuriya et al., 1993; Stoneman, 1993; Câmara, 1999). At larger scales, climate models have been applied at continental to global scales, often producing results that conflict with microscale studies. There is a noticeable lack of regional scale studies of long-term hydrological properties changes caused by deforestation.

The major motivation of this study was to assess how regional-scale hydrological parameters can be affected by deforestation by comparing a mostly undisturbed river basin to a watershed subjected to important forest clearing, over 23 years, from 1978 to 2001.

2. Methods

The study area comprised two regional-scale river basins in Western Amazon (**Figure 1**). The first basin (JI), whose main river is the Ji-Paraná, is situated in the southwestern part of Rondônia State, Brazil, and has shown extensive and progressive decrease of forest cover. The second basin (SUC) is situated in the southwestern part of the Amazonas State and has most of its forest intact. The JI is covered by 4 Landsat TM scenes and has an area of 32,860 km^2. The SUC is covered by 3 Landsat TM scenes and has an area of 13,677 km^2. Both basins are sub-basins of the Madeira river basin.

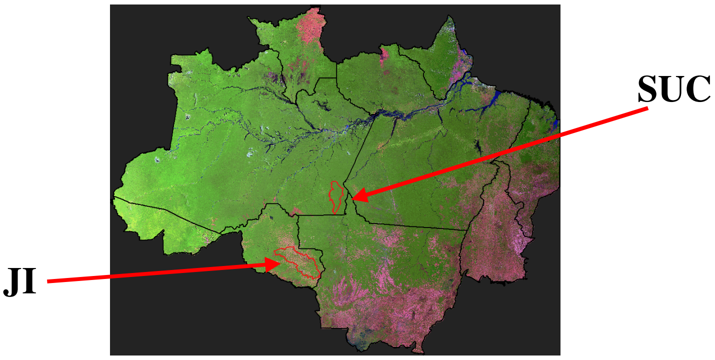

Figure 1 – Study area location, with the JI basin at south, and the SUC basin at northeastern.

Changes in land cover in the two basins were mapped using time series imagery from Landsat satellites. For the JI were used 1:250 000-scale color photographic reproductions of Landsat Multispectral Scanner (MSS) images for years 1978, 1980 and 1983 and digital Landsat Thematic Mapper (TM) images for years 1984 to 2001. Because of its rather undisturbed condition, SUC land cover was mapped only using two dates, a 1978 MSS paper reproduction and 2001 TM digital scene to find out the extent of change between 1978 and 2001. All the images were geometrically rotated, based on the Orthorectified Landsat TM Mosaics products of NASA (NASA, 2002; Silva e Valeriano, 2003) and using nearest neighbor sampling.

Maps of deforested area were created for each year, considering three classes: natural vegetation (‘V’), deforested area (‘NV’) and water (‘W’). The class ‘V’ included all types of natural vegetation, which comprised broad-leaf forest and savannas in the region of study. The class ‘NV’ included all types of human-altered areas such as pastures, annual and perennial crops, fallow occurring in cleared areas, bare soil, fire scars and urban areas. The class ‘W’ corresponded to the area of water bodies broad enough to appear as such on Landsat imagery. The criterion for building this legend was based on the scientific question broached: once deforested, all resulting land-cover classes were grouped into one class.

The earliest thematic maps for 1978, 1980 and 1983 were created through visual interpretation of the MSS 1:250 000-scale photos followed by manual digitizing, resulting in different GIS layers for each year. A multi-step approach was used to produce the thematic maps for 1984 to 2001. First, TM channel 5 bands were sliced after selecting an ideal threshold value (variable from image to image) to maximize separation of the ‘V’ and ‘NV’ classes (Alves et al., 1998a,b). Then, we used manual edition to correct classification errors, like confusion between forest and burned areas. Following manual editing, we removed all polygons smaller than 59.500 m^2, cleaning the visual display of the maps, simplifying and saving editing time. Finally, all the maps were visually assessed for quality and all remaining errors were corrected manually.

The water class only includes the principal rivers and to extract this class, we used the "Normalized Difference Water Index/NDWI" (McFeeters, 1996), which detaches the water from the rest. We established a threshold to create a thematic map only with the 'W' class.

The last stage was to join all three classes for each year and create the maps. We accomplished this task using a mosaic building technique, a function in the SPRING software (version 4.2, Câmara et al., 1996). This procedure warrants a temporal coherence, i.e., once an area is classified as 'NV', no longer returns to 'V' class. With these maps, it was possible to calculate the deforested and the non deforested areas (in square kilometers).

The hydrological data were obtained from the Brazilian Water Agency – ANA (ANA, 2002). Two variables were selected: daily streamflow (m3/s) and daily precipitation (mm).

Although consistent time series existed for each basin, several data gaps were found. Two approaches were used to fill gaps in precipitation. For gaps of seven days or less, a moving average of eight neighbors was adopted. For longer data gaps, we chose the "Regional Weighting Method", using neighboring pluviometers. This is a simple method that does not adversely affect statistical analyses (Bertoni e Tucci, 2002). Data gaps were also present in the streamflow data, including two months for SUC and six months for JI. Most often, gaps in streamflow are filled using regression equations between fluviometers with data gaps and neighboring fluviometers with complete data. However, we found correlations between each river gauge and its neighbors too low to use this approach. To overcome this limitation, regressions were used between months with data gaps and the same months in contiguous years for the same river gauge. Due to a major data gap from April/1989 to October/1990, we removed this period from all analyses.

Daily streamflow values were summed to generate monthly totals, and these totals were summed again to produce annual totals.

The mean precipitation for the basins was calculated using the "Thiessen Polygons Method" (Bertoni e Tucci, 2002) that gives a more representative and real value than an arithmetic average. Daily precipitation values were summed to monthly totals for each pluviometer, which were used to calculate the monthly mean precipitation for the basins (P_m). The P_m value corresponds to a unique monthly mean precipitation for the whole basin. Summing these P_m values, we obtain the annual totals. From the annual precipitation and streamflow totals, it was possible to calculate the hydrological response.

The hydrological response is a non-dimensional variable related to basin water production and is obtained by the ratio between annual streamflow and annual precipitation values. The normalization of streamflow by precipitation turns the hydrological response a variable free of any influences from precipitation oscillations.

All hydrological analyses were based on the hydrological year, which begins in October and ends in September for precipitation. For streamflow, due to the lag existing between peaks of precipitation and streamflow, the hydrological year is from December to November.

3. Results and discussion

We obtained a temporal series of 21 land-cover maps for JI and two maps for SUC (1978 and 2001). In 1978, SUC basin had a deforested area of 2.9 km^2, found in close proximity to BR 230. This deforestation is most likely a product of road construction between 1970 and 1974. By 2001, the deforested area had increased to 52.7 km^2, representing a small percentage of the basin (0.4%) (**Figure 2**). Quantitatively, the deforestation within the SUC basin was negligible and should not interfere on its hydrology. Nevertheless, the deforestation area in 2001 showed the beginning of a 'fish bone' pattern, which may not be coincidental. The SUC basin is enclosed in ‘Apuí’ County, which was founded in 1988 and includes ‘Juma’, the largest planned settlement in Latin America, consisting in an area of 6,890 km^2 and an ability to house 7,500 families.

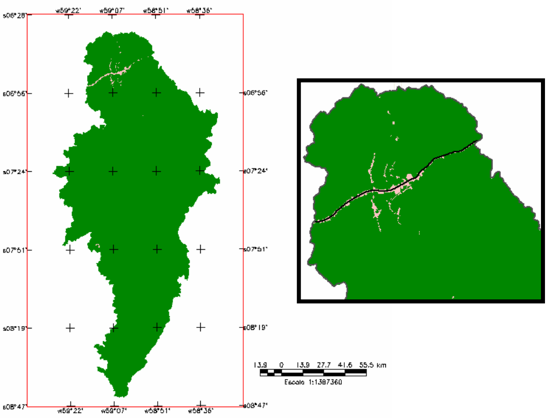

Figure 2 – Sucunduri river basin deforestation map.

The JI basin has experienced a different occupation process resulting in considerable landscape change between 1978 and 2001. In 1978, the basin was rather pristine with only 3.6% deforested area (1,197 km^2). In 2001, the deforested areas were merged and in some places, the characteristic ‘fish bone’ pattern almost disappeared. All the central region of the basin was cleared with the remaining forest areas in the southeast preserved as savanna or inaccessible due to rugged terrain. Another region in the northwest remained largely untouched inside an indigenous reserve (Uru-Eu-Wau-Wau) (**Figure 3**).

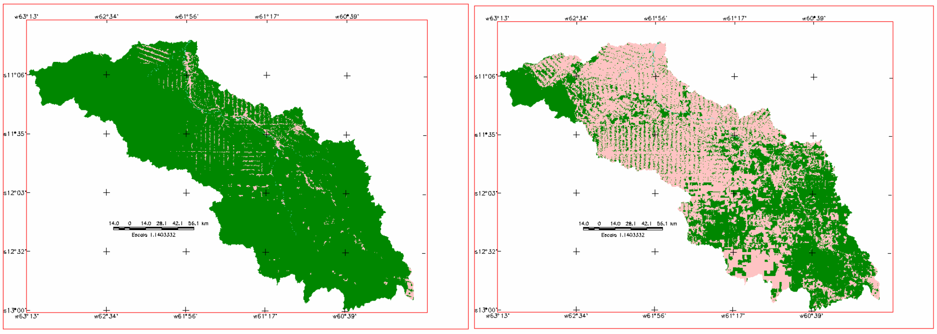

Figure 3 – Ji-Paraná river basin deforestation maps, for 1978 and 2001.

Between 1978 and 2001, 54.75% of the basin was deforested (17,978 km^2) with a mean deforestation rate of 932 km^2/year. Annual deforestation rates have varied over this period because of several causes, including the economy, migratory fluxes, law enforcement efforts and climate variability, like ENSO. At dryer conditions, like when ENSO occurs and decreases the precipitation amounts, as remarked in 1983/84, burning actions tend to increase (INPE, 2004). However, the high deforestation rate in 1984 may be also a consequence of the end of BR 364 asphalting.

The precipitation annual means in JI basin showed an interesting behavior betwen 1987 and 1999, when SUC basin had consistently higher precipitation values than JI before 1987, and then, the basins showed nearly identical precipitation. Following 1999, rainfall patterns apparently returned to the earlier 1987 pattern of greater rainfall in SUC. Possibly, these patterns reflected the interdecadal variability described by some authors (Galdino et al., 1997; Müller et al., 1998; Collischonn et al., 2001; Marengo, 2004). Unfortunately, the temporal sampling of this study is too short to corroborate this, needing a time series of more than fifty years to confirm this hypothesis. Precipitation annual totals were also analyzed to find whether there were statistically significant trends in the time series that could be potentially attribute to climate change, but no trends were found at the 5% level (**Figure 4**).

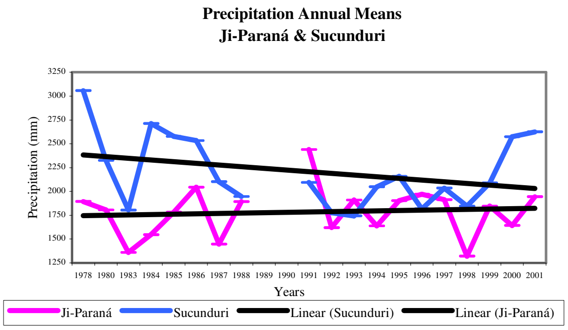

Figure 4 – Annual precipitation means and trend lines adjusted to time series data.

Considering the similar drainage density of both basins and the smaller drainage area of the SUC basin, the fact of this basin has higher streamflow values merits further investigation. The JI basin time series varied less in comparison to the SUC basin, and this may be due to the larger area of JI basin, which would stabilize the river discharge (Tucci, 2002). The geology of the two basins may also have an influence, since sedimentary rocks in JI imply thicker soils than the crystalline rocks of SUC, allowing higher infiltration rates, lower runoff and greater memory effects. Again, the temporal series of this work do not allow us to conclude whether lower oscillation in JI could be attributed to natural reasons or to land-use and land-cover changes. Trend lines were also adjusted for precipitation data, as for streamflow, and, no significant trends were found at the 5% level (**Figure 5**).

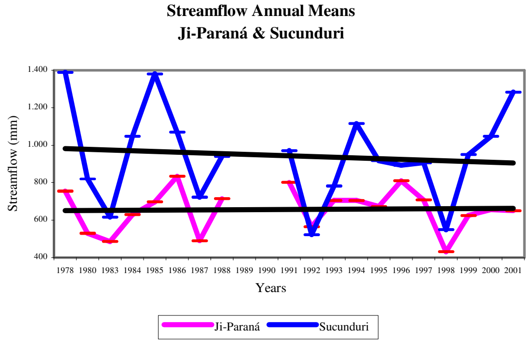

Figure 5 - Annual streamflow means and trend lines adjusted to time series data.

The annual hydrologic response means of the two basins are similar until 1999, except for 1985 and 1992. Interannual fluctuations can not be attributed to changes in precipitation because streamflow was normalized by precipitation amounts. Thus, the variation in hydrologic response reflected real changes in water quantity inside the basin. There are two possible explanations for greater variability on hydrological response in SUC: its smaller size, as was already commented that implies in greater variance, and its localization on crystalline rocks, which reduces the memory effects. The trend lines for hydrological response data were also not significant at 5%, suggesting there were no trends in time that could mean changes in hydrological regime due to deforestation (**Figure 6**).

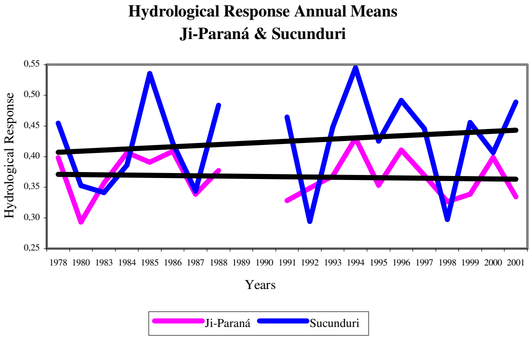

Figure 6 - Annual hydrological response means and trend lines adjusted to time series data.

Although there were no long-term trends in precipitation, streamflow and hydrological response indicative of large temporal scale impacts of land-cover change, there was a clear relation between precipitation and hydrological response with deforestation rates when analyzed on a yearly basis. In fact, when comparing annual deforestation rates with hydrological response and precipitation curves year by year, the two curves were similar in amplitude and phase, suggesting a close relationship between them (Voldoire and Royer, 2004; Chagnon et al. 2004; Chagnon et al. 2005; Correia et al., 2006) (**Figure 7**).

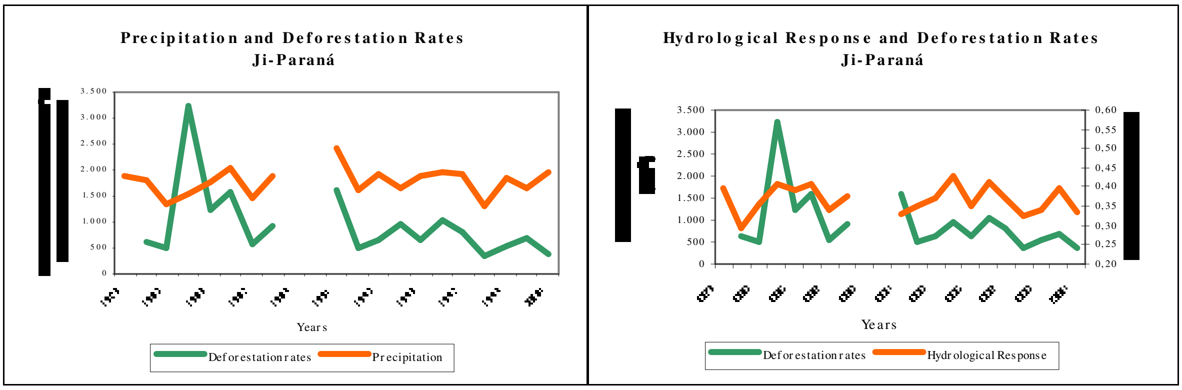

Figure 7 – Precipitation and hydrological response curves related to deforestation rates.

This suggests that forest removal may have a more immediate impact on hydrological dynamic, but this impact may be ephemeral. A plausible explanation for this short-term effects of deforestation may be the pattern of land use in Rondônia, which is characterized by frequent fires, a majority of pastures with low soil compaction and little cattle densities, and a lot of secondary vegetation areas ('capoeiras'). The forest loss can cause rapid changes in hydrological responses, but this could be partly compensated by land use patterns, where vegetation is regenerating and replacing cover in some areas, whereas other areas are being clear-cut. In a basin this size, where water and energy circulates in huge quantities, considerable smoothing occurs, which may compensates for local changes in land cover. Maybe, different types of land use would affect the hydrological regime differently. In this way, secondary vegetation may have an important role in maintaining the basic hydrological processes, such as infiltration, interception, streamflow, and evapotranspiration.

Although soil structure and geology are major factors influencing residence time in a drainage basin (Hewlett, 1982), the results have showed that geology and soils were contributing causes, but the strongest factor in disturbed basins seems to be the land cover change, which controls the water availability and fluxes. Specifically, forest removal should be expected to cause a decline in infiltration capacity at neighboring drainage, thus increasing runoff and decreasing residence time.

To test the significance of the relations between hydrological parameters and deforestation rates it was applied the non-parametric statistic "Spearman's rs" which tests the null hypothesis that two variables are not related (Siegel, 1977). All the 'rs' values were found to be significant, showing that a statistically significant correlation between deforestation rates and hydrological variables exists. Finally, there were not temporal correlations between the variables, discounting the possibility of an overestimate of "Spearman's rs" due to temporal autocorrelation (Marengo et al., 1998).

4. Concluding remarks

In the JI basin, despite its 55% deforestation area, it were not detected long-term trends (positive or negative) in hydrological variable time sets that could suggest climatic change. However, the hydrological response and precipitation were related to annual deforestation rates, which curves have shown the same dynamics and amplitude of the changes. This fast response of hydrological variables indicates that forest removal disturbs the water cycle, determining certain behavior patterns.

The identification of the spatial scale, which the deforestation begins to cause climatic changes, is a big question, and it will continue to be investigated. The real influence of geology, topography, drainage density, and soil depth on hydrological dynamic, combined to land-use and land-cover changes must be further investigate.

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