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# THE RATE AND EXTENT OF DEFORESTATION IN WATERSHEDS OF THE SOUTHWESTERN AMAZON BASIN

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*Abstract*. The rate and extent of deforestation determine the timing and magnitude of disturbance to both terrestrial and aquatic ecosystems. Rapid change can lead to transient impacts to hydrology and biogeochemistry, while complete and permanent conversion to other land uses can lead to chronic changes. A large population of watershed boundaries ($N =$ 4788) and a time series of Landsat TM imagery (1975–1999) in the southwestern Amazon Basin showed that even small watersheds (2.5–15 km$^2$) were deforested relatively slowly over 7–21 years. Less than 1% of all small watersheds were more than 50% cleared in a single year, and clearing rates averaged 5.6%/yr during active clearing. A large proportion (26%) of the small watersheds had a cumulative deforestation extent of more than 75%. The cumulative deforestation extent was highly spatially autocorrelated up to a 100–150 km lag due to the geometry of the agricultural zone and road network, so watersheds as large as $\sim$40 000 km$^2$ were more than 50% deforested by 1999. The rate of deforestation had minimal spatial autocorrelation beyond a lag of $\sim$30 km, and the mean rate decreased rapidly with increasing area. Approximately 85% of the cleared area remained in pasture, so deforestation in watersheds of Rondônia was a relatively slow, permanent, and complete transition to pasture, rather than a rapid, transient, and partial cutting with regrowth. Given the observed land-cover transitions, the regional stream biogeochemical response is likely to resemble the chronic changes observed in streams draining established pastures, rather than a temporary pulse from slash-and-burn.

*Key words: Amazon Basin; deforestation; disturbance; land cover change; pasture; Rondônia, Brazil; scaling laws; tropical forest.*

## Introduction

Large areas of the humid tropics are being deforested for logging and agriculture (DeFries 2002). The regional impact of the deforestation on hydrology, biogeochemistry, and aquatic ecosystems depends on the rate, extent, and scaling behavior of clearing and subsequent land use. Within a region, land-use and land-cover changes have characteristic temporal and spatial scales, and they therefore occupy nested watersheds of diverse scale to varying degrees. In gauging the nature and intensity of various watershed-scale impacts, it is useful to recognize and quantify the probability distributions of such effects. What is the proportion of watersheds of a given size that can be completely deforested in a chosen time interval? To what extent are intensively transformed watersheds contiguous? At what geographic scale is deforestation likely to be diffuse rather than contiguous? These characteristics affect the connectivity of impacted watersheds, as well as the intensity of hydrologic and biogeochemical changes to stream flow.

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Deforestation causes changes in hydrology and stream biogeochemistry that can be either transient or chronic depending on the rate of clearing, the final extent of deforestation, and the subsequent land use. Rapid clearing and burning of forest vegetation produces a pulse of cations and nutrients in soil pore waters (Chorover et al. 1994, Williams et al. 1997) and in stream waters draining small watersheds that have been rapidly deforested (Bormann and Likens 1979, Swank and Vose 1997, Williams and Melack 1997, Swank et al. 2001). These pulses may persist for several years but are generally attenuated less than a decade following disturbance. After clearing, more permanent changes in vegetation and land use can also cause chronic changes in the concentrations of nutrients in receiving streams, including increased nitrogen and/or phosphorus concentrations for watersheds maintained in grass (Swank and Vose 1997) or pasture (Biggs et al. 2004). The changes in the nutrient and light regime can lead to changes in algal production, dissolved oxygen, and ecosystem productivity (Neill et al. 2001). Further changes in land use including cattle establishment, agricultural intensification, fertilizer use, and urbanization also impact nutrient concentrations and biogeochemical functioning in streams (Matson et al. 1997, Downing et al. 1999, Martinelli et al. 1999, Biggs et al. 2004).

In the context of stream biogeochemistry, recognition of the spatial and temporal structure of deforestation leads to two central questions: What proportions of the watershed population in deforesting regions undergo rapid clearing and are likely to show transient stream biogeochemical perturbations of the kind documented by the Hubbard Brook experiments (Bormann and Likens 1979), the Coweeta experimental watersheds (Swank and Vose 1997), and a small (2 ha) catchment in the Central Amazon (Williams and Melack 1997)? What proportion are slowly but heavily deforested, converted to pasture, and likely to show chronic stream biogeochemical perturbations of the kind documented by Neill et al. (2001) and Biggs et al. (2004)?

Studies of the effect of deforestation on stream chemistry and aquatic ecosystems often sample a small number of streams and, even in regional surveys, only a small fraction of the watershed population can be sampled. Understanding the regional impact of deforestation on the stream network requires determination of the probability distributions of the rate of clearing and extent of pasture establishment. Regional analyses of deforestation have often used the pixel or administrative boundaries (Dale et al. 1993, Flamm and Turner 1994, Verburg et al. 1999, Chomitz and Thomas 2001, Weng 2002) but have not used watershed boundaries to answer the questions posed above.

The scaling behavior of land cover controls its cumulative effects on watersheds of different sizes (King et al. 2005). Land cover is often spatially autocorrelated (Qi and Wu 1996) due to patterns in soil type, settlements (Wear and Bolstad 1998), road construction (Chomitz and Gray 1996, Qi and Wu 1996), and zoning. Spatial autocorrelation conserves the moments of the probability distributions of a random variable and will correspond to higher deforestation rates or extents over larger areas than expected under spatial independence. For example, if small watersheds that are heavily deforested (75–100% of the watershed area) tend to be clustered, the probability is increased that a larger watershed will also be heavily deforested. Conversely, if heavily deforested, small watersheds are equally likely to be next to a forested or deforested watershed, then larger watersheds will have a lower probability of being heavily deforested. Autocorrelation therefore increases the size of watersheds that are heavily deforested and likely to experience disturbed stream biogeochemistry. An empirical understanding of the scaling behavior of deforestation is necessary to assess how regional land use transformations may affect regional biogeochemical and hydrological cycles across a range of scales.

The goals of this paper were to quantify the rate, extent, and scaling behavior of deforestation in watersheds of the southwestern Brazilian Amazon Basin and to identify the types of impacts likely to result in stream biogeochemistry given the observed pattern of deforestation. The frequency distribution of clearing sizes and the spatial arrangement of clearing vis à vis administrative zoning boundaries were quantified using a time series of Landsat Thematic Mapper (TM) images (1975–1999) over the Brazilian state of Rondônia in the southwestern Amazon Basin (Fig. 1). A large population of watershed boundaries ($n = 4788$) was overlaid on the time series maps, and a simple mathematical model was fit to the deforestation time series for each watershed to quantify the deforestation rate (Table 1). The probability density functions of the extent and rate of clearing were then determined for the observed watersheds. Geostatistical analysis was used to quantify the spatial autocorrelation of the rate and extent of deforestation and was used to quantitatively explain the observed scaling behavior. Literature on the effects of rapid or extensive deforestation on stream biogeochemistry was summarized to identify the likely types of perturbations expected given the deforestation patterns observed in the watershed analysis.

The specific questions addressed by the research included these questions: What was the rate of deforestation in watersheds of different sizes in Rondônia during periods of active vegetation conversion? What was the final, stable deforestation extent in watersheds where the clearing rate had slowed? Were the clearing rate and extent autocorrelated, and how did this affect their scaling behavior and the size of heavily deforested watersheds? Finally, is deforestation better conceptualized as a rapid transformation of vegetation causing transient pulses of stream nutrients or as a gradual and permanent one leading to chronic changes in stream biogeochemistry?

## Study Area and Methods

### *Study area*

The Brazilian State of Rondônia lies in the southwestern Amazon Basin on the border with Bolivia (7.5–14° S, 59–66° W; Fig. 1). Closed- and open-canopy tropical rainforest dominate the original vegetation cover (RADAMBRASIL 1978). Large-scale colonization of Rondônia began with the construction of the BR-364 highway in the late 1960s (Goza 1994). The population reached 1.3 million people by the year 2000, and ~53 000 km$^2$ (25%) of the forest was cleared for cropping and pasture by 1993 (Pedlowski et al. 1997).

Land in Rondônia has been zoned for different uses, including agriculture (51% of the State's area), extraction of forest products such as nuts, rubber, fruit, and limited selective logging (14%), and protection of forest for indigenous peoples, parks, and biological reserves (35%; Fig. 1). The main agricultural corridor (marked A in Fig. 1) accounted for 99% of the area zoned for agriculture in Rondônia in 1999. The corridor consists of one contiguous block of land that encompasses 117 940 km$^2$, and extends ~600 km along the highway BR-364 and extends 115–300 km wide, perpendicular to the highway (Fig. 1). The 35 protected areas in the State

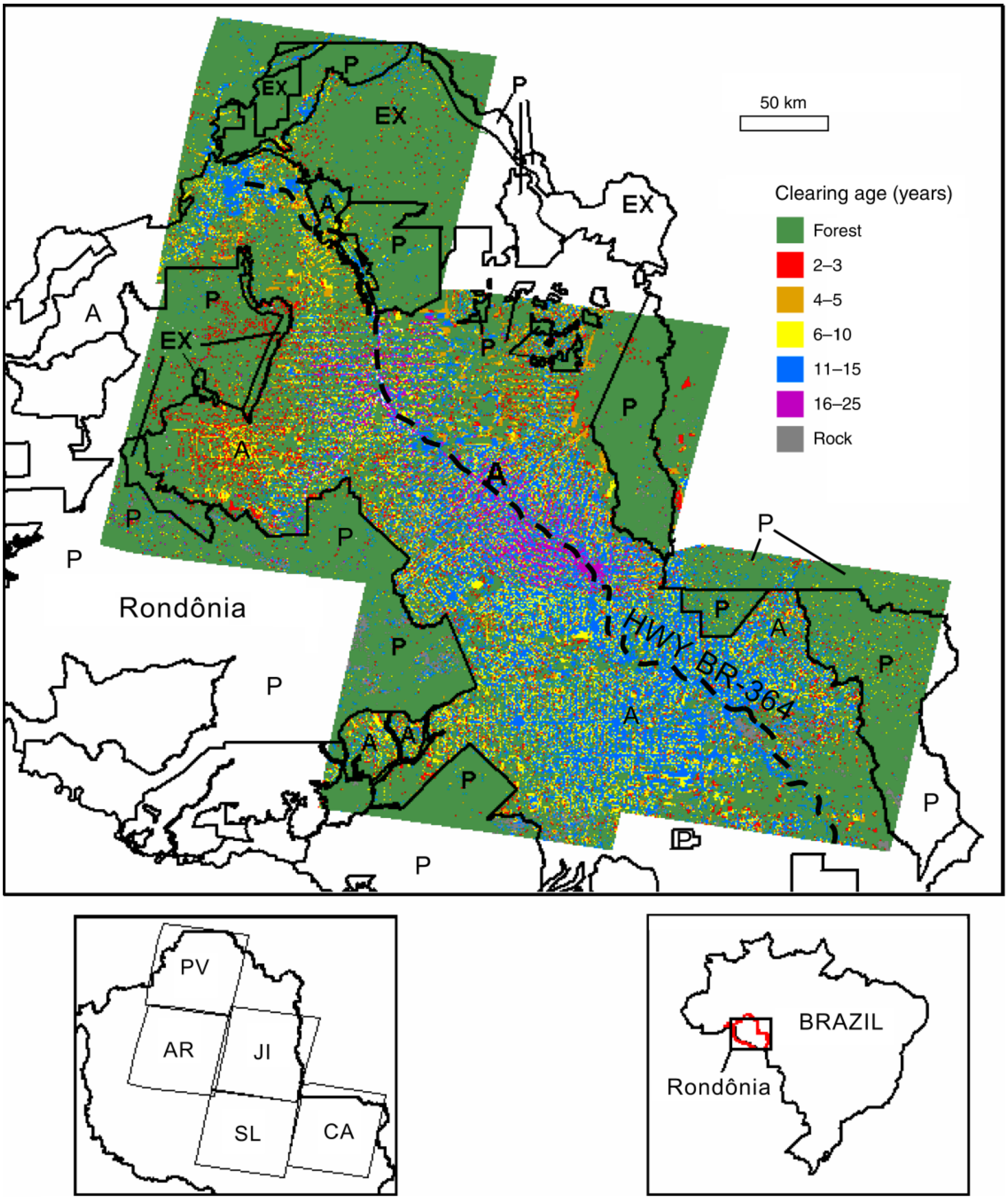


FIG. 1. Zoning boundaries and Landsat TM time series of deforestation extent in Rondônia, Brazil. Codes are: A, agricultural zone; EX, extractive reserve; and P, protected areas. Abbreviations in the lower left-hand map represent the Landsat scenes named in Table 2. The ages are with reference to 2001, so a clearing age of 2 indicates pixels cleared between the 1998 and 1999 image. The most recent image analyzed was from 1999.

(marked P in Fig. 1) border the agricultural zone on both sides and encompass 83 000 km$^2$. Ninety percent of the protected area occurs in seven separate zones between 2150 and 42 000 km$^2$. Zoning maps of Rondônia for 1988 and 1997 were made available by UNEP's Planafloro project (*unpublished data*).

The agricultural corridor crosses four major river systems in the state (Fig. 2): the Candeias, Jamari, Jarú, and Ji-Paraná. The largest watershed, the Ji-Paraná, drains 64 127 km$^2$.

### *Deforestation time series*

The main agricultural corridor and surrounding forested areas of Rondônia were covered by five Landsat TM scenes (Fig. 1). A time series of deforestation maps from 1975 to 1999 was made for those scenes by Roberts

TABLE 1. Summary of criteria used to identify the deforestation stage of a given watershed and variables used to describe the rate and extent of deforestation using the logistic equation.

| Variable | Description | Stage I | Stage II | Stage III |
|---|---|---|---|---|
| Identification of watershed stage | | | | |
| $f_{1999}$ | cumulative deforestation extent in 1999 (fraction of watershed area) | <0.15 | >0.15 | >0.15 |
| $k_{1999}$ | deforestation rate in 1999 | | >0.01 | <0.01 |
| Variables describing deforestation rate and extent | | | | |
| $t_o$ | year of onset of active clearing | | $\min[f''(t)]$ | $\min[f''(t)]$ |
| $t_r$ | year of most recent satellite image | 1999 | 1999 | 1999 |
| $t_e$ | year of end of active clearing | | | $\max[f''(t)]$ |
| $T_d$ | duration of active clearing (years) | | | $t_e - t_o$ |
| $k$ | rate of deforestation during active clearing (fraction of watershed $yr^{-1}$) | | $\left[\frac{f_{1999} - f(t_o)}{1999 - t_o}\right]$ | $\left[\frac{f(t_e) - f(t_o)}{T_d}\right]$ |
| $f_s$ | stable (steady-state) deforestation extent | | | $f(t_r)$ |

et al. (2002; Table 2), who classified the imagery into seven classes (primary forest, pasture, second growth, soil/urban, rock/savanna, water, and cloud) using spectral mixture analysis. Two aggregate classes of "forest" and "deforested" were defined from those seven classes. The forest aggregate class contained primary forest, water, cloud, and rock/savanna. The deforested class included pasture, soil/urban, and second growth. The forest, pasture, and second growth classes accounted for 98% of the study area; so, including water, cloud, and rock/savanna with the forest class and soil/urban with the deforested class had minimal impact on the results. The cumulative deforested area for each year included all areas that classified as deforested in the given year and any previous image. The accuracy, assessed by Roberts et al. (2002) using airborne videography, was greater than 85%. Images were not available for all years, and only two scenes (AR and JI in Fig. 1) had imagery back to 1975 and 1978, which allowed definition of the onset of deforestation as $t_o$ in Eq. 2. The cumulative deforestation extent in 1999 ($f_{1999}$) was determined using all five scenes, and the time series of clearing back to the 1970s was determined using the AR and JI scenes only.

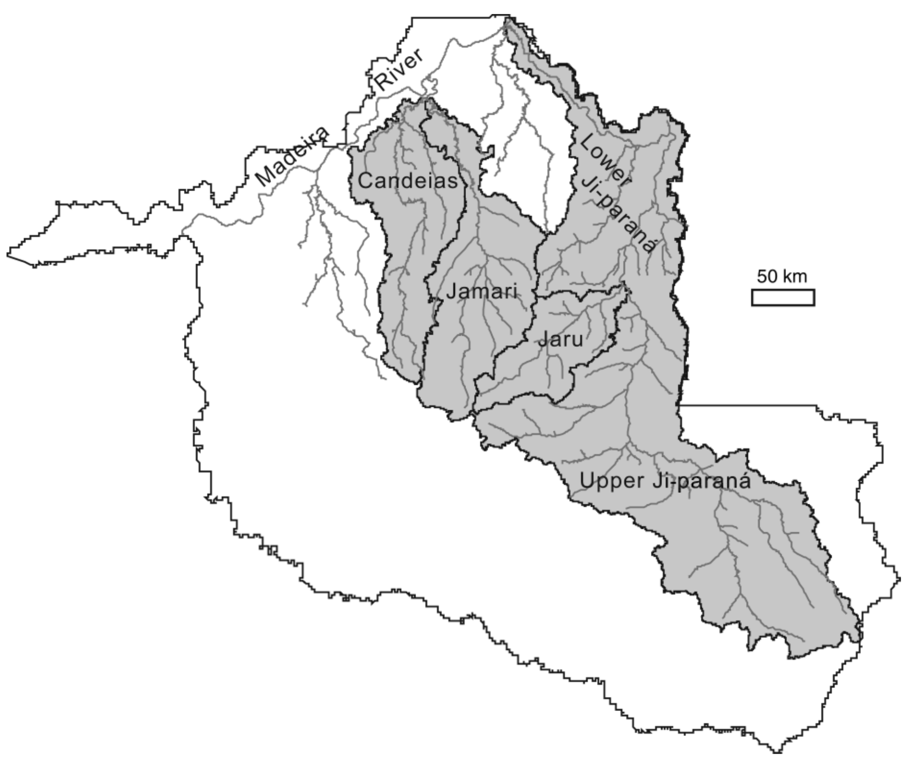


FIG. 2. Major river systems of Rondônia included in the study area. The Candeais, Jamari, Jaru, and Upper Jiparaná are sixth-order watersheds, and the upper and lower Jiparaná combined is a seventh-order watershed.

TABLE 2. Landsat TM time series images.

| Scene name | Map code | Years available |
|---|---|---|
| Porto Velho | PV | 1986, 1988, 1992, 1993, 1996–1998 |
| Ariquemes | AR | 1975, 1984, 1988–1999 |
| Jiparana | JI | 1978, 1986, 1988–1990, 1993, 1996–1999 |
| Santa Luzia | SL | 1986, 1988–1990, 1992, 1995–1997, 1999 |
| Cacoal | CA | 1988, 1989, 1992, 1994, 1996, 1998, 1999 |

The deforested area included all pixels that classified as pasture or secondary growth using spectral mixture analysis. This represents a heterogeneous mix of pasture in different conditions and secondary vegetation in varying stages of regrowth. The remote sensing definition of deforestation did not include other anthropogenic processes, including subcanopy fires or disturbances smaller than $30 \times 30$ m which may impact tropical forests (Nepstad et al. 1999).

The size of clearings made in a single year was determined using two years (1996 and 1997) that had imagery in all five Landsat TM scenes. The boundaries of the clearings defined the cumulative area cleared as a function of clearing size, or the cumulative area function (CAF). The CAF is different from a cumulative distribution function (cdf), which would be the frequency of clearings as a function of clearing size. The CAF, by contrast, is the area or number of pixels in each clearing size and not the number of clearings. The derivative of the CAF gives the probability that a given cleared pixel lies within a clearing of size $x$.

### *Watershed boundaries*

A 90-m resolution digital elevation model (DEM) from NASA's Shuttle Radar Topography Mission was used to delineate watershed boundaries. The final data set had 8994 watersheds of seven Strahler orders with drainage areas ranging from 2.5 to 64 127 km$^2$ (Ji-Paraná basin; Table 3). An eight-direction flow-accumulation algorithm delineated the stream network and watershed boundaries, as coded in ARC/INFO (Jenson and Dominique 1988). The minimum watershed area was set to 2.5 km$^2$, which yielded a stream network that most closely matched the stream network of 1:100 000 topographic maps. A digital elevation model with higher resolution and accuracy may yield slightly different watershed boundaries, particularly in relatively flat areas, which can generate artifacts such as long, straight watersheds (Tribe 1992). Most of the Rondônia study area had sufficient relief to yield channel networks that closely matched the blue lines of the 1:100 000 topographic maps. The seven Strahler orders did not have mutually exclusive area bins; e.g., the largest watersheds of order 2 were larger than the smallest watersheds of order 3. Watersheds less than 90% covered by the Landsat TM data were excluded from the analysis.

The watershed boundaries were overlain on the time series of deforestation maps in order to determine the cumulative deforestation extent in 1999 (all five scenes, 8994 watersheds) and the full time series of deforestation back to 1975–1978 (AR and JI scenes, 4788 watersheds). The analysis was performed by binning the watersheds by order instead of by area to prevent including nested watersheds in a single bin.

### *Mathematical description of deforestation*

Clearing of a given watershed may be modeled as a process with three stages defined by the rate and extent of deforestation (Fig. 3): (I) predisturbance, where cumulative deforestation extent and annual rates of conversion are low; (II) active clearing, where cumulative deforestation extent is intermediate and annual rates of conversion are highest; and (III) stable, where clearing of primary forest has slowed and cumulative deforestation extent has begun to stabilize. The stable deforestation extent of Stage III may be controlled by several characteristics of the watershed and regional economy, including the road network, soil quality, topography, location within the transportation network, farmers' access to capital and labor, population density, and market value of agricultural products (Chomitz and Gray 1996, Kaimowitz and Angelsen 1998).

The cumulative extent of deforestation [$f(t)$] is simply the cumulative fraction of an area classified as deforest-

TABLE 3. Watershed attributes.

| Stream order | Watershed area (km$^2$) | | | | | $N_t$ | $N_{ts}$ |
|---|---|---|---|---|---|---|---|
| | Mean | Minimum | Q05 | Q95 | Maximum | | |
| 1 | 5.5 | 2.5 | 2.7 | 15.3 | 64 | 6824 | 3761 |
| 2 | 26 | 5.5 | 9.5 | 67 | 246 | 1710 | 767 |
| 3 | 113 | 16.7 | 42 | 304 | 559 | 347 | 217 |
| 4 | 534 | 107 | 174 | 1696 | 3137 | 85 | 35 |
| 5 | 2544 | 577 | 667 | 5964 | 6097 | 23 | 10 |
| 6 | 18 792 | 7281 | | | 39 465 | 4 | 0 |
| 7 | 46 760 | 29 392 | | | 64 127 | 2 | 0 |
| Total | | | | | | 8994 | 4788 |

*Notes:* $N_t$ is the number of watersheds in all five Landsat TM scenes used to determine the cumulative deforestation extent in 1999, and $N_{ts}$ is the number of watersheds in the scenes with full time series that were used to determine the rate of deforestation (AR and JI scenes). Q05 and Q95 represent the 5th and 95th percentiles.

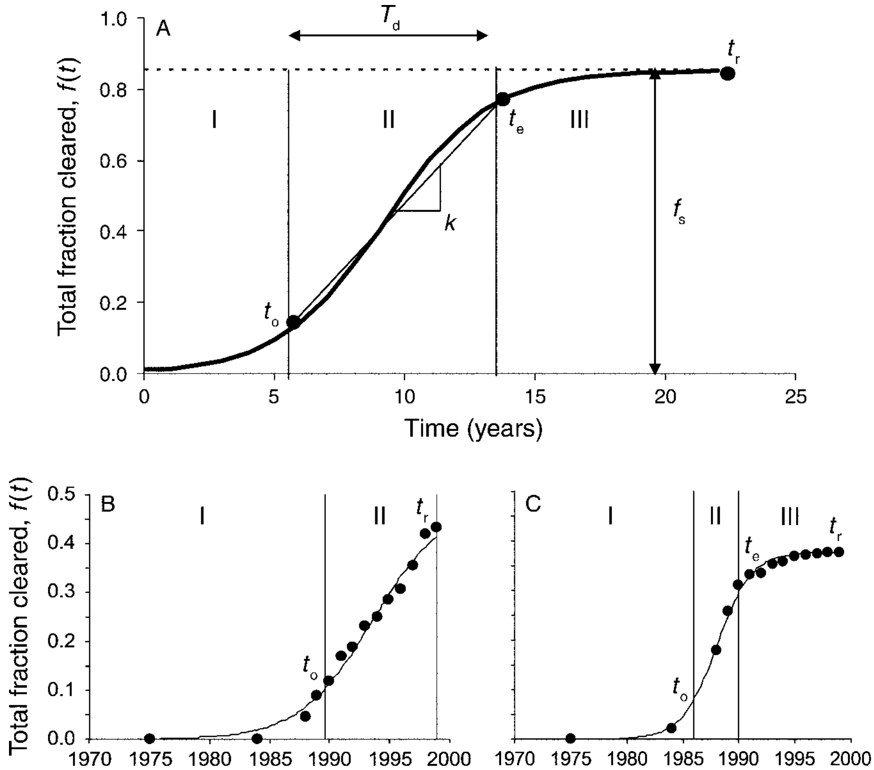


FIG. 3. (A) Logistic model of deforestation in watersheds. (B, C) Observed deforestation time series from 1975 to 1999 for two first-order watersheds in Stages II (for B) and III (for C) with the logistic model fits. Variables are as follows: $T_d$, duration of active clearing (yr); $k$, annual rate of clearing ($yr^{-1}$); $t_o$, year of the onset of active clearing; $t_e$, year of the end of active clearing; $t_r$, year of most recent satellite image; $f_s$, cumulative fraction cleared in stage-III watersheds.

ed up to a given year. Consistent definition and interpretation of the rate of deforestation is not as straightforward. The deforestation rate, $k$, is

$$k = \frac{f_2 - f_1}{t_2 - t_1} \tag{1}$$

where $f_i$ is the cumulative fraction of an area deforested by time $i$, and $t_i$ is the year at time $i$. The value of $k$ depends critically on $t_1$ and $t_2$. In practice, $t_1$ and $t_2$ are often chosen based on the available satellite imagery. This would tend to underestimate the rate during active vegetation clearing if conversion started much after $t_1$ or ended much before $t_2$. Consistent definition of the rate of deforestation requires unambiguous and preferably automated identification of the beginning and end of clearing.

Identification of the beginning ($t_o$) and end ($t_e$) of clearing may be accomplished by fitting an observed deforestation time series to a mathematical function. Transitions in vegetation phenology have been identified using the logistic function (Fischer 1994, Zhang et al. 2003), which is adapted here to describe the deforestation time series,

$$f(t) = \frac{f_s}{(1 + Ae^{-Bt})} \tag{2}$$

where $f(t)$ is the cumulative fraction of the watershed cleared by time $t$, $f_s$ is the stable deforestation extent, $e$ is the base of the natural logarithm, and $A$ and $B$ are fitted parameters. A minimum deforestation threshold (0.15) separates forested (Stage I) watersheds from Stage II and III watersheds. The value 0.15 was used because regional surveys showed minimal impact of deforestation on stream biogeochemistry below a cumulative deforestation extent of 0.15 (Biggs et al. 2004) and because the logistic equation often did not converge to stable values for watersheds less than 0.15 cleared. Stage II and III watersheds may then be separated by the magnitude of the first derivative of Eq. 2, which is the rate of deforestation in 1999 (Fig. 3). Stage III watersheds were defined as those having a deforestation rate less than 0.01 (1%) $yr^{-1}$ in 1999. The stable deforestation extent ($f_s$) is known only for watersheds in Stage III, and is the deforestation extent in the most recent available image (Table 2).

This model assumes that cleared areas remain in pasture or secondary forest and are not permanently abandoned to forest. In 1999, cleared area in Rondônia was mostly (79%) pasture, with some secondary growth (21%; Roberts et al. 2002). In any given pair of years from 1986–1999, transitions from secondary growth to forest occurred in 11% of the second growth area (2.3%

of the total deforested area), but most secondary growth either remained as second growth (~65%), or reverted to pasture (24%). Only 16% of pasture pixels transitioned to secondary growth in the next year, and 84% of pastures remained as pastures (Roberts et al. 2002). This suggests that cleared areas become a dynamic mosaic dominated by pastures with some secondary growth and little permanent abandonment to forest. The stable deforestation extent of Stage III ($f_s$) therefore reflects a decrease in the rate of clearing of primary forest, rather than a state where deforestation rate equals the rate of afforestation.

The rate of deforestation ($k$) during active clearing is defined differently for watersheds in Stage II and III because the end of active deforestation ($t_e$) is not defined for Stage II watersheds:

$$k = \begin{cases} [f(t_e) - f(t_o)]/[t_e - t_o], & \text{Stage III watersheds} \\ [f(t_r) - f(t_o)]/[t_r - t_o], & \text{Stage II watersheds} \end{cases} \quad (3)$$

where $t_o$ and $t_e$ are the years of the onset and end of active deforestation, defined as when the second derivative of $f(t)$ is at its maximum and minimum, respectively (Table 1). $f(t_e)$ and $f(t_o)$ are the deforestation extents at the beginning and end of Stage II, and $t_r$ is the year of the most recent available satellite image. The duration ($T_d$) of active clearing is defined only for Stage III watersheds because the end of active deforestation ($t_e$) is not defined for Stage II watersheds:

$$T_d = t_e - t_o. \quad (4)$$

Time series of deforestation extent by watershed (Fig. 3) were generated by overlaying watershed boundaries on the time series of deforestation maps (Fig. 1). Eq. 2 was then fit to the observed time series using a multidimensional, unconstrained nonlinear minimization algorithm (Nelder-Mead simplex direct search method). Time series with a low deforestation extent until 1997 and a rapid jump in 1998 or 1999 did not converge to a solution of Eq. 2. For those watersheds (5% of all watersheds), $k$ was defined as the difference in deforestation extent between 1999 and 1997, divided by two years.

*Scaling behavior, geostatistics, and spatial configuration*

We hypothesize that the probability distributions of deforestation extent $f(t)$ and the rate of deforestation during active clearing ($k$), and therefore the hydrological, biogeochemical, and other cumulative environmental impacts, should depend on watershed size due to the spatial and temporal structure of clearing activities. A small watershed could be entirely forested or deforested, but as watershed area increases, the watershed boundary intercepts a combination of protected and agricultural zones, thereby decreasing the maximum possible and increasing the minimum possible deforestation extent. Likewise, clearing rates may be high in a small watershed if a single farmer or group of farmers clears a large fraction of their property in a single year. As watershed size increases, the probability of simultaneous clearings also decreases, thereby decreasing the aggregate deforestation rate. Colonists in the Amazon typically clear less than 5–10% of their property in any given year due to restricted access to labor and capital, though initial clearing rates may be up to 50% in a single year (Fujisaka et al. 1996). These limits on clearing rates should cause annual deforestation rates to be relatively low, even on single plots and lower in larger watersheds.

The extent and rate of clearing are random variables that have different means, variance, and scaling behavior. The clearing rate or extent in a watershed of a given order $n$ is the mean of the rate or extent in $M$ watersheds of order $n - 1$. The variance of the sample mean for $M$ independent random variables is

$$\sigma_n = \frac{\sigma_{n-1}}{\sqrt{M}} \quad (5)$$

where $\sigma_n$ is the variance of the deforestation extent in $n$th-order watersheds, and $M$ is the number of watersheds of order $n - 1$ contained in a watershed of order $n$. Eq. 5 assumes that watersheds of order $n - 1$ completely fill the area of the watershed of order $n$. Departures from Eq. 5 can occur if the random variables are spatially autocorrelated.

Geostatistical methods were used to identify spatial autocorrelation in deforestation rates and extents. Semivariograms, which identify how the variance changes with distance from all points in the study area, were constructed for first-order watersheds. Semivariograms identify the small-scale variance (nugget), the range over which a variable is autocorrelated (range), and the regional variance (sill). The range is the distance where the semivariance is ~95% of the sill. Empirical semivariograms were constructed using the classical (Matheron) estimator, and exponential semivariogram models were fit to the empirical semivariograms.

The spatial configuration of deforestation within a watershed may also affect the impact on streams. Riparian zones often exert strong controls on the delivery of sediment and nutrients from upslope and have been demonstrated to influence the transport of nitrogen in forested catchments of the Amazon (Brandes et al. 1996). The spatial configuration of deforestation vis à vis the stream network was quantified for the Rondônia watersheds using buffers around the stream network. The deforestation extent in buffers of 90, 180, 270, and 540 m around the stream network was calculated from the deforestation map of 1999. The deforestation extent in these buffers was compared with the deforestation extent in the area as a whole to establish if deforestation had a spatial pattern vis à vis the stream network.

*Stream biogeochemistry and the effects of deforestation*

The probability distributions of the rate and extent of deforestation were used to estimate the fraction of

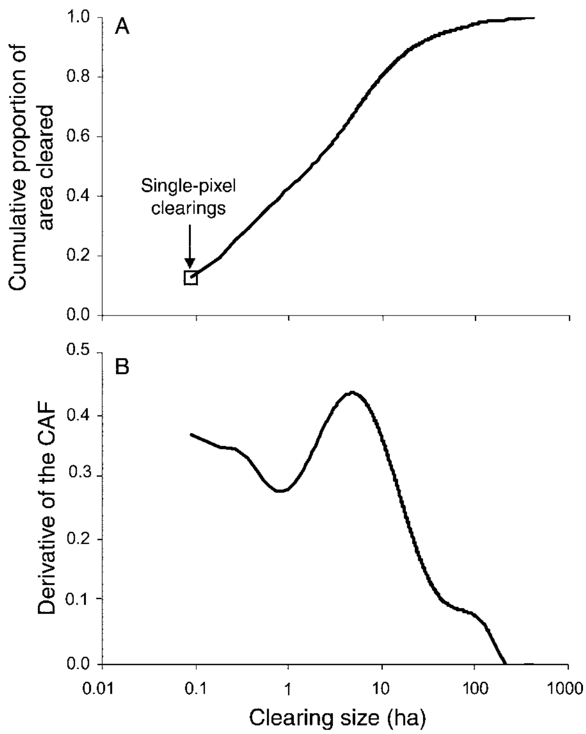


FIG. 4. (A) Cumulative fraction cleared vs. clearing size (log scale) between 1996 and 1997 in the main agricultural corridor of Rondônia. The data include all pixels cleared between 1996 and 1997 and define the cumulative area function (CAF). (B) Derivative of the CAF vs. clearing size (log scale). See *Study area and methods* for further details.

watersheds likely to experience either rapid or extensive clearing. Literature values were used to characterize the type and magnitude of changes in stream biogeochemistry associated with either rapid or extensive deforestation. An intensive study of a small (2-ha) watershed in the Central Amazon (Williams et al. 1997) quantified the effect of slashing and burning of forest vegetation on stream nutrient fluxes and concentrations. More than 80% of the watershed was cut and burned in a single year, so those results were used to characterize changes in stream biogeochemistry caused by rapid clearing without cattle populations. The soil type and depth of the catchment in the Central Amazon differ from soils commonly encountered in Rondônia, so actual changes in stream biogeochemistry in Rondônia may differ from those observed by Williams et al. (1997). The main objective is not to predict precise values for stream nutrient concentrations in all rapidly deforested watersheds in Rondônia, but rather to place data from sampled watersheds in a regional context and to place some values on the likely probability distribution of magnitudes of changes caused by cutting and burning of tropical rain forest.

A regional survey of stream nutrient concentrations in Rondônia was carried out by Biggs et al. (2004). The watersheds included a range of drainage areas (1.8–33 000 $km^2$), orders, and deforestation extents. Deforested watersheds were predominantly in pasture, and heavily deforested watersheds (>80% deforested) had low clearing rates in the 1–3 years prior to sampling and resembled Stage III watersheds in the logistic model. The results showed an increase in stream Cl, total dissolved nitrogen (TDN), and total dissolved phosphorus (TDP) in the dry season and a smaller but detectable increase in Cl and TDP in the wet season, but only for watersheds more than ~60–80% in pasture. The observed stream biogeochemistry was used to characterize the changes expected from extensive cumulative deforestation and pasture establishment.

## RESULTS

### *Clearing sizes*

Clearings made in a single year (1996–1997) ranged from 0.09 ha (1 pixel) to 490 ha (Fig. 4A). Single-pixel clearings accounted for 10% of the total area cleared, and the modal clearing size was 5 ha (Fig. 4B). Clearings of fewer than 22 ha accounted for 90% of the cleared area, and less than 2.4% of the cleared area was in clearings larger than 100 ha. Some of the single-pixel clearings likely represent "noise" or misclassifications due to topographic shading, canopy effects, interannual variability in plant phenology, or natural tree-fall gaps, which may be as large as 0.07 ha (Myers et al. 2000). Other small clearings may be due to anthropogenic vegetation conversion associated with selective logging and clearing along forest edges. The single-pixel clearings represent only 10% of the total cleared area and do not significantly impact the results at the watershed scale.

### *Zoning boundaries and deforestation*

Areas zoned for agriculture (ranching) on the 1997 zoning map had a higher deforestation extent (50%) than protected areas (7%) and extractive reserves (6%; Fig. 5). This large difference in deforestation extent by zone also held for the 1988 zoning map: areas designated for protection, extraction, or agriculture in the 1988 zoning map were 7%, 17%, and 50% cleared by 1999, respectively. Agricultural zones had a higher percentage of fertile alfisol soils (15%) compared with protected areas (3%) or extractive reserves (1.5%), partly due to the inclusion of soil type in the initial planning stages of the development projects in Rondônia. The high rate of clearing in agricultural zones and low clearing rates in protected areas resulted in a contiguous block of deforestation in the central agricultural corridor, flanked by contiguous blocks of forest.

### *Watershed boundaries and deforestation*

The center of the agricultural corridor along Highway BR-364 spans the Jarú and Ji-Paraná watersheds and was largely deforested by 1999 (Figs. 1 and 6). Most first-order watersheds in the center of the agricultural corridor were 76–100% cleared by 1999 (Fig. 6).

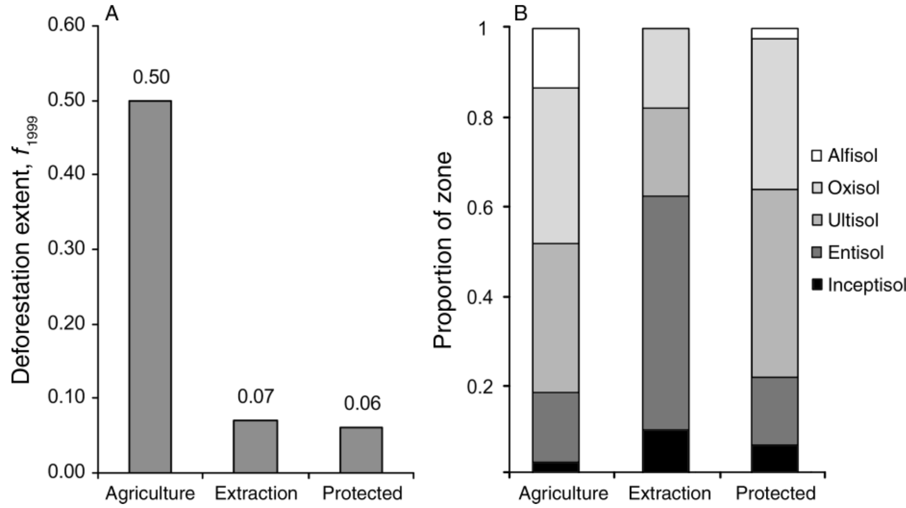


FIG. 5. (A) Deforestation extent in 1999, measured as the cumulative fraction of the area that is deforested, by zone, and (B) distribution of soil types, by zone.

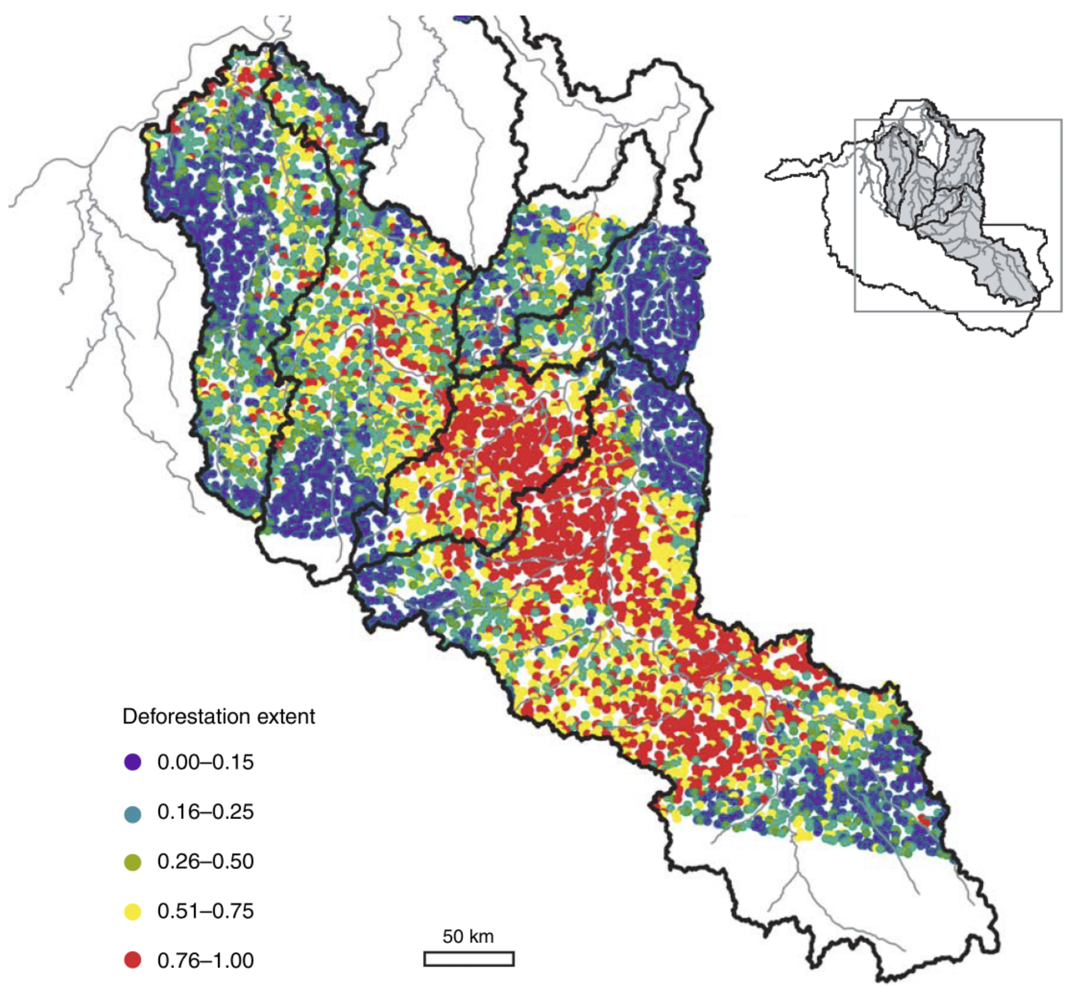


FIG. 6. Map of the cumulative deforestation extent, by 1999, in first-order watersheds (2.5–15 $km^2$). Each dot represents one watershed.

TABLE 4. Mean deforestation extent in 1999 ($f_{1999}$), deforestation rate during active clearing ($k$), and duration of active clearing ($T_d$) by watershed size and stage.

| Watershed size and stage | $N$ | $N_{fit}$ | $R^2$ | $f_{1999}$ | $k$ (yr$^{-1}$) | $T_d$ (years) |
|---|---|---|---|---|---|---|
| Order 1, 2.5–12.5 km$^2$ | | | | | | |
| Stage I | 1089 | | | 0.04 | | |
| Stage II | 1929 | 1715 | 0.96 | 0.54 | 0.045 | |
| Stage III | 743 | 743 | 0.96 | 0.75 | 0.096 | 7.8 |
| Order 2, 12.5–50 km$^2$ | | | | | | |
| Stage I | 175 | | | 0.04 | | |
| Stage II | 488 | 456 | 0.97 | 0.53 | 0.041 | |
| Stage III | 104 | 104 | 0.97 | 0.71 | 0.077 | 9.2 |
| Order 3, 50–220 km$^2$ | | | | | | |
| Stage I | 49 | | | 0.05 | | |
| Stage II | 153 | 147 | 0.97 | 0.51 | 0.034 | |
| Stage III | 15 | 15 | 0.98 | 0.75 | 0.063 | 11.9 |
| Order 4, 220–1020 km$^2$ | | | | | | |
| Stage I | 9 | | | 0.03 | | |
| Stage II | 24 | 24 | 0.97 | 0.51 | 0.027 | |
| Stage III | 2 | 2 | 0.98 | 0.88 | 0.043 | 13.6 |
| Order 5, 1020–5630 km$^2$ | | | | | | |
| Stage I | 2 | | | 0.04 | | |
| Stage II | 8 | 7 | 0.98 | 0.38 | 0.027 | |
| Stage III | 0 | 0 | | | | |

*Notes:* $N$ is the number of watersheds, and $N_{fit}$ is the number of watersheds where the solution to Eq. 2 converged. Mean $R^2$ values for those watersheds in which the solution to Eq. 2 converged are given. The rate ($k$) and duration ($T_d$) of active clearing were determined from the time series of deforestation extent fit to Eq. 2. The stable deforestation extent for watersheds in Stage III ($f_s$) is $f_{1999}$. The table includes only watersheds in the AR and JI scenes.

The parameters of the logistic model (Eq. 2) converged for 93% of watersheds in stages II and III, and the $R^2$ averaged 0.96–0.98 (Table 4). Watersheds had 14 points to fit to the model in the AR scene and 10 in the JI scene (Table 1). These fits were adequate to determine the rate, onset, and duration of active clearing by Eq. 2. The rate and onset of deforestation in first-order watersheds varied over the study area (Fig. 7). The onset of clearing was earliest in the Jaru watershed and in the north-western portion of the Ji-Paraná watershed (Fig. 7B). The probability distributions of the extent and rate of deforestation varied with watershed size (Figs. 8–10). Deforestation extent in first-order watersheds had a mixed bimodal and uniform distribution, where the modes occurred at the forested and deforested extremes. Large watersheds, by contrast, had a more Gaussian distribution, with a mode at the regional mean (~33% deforested). A transition to a Gaussian distribution is expected for any mean of random variables, regardless of the initial distribution (Central Limit Theorem).

The probability distribution of deforestation extent, $f(t)$, changed with time during regional clearing. Prior to extensive clearing in the 1980s, small watersheds had an approximately exponential distribution of deforestation extents, when all small watersheds were in either Stage I or II (Fig. 9). In 1989 the distribution was still roughly exponential, but with fewer forested watersheds compared with 1978. By 1999, as more watersheds became heavily deforested, the fraction of forested watersheds decreased, and the overall probability distribution became bimodal, with peaks at 0–10% and 80–90% cumulative deforestation. The trend toward an increasingly bimodal distribution of deforestation extent is expected to continue, assuming that clearing in agricultural zones continues to the stable deforestation extent observed in Stage III watersheds and that forested zones continue to be protected.

The clearing rate ($k$) was approximately lognormally distributed for all watershed sizes (Fig. 10). The clearing rate fell from 4.4–9.5%/yr for first-order watersheds to 2.7%/yr for large watersheds (Table 4). Large-scale deforestation events in a single year were rare; fewer than 7% of the small watersheds sampled had more than 20% of their area deforested in a single year, and fewer than 1% were more than 50% cleared in a single year.

### *Spatial autocorrelation and configuration*

The deforestation rate ($k$), cumulative extent ($f_{1999}$), and year of onset of clearing ($t_o$) in first-order watersheds showed differing degrees of spatial autocorrelation (Table 5, Fig. 11). $f_{1999}$ was autocorrelated up to a 140-km lag distance in first-order watersheds. The year of the onset of clearing ($t_o$) showed less autocorrelation for short lags, but was autocorrelated up to 210 km. Clearing rate ($k$), by contrast, was dominated by small-scale variability and had little spatial autocorrelation beyond ~30 km.

The ratio of the nugget to the sill of the semivariogram quantifies the fraction of total variance due to local (nugget) and regional (sill) variance. Due to high autocorrelation over small distances, only 17% of the variance of $f_{1999}$ was due to small-scale variability; most

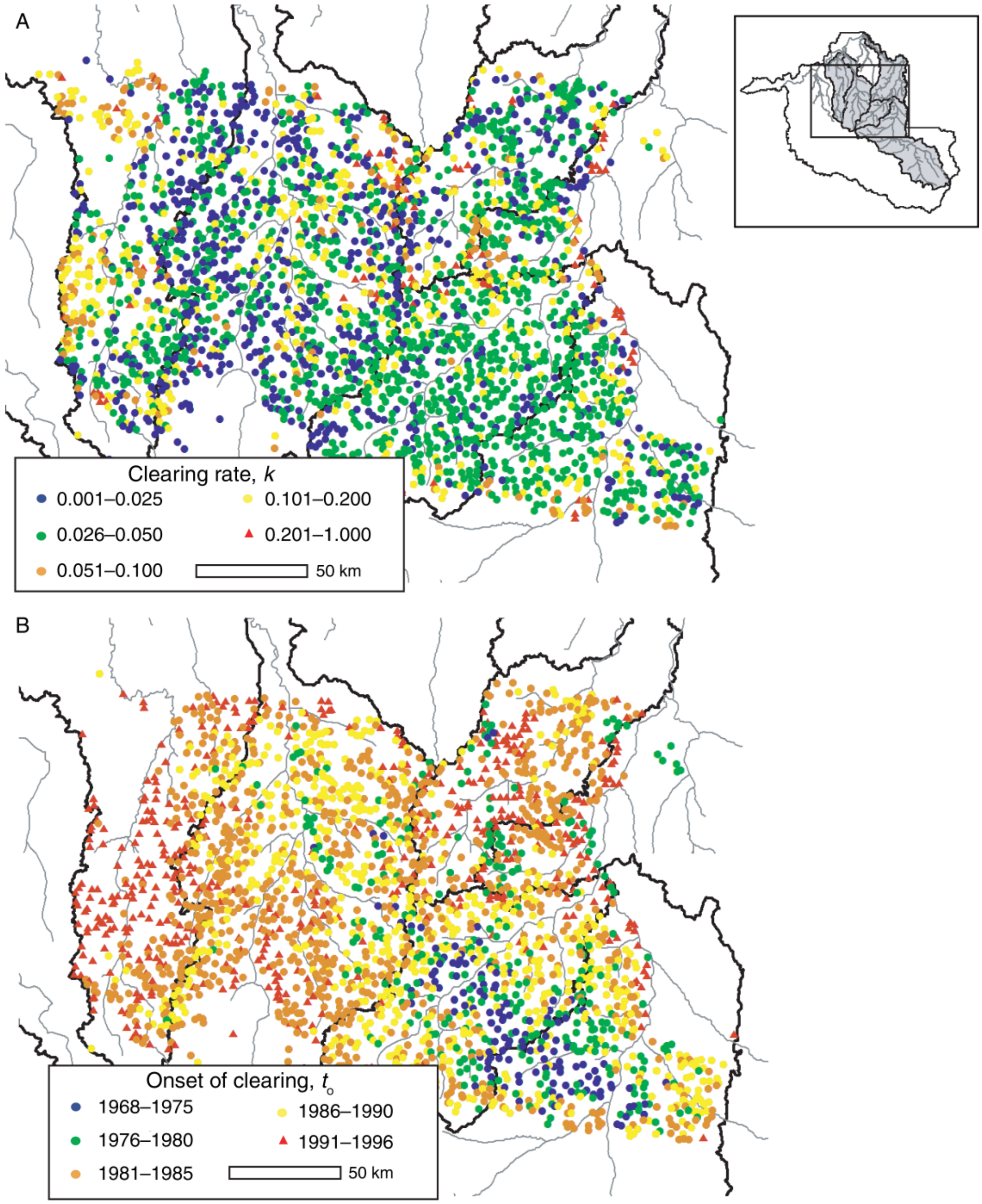


FIG. 7. Maps of (A) the rate and (B) the year of onset of clearing in first-order watersheds (2.5–10 $km^2$). Each dot represents one watershed.

of the total variance comes from larger-scale patterns up to 200 km. By contrast, 81% of the total variance in $k$ was due to small-scale variability.

Due to spatial autocorrelation, the variance in $f_{1999}$ did not decrease with watershed area as predicted by Eq. 5 (Table 6). The standard deviation predicted by assuming spatial independence at the next order ($\sigma_{ind}$) was lower than the observed standard deviation. The standard deviation in $k$, by contrast, decreased with watershed order for second- to fourth-order watersheds (Table 6). Values of $\sigma_{ind}$ predicted assuming spatial independence were smaller than observed for second-order watersheds, reflecting some autocorrelation for short lags (Fig. 11). $\sigma_{ind}$ was equal to or smaller than $\sigma$ observed for third- and fourth-order watersheds due to the low degree of spatial autocorrelation in deforestation rates beyond 50

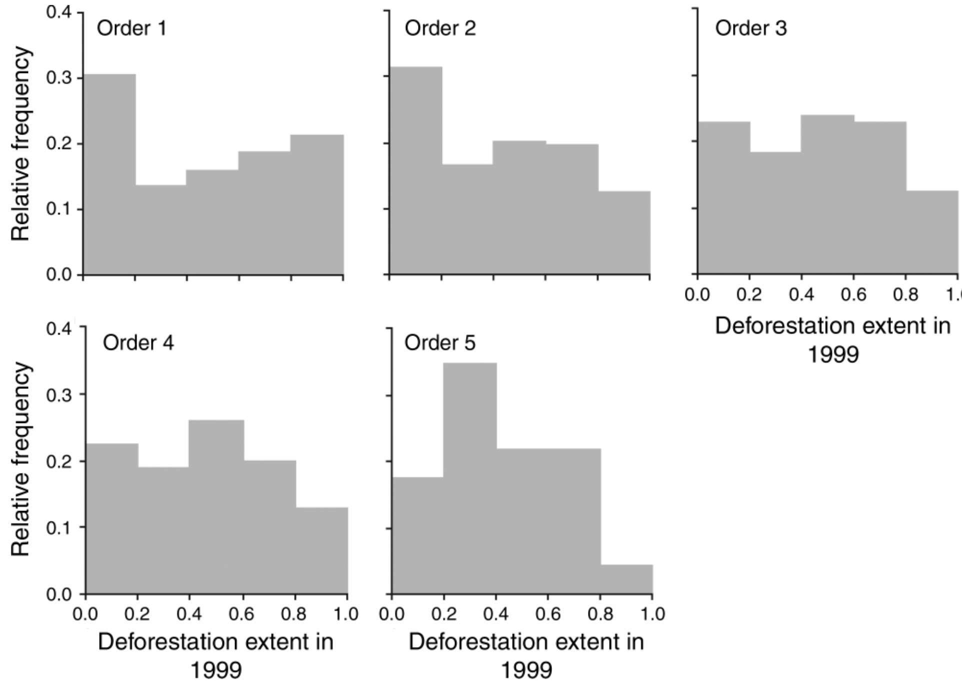


FIG. 8. Probability distributions of the cumulative deforestation extent in first- to fifth-order watersheds in 1999, $f_{1999}$ ($f_{1999}$ is the fraction of the watershed area that was deforested up to 1999). Data include all watersheds and all three stages of deforestation ($N_t$ in Table 3).

km. The analysis suggests that the rate of deforestation was a spatially independent random variable for watersheds of second order and larger.

The spatial autocorrelation structure affected the scaling behavior of extensive and rapid clearing (Fig. 12). The probability that a watershed was heavily deforested by 1999 ($P(f_{1999} > 0.75)$) decreased slightly from first- to second-order watersheds, but was constant from second- through fourth-order watersheds (range: 9.5–1696 km$^2$). $P(f_{1999} > 0.75)$ then decreased for fifth-order watersheds, reflecting the lack of spatial autocorrelation at large lag distances. The probability that a watershed was rapidly cleared ($P(k > 0.10)$) decreased more rapidly than $P(f_{1999} > 0.75)$ due to the low spatial autocorrelation of clearing rates and to spatial variability in the onset of clearing (Figs. 6, 7, and 11).

The semivariogram analysis suggests that clearing events in small watersheds began within a few years of each other, but cumulative clearing proceeded to different extents. Beyond a 30-km lag, the rate of deforestation better resembled an independent random variable, suggesting that the rate of deforestation was relatively uniform over the region. The net effect was that some large watersheds were extensively deforested due to autocorrelation, but the rate of clearing was lower than clearing rates in small watersheds.

The deforestation extent in buffers around the stream network of 90, 180, 270, and 540 m in the AR and JI scenes (0.513, 0.517, 0.521, and 0.524) was not significantly different from the deforestation extent over the images as a whole (0.524). This suggests that clearing depended more on the road network than on the stream network, and the deforestation extent in the watershed was equivalent to the deforestation extent in the near-stream zone. Some small riparian zones not detected by the Landsat TM imagery may still influence nutrient transport, and higher resolution digital elevation models (DEMs) could yield more precise estimates of the location of the stream network vis à vis the riparian

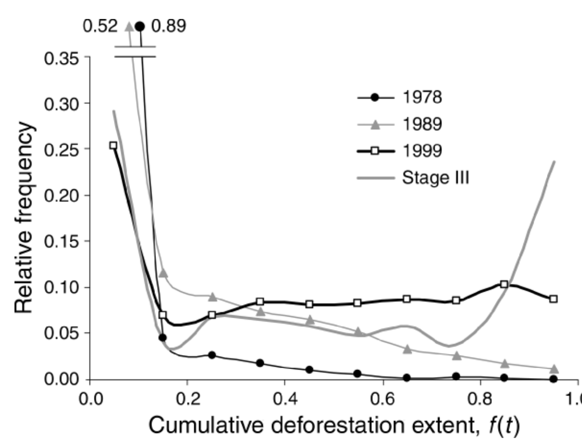


FIG. 9. Probability distribution of the cumulative deforestation extent ($f_{1999}$), measured as a proportion of the area that is deforested, in first-order watersheds (2.5–15 km$^2$) in 1978, 1989, and 1999. Data include all first-order watersheds in all stages of clearing. Frequencies for 1978 and 1989 at the lower deforestation extent were off the scale (0.52 and 0.89).

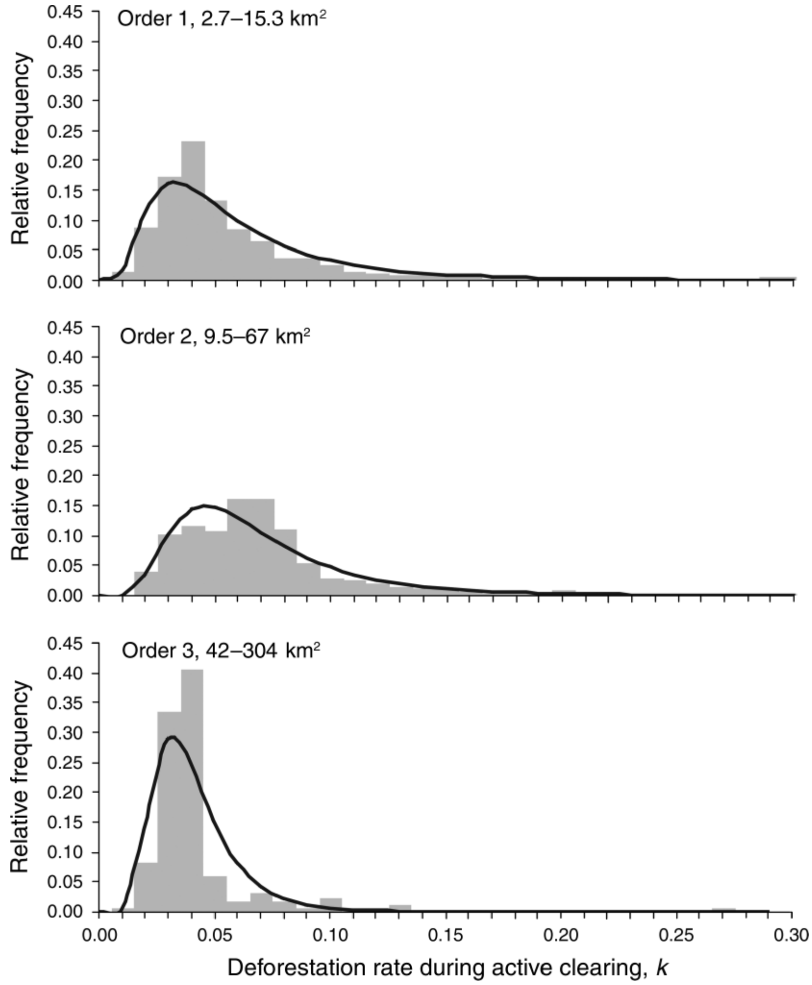


FIG. 10. Frequency distribution of deforestation rates ($k$) by watershed order. The solid black lines are lognormal distributions using the observed mean and variance.

vegetation. The broad pattern documented here suggests that clearing for pasture is largely independent of the stream network.

*Stream biogeochemical effects: transient and chronic*

The land cover analysis suggests that rapid clearing of forests was uncommon, while slow but extensive and nearly complete clearing occurred frequently in watersheds of Rondônia. The potential changes in stream biogeochemistry caused by rapid or extensive clearing

TABLE 5. Parameters of the semivariograms of first-order watersheds.

| Parameter | Nugget | Sill | Nugget : sill | Range (km) |
|---|---|---|---|---|
| Deforestation extent, $f_{1999}$ | 0.02 | 0.115 | 0.17 | 140 |
| Clearing rate, $k$ | 0.005 | 0.0062 | 0.81 | 30 |
| Onset of clearing, $t_o$ | 17 | 44 | 0.39 | 210 |

*Note:* Nugget is the small-scale semivariance, and sill is the regional semivariance.

were characterized using literature values. Table 7 summarizes changes in stream biogeochemistry observed in a small (2-ha) watershed undergoing rapid deforestation (Williams et al. 1997; Central Amazon) and in a regional survey of established pasture systems in Rondônia (Biggs et al. 2004). In the Central Amazon Basin, Williams et al. (1997) monitored stream water chemistry before and after 80% of the watershed was slashed and burned, and they documented increased fluxes of total dissolved nitrogen (TDN), total dissolved phosphorus (TDP), and small increases in fluxes of Cl compared with the pre-disturbance background. While the changes in stream biogeochemistry were relatively large, very few watersheds in Rondônia showed rapid clearing: no watersheds 2.5–15 $km^2$ had the deforestation rate of 0.80 (80%) $yr^{-1}$ observed in the Williams et al. (1997) study, and only 4% had a deforestation rate of 0.2 (20%) $yr^{-1}$. A clearing rate lower than 0.2 would show less than 25% of the response documented by Williams et al. 1997 and is not considered to be "rapid deforestation."

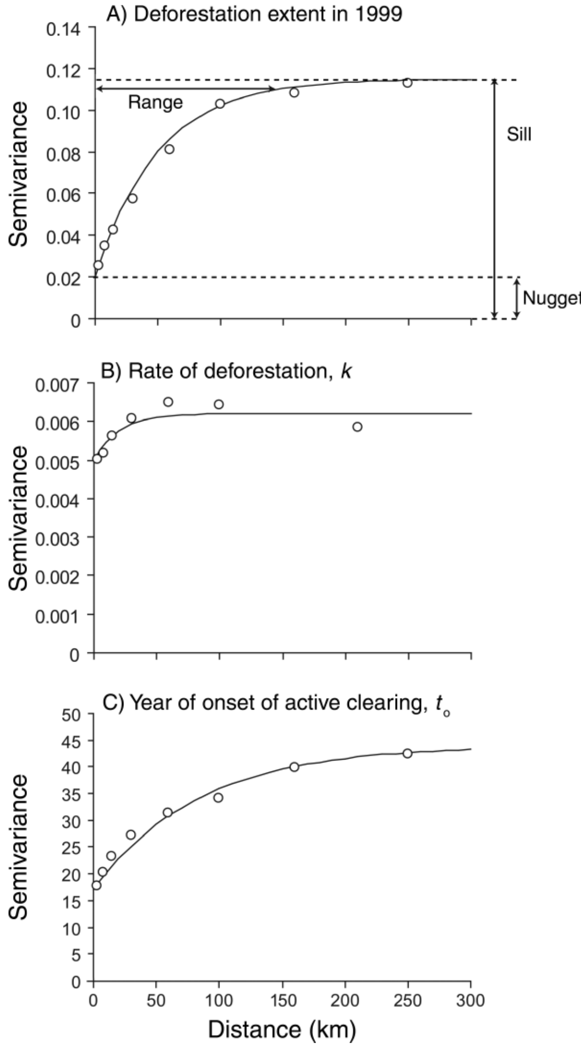


FIG. 11. Semivariance of (A) cumulative deforestation extent in 1999, (B) clearing rate during Stage II, and (C) year of the onset of active clearing. Shown are the small-scale semivariances (nugget), the range over which a variable is autocorrelated, and the regional semivariance (sill). The range is the distance where the semivariance is 95% of the sill.

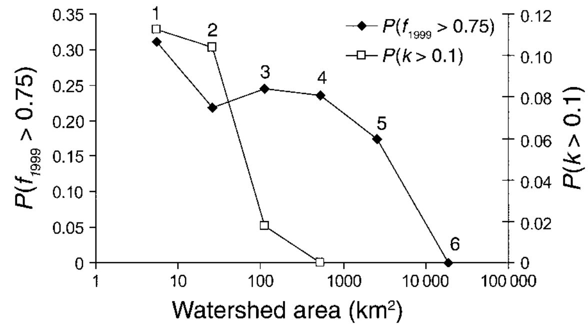


FIG. 12. The probability that a watershed had a cumulative deforestation extent greater than 75% [$P(f_{1999}) > 0.75$] or a clearing rate ($k$) greater than 10%/yr [$P(k > 0.1)$] vs. watershed area (note the log scale). The numeral near each point indicates the order of the watershed (first through sixth order) in each area bin.

A regional survey of streams in Rondônia by Biggs et al. (2004) showed that streams draining pastures had increased Cl, TDN, and TDP concentrations in the dry season compared with streams draining forests, but only for watersheds more than ~75% deforested. In the wet season, streams draining pastures had higher concentrations of CI and TDP than streams draining forests. The regional deforestation analysis presented here shows that 26% of the population of small watersheds in Rondônia were heavily (>75%) deforested by 1999 and susceptible to the types of stream nutrient perturbations found in pasture systems. The magnitude of the stream nutrient disturbance due to extensive deforestation and pasture establishment, as measured by the regional survey, was comparable to the disturbance caused by rapid clearing reported by Williams et al. (1997) in the Central Amazon. Streams in Rondônia are not likely to experience a temporary perturbation in stream nutrients from clearing, but rather show chronic disturbance due to permanent changes in land cover and conversion to pasture.

## DISCUSSION

The central arguments of this paper are that (1) deforestation has a temporal and spatial structure that determines the rate and spatial density of biomass disturbance in watersheds of different sizes and (2) the rate and extent of land cover change then determines the type of stream biogeochemical disturbance expected during regional vegetation conversion. Rapid cutting and burning of vegetation, which was uncommon even in small watersheds, is expected to cause a transient

TABLE 6. Statistics of the extent and rate of clearing by watershed stream order.

| | Deforestation extent, $f_{1999}$ | | | | Clearing rate, $k$ | | | |
|---|---|---|---|---|---|---|---|---|
| Order | μ | σ | $\sigma_{ind}$ | Maximum | μ | σ | $\sigma_{ind}$ | Maximum |
| 1 | 0.47 | 0.33 | | 1.00 | 0.059 | 0.057 | | 0.46 |
| 2 | 0.43 | 0.29 | 0.16 | 0.97 | 0.066 | 0.052 | 0.029 | 0.38 |
| 3 | 0.47 | 0.27 | 0.13 | 0.94 | 0.037 | 0.025 | 0.026 | 0.26 |
| 4 | 0.46 | 0.27 | 0.13 | 0.88 | 0.027 | 0.008 | 0.013 | 0.05 |
| 5 | 0.42 | 0.24 | 0.15 | 0.57 | | | | |

*Notes:* The $\sigma_{ind}$ column reports the standard deviation for a given order if the values in the previous order had minimal spatial autocorrelation, as computed in Eq. 5. The data for $f_{1999}$ include watersheds in all five scenes, and the data for $k$ include watersheds in the AR and JI scenes only.

TABLE 7. Perturbations in stream biogeochemistry documented for a rapidly deforested watershed and slowly, but extensively, deforested watersheds, as well as watershed frequency by deforestation rate and extent.

| Type of deforestation | Stream biogeochemical perturbation ($C_{defor}$:$C_{for}$)† | | | Frequency of small (2.5–10 km$^2$) watersheds in Rondônia | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Rapidly cleared $k$ (yr$^{-1}$) | | | Extensively cleared $f_{1999}$ | | |
| | Total dissolved N | Total dissolved P | Cl | >0.8 | >0.5 | >0.2 | >0.90 | >0.75 | >0.60 |
| Rapid | 1.4 | 5.2 | 1.1 | 0 | 0 | 0.04 | | | |
| Extensive | | | | | | | 0.09 | 0.26 | 0.40 |
| Dry season | 1.7 ± 0.1 | 2.3 ± 1.5 | 12.5 ± 6.4 | | | | | | |
| Wet season | 1.1 ± 0.2 | 1.9 ± 1.1 | 3.4 ± 1.4 | | | | | | |

† Values shown are the means of the ratio of the concentration in streams draining deforested watersheds ($C_{defor}$) to the concentration in streams draining forested watersheds ($C_{for}$). Williams et al. (1997) reported annual volume-weighted mean concentrations under rapid deforestation (80% cleared in a single year: $k = 0.8$ yr$^{-1}$), and data (means ± SD) for extensive deforestation (cumulative deforestation extent $f > 0.75$) are from Biggs et al. (2004).

pulse of stream nutrients, while slow but permanent conversion to pasture, which was relatively common, caused chronic disturbance to the stream biogeochemical regime. The main conclusions of the analysis are summarized as follows: (1) Deforestation of more than 75% of a watershed was a relatively slow process that took more than 7–21 years even in small watersheds, so the pulse-and-recovery type signal anticipated for rapidly converted areas is not likely to be common in the Amazon. (2) Zoning had important impacts on deforestation patterns and their realization in watersheds of different sizes. Protected areas had much lower deforestation extents than agricultural zones, which created large blocks of forest on either size of the deforested agricultural corridor. (3) Deforestation proceeded to >75% in most (26%) of watersheds located in agricultural zones. (4) The cumulative extent of deforestation was highly spatially autocorrelated, so watersheds as large as 2889 km$^2$ were heavily deforested (>75%), and watersheds as large as 39 466 km$^2$ had a deforestation extent more than 50%. (5) The slow but complete clearing and conversion to pasture of watersheds likely results in chronic nutrient disturbance controlled by pasture ecosystems, rather than transient disturbance controlled by forest clearing.

### *Deforestation dynamics in watersheds*

The Landsat TM time series showed that deforestation for pasture at the watershed scale did not happen rapidly (1–3 years), but was rather a relatively gradual but permanent land-use transition that took more than a decade, even in small watersheds (2.5–10 km$^2$). While some small watersheds experienced rapid deforestation (<3 years), less than 7% were more than 20% cleared in a single year, and very few were more than 50% deforested in a single year. The slow rate of deforestation was due to two main characteristics of clearing: first, individual clearings were small (0.06–0.07 km$^2$) relative to both properties (~1 km$^2$) and watersheds (Fig. 3); second, clearings were not simultaneous.

The observation that deforestation happened slowly in Rondônia watersheds is corroborated by farm-level data. Access to labor and capital limits the rates at which smallholders clear forest to less than 5–10% (Fujisaka et al. 1996) or 1–18% (Moran and McCracken 2004) of their holding area in any given year. Given these small clearing rates, even small watersheds (<10 km$^2$) had a low probability of being cleared in a short time. Though farmers may arrive in a new area as a cohort and clear forest together in a short time (Moran and McCracken 2004), household demographics also influence clearing rates, which translates into staggered clearing behavior (Perz 2001).

The results suggest that deforestation in small watersheds in Rondônia was not a rapid "shock," but rather a gradual transition that averaged 4.5–9.6% of the watershed area per year during active clearing (Stage II). Large watersheds had lower clearing rates (2.7%/yr) than small watersheds (4.5–9.6%/yr), since their clearing resulted from a larger number of spatially independent and asynchronous clearing events.

### *Zoning and autocorrelation effects on scaling behavior*

The spatial extent and arrangement of agricultural zones and protected areas had important implications for regional deforestation patterns. Though the effect of establishing reserves on deforestation rates is debated (Lele et al. 2000) and though some deforestation occurs within the boundaries of preserved areas (Figs. 2, 4), the extensive and permanent deforestation that occurred in agricultural zones, including state-sponsored road building, systematic land occupation, and urbanization, did not occur in protected areas in Rondônia up to 1999. Most deforestation in protected areas occurred in small, single-pixel (0.09 km$^2$) clearings, not the 0.06–0.07 km$^2$ modal clearing size observed in agricultural zones. Some of these clearings may represent canopy gaps created by natural tree fall or selective logging (Asner et al. 2002) rather than clearing for agriculture. In addition, areas protected in 1988 had a low cumulative deforestation rate between 1988 and 1999 (6% in protected areas vs. 39% for agricultural zones), suggesting that protection reduced deforestation rates. Soil type likely also has some influence on deforestation rates, which prevents ascribing all of the low deforestation rates in reserves to the effectiveness of zoning. The boundaries of protected areas may change over time; of the 93 800 $km^2$ protected in 1988, 15% was converted to agricultural zones and 15% to extractive reserves by 1998. Such changes in protection status will change the projected state-wide probability distributions of deforestation extent in watersheds.

By contrast with the low deforestation extent in protected zones, clearing averaged 50% in the agricultural zone and proceeded toward a mean of more than 80% in the most intensively occupied watersheds. This high mean value contrasts with the 20% clearing limit stipulated by Brazilian policy (Nepstad et al. 2002) and suggests that while zoning has been relatively successful at limiting clearing at the regional scale, mandates limiting clearing on individual properties have been difficult to enforce.

The high concentration of deforestation in the agricultural zone coincided with high spatial autocorrelation of deforestation among small watersheds. The autocorrelation affected scaling behavior: large watersheds were more heavily deforested than expected if clearing were spatially random; some watersheds as large as 39 466 $km^2$ were more than 50% cleared by 1999. Autocorrelation at small separation distances may be governed by rocky terrain, soil type, location of roads (Chomitz and Gray 1996), or demographics. The rate of conversion, by contrast, showed little autocorrelation and scaled as a random variable, resulting in relatively low conversion rates in large watersheds (mean 2.7%/yr). The homogeneity of clearing rate over Rondônia suggests that the technological and social factors that control clearing rates (Fujisaka et al. 1996, Perz 2001, Moran and McCracken 2004) have been consistent for the duration of colonization.

Due to the low extent of clearing in protected areas and high extent of clearing in agricultural zones, the size and spatial arrangement of administrative zones determined the fraction of small watersheds that remained forested or were heavily deforested, and also controlled the cumulative deforestation extent in large watersheds and the largest watershed with a high deforestation extent. In Rondônia, deforestation was largely confined to the main agricultural corridor (Figs. 1, 2). The geometry of this block and its intersection with the watershed network controlled the largest watershed heavily deforested. In other regions with different spatial arrangements of protected areas and infertile soils, the largest deforested area and watershed may be larger or smaller than observed in Rondônia, but the patterns would be quantifiable by the watershed-based approach used here.

### *Implications for stream biogeochemistry*

Watersheds in Rondônia were cleared slowly and completely in ways that affected stream biogeochemistry. Only 4% of the watersheds were rapidly cleared ($k >$ 0.2 $yr^{-1}$), but a large percentage (26%) were slowly but extensively deforested to pasture and were likely susceptible to the types of biogeochemical perturbation documented in Biggs et al. (2004) and Neill et al. (2001). The chronic perturbations were characterized by a large chloride signal, increased phosphorus concentrations, slightly increased nitrogen concentrations, and low oxygen concentrations.

The interpretation of deforestation as "rapid" or "slow but extensive" depends on the rate or extent that is sufficient to impact stream biogeochemistry. The cumulative extent of deforestation ($f_{1999}$) sufficient to impact stream chemistry was determined using the regional survey of Biggs et al. (2004), which suggested that more than 60–75% of a watershed needs to be cleared to pasture before significant impacts on stream biogeochemistry are observed. Determination of the rate ($k$) sufficient to impact stream chemistry and the duration of the pulse in stream nutrients from clearing of vegetation in Rondônia was more difficult to establish. Multiyear time series of stream chemistry of the type available at the Hubbard Brook watershed in the northeastern United States (Bormann and Likens 1979) and the Coweeta watershed in the southeastern United States (Swank and Vose 1997) are not available in the Amazon Basin. The study by Williams et al. (1997) in the Central Amazon covers only the first year following deforestation, so it is not possible to determine the magnitude or duration of a pulse of nutrients in stream waters. Multiyear time series suggest that maximum impacts of forest clearing on stream biogeochemistry may be observed up to three years following disturbance (Swank et al. 2001), so the values from Williams et al. (1997; Table 7) may underestimate the magnitude of the impact from rapid forest clearing. The catchment sampled by Williams et al. (1997) was also significantly smaller (2 ha) than the smallest watershed delineated in Rondônia, and occurred on different soil types than those found in Rondônia. Future research could more precisely determine the magnitude and duration of any transient pulse in stream biogeochemistry caused by rapid forest clearing in Rondônia. The results from the Central Amazon establish preliminary estimates of the type and magnitude of changes in stream biogeochemistry possible during rapid clearing of forest in the Amazon. In addition, the analysis of deforestation rates suggests that relatively few watersheds were cleared as rapidly as the Williams et al. (1997) catchment, and regional stream biogeochemistry is more likely to be controlled by the extensive pasture systems that dominate land use.

Permanent conversion of forest to grassland can have a larger and more lasting impact on stream biogeochemistry than cutting and regrowth of forest (Swank and Vose 1997). In Rondônia, pastures cleared for more than 20 years produce overland flow that transports nutrients, especially phosphorus, to receiving streams (Biggs et al. 2006), and established pasture systems can have chronically low oxygen concentrations, particularly in the dry season (Neill et al. 2001). Given the low clearing rates, high cumulative clearing extent, and establishment of pasture observed in the watersheds of Rondônia, we expect the regional impact of deforestation on stream biogeochemistry to be controlled by pasture systems. Other land-cover changes, including urbanization and agricultural intensification, also impact stream biogeochemistry and could result in a gradual deterioration of water quality in the Amazon (Downing et al. 1999), rather than a "shock-and-recovery" type response observed in small experimental watersheds.

## Conclusion

The rate and extent of deforestation were quantified for a large population of watersheds in a region experiencing rapid deforestation in the Amazon Basin. The conclusions about clearing and its implications for stream biogeochemistry in Rondônia included the following:

1) Deforestation in areas larger than a few square kilometers was a relatively gradual process, resulting in mean clearing rates of 4.5–9.5% of the watershed per year. Annual clearings were small relative to watershed areas. Only a small fraction of all watersheds were cleared rapidly, so very few streams are likely to show a transient pulse of nutrients in streams as observed in watershed experiments where natural revegetation was allowed.

2) Thirty-one percent of all small watersheds were heavily deforested (>75%) and subject to chronic disturbance of stream biogeochemistry. Chronic disturbance includes elevated chloride, phosphorus, and nitrogen, increased light availability, and decreased oxygen concentrations.

3) Zoning, particularly protection of large forest tracts that prevented large-scale settlement and infrastructure development, affected the spatial probability distributions of deforestation in watersheds. The cumulative deforestation extent between 1975 and 1999 exceeded 50% in agricultural zones, but was lower than 7% in protected areas. The zones were large and contiguous, so small watersheds tended to fall in either agricultural zones and be heavily deforested or in protected areas and be mostly forested. Large watersheds intersected both agricultural zones and protected areas and had intermediate deforestation extents. The geometry of the intersection of agricultural zones, protected areas, and watershed boundaries controls the deforestation extent in large watersheds.

4) The cumulative clearing extent showed high degrees of spatial autocorrelation, which resulted in high cumulative deforestation extents (>50%) in watersheds as large as 39 466 $km^2$. This suggests that even large watersheds may be heavily deforested and experience stream biogeochemical impacts. The rate of clearing was not autocorrelated beyond 30 km, suggesting that the clearing process was relatively homogenous over the study area, but the final deforestation extent was a function of local factors, the timing of the onset of clearing, and zoning boundaries.

5) The pattern of deforestation in watersheds indicates that streams in Rondônia are not likely to experience large, transient pulses in stream nutrients during deforestation, but rather are more susceptible to gradual but chronic changes culminating in a pasture-dominated biogeochemical regime.

## Acknowledgments

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