Legacy of fire slows carbon accumulation in Amazonian forest regrowth

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Amazonian farmers and ranchers use fire to clear land for agriculture and pasture as part of extensive land-use strategies that have deforested 500 000 km^2 over the past 25 years. Ash from burning biomass fertilizes crops and pastures, but declining productivity often occurs after a few years, generally leading to land abandonment and further clearing. Subsequent forest regrowth partially offsets carbon emissions from deforestation, but is often repeatedly cleared and burned. In the first quantitative, basin-wide assessment of the effect of repeated clearing and burning on forest regrowth, our analysis of data from 90 stands at nine locations across the region indicates that stands with a history of five or more fires suffer on average a greater than 50% reduction in carbon accumulation. In the absence of management interventions, Amazonian landscapes dominated by this pronounced legacy of fire are apt to accumulate very little carbon and will remain highly susceptible to recurrent burning.

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Recent research has focused on the importance of fire in shaping the anthropogenic landscapes of Amazonia (Cochrane 2003). For millennia, fire has been used extensively by indigenous people to clear land for agriculture and for game management. The frequency and area of burning by indigenous people prior to European colonization is a subject of ongoing debate, and the extent to which forests that currently exhibit old-growth structure were previously burned is unknown. Burning continues to be the dominant land-clearing method throughout the region, and is practiced by most farmers and ranchers (Figure 1). The fires they set often spread beyond their landholdings to adjacent fire-prone areas, including other farms and ranches, areas of forest regrowth, logged forest, and even unlogged old growth, especially during extended droughts associated with El Niño/Southern Oscillation events. The degrading influence of fire on forest structure has been well documented, and studies reveal an unfortunate positive feedback, in which even relatively mild surface fires make forests more susceptible to future burning. Over the past 25 years, approximately 500 000 km^2 of the Brazilian Amazon has been deforested (INPE 2004). However, there have been no previous systematic examinations of the role of fire history in altering the trajectory of forest regrowth on previously cleared lands, even though 30–50% of the deforested area is in some stage of abandonment (Fearnside 1996; Houghton *et al.* 2000), and much of it is subject to repeated burning (Skole *et al.* 1994; Fearnside 1996). Here, we examine the relationship between fire history and the accumulation of carbon (C) by Amazonian forest regrowth. We define fire history as the number of times that a given plot of land was previously burned. Several other factors, including land-use intensity (Uhl *et al.* 1988) and proximity of seed sources (Mesquita *et al.* 2001) may also be important determinants of regrowth trajectories, but the available data are insufficient to include them in this region-wide analysis. We also recognize that the number of previous burns may often serve as a proxy for the number of land-use cycles, and that other recurrent activities in the land-use cycle, such as slashing, weeding, and harvesting, may contribute to the effects reported here. However, data that adequately characterize those activities at sites across the region are similarly lacking.

Forest regrowth restores hydrological functions (Sommer *et al.* 2002), provides plant and animal habitats (Baar *et al.* 2004), re-establishes landscape connectivity (Metzger 2003), and has some effect on the regional C balance (Houghton *et al.* 2000), although it currently offsets < 5% of the deforestation flux (Steininger 2004). Currently, prediction error associated with modeling forest regrowth C accumulation in the region is > 50% (Zarin *et al.* 2001), some of which may be related to variance in fire history.

Methods

We compiled published and unpublished data for nine sites in the Brazilian Amazon for which information

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Figure 1. *Slashing and burning of 4-year old forest regrowth near Igarapé-Açu (Zona Bragantina), in the eastern Amazon. This stand had previously been burned more than five times.*

Courtesy of M Denich

about aboveground C stocks and fire history were available. This compilation represents a total of 90 forest regrowth stands, and includes new field data collected under the auspices of the Brazilian-led Large-Scale Biosphere–Atmosphere Experiment in Amazonia. In all cases, C stocks were determined by the application of allometric equations to stand inventory data and fire history was determined by interviews with local inhabitants (see Web-only material for site- and stand-level data). Sites are defined as 1 x 1 degree grid cells and may include stands from multiple studies conducted within those cells. We calculated potential aboveground C accumulation for each site using a previously validated empirical model (Zarin *et al.* 2001). Model predictions of dry aboveground biomass (B, Mg ha^{-1}) are a function of stand age (A, years), the proportion of the year with monthly rainfall in excess of 100 mm (R, percent), and the average temperature during that part of the year (T, degrees Celsius); separate algorithms are calculated for non-sandy and sandy soil textures (for C divide by two):

$$B_{\text{non-sandy}} = 0.67 + 0.43(ART)$$

(Equation 1)

$$B_{\text{sandy}} = -131.05 + 34.70 \ln (ART)$$

(Equation 2)

The basic structure of this model indicates that forest regrowth accumulates C more quickly on non-sandy soils than on sandy soils, and that C accumulation also occurs more quickly where the dry season is shorter; the model is linear for non-sandy soils and logarithmic for sandy soils. Consistent with the structure of the model, Laurance *et al.* (1999) found a strong negative correlation between soil sand content and the biomass of central Amazonian old-growth forests. We surmise that moisture and/or nutrient limitation underlie the empirical relationships that drive the model, but the model itself does not attempt to formally decouple the effects of those two constraints on biomass accumulation.

Equation 1 was empirically derived from a global dataset, analyzed by Johnson *et al.* (2000) and later validated for the Brazilian Amazon by Zarin *et al.* (2001), using data not included in the global synthesis. Equation 2 is a regional modification, described in Zarin *et al.* (2001), of the global algorithm derived by Johnson *et al.* (2000). While the linear accumulation rate posited by the non-sandy sub-model fits the data quite well, we caution that it is unrealistic for later stages of forest succession outside the bounds of this analysis. Because the model was developed based on forest regrowth data only (Johnson *et al.* 2000), it lacks a term (eg mortality) to constrain the increase in C accumulation as succession progresses. Conversely, the sandy sub-module predicts negative values if $A \leq 2$, a condition not met by any of the data used in this analysis. In spite of these limitations, the model provides reasonably unbiased and accurate predictions of forest regrowth C accumulation for the entire Brazilian Amazon, and is the only validated, published model to do so (Zarin *et al.* 2001).

We calculated the difference between observed and predicted aboveground C for each stand (from Equations

1 and 2) and divided by stand age to generate annualized stand residuals. We used mixed-effects linear regression with site as a grouping factor to determine if the number of burns had a significant effect on these residual values, while accounting for the possible lack of independence between stands at the same site. We also compared the results of this analysis with an independent model (Miami Biomass), described in the supplemental Web-only material.

To evaluate possible non-linear effects, we then aggregated the data into four fire history classes (0 fires = cleared without burning; 1–2 previous fires; 3–4 previous fires; and >5 previous fires). We then used one-way analysis of variance to test for a significant effect of fire history class on the size of the annualized stand residuals, incorporating a mixed-effect model with site as a grouping factor as before. We used Dunn's method of all pairwise multiple comparisons on ranked data to determine whether the fire history classes were biased by significant between-class differences in stand ages.

Results

Figure 2 illustrates the relationship between model predictions and observations at the nine sites. Three of the nine sites are on sandy soils (Pedra, Tome-Açu, and Zona Bragantina) and observed aboveground C values in these areas are generally lower than for the non-sandy sites, as the model predicts.

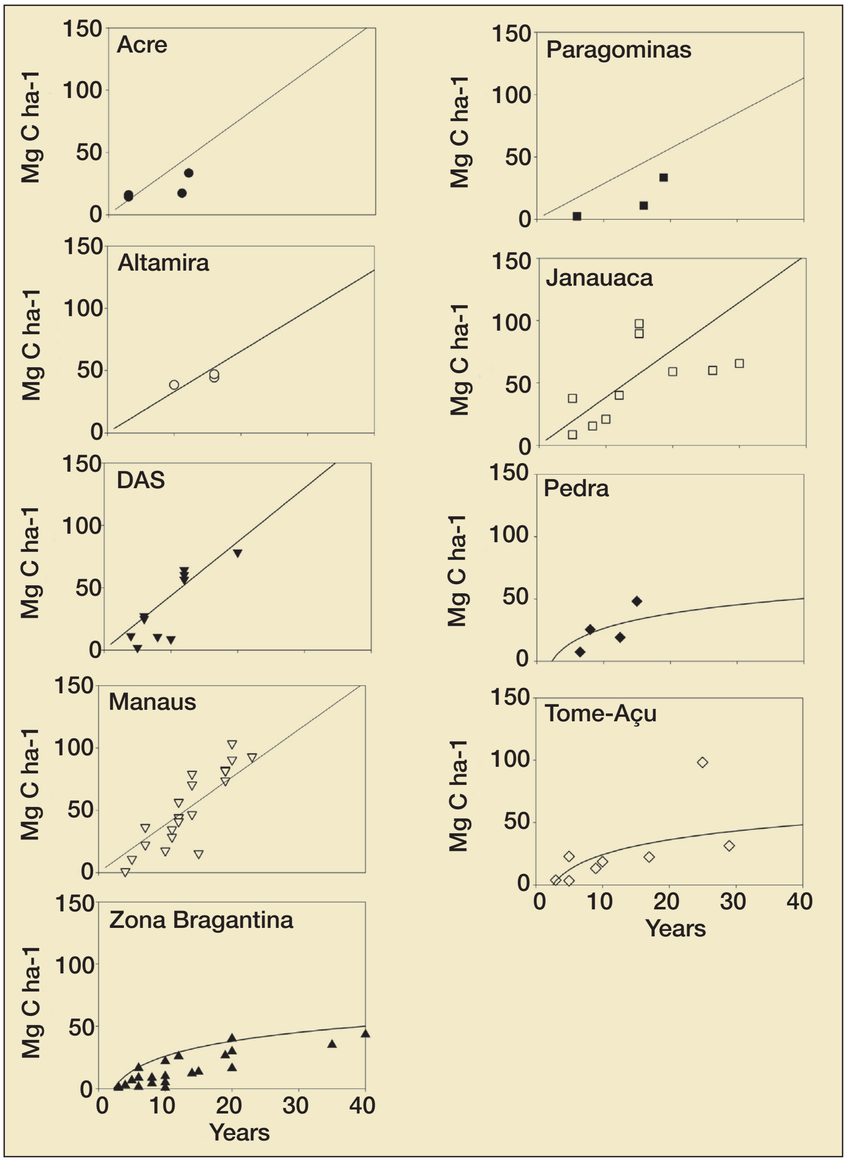

Figure 2. *Forest regrowth C accumulation at nine Amazonian sites. Symbols indicate stand-level observations. Curves illustrate model predictions for sites underlain by sandy (Pedra, Tome-Açu, and Zona Bragantina) and non-sandy soils (all others); slopes differ across sites as a reflection of the climatic influence on model predictions (Equations 1 and 2). (See Zarin* et al. *[2001] and Web-only material for additional information).*

In Figure 3, a reduction in actual C accumulation relative to model predictions is shown to be associated with an increasing number of burns (intercept = –0.058 ± 0.222; $P = 0.795$; slope = –0.242 ± 0.060; $P < 0.001$). The grouping factor of site had a significant random effect on the regression, but only on the intercept term, indicating that while the rate of C accumulation at one or more sites differed from that predicted by the model (Figure 2), site did not influence the effect of the number of burns on stand-level C accumulation. The negative effect of an increasing number of burns on C accumulation was confirmed using the Miami Biomass model, although larger residual variability associated with that model resulted in a marginally significant result ($P = 0.11$).

Stands burned five or more times accumulated C at a slower rate than stands that were either cleared without burning, or that were burned 1–2 times (Figure 4; $P < 0.10$). Relative to the model prediction, the reduction in C accumulation for stands with this legacy of five or more fires is 1.7 ± 0.6 Mg C ha^{-1} y^{-1}, compared to predicted accumulation rates of 3.2 ± 0.6 Mg C ha^{-1} y^{-1} (mean ± 90% confidence interval). None of the pairwise multiple comparisons (Dunn's method) revealed any significant differences in stand ages between the fire history classes.

Discussion

Prior site-specific studies have shown that increasing land-use intensity can diminish the rate of post-abandonment C accumulation (Uhl *et al.* 1988), and that overgrazing can result in a substantial lag before forest re-

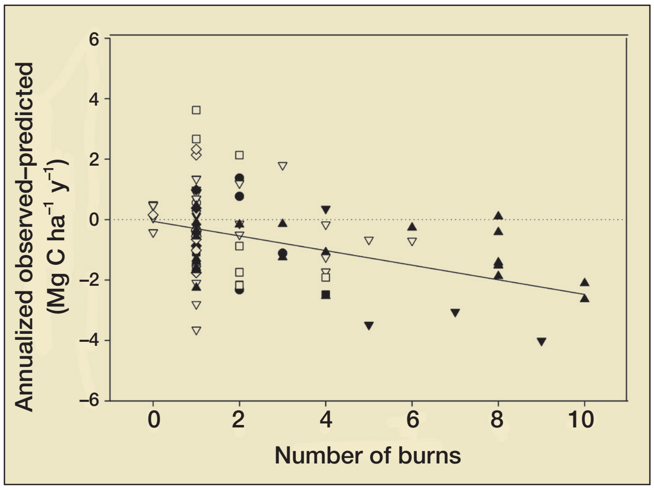

Figure 3. *Reduced C accumulation relative to model predictions is associated with fire history. Dotted line indicates expected relationship if there were no differences between observed and predicted values; solid line illustrates the mixed effects linear regression* ($P < 0.001$; RMSE = 1.34)*. Symbols indicate stand-level observations.*

establishment can begin on abandoned pastures (Fearnside and Guimarães 1996). Steininger (2000) compared simple linear regression equations of forest regrowth biomass as a function of stand age, following (a) pasture used for > 5 years and (b) 1 year of crop cultivation in plots cleared from mature forest and subsequently abandoned. He found significant differences in the intercept terms (pasture < crop cultivation) but not between slopes, suggesting that the marginal negative effect of pasture on C accumulation was limited to the first 5 years of forest regrowth. Although some evidence from site-specific studies suggests that forest regrowth may be generally slower on abandoned pastures compared to shifting cultivation fallows (Fearnside and Guimarães 1996), the only basin-wide analysis of that hypothesis showed no systematic differences in C accumulation (Zarin *et al.* 2001). This is probably because both cattle ranching and shifting cultivation encompass a wide and overlapping range of land-use intensity. The results we report here are the first to demonstrate a region-wide, quantitative reduction in forest regrowth C accumulation related to prior land-use activity, and specifically to fire history.

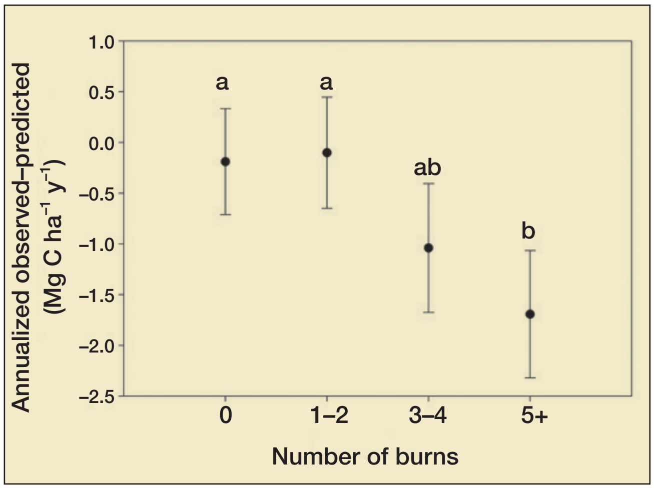

Figure 4. *Reduction in C accumulation relative to model predictions for Amazonian forest regrowth with a history of many fires. Ninety percent confidence intervals around the means are illustrated. Different letters indicate significant differences at* $P < 0.10$.

A number of mechanisms may contribute to the decrease in rates of regrowth in frequently burned stands. Where land use has been intense, slower regrowth may be due to soil compaction and/or impoverishment of the seed bank (Buschbacher *et al.* 1988; Uhl *et al.* 1988). Reduced regeneration of woody species due to repeated cutting and burning of root and stump sprouts may also contribute to slower regrowth (Nepstad *et al.* 1991). The number of previous burns often represents the number of land-use cycles that a regrowth stand has experienced. Thus, other activities associated with those land-use cycles (eg tilling, weeding, and harvesting) may also contribute to the reduction in C accumulation reported here.

Repeated burning can also affect rates of regrowth by depleting pools of actively cycling nutrients. Phosphorus (P) availability is consistently low in the highly weathered soils of lowland Amazonian forests, and indices of nitrogen (N) availability decline with forest clearing (McGrath *et al.* 2001). The results of recent nutrient amendment experiments have revealed nutrient limitation to plant growth in young successional forests of the eastern Amazon region. Where repeated fires had occurred in both abandoned cattle pastures (Davidson *et al.* 2004) and fallow slash-and-burn agricultural fields (Gehring *et al.* 1999), N and/or P additions had a significant, positive effect on total plant biomass and on the growth of several early successional tree species. Losses of N and P through volatilization, transport of ash, and erosion may therefore impede vigorous regrowth rates where there is a history of frequent clearing and burning (Hughes *et al.* 2000). Sommer *et al.* (2004) have shown that experimental no-burn, slash-and-mulch systems are far more conservative of nutrient capital than typical slash-and-burn farming practices in this region.

This analysis contributes to a growing body of literature demonstrating the pervasive negative effects that increased incidence of fire is having on the future of Amazonian forests (Cochrane 2003), in this case by reducing the rate of forest regrowth. Stands with a pronounced fire history are likely to retain an enhanced susceptibility to wildfire for a longer period of time than regrowth stands with fewer previous burns. This is because slower growth results in delayed canopy closure and delayed development of a humid microclimate at the forest floor. Where such a legacy is pervasive in landscapes dominated by large cattle ranches, permanent conversion to intensive agriculture, pasture, and/or tree plantations may be appropriate (Nepstad *et al.* 1999). In regions dominated by smallholder agriculture, enrichment planting has been shown to hasten the pace of forest regrowth, and may also enhance financial returns (Denich *et al*. 2004). Where fires have burned over and over again, the alternative scenario (ie no intervention) is a degraded, fire-prone landscape.

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References

Baar R, Cordeiro MR, Denich M, *et al*. 2004. Floristic inventory of secondary vegetation in agricultural systems of East-Amazonia. *Biodivers Conserv* **13**: 201–528.

Buschbacher R, Uhl C, and Serrão EAS. 1988. Abandoned pastures in eastern Amazonia. II. Nutrient stocks in the soil and vegetation. *J Ecol* **76**: 682–99.

Cochrane MA, Alencar A, Schulze MD, *et al*. 1999. Positive feedbacks in the fire dynamic of closed canopy tropical forests. *Science* **284**: 1832–35.

Cochrane MA. 2003. Fire science for rainforests. *Nature* **421**: 913–19.

Davidson EA, Carvalho CJR, Vieira ICG, *et al*. 2004. Nutrient limitation of biomass growth in a tropical secondary forest: early results of a nitrogen and phosphorus amendment experiment. *Ecol Appl* **14**: S150–63.

Denich M, Vielhauer K, Kato MS de A, *et al*. 2004. Mechanized land preparation in forest-based fallow systems: the experience from eastern Amazonia. *Agroforest Syst* **61**: 91–106.

Fearnside PM. 1996. Amazonian deforestation and global warming: carbon stocks in vegetation replacing Brazil's Amazon forests. *For Ecol Manage* **80**: 21–34.

Fearnside PM and Guimarães WM. 1996. Carbon uptake by secondary forests in Brazilian Amazonia. *Forest Ecol Manage* **80**: 35–46.

Gehring C, Denich M, Kanashiro M, *et al*. 1999. Response of secondary vegetation in Eastern Amazonia to relaxed nutrient availability constraints. *Biogeochemistry* **45**: 223–41.

Houghton RA, Skole DL, Nobre CA, *et al*. 2000. Annual fluxes of carbon from deforestation and regrowth in the Brazilian Amazon. *Nature* **403**: 301–04.

Hughes RF, Kauffman JB, and Cummings DL. 2000. Fire in the Brazilian Amazon. Dynamics of biomass, C, and nutrient pools in regenerating forests. *Oecologia* **124**: 574–88.

INPE. 2004. Monitoramento da floresta amazônica brasileira por satélite – Projeto Prodes. www.obt.inpe.br/prodes/. Viewed 23 June 2005

Johnson CM, Zarin DJ, and Johnson AH. 2000. Post-disturbance aboveground biomass accumulation in global secondary forests. *Ecology* **81**: 1394–1401.

Laurance WF, Fearnside PM, Laurance CG, *et al*. 1999. Relationship between soils and Amazon forest biomass: a landscape-scale study. *For Ecol Manage* **118**: 127–38.

McGrath DA, Smith CK, Gholz HL, *et al*. 2001. Effects of land-use change on soil nutrient dynamics in Amazonia. *Ecosystems* **4**: 625–45.

Mesquita RCG, Ickes K, Ganade G, and Williamson BB. 2001. Alternative successional pathways in the Amazon Basin. *J Ecol* **89**: 528–37

Metzger JP. 2003. Effects of slash-and-burn fallow periods on landscape structure. *Environ Conserv* **30**: 325–33.

Nepstad D, Uhl C, and Serrão EAS. 1991. Recuperation of a degraded Amazonian landscape: forest recovery and agricultural restoration. *Ambio* **20**: 248–55.

Nepstad DC, Veríssimo A, Alencar A, *et al*. 1999. Large-scale impoverishment of Amazonian forests by logging and fire. *Nature* **398**: 505–08.

Skole DL, Chomentowski WH, Salas WA, and Nobre AD. 1994. Physical and human dimensions of deforestation in Amazonia. *BioScience* **44**: 314–22.

Sommer R, Sá TD de A, Vielhauer K, *et al*. 2002. Transpiration and canopy conductance of secondary vegetation in the eastern Amazon. *Agr Forest Meteorol* **112**: 103–21.

Sommer R, Vlek PLG, Sá TD de A, *et al*. 2004. Nutrient balance of shifting cultivation by burning or mulching in the Eastern Amazon – evidence for subsoil nutrient accumulation. *Nutr Cycl Agroecosyst* **68**: 257–71.

Steininger MK. 2000. Secondary forest structure and biomass following short and extended land-use in central and southern Amazonia. *J Trop Ecol* **16**: 689–708.

Steininger MK. 2004. Net carbon fluxes from forest clearance and regrowth in the Amazon. *Ecol Appl* **14**: S313–22.

Uhl C, Buschbacher R, and Serrão EAS. 1988. Abandoned pastures in eastern Amazonia. I. Patterns of plant succession. *J Ecol* **76**: 663–81.

Zarin DJ, Ducey MJ, Tucker JM, *et al*. 2001. Potential biomass accumulation in Amazonian regrowth forests. *Ecosystems* **4**: 658–68.