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Mesoscale vegetation-atmosphere feedbacks in Amazonia

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[1] This paper investigates vegetation-climate interactions in disturbed rain forests of Amazonia. The scientific objective of this paper is twofold. The first goal is to reconcile the discrepancy between the decrease in precipitation predicted by general circulation models and the observed increase in precipitation due to deforestation in Rondonia. Numerical experiments with the Regional Atmospheric Modeling System (RAMS) show that sharp gradients in land cover due to fishbone deforestation trigger organized mesoscale circulations, leading to more clouds and rain over the deforested patches. The second goal is to develop and implement a modeling framework to identify and explore the fundamental pathways involved in deforestation-climate feedback over seasonal timescales. For this purpose, RAMS model outputs are combined with tower observations to develop a synthetic meteorological data set representing the impacts of deforestation on local hydrometeorology. A vegetation model forced by these data shows that extra rain promotes plant growth in the deforested patches during the water-limited dry season. This phenomenon constitutes a seasonal-scale "negative feedback" because accelerated vegetation recovery compensates for the effects of deforestation. This paper suggests that the regional climate observation infrastructure must be upgraded to resolve mesoscale feedbacks to accurately estimate the impact of deforestation in Amazonia. Moreover, these findings can significantly improve our understanding of ecosystem resiliency in disturbed tropical forests.

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1. Introduction

[2] Land is an integral component of the climate system and changes in land cover can significantly influence terrestrial weather and climate [*Pielke et al.*, 1998, 2002; *Bonan*, 2002]. Land-atmosphere interactions are not confined to a one-way forcing response mechanism but also involve dynamic feedbacks between the atmosphere and the biosphere. Feedbacks are processes internal to a dynamical system that affect the impact of an external forcing on that system [*Robock*, 1985; *Hartman*, 1994]. For example, anthropogenic activities such as logging or grazing can lead to loss of vegetation cover. The resulting change in climate patterns can in turn impact vegetation cover, thereby completing the feedback loop. A further loss in vegetation cover due to the climate change will constitute a positive feedback while vegetation recovery will imply a negative feedback.

[3] Starting with the pioneering work of *Charney et al.* [1975], modeling [e.g., *Foley et al.*, 1998] and observational [e.g., *Liu et al.*, 2006] studies have shown that these feedbacks play an important role in climate and climate change dynamics over a wide range of spatial and temporal scales. This paper investigates regional-scale vegetation-climate feedbacks in the context of deforestation in Rondonia, a Brazilian state in the Amazon basin, over seasonal timescales.

[4] Large-scale deforestation in Amazonia started in the 1970s and continues unabated today [*Fearnside*, 1993; *Skole and Tucker*, 1993; *Laurance*, 2000; *Asner et al.*, 2005, 2006; *Morton et al.*, 2006]. At the current rate, the Brazilian Amazon is likely to lose most of its forest cover within the next few decades [*Soares-Filho et al.*, 2004]. This deforestation is mostly caused by anthropogenic processes like clear-cutting of forests for agriculture, pasture, and timber harvesting. The state of Rondonia is an epicenter of such activities. To understand vegetation-climate feedbacks in Rondonia, we need to answer the following two questions.

[5] 1. How will the local climate, especially precipitation, in Rondonia respond to the deforestation? Many numerical experiments with general circulation models (GCMs) have investigated the impact of basin-wide deforestation on precipitation in Amazonia [*Henderson-Sellers and Gornitz*, 1984; *Lean and Warrilow*, 1989; *Shukla et al.*, 1990; *Nobre et al.*, 1991; *McGuffie et al.*, 1995; *Lean and Rowntree*, 1999; *Costa and Foley*, 2000; *Zhang et al.*, 2001; *Werth and Avissar*, 2002; *Findell et al.*, 2006]. Apart from *Polcher and Laval* [1994], all studies report a drastic reduction in precipitation by up to 640 mm yr^{-1}. Numerical experiments by *Ramos da Silva et al.* [2008] show a progressive decrease in basin-averaged rainfall with increasing deforestation accompanied by an increase along the forest-clearing boundary. In contrast, observational evidence based on rain

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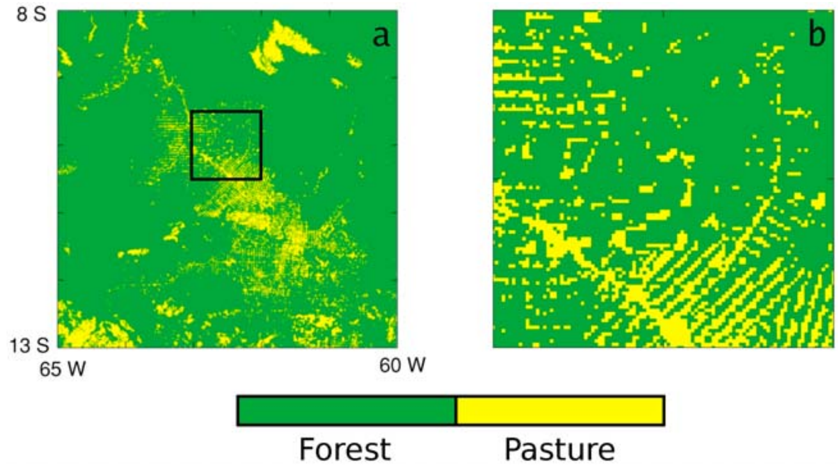

Figure 1. (a) Deforestation pattern in a 5° × 5° cell in Rondonia, a state in southwestern Amazonia, Brazil. Most of the deforestation is centered on the highway BR-364 that runs diagonally through the cell. Land cover data are from *Calvet et al.* [1997]. (b) Fishbones are clearly visible in a 100 km × 100 km box within the cell. Original data are at 0.01° resolution but aggregated to 1 km resolution.

gauge data indicates a consistent increase in rainfall [*Chu et al.*, 1994; *Easterling et al.*, 1996, 2000; *Chen et al.*, 2001; *Folland et al.*, 2001; *Negri et al.*, 2004; *Chagnon et al.*, 2004; *Chagnon and Bras*, 2005] despite the ongoing deforestation.

[6] 2. How will the change in local climate affect vegetation recovery in deforested patches? This question has not been explored in detail yet, but on the basis of the previous discussion, two distinct possibilities can be envisioned. A climate response, e.g., an increase in precipitation, that accelerates plant growth in the cleared patches will imply that deforestation exerts a negative feedback on itself. On the other hand, a climate response that hinders vegetation recovery will indicate a positive feedback.

[7] The scientific objective of this paper is twofold. The first goal is to reconcile the discrepancy between the observed and simulated precipitations in Rondonia. The second goal is to develop and implement a modeling framework to identify and explore the fundamental pathways involved in deforestation-climate feedback over seasonal timescales.

2. Impact of Deforestation on Local Hydrometeorology in Rondonia

[8] The scientific opinion on the nature and strength of the impacts of deforestation is divided. GCMs predict that deforestation will drastically reduce precipitation but observations report an increase in spite of the ongoing deforestation. One explanation for this discrepancy is that the spatial scale of Amazonian deforestation is much smaller than that assumed in the GCM experiments. Deforestation has affected less than 20% of Amazonia [*de Filho and Metzger*, 2006], and hence, its impact is likely to be smaller than that from complete basin-wide deforestation.

[9] The limited spatial-scale argument, however, cannot explain the observed increase in rainfall. A possible answer lies in the unique spatial pattern of deforestation in Rondonia. Forest clearings for human settlements, farms, and pastures along a rapidly expanding network of highways and local roads [*de Filho and Metzger*, 2006; *Skole and Tucker*, 1993] have created the well-known "fishbone" structure (Figures 1a and 1b). These fishbones trigger 5–10 km wide organized mesoscale circulations called "vegetation breezes" that are similar to sea and lake breezes [*Silva Dias and Regnier*, 1998; *Baidya Roy and Avissar*, 2002; *Baidya Roy et al.*, 2003; *Weaver et al.*, 2002]. Warmer temperatures over deforested areas create horizontal pressure gradients, forcing cool, moist air from adjacent forests to converge over the clearings. This increased convergence generates shallow cumulus clouds preferentially located over the bare patches. Many authors [*Chagnon et al.*, 2004; *Negri et al.*, 2004; *Chagnon and Bras*, 2005; *Wang et al.*, 2009] have hypothesized that the vegetation breezes are also responsible for increased cloud cover and precipitation on the bare patches (Figure 2). This effect is strongest in the dry season and at times during the wet season [*Ramos da Silva et al.*, 2008]. It is also clearly evident in data from the Geostationary Operational Environmental Satellite (GOES) and Tropical Rainfall Measuring Mission satellites [*Chagnon et al.*, 2004; *Chagnon and Bras*, 2005; *Wang et al.*, 2009].

[10] In this work, a set of high-resolution simulations was conducted with the Regional Atmospheric Modeling System (RAMS) [*Pielke et al.*, 1992; *Cotton et al.*, 2003] to test if the vegetation breezes are capable of enhancing dry season precipitation on bare patches. *Baidya Roy and Avissar* [2002] have earlier simulated vegetation breezes due to the fishbone land cover heterogeneity in this region. However, the current simulations are a marked improvement in several respects:

[11] 1. The most important new feature of the simulations was the use of dynamic bottom boundary conditions derived from the Land Ecosystem-Atmosphere Feedback-2 model (LEAF2) [*Walko et al.*, 2000] dynamically coupled to RAMS. In contrast to prescribing surface sensible and latent heat fluxes like the work of *Baidya Roy and Avissar* [2002], this approach allowed for dynamic two-way interactions between the land and the atmosphere.

[12] 2. A two-stream radiative transfer scheme [*Harrington*, 1997] that treats the interaction of three solar and five

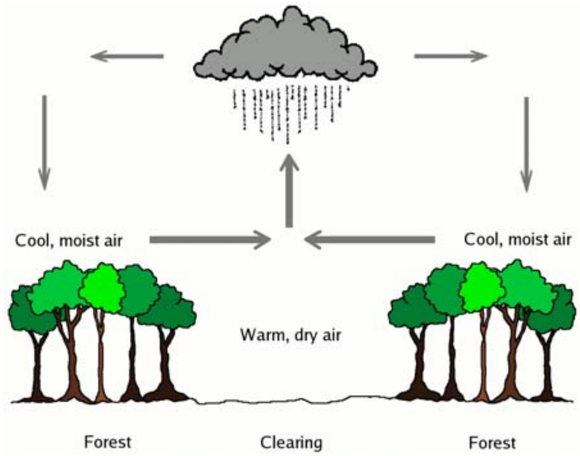

Figure 2. Schematic diagram of vegetation breeze. A horizontal temperature gradient forces cool, moist air from adjacent forests to converge over the clearings. Convergence generates strong updrafts, shallow cumulus clouds and precipitation, preferentially located over the bare patches.

infrared bands with the atmospheric gases and hydrometeors was used instead of the simple Chen-Cotton scheme to improve simulation of cloud radiative effects.

[13] 3. To better simulate clouds and precipitation, a detailed bulk microphysical model [*Walko et al.*, 1995; *Meyers et al.*, 1997] was used to prognose mixing ratio and number concentration of cloud, rain, pristine ice crystals, snow, aggregates, graupel, and hail for all resolved processes using a generalized gamma distribution. Hail and graupel hydrometeors are allowed to contain some liquid water. The model includes heterogeneous nucleation of pristine ice and conversion of ice between large and small categories resulting from vapor deposition and sublimation. It also allows for differential fall speeds based on the gamma size distribution.

[14] The study domain was a 100 km × 100 km region (Figure 1b) in Rondonia, discretized by a high-resolution grid with uniform 1 km spacing in the horizontal. This high-resolution grid was nested within 2 coarser grids: (1) 300 km × 300 km with 4 km grid spacing and (2) 900 km × 900 km with 16 km grid spacing. RAMS solved the full three-dimensional, compressible, nonhydrostatic dynamic equations, thermodynamic equation and a set of microphysics equations. The system was closed with the Mellor-Yamada level 2.5 scheme [*Mellor and Yamada*, 1982] that explicitly solves for turbulent kinetic energy while parameterizing other second-order moments. The coordinate system was rectangular Cartesian in the horizontal and terrain-following σ-type [*Clark*, 1977] in the vertical. A modified Kain-Fritsch scheme [*Kain and Fritsch*, 1990] was used to parameterize convection in the coarsest grid. Convection was explicitly resolved in the 2 finer grids. The National Centers for Environmental Prediction–Department of Energy AMIP-II reanalysis data [*Kanamitsu et al.*, 2002] were used as atmospheric initial and lateral boundary conditions. The same data were also used for initializing soil temperature and moisture profiles. Soil-type data were obtained from the Food and Agriculture Organization soil data set [*Buckley*, 2001].

[15] This model configuration was used to conduct an ensemble of 12 h long (0600–1800 LT) case studies for eight randomly chosen typical dry season (July–August) days in 2004. This year is in the middle of a 3 year long neutral El Niño–Southern Oscillation (ENSO) phase according to the Center for Ocean-Atmosphere Prediction Studies (available at http://coaps.fsu.edu/jma.shtml). Land-atmosphere interactions during this period are likely to be free of ENSO effects as suggested by *Ramos da Silva et al.* [2008] and *Voldoire and Royer* [2004]. Two simulations were run for each day: (1) pristine scenario, assuming the land cover to be completely forest, and (2) deforested scenario, using LANDSAT data [*Calvet et al.*, 1997] for land cover. To estimate the impact of deforestation, the ensemble-averaged outputs of hydrometeorological parameters for the pristine and deforested scenarios were compared.

[16] The numerical experiments showed that due to higher surface sensible heat flux over deforested patches, daytime near-surface air temperature increased by more than 0.4°C (Figure 3a). The horizontal air temperature gradient between forested and deforested regions forced organized mesoscale circulations with strong updrafts preferentially located over the bare patches. Clouds generated by these circulations reduced shortwave radiation by more than 50 W m^{-2} (Figure 3b) and increased rainfall by more than 15 mm d^{-1} (Figure 3c) in some locations. Welch's t test [*Welch*, 1947] for samples with unequal variance showed that all effects were statistically significant at $P < 0.0001$. It is evident from these experiments that, as hypothesized by some earlier studies [*Chagnon et al.*, 2004; *Chagnon and Bras*, 2005; *Negri et al.*, 2004], vegetation breezes are capable of enhancing dry season rainfall over deforested patches in Rondonia.

3. Deforestation-Climate Feedback in Rondonia

[17] The impact of fishbone deforestation goes beyond one-way forcing response behavior and includes complex feedback loops. The immediate atmospheric response to deforestation-induced perturbations in land cover occurs in the form of organized mesoscale circulations. These mesoscale circulations alter local hydrometeorology and consequently affect vegetation dynamics in the deforested patches, thereby completing the feedback loop. A complex system such as the Amazonian rain forest can exhibit multiple feedbacks over different timescales. For simplicity, this paper focuses only on seasonal-scale feedbacks, i.e., the ecosystem response in the 2 dry season months (July–August). Complete forest recovery is impossible within this time period. Hence, the fishbone spatial structure of the land cover heterogeneity is likely to remain intact.

[18] In the absence of field data, the best way to study the seasonal-scale feedbacks is to conduct numerical experiments with a coupled atmosphere-ecosystem model. However, the spatial resolution required to resolve the mesoscale vegetation breezes is very high (~1 km). Conducting a seasonal-scale, high-resolution simulation with a coupled atmosphere-ecosystem model is computationally very expensive. Conducting a large ensemble of such simulations for a rigorous statistical analysis is almost impossible.

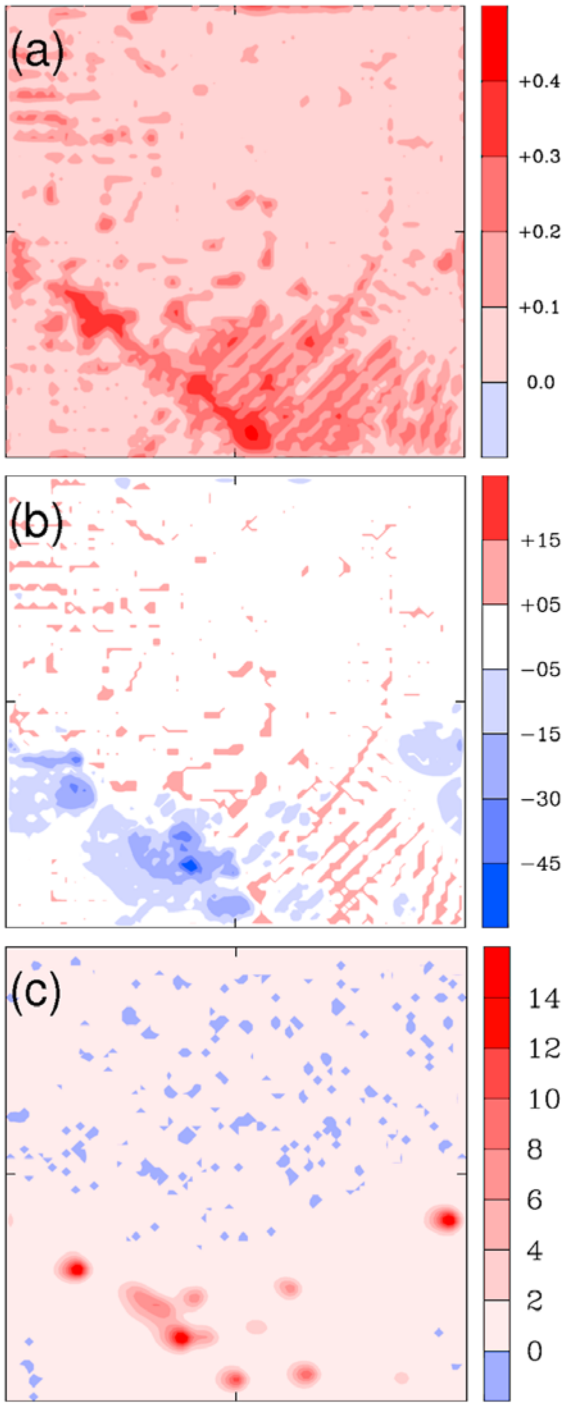

Figure 3. (a) Increase in daily mean temperature (°C), (b) decrease in daily mean incoming shortwave radiation (W m^{-2}), and (c) increase in daily total precipitation (mm d^{-1}) due to fishbone deforestation simulated by the model. All figures are ensemble averaged over the eight simulations.

Hence, a different approach was used for this work. Following the principles of off-line coupling, a plant growth model was driven by a synthetic meteorological data set representing atmospheric conditions over the deforested patches. This approach cannot predict the exact trajectory of the feedback in any given season. However, the stand-alone plant model being very fast, this approach allows for a large ensemble of simulations to obtain a robust statistical description of the feedback.

[19] The plant growth model was based on SUCROS [*Goudriaan and van Laar*, 1994], a mechanistic crop model, calibrated for c3 grasses for this study. C3 grasses colonize deforested regions immediately after logging and often are also maintained as fodder on forest lands converted to cattle pastures. The model simulates growth processes, i.e., net carbon assimilation and partitioning of accumulated biomass into different plant organs. Plant physiological processes including photosynthesis, respiration, organ development, and senescence are functions of environmental conditions like temperature, humidity, and soil wetness as well as age and the photosynthetic characteristics of the plant species.

[20] Since a detailed description of SUCROS is available from *Goudriaan and van Laar* [1994], only a brief description of the prominent features is provided here. SUCROS computes CO_2 assimilation by photosynthesis as a function of the incoming radiation and the leaf area index (LAI). Since SUCROS uses a daily timestep, temporal and spatial variability in radiation is treated implicitly. It parametrically estimates direct and diffuse radiation fluxes above and within the canopy to calculate instantaneous carbon assimilation rates. These rates are then integrated using Gaussian integration method to estimate daily carbon assimilation. Respiration is a simple function of temperature and a threshold temperature. Net carbon assimilation is due to the difference between photosynthesis and respiration. Assimilated carbon or biomass is then partitioned among roots, shoots, and leaves, using partitioning functions that are functions of the phenological development stage of the plant. Growth of different organs depends on accumulated biomass as well as various environmental factors and the development stage. For example, in the juvenile stage, when leaf growth is constrained by temperature through its effect on physiology, rather than by the supply of assimilates, growth in LAI is just an exponential function of temperature. However, in the mature stage, LAI is affected by (1) growth due to biomass accumulation, (2) death due to aging that linearly increases with age in mature plants, and (3) death due to self shading, a linear function of LAI in mature plants. Since length of fibrous roots can vary enormously without much relation to root biomass, root depth depends mainly on soil temperature and continues until the soil moisture falls below the wilting point or till the predefined maximum rooting depth of 5 m is reached. This model was used to simulate vegetation growth over the 2 month dry season period in the study domain.

[21] The plant growth model was driven with a synthetic meteorological data set. Artificial meteorological data from so-called weather or climate generators are widely used to provide atmospheric boundary conditions to ecological and hydrological models [*Parlange and Katz*, 2000; *Grondona et al.*, 2000; *Kittel et al.*, 2004; *Li et al.*, 2005; *Hansen et al.*, 2006; *Apipattanavis et al.*, 2007; *Ivanov et al.*, 2007; *Schuol and Abbaspour*, 2007; *Furrer and Katz*, 2008]. *Wilks and Wilby* [1999] have reviewed earlier works in this field. While a few are purely stochastic, most of the synthetic data generators embed a stochastic field within a mean climatology. This approach was adopted to generate the

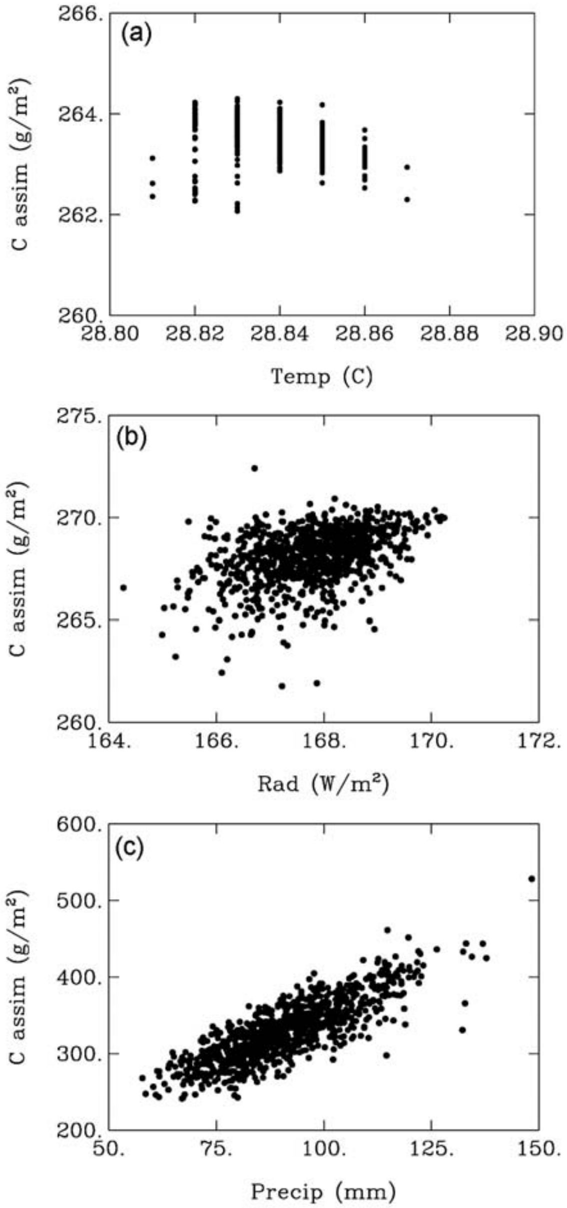

Figure 4. Scatterplot of 1000 realizations showing the simulated impact of (a) temperature, (b) shortwave radiation, and (c) precipitation on net carbon assimilation in deforested patches. While all hydrometeorological parameters affect plant growth, the impact of enhanced precipitation is the strongest.

synthetic data set representing daily meteorological conditions over deforested patches in Rondonia.

[22] The data set was a 62 day long time series, consisting of an observed climatological mean and a mesoscale perturbation. The climatological mean was calculated by averaging the European Studies on Trace Gases and Atmospheric Chemistry as a contribution to the Large Scale Biosphere-Atmosphere Experiment in Amazonia (EUSTACH-LBA) data for the 1999–2002 dry seasons from the automated weather station at Reserva Jaru, a forested site in Rondonia, conveniently located within the domain of interest. (This data set is available online at: ftp://lba.cptec.inpe.br/lba_archives/CD/CD-207/Manzi.) The mesoscale perturbation, representing the effects of deforestation, consisted of simulated daily rainfall, temperature and incoming shortwave radiation from a randomly picked cell in the RAMS domain. For each pair of control and deforested simulation, one of the 8106 forested and 1894 deforested cells, respectively, were used. The major advantage of this synthetic data set is that it allows us to study the impacts of temperature, radiation, and precipitation individually and in various combinations, such as temperature and radiation but no precipitation, etc., on vegetation growth.

[23] For each case, an ensemble of 1000 realizations was conducted using atmospheric conditions from different randomly picked cells. The simulated growth parameters were compared to estimate the impact of the 3 meteorological factors on vegetation growth. The statistical significance of the result was estimated using Welch's t test [*Welch*, 1947] for samples with unequal variance.

[24] Numerical experiments showed that deforestation-induced changes in individual climate drivers have divergent effects on simulated plant growth. Warming increased respiration rate and cloud shading–reduced photosynthesis, both of which reduced the rate of carbon assimilation (Figures 4a and 4b). More rain reduces water stress, thereby increasing the carbon assimilation rate (Figure 4c). While all 3 factors were statistically significant ($P < 0.001$), rainfall had the strongest impact. Increase in rainfall increased carbon assimilation by 48 g^{-2} (approximately 17%) over a 2 month period while warming and cloud-shading resulted in 16 g^{-2} and 11 g^{-2} reductions, respectively. The dominance of the rainfall effect was also observed in experiments with multiple climate drivers.

[25] The overall effect of the mesoscale circulations was a net increase in carbon assimilation and consequently plant growth rate in deforested regions during the dry season in Amazonia. This constitutes a seasonal-scale negative feedback because faster growth compensates for the impacts of deforestation by accelerating the vegetation recovery process. In other words, the dry season vegetation-climate coupled system in the disturbed Amazon forest responds to minimize the effects of deforestation.

4. Discussion

[26] This study demonstrates the importance of mesoscale feedbacks in shaping the local climate and ecosystem dynamics in the disturbed Amazon rain forest. Sharp gradients in land cover due to fishbone deforestation triggers organized mesoscale circulations leading to an enhancement of shallow cumulus clouds and convective precipitation over the cleared patches. The shift in local hydrometeorology significantly affects dry season vegetation growth in the deforested patches. Extra precipitation reduces water stress during the dry season to facilitate plant growth. On the other hand, warming increases respiration rate, and cloud-shading reduces photosynthesis, both of which tend to impede plant growth. However, the precipitation effect dominates the other two and the net result is an increase in plant growth over the bare patches. Thus, deforestation in Rondonia can exert a seasonal-scale negative feedback on itself via the mesoscale atmospheric pathway.

[27] This study is a first look at mesoscale deforestation-climate feedback. The offline coupling approach used in this work provides a modeling framework to identify and understand the fundamental pathways involved in these feedbacks. This approach is necessary for studying interactions between 2 processes with widely different time-scales. However, it cannot predict the exact trajectory of the feedback. For that purpose, a dynamically coupled meso-scale climate-ecosystem model is required. Another area that needs attention is the treatment of diffuse radiation. Clouds cut off direct radiation but increase diffuse radiation to the surface. Diffuse radiation can penetrate deeper into the canopy, thus increasing plant productivity [*Matsui et al.*, 2008]. SUCROS is capable of simulating this effect but RAMS does not distinguish between direct and diffuse radiation. These modifications can substantially improve our understanding of mesoscale feedbacks.

[28] This paper provides an explanation for the puzzling discrepancy between observed and simulated impacts of deforestation on precipitation in Amazonia. Current climate monitoring infrastructure cannot adequately resolve small-scale deforestation and the mesoscale feedbacks. For example, rain gauges in Amazonia are almost exclusively located in forest clearings [*Negri et al.*, 2004]. Sampling error due to this siting bias is likely responsible for the observed increasing trend in rain gauge data. This bias also affects remote-sensing data because satellite sensors are calibrated with rain gauges. Hence, regional climate observation infrastructure must be significantly upgraded to understand and accurately estimate the impact of tropical deforestation on local climate and ecology.

[29] Mesoscale feedbacks triggered by small-scale deforestation are critically important for the timber-based economy of tropical forest regions. Acknowledging the severe environmental impacts of clear-cutting, timber companies have recently started to adopt a selective logging approach where only a limited number of valuable tree species are harvested [*Nepstad et al.*, 1999; *Curran et al.*, 2004; *Asner et al.*, 2005, 2006]. Land-cover gaps in selectively logged forests are transient since the vegetation regenerates itself over time. However, logging roads built for selective logging are quasi-permanent because they are used repeatedly. Even though these roads are narrow, their actual footprint can be 800 m to 4 km wide due to edge effects [*Cochrane*, 2003; *Cochrane and Laurance*, 2002; *Laurance et al.*, 1998, 2001]. Forest fragmentation by the logging roads is likely to trigger mesoscale circulations that redistribute rainfall away from the forest core toward the periphery. Hence, to ensure long-term sustainability of selective logging, the logging roads must be abandoned quickly so that the vegetation cover can revert to its pristine homogeneous state.

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