Positive feedbacks of fire, climate, and vegetation and the conversion of tropical savanna

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[1] We combine general circulation modeling (GCM), remote sensing, and field results to identify a positive feedback loop in which clearing of tropical savannas results in warmer and drier climate, accelerated fire frequencies, and further tree cover loss. The GCM simulations indicate that ongoing clearing of tropical savannas increases temperatures and wind speeds and decreases precipitation and relative humidity, substantially increasing fire frequency. Using NOAA-12 satellite images and meteorological data, we estimate that complete savanna clearing will increase fire frequency by 42%. Combining these data with long-term fire studies, we demonstrate that this fire-mediated feedback may already be contributing to declining tree densities in the world's savannas and will become increasingly important as vegetation change continues in the coming century. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1851 Hydrology: Plant ecology; 3210 Mathematical Geophysics: Modeling; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; *KEYWORDS:* Savanna, Fire, GCM Modeling, remote sensing, fire meteorology, climate change. **Citation:** Hoffmann, W. A., W. Schroeder, and R. B. Jackson, Positive feedbacks of fire, climate, and vegetation and the conversion of tropical savanna, *Geophys. Res. Lett.*, *29*(0), XXXX, doi:10.1029/2002GL015424, 2002.

1. Introduction

[2] Fire plays a dominant ecological role over much of the earth's land surface, influencing ecosystem productivity [*Reich et al.*, 2001], biogeochemical cycling [*Wan et al.*, 2001] and biome distributions [*Kershaw*, 1986]. Fire frequency and intensity are highly sensitive to meteorological conditions and will likely respond quickly to climate change. At the global scale, greenhouse warming is predicted to increase fire risk [*Flannigan et al.*, 2000; *Williams et al.*, 2001] and, in consequence, emissions of greenhouse gases [*Kasischke et al.*, 1995]. At the local scale, thinning of tree cover by fire results in warmer and drier understory microclimate and further fuel drying and increased fire risk [*Cochrane et al.*, 1999]. Understanding such feedbacks is important for predicting future climates and vegetation properties.

[3] Here we quantify a new mechanism of regional-scale feedback among fire, vegetation, and climate in which clearing of tropical savannas results in warmer and drier climate, accelerated fire frequencies, and further tree cover loss. We examine this feedback for moist tropical savannas, but it applies in a number of ecosystems. Savannas are currently subject to intense human pressure, with nearly one fifth of the global population living in tropical savanna regions [*Solbrig et al.*, 1996]. The ensuing expansion of agriculture and grazing lands is driving conversion of the original mixture of trees and grasses to predominantly herbaceous vegetation, with frequent anthropogenic burning disturbing many sites not yet cleared [*Barbosa et al.*, 1999; *Russell-Smith et al.*, 1997].

[4] To quantify the feedback among vegetation, climate and fire, we estimated the effect of tree density on climate, the effect of climate change on fire frequency, and the effect of fire frequency on tree density. To quantify these three relationships, we used general circulation (GCM) modeling, remote sensing, and vegetation modeling, respectively. Subsequently, we used these results to perform offline simulations to estimate the strength of the feedback.

2. Climate Modeling

[5] We used the NCAR Community Climate Model (CCM3.2) [*Kiehl et al.*, 1998], coupled with Land Surface Model (LSM) [*Bonan*, 1996] to simulate the climatic effects of converting tropical savanna to pasture and cropland. Three scenarios were run, a savanna scenario with 50% tree cover, an intermediate scenario with 25% tree cover, and a grassland scenario with no tree cover. Twelve years of model climate were simulated for each scenario using climatological mean monthly sea surface temperatures, with the first two years omitted from all analyses. Scenarios and parameters were identical to *Hoffmann and Jackson* [2000], but with daily output of precipitation, surface temperature, relative humidity, and wind speed at 10 m in the open. The output variables were used to calculate daily values of the McArthur Forest Fire Danger Index (FFDI) [*Nobel et al.*, 1980]. In LSM, savannas are represented as separate sub-grid patches of tropical seasonal trees, grass, and bare soil, with output variables being a weighted average over these

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Table 1. Simulated Effects of Vegetation Change on Mean Annual Values of the Four Meteorological Variables Used to Calculate the Forest Fire Danger Index (FFDI)

	Precipitation ($mm\ yr^{-1}$)		Dry season max. Temperature (°C)		Dry season max. wind speed ($m\ s^{-1}$)		Dry season min. Relative humidity (%)	
	Control	Change	Control	Change	Control	Change	Control	Change
Cerrado	1530	-30^{ns}	30.8	1.5^{c}	5.51	0.77^{c}	36.6	-2.4^{a}
Llanos	1718	0^{ns}	32.5	2.0^{c}	5.10	0.46^{c}	40.0	-2.6^{a}
Southern Africa	1104	-119^{c}	27.5	1.4^{c}	5.58	0.99^{c}	37.3	-1.8^{b}
NorthernAfrica	1108	-93^{c}	33.7	1.4^{c}	5.52	1.07^{c}	21.0	-0.4^{ns}
Australia	872	-12^{ns}	29.3	1.2^{c}	6.16	1.05^{c}	38.5	0.0^{ns}

Dry season values were averaged over periods with mean precipitation less than 2 mm d^{-1} in the savanna scenario. The t-test was used to compare scenarios by first taking daily means over all grid cells in a region, then accounting for temporal autocorrelation using the approach of [*Zweirs and von Storch*, 1995].

[a] $P < 0.05$.

[b] $P < 0.01$.

[c] $P < 0.005$.

[ns] Not Significant.

subgrid patches. However windspeed was output only over grass subgrid patches to ensure that the changes were due to regional effects rather than local effects of roughness length and because FFDI was developed for use with wind speed in the open.

3. Remote Sensing

[6] To relate FFDI to actual fire activity, FFDI was calculated for 1998–2001 at five sites in the Cerrado region of Brazil from meteorological data obtained from the Centro de Previsão do Tempo e Estudos Climáticos (CPTEC/INPE). Daily fire counts within a 100 km radius of each meteorological station were obtained from the evening pass (16:30 to 19:00 local time) of NOAA-12. Evening passes were used to avoid spurious hotspots from warm or bright surfaces. To avoid problems resulting from uncertainty in the absolute area or number of fires, we limit our interpretation to relative changes in fire number.

[7] Using the empirical relationship between FFDI and hotspot number, we estimated the increase in fire frequencyresulting from the simulated climate change. To estimate the increase in fire frequency for intermediate levels of savanna clearing, we interpolated linearly after using the intermediate scenario of savanna transformation to ascertain that fire risk increases linearly in response to reduced tree cover.

4. Vegetation Modeling

[8] We used periodic matrix modeling [*Hoffmann*, 1999], to simulate the effect of increased fire frequency on tree cover for estimating the strength of the vegetation-climate-fire feedback. This model was parameterized with detailed data on the effects of fire on stand dynamics in the Brazilian savannas, including nearly 18,000 plant-years of data on survival, topkill, growth, seed production, vegetative reproduction, and seedling establishment within a controlled and replicated fire experiment [*Hoffmann*, 1999]. Projections of tree and shrub dynamics using periodic matrix modeling based on these data closely matched observed abundances [*Hoffmann*, 1999]. We projected tree cover for two scenarios. In the first scenario, we disregarded any increase in fire due to vegetation-climate feedbacks, considering only the effects of a 3-year fire interval and savanna clearing, using current rates in the Brazilian cerrado (approx 1.7% yr^{-1}). In the second scenario, we took into account the vegetation-climate feedback described here. The gradual climate change resulting from progressive savanna clearing was used to adjust the fire frequency and thus feed back onto tree density.

5. Results and Discussion

[9] Conversion of savanna to grassland significantly altered the four climatic variables most relevant to fire risk (Table 1). Daily maximum surface temperatures and wind speeds increased significantly in all savanna regions while precipitation declined significantly in northern and southern Africa, as did relative humidity in the cerrado, the llanos, and southern Africa (Table 1). Each of these changes increases fire risk [*Nobel et al.*, 1980].

[10] Using the GCM model outputs, the McArthur Forest Fire Danger Index (FFDI) [*Nobel et al.*, 1980] increased significantly in every region as the result of converting savanna to grassland (Figure 1a). FFDI in turn was strongly and positively correlated with the probability and number of fires observed with NOAA-12 satellite images in savanna systems (Figure 2). Pooling data from all sites yielded the relationship $f = 0.594 \exp(0.0453 \cdot FFDI)/(1 + \exp(2.68 - 2.77\ FFDI))$, where f is the mean number of fires per day within a 100 km radius. Using this relationship to estimate daily fire numbers for the climate scenarios, we estimate

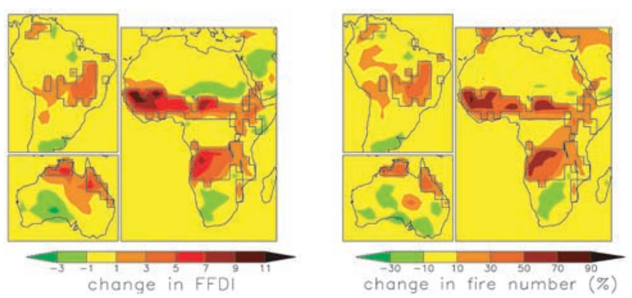

Figure 1. Change in fire risk resulting from conversion of tropical savanna to grassland. Left: Change in Forest Fire Danger Index (FFDI). Right: Relative change in fire frequency. Tropical savanna regions are outlined.

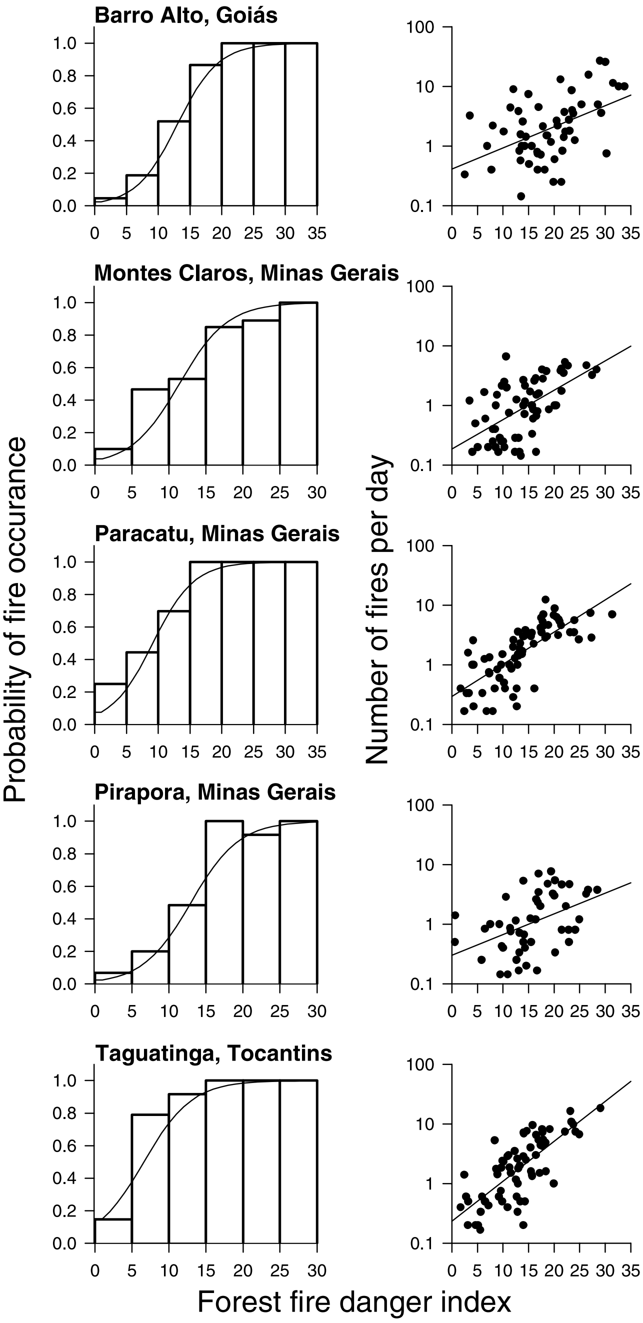

Figure 2. The relationship between FFDI and fire occurrence over a four-year period as determined from NOAA-12 images for five sites. Left: The probability of at least one fire per 7-day interval. Right: The relation ship between FFDI and the number of fires observed per day for those intervals in which fires were observed. Each point represents a 7-day mean within a 100 km radius of the meteorological station used to calculate FFDI.

that complete conversion of tropical savanna to grassland should increase fire frequency by 42% due solely to climatic effects (Figure 1b).

[11] At present, fire intervals are commonly 2–3 yr in these moist tropical savannas [*Barbosa et al.*, 1999; *Russell-Smith et al.*, 1997], rates that are already driving reductions in tree density. With ongoing savanna clearing, the continuous, climate-driven increase in fire frequency will accelerate further decreases in tree cover. Coupling the GCM results with projections of tree density we estimate that when 50% of the total land area is cleared (year 41 with a clearing rate of 1.7% yr^{-1}), the approximate state of the Brazilian cerrado today, this feedback should account for an additional 28% of loss of tree cover in those areas not actively cleared. With 75% land clearing, the feedback will account for 60% loss in tree cover of these uncleared areas (Figure 3).

[12] In the simulations presented here, the use of climatological sea surface temperatures eliminates an important source of variability in tropical climates. In many regions of the tropics, extreme fire years are associated with events such as el Niño [*Siegert et al.*, 2001]. Because of the nonlinearity in the fire response to climate (Figure 2), an increase in the fire danger index should have a larger impact in years with severe fire weather than in milder years, so the mean effect of climate change on fire frequency may be larger than predicted here. Furthermore, vegetation clearing and greenhouse gases are likely to have additive effects on climate [*Costa and Foley*, 2000; *Zhang et al.*, 2001], so the increase in fire risk shown here will be compounded with that expected from greenhouse warming [*Flannigan et al.*, 2000; *Williams et al.*, 2001]. Likewise, the local micrometeorological effects of reduced tree cover, such as increased fuel drying and increased grass biomass accumulation, will further increase fire risk, particularly in dense savanna woodland and seasonal tropical forests [*Cochrane et al.*, 1999]. Though the latter are distinct from savanna, they lie within and peripheral to the main savanna regions,

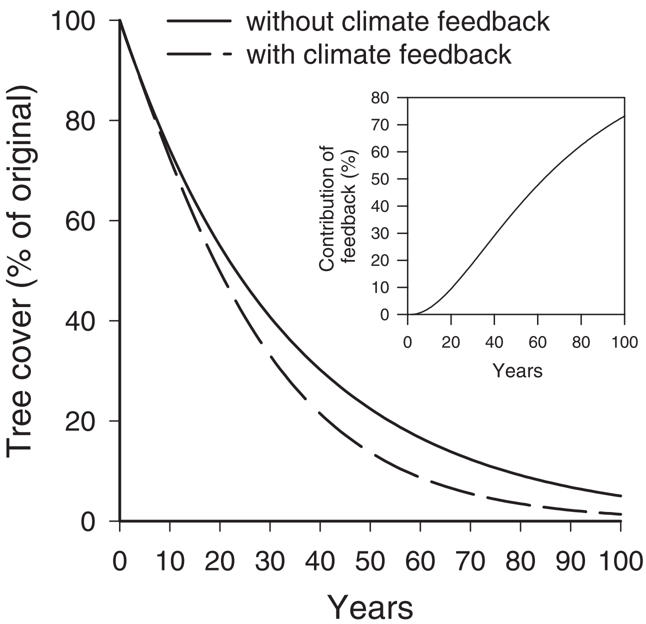

Figure 3. The contribution of the vegetation-climate-fire feedback to the decline in tree cover in the cerrado region. The case without climate feedbacks shows the decline in tree cover, based on a clearing rate of 1.7% yr^{-1} and a background fire interval of 3 years. Projected tree cover is relative to the tree cover present at the onset of clearing at year 0. Inset: The reduction in tree cover due to feedback, as a percentage of remaining tree cover.

thus contributing to the same regional vegetation-climate system. All of these increases in fire risk, including those due to vegetation-climate feedbacks, would also increase fire intensity.

[13] Humans play an important role in this vegetation-climate feedback by igniting the majority of fires in tropical savannas. Climate largely determines observed fire frequencies even where most fires are set by people [*Barbosa et al.*, 1999] because meteorological conditions and fuel drying determine the success of both intentional and accidental ignitions, rate of fire spread, likelihood that a fire escapes control, and total fire area [*Cheney*, 1981]. Fire remains the most viable land management tool for large numbers of subsistence farmers, with population pressure in these regions intensifying land use. As long as this remains true, ignition is unlikely to limit fire frequencies in tropical savannas, permitting fire frequency to respond to future climates.

[14] Understanding vegetation-climate feedbacks is essential for predicting the consequences of land-use change[*Copeland et al.*, 1996; *Hahmann and Dickinson*, 1997; *Hoffmann and Jackson*, 2000; *Shukla et al.*, 1990] and other forcings [*Kutzbach et al.*, 1996] on future vegetation and climates. As we demonstrate here, fire will play an important role in these feedbacks, a result that emphasizes the need to represent fire processes in global-scale modeling. The rapid response of vegetation to fire suggests that fire-driven feedbacks could have important consequences within the scale of human life-spans.

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