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Assessing Fire Potential in a Brazilian Savanna Nature Reserve[1]

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ABSTRACT

Fire is a natural ecological force in the *cerrado*. However, the increasing use of fire by people means that conservation areas are subject to frequent burns. The aim of this study was to assess the potential of fire in an ecological reserve in the Brazilian savannas (*cerrado*) of central Brazil. Data about vegetation type, topography, climate, and fuel characteristics were input into the fire prediction models BEHAVE and FARSITE to simulate fire behavior during different weather conditions and from different entry points into the conservation area. The results indicated that there is a higher probability of fire entry from particular border regions as a result of the fuel characteristics. The presence of invasive grasses, such as *Melinis minutiflora*, within parts of the reserve also significantly affected the pattern of fire spread. Wind speed greatly increased the spread and extent of fire. The study showed that significant improvements in modeling fire behavior in savannas still need to be made. This study was the initial stage in the development of a decision support system for fire management in the *cerrado*.

RESUMO

O fogo é uma das forças naturais que atuam sobre o cerrado. Entretanto, o aumento do uso do fogo pela população faz com que áreas de conservação também estejam permanentemente sujeitas a incêndios freqüentes. O objetivo do presente estudo foi avaliar o potencial de dano pelo fogo em uma unidade de conservação da vegetação de cerrado no Planalto Central do Brasil, por meio de ferramentas de modelagem. Dados sobre o tipo de vegetação, topografia, clima e material combustível foram utilizados na aplicação dos modelos BEHAVE e FARSITE, para similar o comportamento do fogo em diferentes condições climáticas e a partir de diferentes pontos de entrada na unidade de conservação. Os resultados indicam que a probabilidade de incêndios é elevada especialmente a partir de algumas zonas de borda, como resultado das características do material combustível nesses locais. A presença de gramíneas invasoras no interior da área protegida, tais como *Melinis minutiflora*, afetou também, significativamente, o padrão de disseminação do fogo. A velocidade do vento fez aumentar muito o alcance e a extensão do incêndio. Este estudo demonstrou que a modelagem do comportamento do fogo no cerrado ainda precisa ser aprimorada. Foi, portanto, o estágio inicial no desenvolvimento de um sistema de suporte à tomada de decisão sobre o manejo do fogo no cerrado.

Key words: BEHAVE; cerrado; FARSITE; fire; fire behavior; Melinis minutiflora; *modeling*

THE BRAZILIAN SAVANNA, COMMONLY KNOWN AS *CERRADO*, covers approximately 22 percent of Brazil, and is considered to be a "hotspot" of biological diversity (Da Silva & Bates 2002). Fire is a major determinant of the *cerrado*, and many plants and animals are adapted to the long history of natural periodic burning (*e.g.*, Hoffman *et al.* 2003, Briani *et al.* 2004). Today, however, most ignition sources are anthropogenic. Most of these burns arise from agricultural activities during the dry season (June–September), when fire is used to promote fresh re-growth of grass in pastures for cattle, and to clear land for cultivation in the wet season (Mistry 1998a). Other anthropogenic burns include arson and accidental fires. With population densities increasing and agricultural land use expanding in the *cerrado* region, burning rates have also risen, and large areas still covered in natural vegetation are now burned almost every year (Klink *et al.* 1993).

As a result of this rise in both the spatial and temporal occurrence of fire, the study of fire in the *cerrado* is seen as increasingly important. The frequency, intensity, and extent of these fires are threatening the survival of native species, contributing to atmospheric gas emissions and its associated effects on greenhouse warming, as well as impacting local communities that depend on *cerrado* natural resources for their livelihoods. However, the intrinsic interdependence of *cerrado* species and key ecosystem processes (such as nutrient cycling) with fire, suggest that if used in an appropriate way, fire can be an effective management tool. For example, in the Australian savannas, prescribed fires based on Aboriginal burning techniques have been applied in national parks such as Kakadu (Russell-Smith 1995) and Uluru (Saxon 1984), and have helped prevent excessive build-up of plant necromass thus reducing the impact of wildfires. The lack of scientific research with fire management objectives has obstructed the development of fire policies for the *cerrado*.

The lack of coherent fire management policies is particularly poignant for areas of conservation, such as reserves and national parks, where delimited areas set aside for protection are surrounded by a mosaic of other land uses and management objectives. As a result, criminal and/or accidental wildfires constantly invade these areas. In some national parks, such as Emas National Park, severe fires occur every 3 to 4 yr—between 1973 and 1995, 74 to

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93 percent of the 132,133 ha of the park burned (França & Setzer 1997). Fire management in these areas needs to assess the probability of fire, taking into account both the physical and environmental variables, such as climatic conditions and the nature of the fuel type, and the nature and timing of potential fire entry from surrounding areas determined primarily by fire users inhabiting or traveling along the borders of the area. Assessment of the threat of fire in different parts of an area can be used as a basis for prescribed fires and/or fire prevention measures including fire patrols and construction of firebreaks.

An assessment of fire potential tries to predict the probability of ignition within the area, and then the likely spread rates and intensities of fire. The majority of past research into fire potential has depended on several basic indicators that control fire ignition and behavior. For example, the National Fire Danger Rating System (NFDRS) in the United States is based on a model developed by Rothermel (1972) which uses data on fuel, weather, and topography for predicting fire threat. The Australian fire danger rating system is based on a model by McArthur (1966, 1967), which uses weather inputs such as air temperature, relative humidity, and wind speed to calculate the potential rate of fire spread. Remote sensing is also becoming an important tool for assessing fire potential. Studies by Prosper-Laget *et al.* (1998) and Maselli *et al.* (2000) assess fire threat in Mediterranean forests using imagery on vegetation cover and surface temperatures. Sannier *et al.* (2002) have used remote sensing techniques to estimate the biomass of savanna vegetation in Etosha National Park, Namibia, for the assessment of fire risk. Integrating remotely sensed data into geographical information systems, with other information (*e.g.*, Jain *et al.* 1996, Maselli *et al.* 1996), has also been used to ascertain the important factors, such as settlement and topography, favoring fires in particular forest landscapes. As more is known about fire behavior, the ultimate aim has focused on simulating as realistically as possible the actual behavior of fire.

Assessing the potential behavior of fire can be done using computer models. Recent advances in computer technology have allowed the development of several spatially explicit fire behavior simulation models (*e.g.*, Anderson *et al.* 1982, Ball & Guertin 1992, Green *et al.* 1995) (see Perry 1998 for review of fire models). These models predict the spread and intensity of fire as it moves across a landscape, allowing users to project future fire scenarios as well as real-time simulations. FARSITE is one of the foremost fire behavior models (Finney 1993, 1997, 1999), widely used by public land management agencies in the United States. It is a spatially explicit two-dimensional fire growth computer model that uses data on fuels, slope, aspect, elevation, canopy cover, tree height, height to live crown base, crown density, and weather as inputs. Spatial variables including topography and fuels are defined using raster geographical information system (GIS) data, while weather inputs such as wind are defined using data streams. FARSITE runs with real-time, on-screen graphics so the user can view the spread of the fire over the stimulated landscape, and select a number of outputs as GIS polygon layers. The latest version and documentation may be found at http://www.farsite.net.

FARSITE has been used for a number of applications, including fire succession models (Keane *et al.* 1999), to evaluate the effects of silvicultural and fuel treatments on potential fire behavior (Stephens 1998), to assess the cost-effectiveness of landscape-prescribed fires (Omi *et al.* 1999), to quantify the differences between historic and current fire spread distributions (Duncan & Schmalzer 2004) and to assess the risk of fire propagation in the savannas of Senegal (Mbow *et al.* 2004). In the latter study, FARSITE simulations were compared to real fire scar maps derived from remote sensed images. Their results found that approximately 55 percent of the real burned areas were located in the FARSITE simulated burned areas (Mbow *et al.* 2004). The spatial shift between real fires and simulated fires are probably associated with the variability of parameters such as wind, topography, and fuel biomass, which are averaged in the model, although they are extremely variable in the real world.

BEHAVE is another fire model, developed by the USDA Forest Service for predicting fire behavior from weather condition inputs (Burgan & Rothermel 1984, Andrews 1986, Andrews & Chase 1989). The BEHAVE system is made up of two subsystems: the fuel modeling subsystem, FUEL, which allows users to build custom fuel models for specific situations (see the Methods section); and the fire prediction subsystem, BURN, which uses inputs such as weather, fuel moisture, and time of year, to calculate major fire characteristics, including flame height and rate of fire spread. Although used mainly by land managers and fire control units, BEHAVE has been applied by researchers for testing hypotheses on the impacts of fire in different vegetation types. Working in Hawaii, Freifelder *et al.* (1998) compared unburned woodland to grass-dominated burned woodland, to evaluate whether the replacement of woodland with grass could increase the probability and spread of future fires. Their results from BEHAVE indicated that a fire started in the grassland can be expected to spread an order of magnitude faster than one started in the woodland, primarily as a result of greater wind speeds in the grassland. Another study in Hawaii by Blackmore and Vitousek (2000) used BEHAVE to compare the potential fire behavior of two grazed introduced grass species, *Pennisetum clandestinum* and *Pennisetum setaceum*. Their results indicated that grazed grasses have a much lower fire potential than ungrazed grasses, and that under ungrazed conditions, *P. setaceum* poses a greater fire danger than *P. clandestinum*.

The objective of this study was to assess the potential of fire in a conservation area of *cerrado* by simulating fire behavior using FARSITE and modeling fuels using BEHAVE. The Reserva Ecológica do Roncador (RECOR) in central Brazil is used as a case site. This is because the reserve has freely available data on its web site that can be used for analyses (http://www.recor.org.br), and the past field experience of the authors at the site. Most fires entering the reserve in the past have come from deliberate or accidental fire ignitions on the reserve borders. The aim, therefore, was to simulate fire behavior in the dry season from a variety of entry points into the reserve. This would allow the identification of high fire potential areas, including borders and fire propagation corridors into the reserve. Simulations under different climatic conditions would also allow the identification of which vegetation types are under risk during particular climatic conditions. After assessing the available climatic data from the reserve, we simulated fire behavior for three different situations that we defined as "low" (1990), "moderate" (1994), and "extreme" (1998) fire climatic conditions. In 1998, major fires burned in various reserves around Brasilia, aided by the extremely dry weather (D. Rocha, pers. comm.). A previous study (Mistry 1998b) identified late August as being the main time for lighting fires by local people, so it was decided to limit the simulations to days during this period. In this study, we focused on the analysis of single wildfire simulations. It is questionable whether the averaging of multiple simulations would have provided any additional benefits. One would need to carry out averaging if the simulations had a stochastic component. In real life, variability in wind speeds combined with patchy fuel distributions sometimes contribute to relatively unpredictable fire behavior. Unfortunately, FARSITE does not allow for the inclusion of a randomizing factor, especially on wind speeds. If this had been the case, then the averaging of multiple simulations would have been a sensible procedure, and would have provided useful additional information on the relative predictability of fire behavior within particular environmental and fuel distribution scenarios. Fire behavior is also affected by the fires that have gone before, *i.e.*, time since the last fire, especially in terms of fuel loads. To take this into account, we have assumed a fire frequency of 2–4 yr for *cerrado* vegetation when estimating fuel biomass, and no past fires for the wetter non-*cerrado* vegetation types that rarely burn.

METHODS

STUDY SITE.—The Reserva Ecológica do Roncador (RECOR) was created in 1975, and covers an area of 1300 ha in central Brazil, with an altitude of between 1048 and 1150 m, and an average slope of 3.5 percent (Pereira *et al.* 1989). It is located 35 km south of the center of Brasilia (DF), and is bordered to the northeast and northwest by the Jardim Botanico de Brasilia (Botanical Gardens of Brasilia), to the southwest by the Fazenda Água Limpa (The University of Brasilia's experimental farm), and to the southeast by a main road connecting Brasilia to Unaí in Minas Gerais.

The reserve resides in a *chapada* (a high tableland) in the epicenter of the Brazilian *Planalto* (Ab'Saber 1971). The soils are mostly covered by detrites-lateritics and are predominantly red-yellow and dark-red latosols (EMBRAPA 1980, 1987). They are characteristically deep (>3 m), well-drained, clay-rich, acidic, structurally strong but nutrient-poor, and contain high concentrations of aluminum, reaching toxic levels in some areas (Haridasan 1994). The vegetation within the reserve is complex and diverse, represented by the major forms of *cerrado*, including *campo limpo*, *campo sujo*, *campo cerrado*, *cerrado sensu stricto*, and *cerradão*. Forests and swamps are present by the permanent waterways. Table 1 describes the main characteristics of the vegetation types found in and around the reserve.

The climate of the study site has two well-defined seasons: the rainy season (September to April/May), during which about 75 percent of the total annual precipitation (mean 1667 mm) falls, and the dry season (June through September), when the average relative humidity is 20 percent but can fall to minima of 11 percent, and wind speeds can be high (Pereira *et al.* 1989). It is during this latter period that conditions are ideal for the propagation of fire. This potential for fire in the reserve is exacerbated by the presence of a highly flammable African invasive grass, *Melinis minutiflora*, which covers large tracts of the reserve.

FIRE PREDICTION MODELLING.—The key inputs to the FARSITE model are spatial data (elevation, slope, aspect, fuel type, canopy cover), fuel data (including moisture content), and weather data (relative humidity, maximum and minimum air temperature, precipitation, wind speed, wind direction, cloudiness). Elevation, slope, and aspect, representing topography, are required to be spatially defined. Maps of these parameters, together with a vegetation map (used as the basis of the spatially defined fuel and canopy cover inputs

TABLE 1. *The main vegetation types found in and around RECOR (definitions after Eiten, 1972; Sano and Almeida, 1998).*

Vegetation type	Description
Invasive grasses	Grasses not native to Brazil, usually African origin, dominated by *Melinis minutiflora*.
Campo limpo	A pure or almost pure grassland.
Campo sujo	A tree and shrub savanna, with widely scattered woody species.
Campo cerrado	A wooded savanna, where the scattered low trees have a total crown cover of 5–20 percent, and the herbaceous species appear as a conspicuous part of the landscape.
Cerrado sensu stricto	A savanna woodland where trees are 5–8 m high and the total woody cover is from 20 to 50 percent.
Cerradão	A woodland or open low forest, with trees from 8–15 m high, and a canopy cover between 50 and 90 percent.
Mata ciliar	Forest found on the margins of rivers, with trees from 20 to 25 m high, and canopy cover of between 50 and 90 percent.
Murundu	Found on hydromorphic soils where vegetation consists of herbaceous layer dotted with mounds supporting trees of *cerrado*.
Brejo-murundu	Found on hydromorphic soils. *Brejo* is dominated by the palm *Mautitia flexuosa*, whereas *murundu* consists of herbaceous layer dotted with mounds supporting trees of *cerrado*.
Brejo-veredas	Marshy areas influenced by rivers where soils are hydromorphic. *Brejo* is dominated by the palm *Mautitia flexuosa*, whereas *veredas* consist of dense herbaceous layer and emergent individuals of *M. flexuosa*.
Eucalyptus plantation	Dominated by species of *Eucalyptus*, and a herbaceous layer underneath.

TABLE 2. *Weather information from the RECOR web site used for input into FARSITE.*

	Weather variables				
	Relative humidity (%)	Maximum temperature (°C)	Minimum temperature (°C)	Wind speed (km/h^{-1})	Cloudiness (%)
August 1990					
25	56	26	18	11	19
26	51	26	12	7	17
27	44	30	15	6	18
28	56	26	14	8	82
29	59	25	15	10	81
30	59	20	15	5	81
August 1994					
25	27	32	12	6	16
26	30	32	15	6	22
27	34	31	15	9	17
28	34	31	14	9	13
29	35	31	16	8	13
30	34	31	14	8	17
August 1998					
25	38	30	12	8	14
26	37	31	13	6	15
27	28	32	13	8	16
28	29	32	16	10	15
29	34	31	17	11	17
30	35	32	19	15	15

to FARSITE), were derived from maps available on the RECOR web site (http://www.recor.org.br). These were geo-referenced in the geographical information system, ArcView 3.1 (ESRI 1996), at a resolution of 10 m and converted into raster formats readily accepted by FARSITE.

FARSITE uses daily maximum and minimum temperatures and humidities, and the time at which these temperatures occurred to determine fuel moisture conditions at each time step during the stimulation. Wind parameters are particularly important for fire, affecting the rate of spread, its direction, and the flame heights attained. Weather data for the 3 yr, 1990, 1994, and 1998, was downloaded from the RECOR web site (http://www.recor.org.br), and various parameters were extracted for the period August 25–30. These are shown in Table 2, and include relative humidity, maximum temperature, minimum temperature, wind speed, and cloudiness (derived from insolation). Note that rainfall and wind direction did not change throughout the study period, with values of 0 mm and 90°, respectively. Weather data are not input as a spatial data layer into FARSITE, but as a set of ASCII files composed of a stream, *i.e.*, a list of hourly or daily temperatures, precipitation, and relative humidities. Wind is treated differently in that wind speeds and directions are specified by time of day in a separate set of wind ASCII files.

A number of standard fuel types are built into FARSITE based on North American vegetation types. However, the model also gives the user the option to define new fuel types. The classes of fuels found in the *cerrado* are quite different from the standard fuel types included in FARSITE, so new custom fuel models (*i.e.*, variables that characterize a fuel type) had to be developed. This was done using the NEWMDL submodel of the model BEHAVE (Burgan & Rothermel 1984, Andrews 1986). These modifications allow the user to input data on the quantity and distribution of each fuel type found at a specific site, which is then used to compute variables that can be input into FARSITE. Creating the custom fuel models involved collating data from fire behavior studies carried out in the *cerrado*. This was primarily from Ottmar *et al.* (2001), Kauffman *et al.* (1994) and Miranda and Miranda (1993), which included fuel load and fire behavior data for different *cerrado* types. Information for other vegetation types, such as gallery forest, was obtained from Ribeiro (1998) and Sano and Almeida (1998). Once a fuel model (for each fuel type) was created, sensitivity analyses were performed using another submodel TSTMDL, allowing the user to input different weather conditions and test how the fuel model behaves accordingly. Outputs including flame height, rate of spread, and fire intensity were compared with fire behavior results from the secondary data mentioned above. The characteristics of the 11 custom fuel models created are given in Table 3.

Dead and live fuel moistures have a great effect on fire behavior. Fuel moisture values for *cerrado* vegetation used in this study were derived from a study carried out in Assis Ecological Station, São

TABLE 3. *Characteristics of custom fuel models developed from BEHAVE, and used as an input into FARSITE.*

	Model number and vegetation type										
Model parameter	14, Invasive grasses	15, *Campo limpo*	16, *Campo sujo*	17, *Campo cerrado*	18, *Cerrado sensu stricto*	19, *Cerradão*	20, *Mata ciliar*	21, *Murundu*	22, *Brejo-murundu*	23, *Brejo-veredas*	24, Eucalyptus plantation
1-h fuel load (t/ha)	15.9	5.5	3.5	2.9	2.9	2.9	3.8	1.5	0.7	0.7	2.9
10-h fuel load (t/ha)	0	0	0	0.7	0.8	2.1	3.1	0.1	0	0	1.3
100-h fuel load (t/ha)	0	0	0	0.4	0.9	3.4	5.5	0.1	0	0	0.67
Live herbaceous fuel (t/ha)	2.1	0.4	0.2	0.1	0.1	0.1	0.6	1.4	2.3	3.0	0.1
Live woody fuel (t/ha)	0	0	0.2	2.9	2.8	3.1	3.9	0.7	0.1	0	1.7
Fuel depth (m)	0.7	0.5	0.5	0.5	0.5	0.3	0.3	0.3	0.4	0.4	0.5
Surface area/volume ratio of 1-h fuel (/cm)	57	90	90	90	90	90	90	90	90	90	91
Surface area/volume ratio of live herbaceous fuel (/cm)	39	39	39	39	39	39	39	39	40	41	42
Surface area/volume ratio of live woody fuel (/cm)	39	39	39	39	39	39	39	39	40	41	42
Extinction moisture content (%)	25	25	25	25	25	25	25	25	20	20	25
Heat content of dead fuel (KJ/kg)	23,300	17,200	17,200	17,200	17,200	17,200	17,200	17,200	17,200	17,200	19,500
Heat content of live fuel (KJ/kg)	18,600	16,300	16,300	16,300	16,300	16,300	16,300	16,300	16,300	16,300	17,000

Paulo state in August 2001 (J. Mistry & A. Berardi, pers. obs.). All the vegetation in eight plots of 1 × 1 m in *cerrado sensu stricto* was clipped and sorted into different life forms and sizes (1 h (0–0.64 cm diameter), 10 h (0.64–2.54 cm diameter), 100 h (2.54–7.62 cm diameter), live woody and live herbaceous). One-, 10-, and 100-h sizes refer to the probable moisture content of fuels that have a time lag constant of 1 h or less, 10 h, or 100 h, respectively (Burgan & Rothermel 1984). The moisture content of each sample was determined from weights before and after 72 h of drying at 70°C. For this study, the moisture content values were grouped according to fuel size, and a mean and standard deviation was calculated. Of the non-*cerrado* vegetation, eucalyptus plantation is given the same values as *cerrado*, but for the generally moister *mata ciliar* and marshy vegetation types, the live herbaceous and woody fuels are given higher moisture contents. All the fuel moisture values are shown in Table 4. These initial fuel moisture values are then used by FARSITE to calculate moisture content on an hourly basis for 1 and 10 h fuels and daily for 100 h fuels using the weather, wind, terrain, and canopy cover data. The moisture content of live fuels was not modified by the simulations.

FARSITE uses canopy cover to determine average shading of surface fuels, which in turn affects fuel moisture calculations. Canopy cover and tree height are also important for determining to what extent the wind speed values, normally measured above the vegetation height, need to be reduced to affect surface fires. Canopy cover and average tree canopy height for each fuel type was derived from the literature, namely Sano and Almeida (1998) and Ribeiro (1998). Crown height and crown density are used to determine a

TABLE 4. *Initial fuel moisture values assigned to each fuel type.*

	Model number and vegetation type										
	14, Invasive grasses	15, *Campo limpo*[a]	16, *Campo sujo*	17, *Campo cerrado*	18, *Cerrado sensu stricto*	19, *Cerradão*	20, *Mata ciliar*	21, *Murundu*	22, *Brejo-murundu*	23, *Brejo-veredas*	24, Eucalyptus plantation
1-h fuel moisture (%)	16	16	16	16	16	16	16	16	16	16	16
10-h fuel moisture (%)	18	18	18	18	18	18	18	18	18	18	18
100-h fuel moisture (%)	19	19	19	19	19	19	19	19	19	19	19
Live herbaceous fuel moisture (%)	107	107	107	107	107	107	150	200	200	200	107
Live woody fuel moisture (%)	79	79	79	79	79	79	100	150	150	150	79

[a] The standard deviation for *cerrado* fuels were as follows: 1 h ±5.2; 10 h ±5.7; 100 h ±6.7; live herbaceous ±30.7; live woody ±18.8.

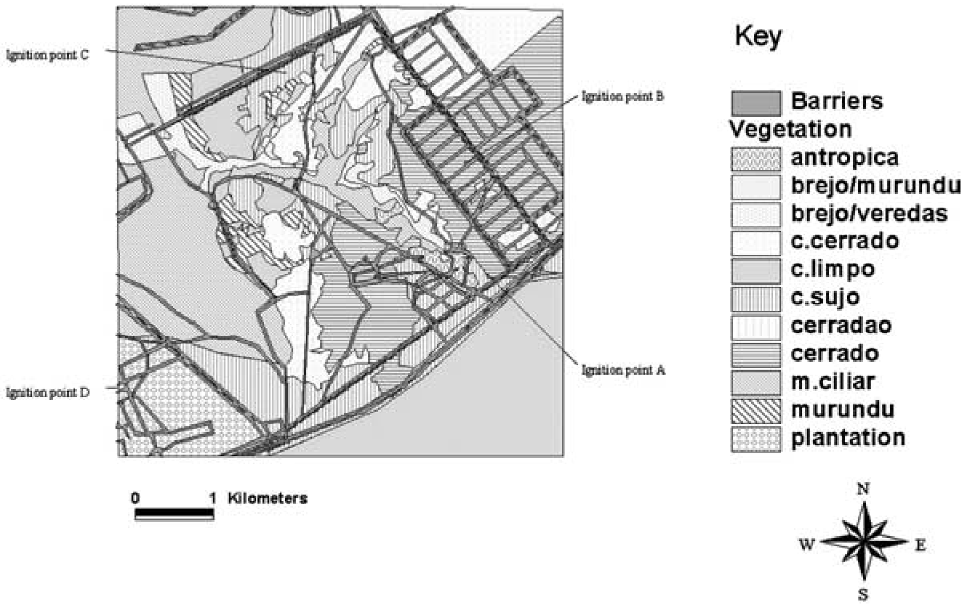

FIGURE 1. GIS map of the vegetation and the main barriers to fire for the Reserva Ecológica do Roncador (derived from its web site at http://www.recor.org.br). The figure also shows the ignition points for the four different scenarios used in the FARSITE fire simulations.

threshold for achieving active crown fire. However, crown fires are rare in the *cerrado* and were therefore not modeled in this research.

Since we were interested in how the vegetation, and hence fuel type, influenced fire behavior, we decided to place ignition points within the main vegetation types found inside the borders of the reserve. The FARSITE simulations were run for the following four ignition scenarios (see Fig. 1):

1. Scenario A—entry from the southeast. This would be from the vegetation along the border parallel to the main road, dominated by *campo limpo, campo sujo*, and tracts of the invasive grass *Melinis minutiflora*;
2. Scenario B—entry from the northeast. This would be on the border with the Jardim Botanico de Brasilia, where there are more dense forms of *cerrado* such as *campo cerrado* and *cerrado sensu stricto*;
3. Scenario C—entry from the north. This would be on the border with the Jardim Botanico de Brasilia, where there are more open forms of *cerrado*, particularly *campo sujo*;
4. Scenario D—entry from the southwest. This would be on the border with the Fazenda Água Limpa, particularly from the *campo sujo*.

These simulations were run over one day from August 28, 1300 h to August 29, 1300 h for each year. A barrier file was also incorporated into the simulations to represent the watercourses, main roads, and paths around and within the reserve. All ignition points were placed at the same points, and all fire simulations were unconstrained by suppression activities.

The FIRE1 module of BEHAVE was used to model fire behavior using the custom built fuel models developed from the NEWMDL submodel (Burgan & Rothermel 1984, Andrews 1986). Various data about the fuel moisture, wind speed, and slope of a fuel type can be used to derive outputs including fire intensity and heat per unit area. For this study, rate of fire spread, fire intensity, and flame height were modeled for the five fuel types: invasive grass (the majority of which is *Melinis minutiflora*); *campo limpo*; *campo sujo; campo cerrado,* and *cerrado sensu stricto*. These correspond to the dominant vegetation types for the four scenarios outlined above.

RESULTS

FARSITE SIMULATION RESULTS.—Table 5 gives an indication of the area burned for the different scenarios. As was expected, for all scenarios (except Scenario B), the extent of fire increased from 1990 to 1994 to 1998, as weather became more conducive to fire propagation and sustenance. In Scenario B, the presence of firebreaks on all sides of the ignition point confined the fire to a small area. In

TABLE 5. *The area burned in hectares from fire simulations for the four scenarios (A–D) in years 1990, 1994, and 1998.*

Scenario	1990	1994	1998
A	163	155	211
B	11	11	11
C	146	153	165
D	47	64	82

TABLE 6. *Fire simulation results for the 1990, 1994, and 1998 scenarios.*

Scenario	Simulation result
Scenario A, 1990	The fire moved quickly through the *campo sujo*, which helped to propagate the fire in three main directions. The first is in a north easterly direction into *campo cerrado* and *cerrado sensu stricto* vegetation within which the fire moved slowly. The fire moved quickly in a westward direction through *campo sujo* and then more slowly in *cerrado sensu stricto*. The fire also propagated northwardly, where it encountered invasive grass, through which it moved extremely fast, and which helped to propagate the fire into nearby gallery forest.
Scenario B, 1990	The fire burned a small area of *cerrado sensu stricto* and was confined by the firebreaks.
Scenario C, 1990	The fire moved rapidly through the *campo sujo* and adjacent *campo limpo*, and then more slowly through *campo cerrado*.
Scenario D, 1990	The fire moved easterly through campo sujo, and northerly into *campo cerrado*, burning some gallery forest.
Scenario A, 1994	The fire behaved similarly to that described for *Scenario A 1990*. However, there was a greater extent of burning in the north easterly direction of *cerrado sensu stricto* and *campo cerrado*, and northwardly in the gallery forest and *brejo* vegetation.
Scenario B, 1994	The fire burned a small area of *cerrado sensu stricto* and was confined by the firebreaks.
Scenario C, 1994	The fire behaved similarly to that described for *Scenario C 1990*.
Scenario D, 1994	The fire behaved similarly to that described for *Scenario D 1990*. However, the fire moved further through the *campo cerrado* and then entered *campo limpo* within which it moves very fast.
Scenario A, 1998	The fire behaved similarly to that described for *Scenario A 1994*. However, there was a greater extent of burning in the northwardly direction into gallery forest, *brejo* vegetation and then more open forms of *cerrado*.
Scenario B, 1998	The fire burned a small area of *cerrado sensu stricto* and was confined by the firebreaks.
Scenario C, 1998	The fire behaved similarly to that described for *Scenario C 1990*. However, the fire attained a greater extent as it moved through the *campo cerrado*.
Scenario D, 1998	The fire behaved similarly to that described for *Scenario D 1994*.

all years, Scenario A resulted in the largest fires, and Scenario C the second largest fire, followed by Scenarios D and B. A more detailed description of the results of each simulation is given in Table 6.

BEHAVE FIRE PREDICTIONS.—Figures 2, 3, and 4 compare the predicted rate of fire spread, flame heights, and fireline intensities, respectively, of the five fuel types across a range of 1 h (fine) dead fuel moistures (8–23% moisture) at three different wind speeds (5, 10, and 15 km/h). The range of fuel moistures reflected that observed during the late dry season (late August, early September) for *cerrado* fuel by Miranda *et al.* (1996). The wind speeds correspond to the range found in the same period at the IBGE reserve from 1990, 1994, and 1998 weather data (see Table 2).

Figure 2 indicates that for all fuels, as 1-h dead fuel moisture increased, the rate of fire spread decreased. The rate of spread is much higher in the more grass-dominated fuels (invasive grass, *campo limpo*, and *campo sujo*), than more woody-dominated types (*cerrado cerrado* and *cerrado sensu stricto*). At the lower wind speed (Fig. 2a), invasive grass had the highest rate of spread at 18.8 m/min, followed by *campo limpo* and *campo sujo*. Above a value of 15 percent moisture, the rate of spread of these fuel types declines sharply. At the higher wind speeds (Fig. 2b and 2c) *campo limpo* and *campo sujo* have the highest rate-of-spread values, followed by the invasive grass. Again, the values declined around 15 percent moisture.

For flame height and fireline intensity, the sharp difference is between invasive grass and the other *cerrado* types (Figs. 3 and 4). At a fuel moisture content of 8 percent, flame heights in invasive grass reached 5, 8, and 11 m at wind speeds of 5, 10, and 15 km/h, respectively. *Campo limpo* had the second highest values, followed by *campo sujo*, and then *campo cerrado* and *cerrado sensu stricto* that have comparable results. Fireline intensity showed similar patterns as flame height, although for invasive grass there was an almost exponential decrease in intensity with increasing fuel moisture. Even at the higher fuel moisture values, invasive grass produced very high flames and intense fires.

DISCUSSION

The BEHAVE results indicated that, in general, the grass-dominated vegetation types, such as *campo limpo* and *campo sujo*, have fuel characteristics, such as high fuel biomass, susceptible to greater flame heights, higher fire intensities, and faster rate of spread. These results are substantiated by previous studies in the *cerrado* (Miranda & Miranda 1993, Kauffman *et al.* 1994). The FARSITE results also show that fires that started and propagated through *campo limpo* (Scenario A) and *campo sujo* (Scenario C) led to burning of larger areas.

The presence of invasive grasses, particularly *Melinis minutiflora*, is a constant worry for the reserve's manager (M. Gonzales, pers. comm.), because it reduces biodiversity and influences fire behavior. The BEHAVE results show that at a dead fuel moisture <15 percent, fires in invasive grasses can spread quite rapidly even at low wind speeds. Flame heights and fireline intensities for these fires are also high indicating that many trees would be killed, a phenomenon that does not normally occur in *cerrado* vegetation fires. In fact, a study by Berardi (1994) found that fire temperatures in an area of *M. minutiflora* burnt in late August had peak temperatures between 800°C and 1006°C, and flames over 6 m. These flame heights are similar to those predicted in this study of 6.6 m, if we use a 1-h

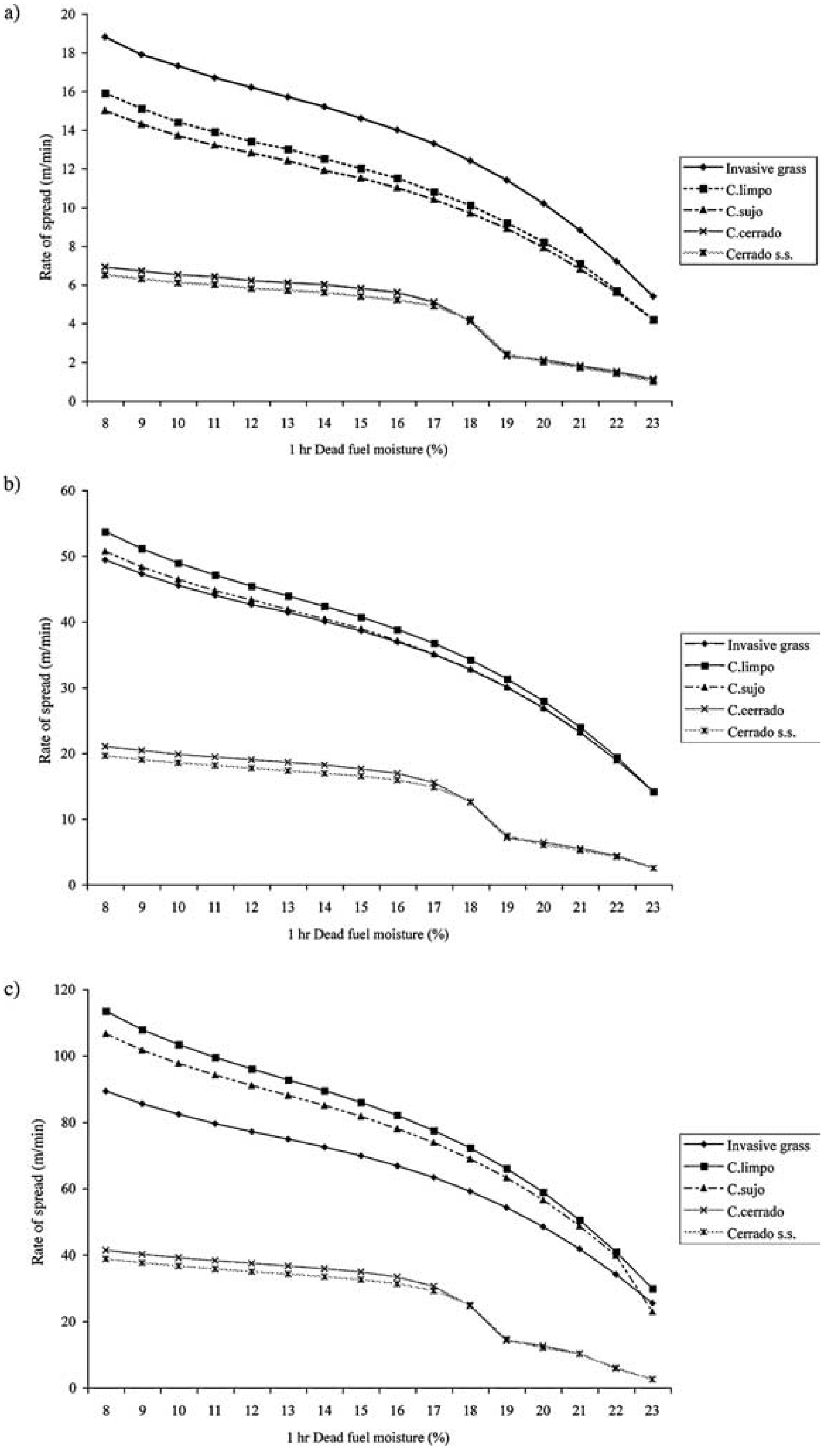

FIGURE 2. Rate of spread (m/min) for five fuel types with increasing 1 h dead fuel moisture at wind speeds of (a) 5 km/h, (b) 10 km/h, and (c) 15 km/h.

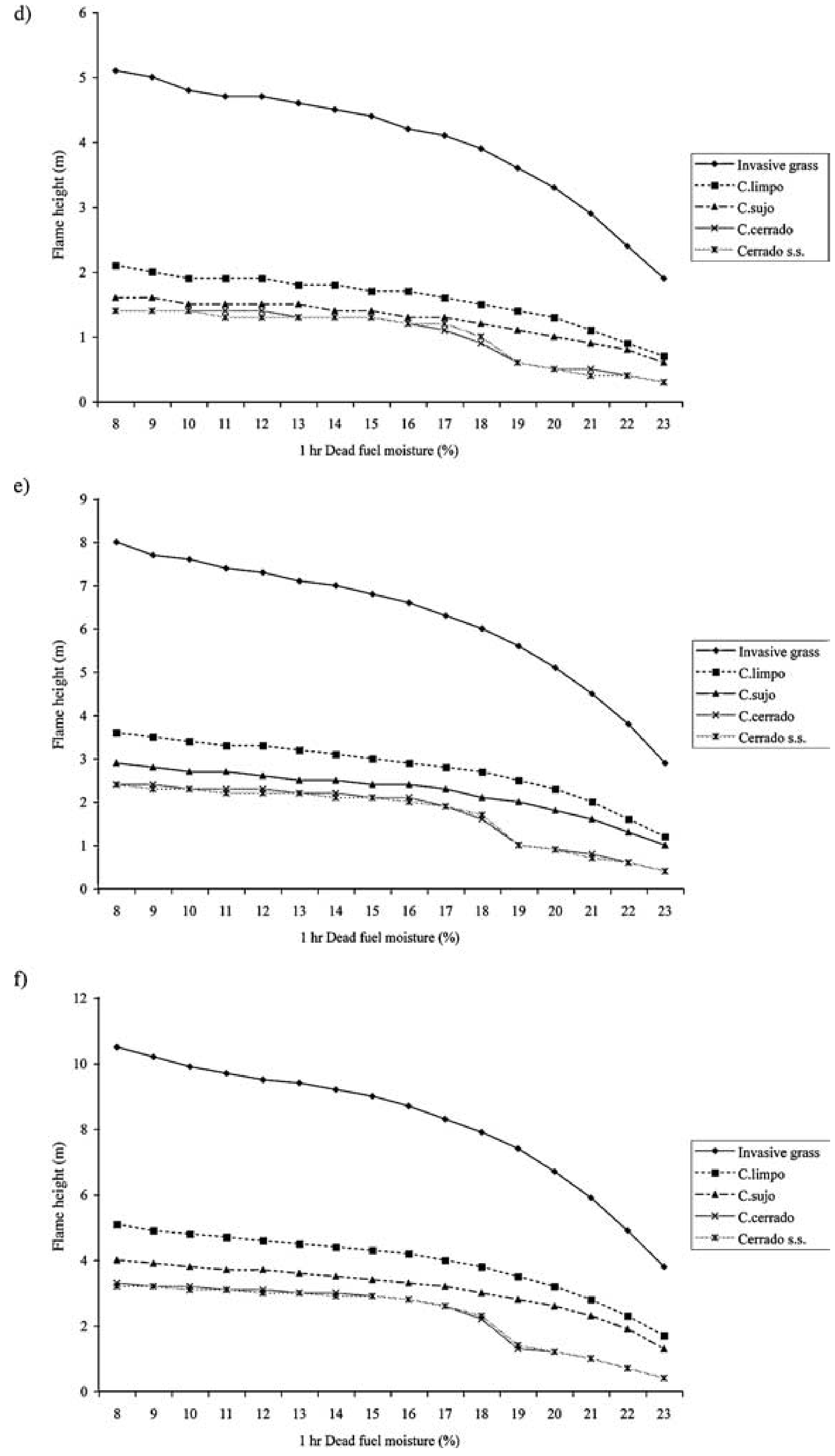

FIGURE 3. Flame height (m) for five fuel types with increasing 1 h dead fuel moisture at wind speeds of (a) 5 km/h, (b) 10 km/h, and (c) 15 km/h.

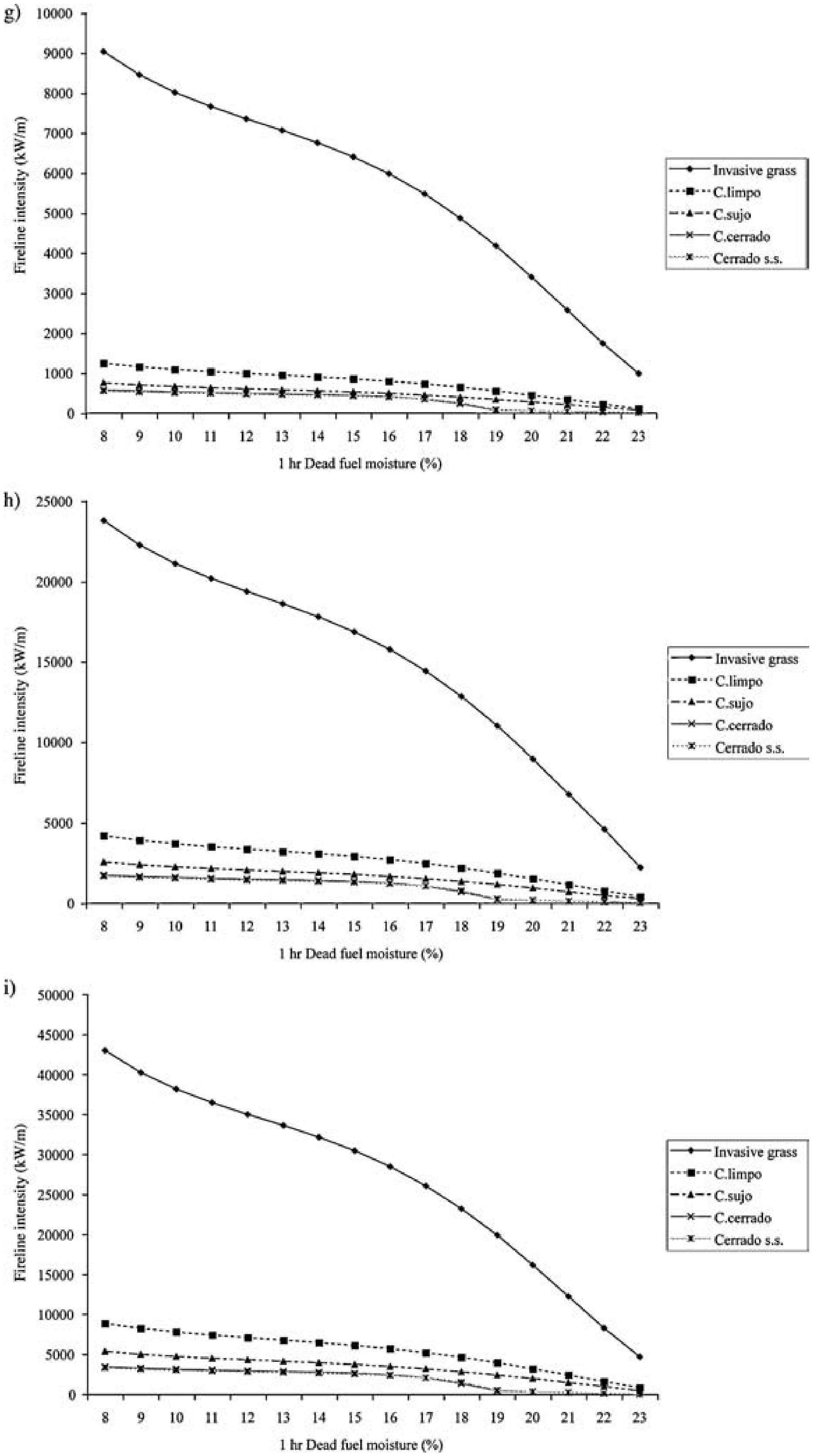

FIGURE 4. Fireline intensity (kW/m) for five fuel types with increasing 1 h dead fuel moisture at wind speeds of (a) 5 km/h, (b) 10 km/h, and (c) 15 km/h.

dead fuel moisture of 16 percent (the value used in this study) and an average wind speed of 10 km/h, and are probably a result of the higher fuel loads in *M. minutiflora*-invaded sites. Berardi (1994) also found that residence time in a *M. minutiflora* fire lasted over 3 min at average temperatures of 300°C. This was probably a result of the mat-forming nature of the grass when it dries, the thick dead fuel allowing the fire to continue burning slowly at a high temperature, although the fire front has passed. D'Antonio *et al.* (2000) working in Hawaii found that where *M. minutiflora* was a dominant or co-dominant species, fire impacts were more severe than where it was absent regardless of the climatic zone. The impact of invasive grasses such as *M. minutiflora* in the reserve can be devastating. The FARSITE results indicate that even in "low" fire climatic conditions, *M. minutiflora* significantly contributed to the spread of fire in the reserve, as shown by Scenario A in 1990. The invasive grass areas act as corridors of propagation through which fire moves extremely fast. Recent studies have also indicated that *M. minutiflora* is particularly abundant near gallery forests edges (Hoffman *et al.* 2004). The high flame heights attained in *M. minutiflora* fires most likely help to propagate fire into this fire-sensitive vegetation form, as was found in our simulations, thereby increasing the likelihood of gallery forest retreat over long periods.

In addition to fuel characteristics, the BEHAVE and FARSITE results also point to the critical importance of weather conditions, especially wind. Although large fires can occur during hot, dry days, catastrophic fires are probably a result of high wind speeds at ground level. This is particularly important in the more open forms of vegetation, where the tree canopy is sparse and the combustible grasses are exposed to the wind (Rothermel 1983, Freifelder *et al.* 1998, Blackmore & Vitousek 2000).

The potential of fire entering RECOR is greatest from the southeast, dominated by *campo limpo*, and from the north, dominated by more open forms such as *campo sujo*. Once fire has entered the reserve from these two entry points, it can move fast and burn a large area as a result of adjacent highly susceptible fuel types including *campo sujo* and invasive grasses. As seen from Table 2, RECOR has very high wind speeds in late August. Therefore, it will be vital to monitor wind speed, which could greatly enhance a fire already started.

This study brings to light many questions about predicting fire behavior in reserves such as RECOR. First, the vegetation of the reserve comprises a mosaic of forms, many of which have gradual transitions from one form to another. This is not modeled in FARSITE where sharp boundaries are created between one vegetation type and another. Linked to this, FARSITE assumes a homogeneous fuel load within each cell of the GIS files, which is a simplification of the actual landscape because small-scale variations in topography, fuels, and canopy cover will affect fire behavior. BEHAVE allowed the authors to create custom fuel models for the different vegetation types. Although we modeled fuel types on the assumption of having been burned every 2–4 yr, we did not take into account the variability in fire frequency over the landscape. Patchiness is an inherent characteristic of fire in savannas, where even within savanna types, patches are burned at different frequencies. Patchy fuel loads need to be taken into consideration in future modeling studies.

Our objective now is to improve fire simulations and testing for savannas. Three-dimensional simulation of fire behavior would incorporate more realistically the heterogeneity in fuel distribution within savannas. Improvements in representing vertical heterogeneity could be achieved by simultaneously running FARSITE for the herbaceous, shrub, and tree layer, thus allowing not only the horizontal spread of fire but also vertical. Horizontal fuel heterogeneity could be simulated by introducing a stochastic function, which varied the fuel characteristics, especially at ecotonal boundaries. Measuring the great variability in weather conditions during fires, most notably in wind parameters and incorporating this stochasticity within simulations, is another issue that needs to be addressed for future work.

Building on previous work by the leading author, the Lichen Fire History Key (Mistry 1998c,d), a bio-indicating tool, could be used for estimating the degree to which past fires (frequency and intensity) have affected the vegetation and consequently fire fuel load. The patchiness of past fires could be mapped using remote sensed information, as has already been done for other savanna regions (*e.g.*, Russell-Smith *et al.* 1997, 2002, 2003; Edwards *et al.* 2001). Finding out why and how people use fire is vital for testing different scenarios when assessing fire risk, but also for testing how different fire management techniques may influence the landscape. Interviews with farmers in the Distrito Federal have already shed some interesting information on when, how and why fires are set in the *cerrado* (Mocelin 1996, Mistry 1998b). This has been extended to include other fire users, such as indigenous groups, for an assessment of the cultural habits in fire use and the factors that determine fire potential (Mistry *et al.* 2005).

Testing fire simulations with reality has always been the greatest challenge. We are currently experimenting with a digital video camera suspended on a helium blimp at 60 m above land surface, which will be able to video fuel heterogeneity, the rate of fire spread, and flame height (from which fire intensity could be estimated). These data will hopefully provide us with the necessary information to improve the realism of fire simulations.

This study is the first step in the development of a decision support system for facilitating fire management planning within small reserves in the *cerrado*. The authors hope to tackle some of these questions, so more realistic fire prediction can take place, aiding managers in decisions such as when and where to apply prescribed fires, as a basis for discussion with local fire users, for the allocation of resources for catastrophic wildfire prevention, and ultimately to develop a strategy for fire prescription to retain species, genetic and natural resource diversity.

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