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Fire simulations in the Everglades Landscape using parallel programming

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Abstract

Fire can significantly influence vegetation patterns in the Everglades. Unfortunately, fire is a difficult process to experimentally manipulate, especially at a landscape level. An Everglades Landscape fire model (ELFM) was developed using parallel-processing algorithms and transputer-processors to understand fire behavior in Water Conservation Area 2A (WCA 2A) in the Everglades. Fuel characteristics, water depth, wind velocity and direction, rainfall, lightning, and humidity determined the physical state and rate at which fire spreading and spotting occurred in the ELFM. The ELFM simulated fire spread across a heterogeneous landscape using a grid-based system. Parallel processing enabled the model to simulate fire on a large spatial scale with fine resolution (i.e., 1755 × 1634 pixels with 20 × 20 m resolution). The model was designed as a multiprocessor program with the ability to compile and run on UNIX workstations, the CM-5 supercomputer, and Mac Transputers with no change in the code. The ELFM was used to conduct a series of fire experiments that indicated how current fire regimes differ from historical ones due to cattail (*Typha* spp.) invasion and longer and deeper water depths. In an Everglades dominated by cattail, the predicted average annual area burned and fire frequency were significantly reduced by 23% and 21%, respectively. The ELFM experiments also suggested that altered hydroperiod have changed fire patterns by reducing fire frequency 63% while increasing fire size during drought years. Airboat trails did not significantly influence total area burned in the ELFM. However, they did seem to function as breaks in upwind fires and tended to reduce the size of potentially large fires.

Keywords: Fire; Computer simulation; Landscape; Parallel programming; Everglades; *Cladium jamaicense*; *Typha* spp.

1. Introduction

The Everglades landscape is a vast freshwater marsh in South Florida, USA, and one of the largest subtropical wetlands in the world (Cowardin et al., 1979; Hefner, 1986; Kushlan, 1990). The Everglades has changed dramatically during this century with vast areas being converted to urban and farming land use. More than 2000 km of canals have been built throughout this period to convert these Everglade lands. Indirect impacts from agriculture, water management, and urban development have caused alterations in water quality, hydroperiod, and invasion of exotic species (Urban et al., 1993, Wu et al., 1996). These changes may significantly affect efforts to restore 'natural' vegetation and hydroperiods in the remaining Everglades.

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Fire has been an important ecological process in the Everglades and a primary factor shaping the Everglades vegetation patterns (White, 1970; Cohen, 1974; Duever et al., 1976; Wade et al., 1980). We cannot fully understand the Everglades without understanding the function of fire (Wade et al., 1980). However, fire is a difficult process to experimentally manipulate at a landscape level. Computer simulations can reduce the time it takes to evaluate impacts and understand ecosystem dynamics. Spatial ecosystem modelling has been an efficient approach in predicting ecosystem dynamics (Sklar and Costanza, 1991; Wu, 1991; Turner et al., 1993, 1994). This approach combined with fire modelling techniques (Rothermel, 1972; Rothermel and Philpot, 1973; Kessell, 1979; Minnich, 1983; Albini, 1984; Burgan and Rothermel, 1984; Andrews, 1986; Brown and Bevins, 1986; Malanson and Trabaud, 1988; Andrews and Chase, 1989; Keane et al., 1990; Van Wilgen et al., 1990) can lead to a better understanding of large-scale spatial processes (Kessell, 1979; Turner, 1987; Green, 1989; Costanza et al., 1990; Zack and Minnich, 1991; Baker, 1992; Turner et al., 1993; Hargrove et al., 1994). However, fire is a difficult process to simulate because it requires an extensive understanding of both fire ecology and modelling techniques (Wu, 1991).

Ecologists are beginning to utilize more powerful computation technologies such as parallel programming and multiple processor designs to deal with large spatial extent and complex ecological processes (Haefner, 1992). Computers with multiple processors are able to simultaneously compute different algorithms or different data sets. Macintosh computers with multiple transputers (a form of processor) were used to divide a large landscape space into smaller spatial domains (Costanza and Maxwell, 1991). Interprocessor communication and information exchange was developed to link the smaller domains.

The objectives of this research were to (1) develop a 20×20 m resolution Everglades Landscape fire model (ELFM) using parallel programming, and (2) conduct model experiments using the ELFM to understand: (a) if current fire regimes are different from historical ones; (b) how water regulations affect fire frequency and burning patterns; and (c) how disturbances such as cattail invasions and airboat trails may alter fire behavior.

2. The study area

The ELFM was used to simulate fire in the Water Conservation Area 2A (WCA 2A) in the north Everglades (Fig. 1a). The WCA 2A landscape (43 281 ha) is a mosaic of sawgrass marshes, sloughs (relatively deep areas with submerged aquatic vegetation), shrub and tree islands (relatively high elevation), and invasive cattail communities. Sawgrass (*Cladium jamaicense*), the dominant Everglades monocot (Davis, 1943; Loveless, 1959), is well adapted to fire, conditions of prolonged hydroperiod, and deep organic soils (Lynch, 1942; Alexander, 1971; Hofsetter, 1974). Monotypic cattail stands in WCA 2A have increased from 920 to 4899 ha between 1973 and 1991 (Jensen et al., 1995). A landscape that was once predominantly sawgrass has become more patchy (Wu et al., 1996). Before 1980, water regulation reduced the frequency of dry periods and maintained water depths of 0.58 to 1.04 m. After 1980, water regulation increased the frequency of dry periods and maintained water depths from 0.48 m below ground elevation to 0.43 m (Urban et al., 1993). No study has been undertaken to understand how water regulations have influenced fire regimes. Five vegetation maps, classified from SPOT and LandSat image data (Jensen et al., 1995), documenting habitat changes in WCA 2A from 1973 (Fig. 1b) until 1991 (Fig. 1f), were used as base maps for the ELFM simulations.

3. Method

3.1. Parallel programming and transputers

The ELFM works at a resolution of 20 m which, in terms of grid cells, comes to 1755×1634. A basic assumption for a spatial model is that each cell is homogenous. Higher resolution data sets can potentially decrease the uncertainty for predicting fire spread (Wu, 1991). There are two reasons for this concern (Berry, 1987). One is data availability, which fortunately we have the SPOT and LandSat image data from Jensen et al. (1995). The other is computing time (CPU-h) and the limit of computer memory. Since the ELFM has such a large landscape, in terms of grid cells, we used data decomposition techniques

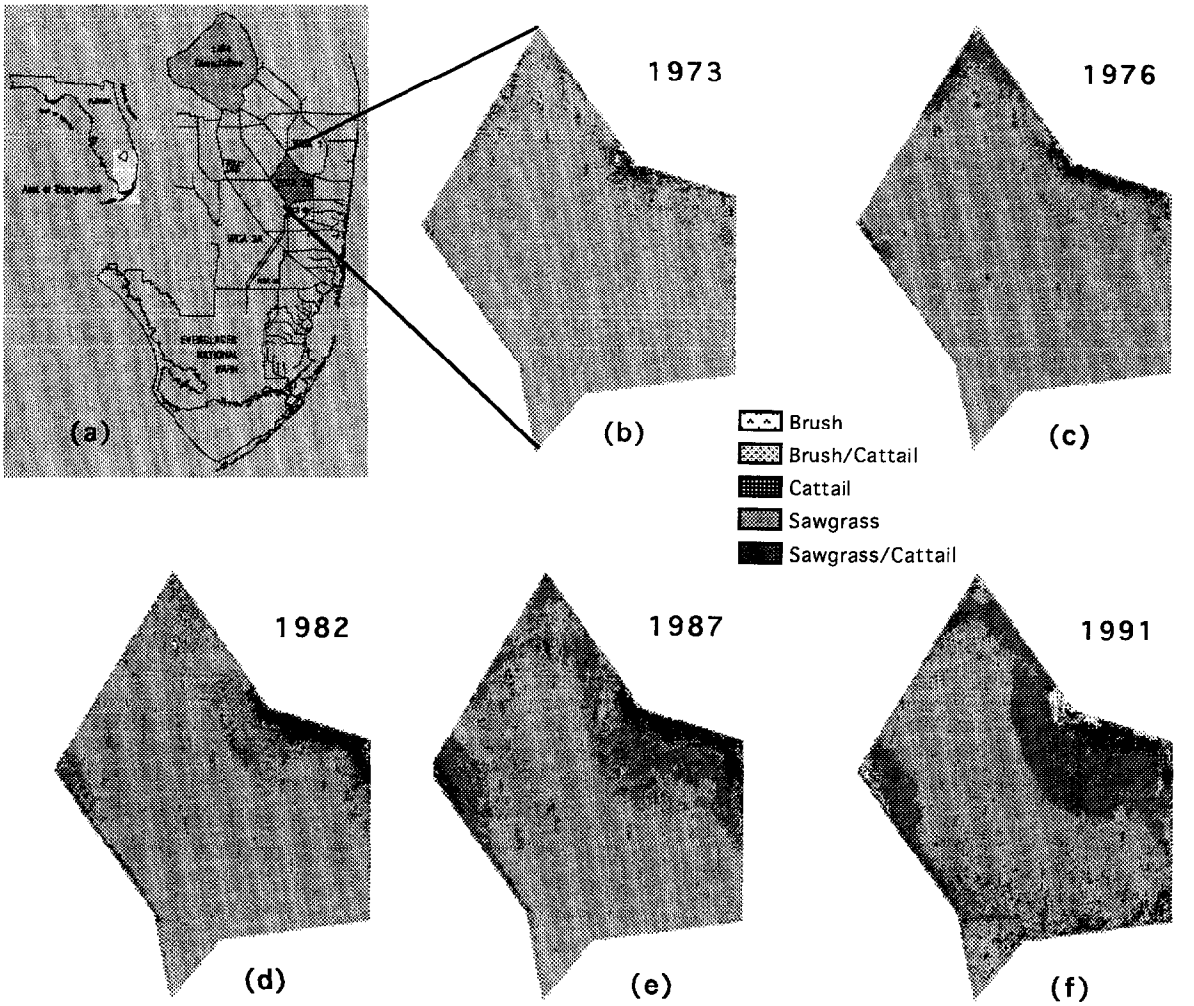

Fig. 1. The geographical location of Water Conservation Area 2A (a) and vegetation maps of 1973 (b), 1976 (c), 1982 (d), 1987 (e), and 1991 (f) for the Water Conservation area 2A. Note the cattail area increasing in the map of 1991 (f).

to distribute the landscape over the available number of processors. With a large number of fires in the landscape, the computing time on a serial system would be more, thus making parallel programming of the ELFM more justifiable.

Two separate platforms (CM-5 and Macintosh transputers) were used for the ELFM parallel programming. The CM-5 Connection Machine is a Risc-based main frame multiprocessor designed for large-scale simulations. The CM-5 consists of a large number (512 or more) of processing nodes connected by a pair of networks. The current implementation of the CM-5 uses a SUN SPARC-based processing node, operating at a 32 or 40 MHz clock rate, with 32 MB of memory per node (Hills and Tucker, 1993). In our study, we used 32 processing nodes. A Macintosh transputer is a 25 MHz parallel processing microcomputer board with its own local memory of 4 MB RAM and 4 built-in communication links. Each transputer performs all calculations in its spatial domain, and communication among transputers is accomplished via 4 bi-directional high speed serial

communication links. Sixteen transputers installed on a Macintosh Quadra 950 were used for this modelling effort.

The model was initially developed for a serial platform on a Sun workstation and later ported to other parallel platforms with the help of parallel programming libraries. We used Express, a parallel programming environment, by Parasoft, on Macintosh and, CMMD, a message passing library, on CM-5. In order to run the model on CM-5, we developed generic decomposition functions for 2-dimensional spatial grids, such as splitting the landscape into equal number of grid cells, which are not part of CMMD library. Both the libraries Express and CMMD belong to the category of explicit message-passing mechanisms.

Parallel programming was accomplished by decomposing the landscape grid into the available number of transputers or processors. For example, the 1755×1634 landscape grid was decomposed into sixteen 439×409 grids for sixteen Macintosh transputers (Fig. 2a). Information exchanges and communications among transputers or CM-5 processors occurred at the end of each iteration and were basically similar for both platforms.

Information about fire spread in border cells of transputers is exchanged using neighborhood communication routines (Fig. 2b). There is an additional column and row surrounding the grid of a transputer's spatial domain (Fig. 2b), where Transputer B (B_{Tb}) passes its border cell information to Transputer A (A_{Tb}). At the same time, border cell information of Transputer A (A_{Ta}) is transferred to Transputer B (B_{Ta}).

Information about fire spotting (i.e., fire jumping distance) across to non-border cells of adjacent or non-adjacent transputers is saved and distributed to the receiving transputer at the end of an iteration (Fig. 2c). This communication approach is based on an ability to 'write out' and 'read in' information synchronously from each transputer at the end of an iteration. A transputer identifies which grid cell and which spatial domain the fire is jumping to and 'writes out' the necessary information to the appropriate transputer. The 'write out' does not evaluate the suitability of the receiving cell to burn. The transputer of the receiving cell needs to 'read in' the information and evaluate its ability to burn and spread. In fire spotting, three probabilities are considered for different transputers in each time step as follows;

(1) Probability of spotting (P_{sp})
$P_{sp} = f$(wind coefficient, fuel complex, humidity)

(2) Probability of spotting distance (P_{sd})
$P_{sd} = f$(wind speed, wind direction, fuel complex)

(3) Probability of ignition in a spotted cell (P_{ig})
$P_{ig} = f$(heat carried-over, fuel complex, spotting distance)

Although these equations refer to many complex processes (discussed below), probabilities of fire spotting are specific to each grid cell and its unique set of conditions.

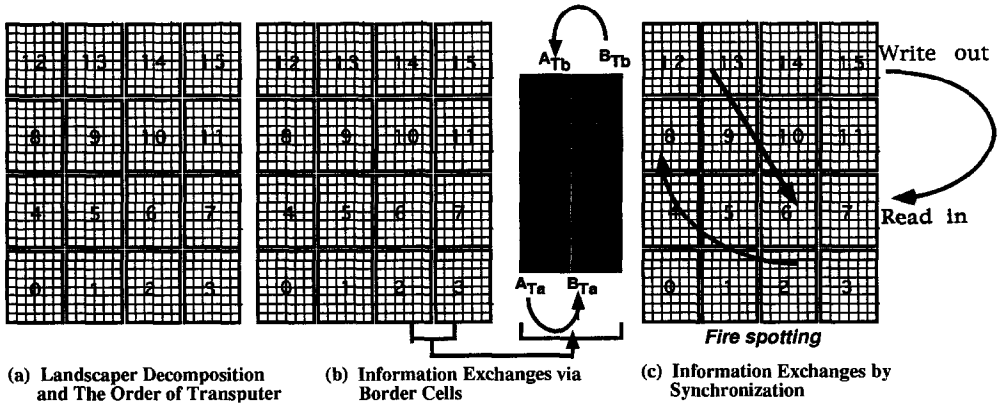

Fig. 2. Demonstrations of landscape decomposition and the order of transputer (a), information exchanges via border cells (b), and information exchanges by synchronization (c).

3.2. Model structure

The theoretical base of fire models was developed by Rothermel (1972) and improved by Albini (1976), Kessell (1979), Burgan and Rothermel (1984), Andrews (1986), Andrews and Chase (1989), Keane et al. (1990), Wu (1991), Zack and Minnich (1991), Baker, 1992, Vasconcelos and Guertini (1992), Turner et al. (1993), and Hargrove et al. (1994). In their models, the analysis led to development of a series of parameters and equations. The equations apply the conservation of energy principle to a volume of fuel ahead of an advancing fire in a homogeneous fuel bed, and can be expressed as,

$$R_s = \frac{I_r \zeta (1 + \Phi_\omega + \Phi_s)}{\rho_b \varepsilon H_p}$$

where:

R_s rate of spread, m min^{-1}.
I_r reaction intensity, kJ m^{-2} min^{-1}.
ζ propagating flux ratio.
Φ_ω wind coefficient.
Φ_s slope coefficient.
ρ_b oven dry bulk density, kg m^{-1}.
ε effective heating number.
H_p heat of preignition, kJ kg^{-1}.

Using the parameters and equations, the ELFM simulates fire spread from a cell to its adjacent cells based on sets of fire behavior algorithms. Fire spread in a fuel bed is considered as a series of successive ignitions. Thus, spread rate is controlled by ignition time, which means the quicker the adjacent fuel is ignited the further the fire spreads. For example, when a fire starts, heat is supplied from the fire to the adjacent cell fuel and the surface is then dehydrated. Further heating raises the surface temperature until the fuel ignites, after which heat is released to another adjacent fuel patch (Fons, 1946; Rothermel, 1972; Wu, 1991).

Simulations of rain and lightning on a daily basis were based on historical data (Chen and Gerber, 1990). Lightning strikes and fire ignitions were simulated as a stochastic function of lightning frequency, fuel complex, and rain (Table 1). Lightning frequency data were obtained and analyzed from historical data (Gunderson, unpublished data). Fuel complex was composed of different fuel categories such as 1-h, 10-h, and 100-h dead fuels, live herbaceous fuels, live leaf/twigs fuels, and fuel moisture, as defined by Rothermel (1972). Fuel loadings varied with different vegetation (Urban et al., 1993; Davis and Ogden, 1994). Fuel moisture, simulated hourly, varied with fuel categories and was dependent on the periodicity and length of no-rain. Rains were an important form of fire extinction and were simulated based on weather station data in the area. Intracellular fire behavior was simulated with a time step of one minute. Fire spread to the adjacent eight cells (i.e., extracellular behavior) was dependent on the heat source being carried to a new cell, the fuel complex in that new cell, wind speed, wind direction, and rain. Upwind fires were simulated when wind speeds were low.

Fire in each cell was tracked and timed from start to extinction in the ELFM. As a cell burned, fuels were consumed and set to zero. Vegetation recovery and dead material accumulation were simulated daily with a linear function based on previous studies

Table 1
Parameters used in the ELFM simulations

Parameter	Value	Source
Lightning frequency	0.07/day	Gunderson, unpublished data (1948–92)
Sawgrass 1-h fuel	2.8 kg/m^2	Miao, personal communication
Sawgrass live herbacous fuel	6.7 kg/m^2	Duever et al., 1976; Urban et al., 1993; Miao and Sklar, manuscript
Cattail 1-h fuel	1.3 kg/m^2	Miao, Personal communication
Cattail live herbacous fuel	4.4 kg/m^2	Duever et al., 1976; Urban et al., 1993; Miao and Sklar, manuscript.
1-h fuel moisture	0.05	Estimated
10-h fuel moisture	0.09	Estimated
Live herbacous fuel moisture	0.35	Miao and Sklar, manuscript
Max. fire spotting distance	15 m	Van Hone, personal communication

(Loveless, 1959; Forthman, 1973; Herndon and Taylor, 1985). A newly burned patch may function as a fire break depending on wind conditions. When regrowth of vegetation occurred, dead and live fuel accumulated making the cell more flammable.

Hydroperiod was simulated in the ELFM. Average water levels of 0.02 m for low water depth and of 0.82 m for high water (Urban et al., 1993) were used as initial conditions. The seasonal dynamics of water depth were based on historical rainfall data. Low water depths were regulated from 0.48 m below ground elevation to 0.43 m and high water depths from 0.58–1.04 m. Water depths for two drought years (1971 and 1974) were based on South Florida Water Management District historical gage and rainfall data within the study area.

3.3. Model inputs

The spatial data inputs for the ELFM included: (1) vegetation maps of 1973, 1976, 1982, 1986, and 1991 (Fig. 1b–f) classified and rectified from SPOT image data by Jensen et al. (1995); (2) fuel complex (i.e., dead fuels, live fuels, and fuel moisture) estimated from our field data and references (Miao, personal communication; Duever et al., 1976; Urban et al., 1993); (3) daily rainfall data from the weather stations in the study area (missing data were filled with mean values); (4) lightning frequency (averaging across the landscape based on historical data provided by Gunderson (unpublished data); (5) airboat trails (mapped by the SFWMD); and (6) hydroperiod (water levels obtained from the SFWMD's DBhydro database). Wind speed was input as a normally distributed function with a mean of 4 miles/hr (unpublished field observations). Based on data from local weather stations, wind directions were input with high probabilities of Northwesterlies in winter and Southeasterlies in summer. Parameters for fire behavior equations were obtained from Rothermel's (Rothermel, 1972) model and our field observations. Parameters used in the ELFM simulations were included in Table 1.

3.4. Simulation experiments

Each ELFM simulation was replicated five times due to the many stochastic processes (i.e., lightning, rain time, wind velocity, and ignition sites) in the model. Rainfall, lightning, and wind velocity were simulated with the same data set for each experiment. The simulation experiments were designed to;

(1) Compare simulated fires to historical fires: Vegetation maps from 1982, 1986, and 1991 were used in the simulation to evaluate fire/vegetation interactions during the last 12 years (1980–91). These simulations included airboat trails and historical records of low water depths (0.48 m below ground elevation to 0.43 m). The results were compared with the historical fire data.

(2) Evaluate the effects of low vs. high water depths on fire: Mean water depths of 0.02 m below ground elevation (low) and 0.82 m (high) were used in two scenario simulations as initial water depths to simulate fire from 1970 to 1990. However, it was assumed that there were no vegetation changes and only 1973 vegetation was used.

(3) Simulate impacts of cattail invasion on fire frequency and extent: The 1991 vegetation map was used as the base map to simulate fire regimes from 1970 to 1990. Airboat trails were excluded. Low water depths were applied. The results were compared to simulations with a 1973 base vegetation map and low water depths.

(4) Evaluate effects of airboat trails on fire: In this experiment, conditions were kept the same as (3), except that airboat trials were added.

4. Model results

4.1. Model calibration and verification

The ELFM was written in C language with more than 3000 lines and coded for either serial or parallel processing. As a result, it can be compiled and run on different platforms such as UNIX workstations, CM-5 multiprocessors, or Macintosh transputers without changing the code. For the ELFM, the computing time for one simulation took about 59.5 s on a serial machine, SUN sparc-10, and 2 s on CM-5 with 32 nodes. As communication and synchronization are considered, the timing will be much different. This paper will focus on testing different hypotheses using long-term (20 years) simulations. The question of comparative analysis between serial and parallel

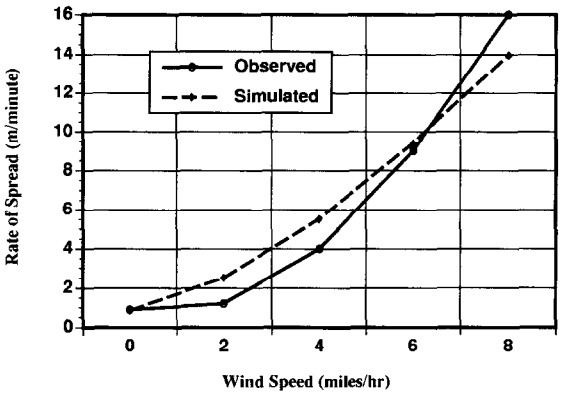

Fig. 3. Observed and simulated data of correlations of wind speed with rates of fire spread were used for model calibration.

computing is an issue that we intend to address in another paper.

The model was calibrated and verified by: (1) comparing simulated and actual rates of fire spread under different wind speeds (Fig. 3); (2) using visualization software such as MAP II™, NCSA Imagetools, and PV-WAVE to examine the 'realism' of fire patterns (Fig. 4); and (3) conducting a sensitivity analysis on the probability of lightning strikes in a cell (P_{ls}). The mean annual area burned (MAAB) was very sensitive to P_{ls}, according to this sensitivity analysis. Increases of P_{ls} from 0.05 to 0.07, increased the MAAB from 7819 ha to 11 347 ha (Table 2).

Historical fire patterns from 1980 to 1991 obtained from Florida Game and Fresh Water Fish Commission were used for model verification. The ELFM used actual vegetation distributions, daily rainfall, lightning probabilities, and water depths for the same period to compare the simulated fires to the historical ones. A statistical summary of the results indicated that the simulated fires were not significantly different from the historical ones in terms of mean annual area burned, mean fire size, and largest fire size (Table 3).

Table 2
Effects of lightning frequency (LF) of striking in a specific landscape cell on mean annual area burned (ha)

LF	0.01	0.03	0.05	0.07	0.09	0.11
MAAB	5348	7549	7819	11347	13235	11782

Table 3
Comparison of mean annual area burned (ha/y), mean fire size (ha/fire), and the largest fire size (LFS, ha) of historical fires to simulated fires between 1980 to 1991

	ha/y (se)	ha/fire (se)	LFS (se)
Simulated	5293 (583)	2117 (487)	14564 (1031)
Historical	4647 (1682)	3505 (1182)	15390

4.2. Simulation experiments

Water management in the Everglades appeared to influence fire regimes significantly (Table 4). Statistical t-tests indicated that the average annual area burned under low water depth (12 324 ha) was significantly ($p < 0.01$) greater than under the high water depth (4419 ha). However, average fire size was not significantly different between the two water depths. Average fire size was 3589 (± 60) and 3482 (± 289) ha for low and high water depths, respectively. For the 20-year simulations, there was an average of 3.4 (± 0.2) fires per year in the low water level run and only 1.3 (± 0.3) fires per year in the high water level run. Average fire frequency for high and low water conditions was significantly ($p < 0.01$) different. Persistent high water depths reduced fire frequency by 63%. It is interesting to note that even though fire frequency was less during the high water depth period, large fires still occurred. Based on the model, the largest fires (se = 37 594 ha) occur during the high water depth simulations (Table 4). Fires did not occur every year during the high depth simulations (Fig. 5). As a result, an extremely large area would burn if a drought year occurred between periods of high water depth. In contrast, during the 20-year low water simulations, relatively small fires occurred every year. Thus, fire consumed fuel stocks

Table 4
Effects of water management on fire patterns (in the Water Conservation Area 2A during low water stages (LW) of −0.48 to 0.43 m and high water stages (HW) of 0.58 to 1.04 m

	ha/y (se) [a]	ha/fire (se)	LFS (se) [b]
LW	12324 (192)	3589 (60)	27715 (1687)
HW	4419 (784)	3482 (289)	37594 (1769)

[a] Statistically significant at $t_{0.01}$ level.
[b] Statistically significant at $t_{0.05}$ level.

every year, which made large inter-annual fires less likely to spread.

The ELFM results also suggested that fire spreading characteristics were altered due to the expansion of cattail within the study area between 1973 and 1991. The mean annual area burned (12 324 ha/y) using the 1973 vegetation landscape (few cattails) was significantly ($p < 0.05$) higher than when using the 1991 vegetation landscape (9435 ha/y; Table 5). A 30.1% increase in cattails reduced mean annual area burned by 23%. Although, cattail expansion did not significantly change average fire size (from 3,589 ha/fire in 1973 to 3,525 ha/fire in 1991), it significantly ($p < 0.05$) reduced the fire frequency (from 3.4 (± 0.06) fires per year in 1973 to 2.7 (± 0.02) fires per year in 1991). Cattail expansion in WCA 2A reduced average annual fire frequency by 21% (Table 5).

Mean annual area burned and average fire size were not significantly influenced by the presence of airboat trails (Table 6). However, there was a significant effect ($p < 0.05$) in terms of the largest fire size

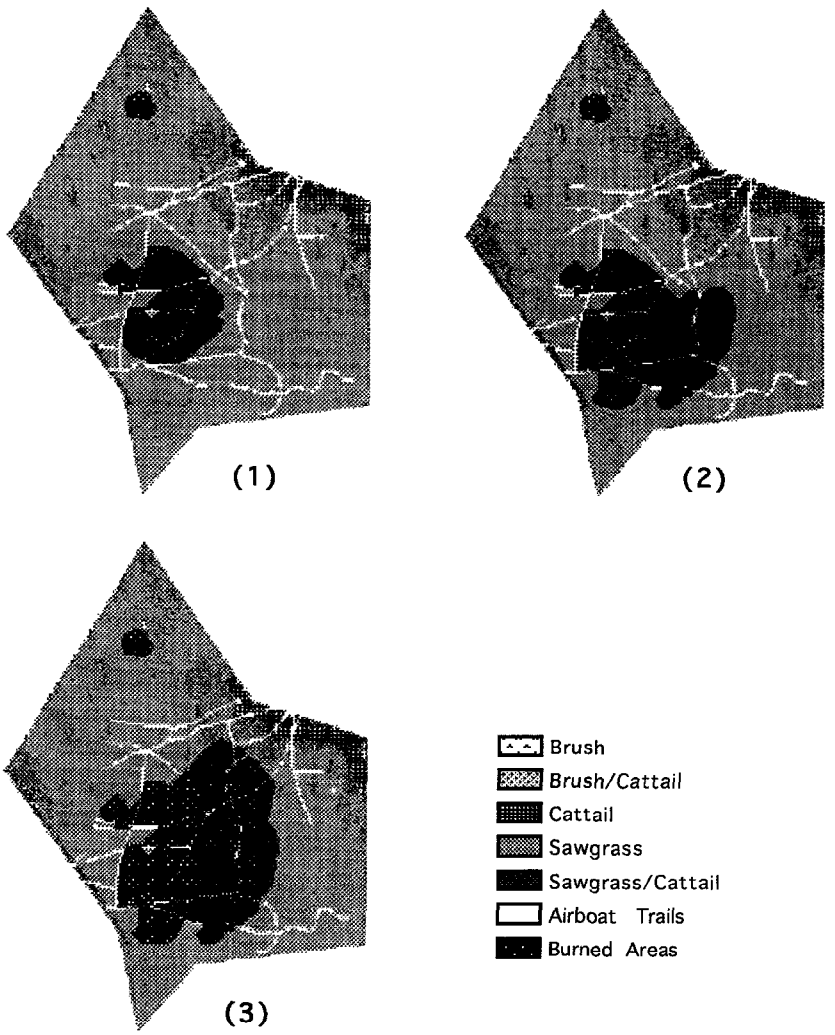

Fig. 4. Three snapshots of fire spread in the cattail invaded landscape (1982 vegetation) with airboat trails shown that the airboat trails might function as breaks for upwind fires.

Table 5
Impacts of cattail invasion on fire patterns resulted from simulations of fires in the 1973 landscape (few cattails) and 1991 landscape (cattail invaded)

	ha/y (se) [a]	ha/fire (se)	LFS (se)
1973	12324 (192)	3589 (60)	27715 (1687)
1991	9435 (94)	3525 (155)	32571 (1326)

[a] Statistically significant at $t_{0.05}$ level.

Table 6
Influences of airboat trails (with vs. without) on fire patterns

	ha/y (se)	ha/fire (se)	LFS (se) [a]
With	8939 (207)	3078 (180)	21644 (1910)
Without	9435 (94)	3525 (155)	32571 (1326)

[a] Statistically significant at $t_{0.05}$ level.

(Table 6). Mean annual area burned in WCA 2A was 8939 (±207) ha with airboat trails and 9435 (±94) ha without airboat trails. With airboat trails, the average fire size was moderately smaller (3078 ha) than without airboat trails (3525 ha). Without airboat trails, the largest fire size (32571 ha) was significantly larger than with airboat trails (21644 ha). Fig. 4 is a 'snap-shot' visualization of the fire spread with airboat trails for three time steps (Fig. 4 1–3). These simulations showed that airboat trails will not stop Everglades fire spread in down wind directions but can influence fires in upwind directions.

5. Discussion

Management of the Everglades ecosystem has become increasingly complex due to growth in human activities (Davis and Ogden, 1994), which include agriculture, waste management, mining activities, and well-fields for drinking water supplies. According to the ELFM simulations, the invasion of cattail has reduced the 'natural' annual burning rate in WCA 2A. This reduction occurred because fire is particularity difficult to ignite and spread in cattails during the wet season, even though the wet season is when the Everglades experiences most of its lightning strike fires (Wade et al., 1980; Gunderson and Snyder, 1994). The ELFM simulation experiments predicted an average of 3.4 fires a year in sawgrass marshes and only 2.7 fires a year in marshes with significant invasion of cattails. However, during dry winter months, a large fuel base of cattail litter becomes available to support large fires (Wade et al., 1980). This may be the reason the average fire size was not significantly different between the 1973 and 1991 simulations (Table 5). The model suggests that the invasion of cattails in the Everglades landscape has altered the fire regime by decreasing fire period-

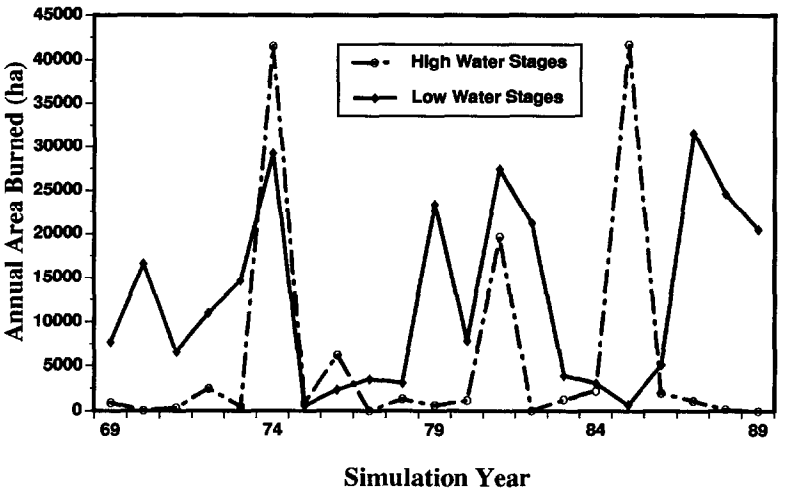

Fig. 5. Patterns of simulated annual area burned for high and low water stage periods.

icity and the annual area burned. Even though the ignition probability is higher for sawgrass than cattail, cattail dominated landscapes are more likely to burn as large fires only during dry winter months.

The ELFM produced spatial simulations that very closely matched historical fire patterns. However, additional work is required since fire behavior is very dynamic and ecosystem response to fire is complex (Gunderson and Snyder, 1994). For example, airboat trails did not play as big a role in fire spread as originally hypothesized. However, they did function as breaks in upwind fires and can reduce the probability of extremely large fires. Since airboat trails change over time and space, they can be a large source of uncertainty when trying to predict the spatial dynamics of fire spread in the Everglades.

While developing the ELFM we discovered that spatial modelling of fire spread with high resolution is computationally intensive. Parallel programming and the utilization of multiprocessors have the potential to reduce the costs and enhance the simulation of complex ecosystem processes (Costanza and Maxwell, 1991). The ELFM successfully utilized these technologies to simulate and analyze fine grain spatial data across a large landscape.

The Everglades is composed of a heterogeneous mosaic of tree islands, shrubs, sawgrass, sloughs, and open water (Kushlan, 1990). The mixed patches of vegetation, sloughs, and open water in the Everglades function as fire breaks (Wade et al., 1980) and may have affected the model predictions captured by the ELFM. In the model, we assumed that each grid cell was homogeneous and fuel was evenly distributed. However, fuel discontinuity may happen in a cell and stop the fire even though there is a high average fuel loading in that cell. This uncertainty has been reduced by having a high resolution data set to use in the model.

Water management is important to both economic and ecological systems in South Florida (Gunderson, 1992). Water was historically managed solely for flood control. However, it is now managed for a spatially complex, often conflicting, array of end uses. The ELFM is a significant advancement because it was able to identify the impact of water management on fire regimes in WCA 2A in the Everglades. As a result, the ELFM is currently being linked to a larger Everglades Landscape Model (Fitz et al., 1994), which will provide a more comprehensive management tool for Everglades restoration.

6. Conclusions

Parallel programming algorithms can be applied to landscape models to simulate complex ecological processes in a large spatial extent. Parallel programming can potentially enhance spatial modelling techniques and enable modelers to simulate large spatial domains with fine resolution.

High water levels can significantly affect fire patterns in the Everglades. They were found to reduce mean annual area burned while simultaneously increasing the probability of extremely large fires. This counter-intuitive result is hypothesized to be due to the lack of fires over long periods of time under high water depths resulting in the accumulation of large fuel supplies that eventually support the spread of large fires.

Invasion of cattails has altered the fire regime in the Everglades landscape by decreasing fire periodicity and annual area burned. Even though the ignition probability is higher for sawgrass than cattail, cattail dominated landscapes are more likely to burn as large fires.

Airboat trails function as breaks in upwind fires and might reduce the probability of extremely large fires. However, they did not significantly affect total area burned or average fire size in this simulated Everglades landscape experiment.

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