# MARKOV LATTICE MODEL OF FIRE SPREAD

Contributors

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Modelling on a planar surface

- Location $(i, j)$ location. Process value at time $t$ is $X(t) = X_t$ with value $x(i, j, t)$ at location $(i, j)$

- Study the evolution of $x(i, j, t)$ over time and space. The evolution might take into account covariate information such as topography and vegitation

- Evolution might be deterministic, modelled by a pde $(i, j \in R)$

  These are often able to take into account some physics or scientific principles : attractive feature.

  Less able to adequately model random phenomena (firebrands and spotting)

  Good information on average behaviour : $\frac{\partial f(i,j,t)}{\partial t}$ equals some function of $\frac{\partial f(i,j,t)}{\partial i}$ etc to model local spatial dependence or rate of change in the system (configuration)

  No information on variability : needed for planning for likely events

- Evolution might be random. $(i, j) \in \mathcal{L}$ (a lattice with integer locations or points)

  Cellular automata ; interacting particle systems (voter model or Williams Bjerknes model)

  Ability to describe average behaviour PLUS variability.

  Variability : needed for planning and a measure of how likely to "go off course"

## LATTICE MODELS

Two types :

### DISCRETE EVENT SIMULATION

at a location $(i, j)$ a *time* $\tau_{i,j}$ to the next event affecting the configuration is randomly chosen.

The configuration changes at the minimum of these competing times. Each location can only generate one "competing time"

Does not easily allow time varying trends ; diurnal cycles

These are not Markov models

### MARKOV LATTICE MODEL

due to Markov nature time varying trends are easily modelled

Rate parameters $r(i, j)$ or $r(i, j, t)$.

These play the role of the rate *parameters* $\frac{\partial f(i,j,t)}{\partial i}$ in pde models

Cellular Automata models are generally not amenable to algebraic analysis

Easy to simulate; programming may be complex

Several THOUSAND WORDS (graphically speaking)

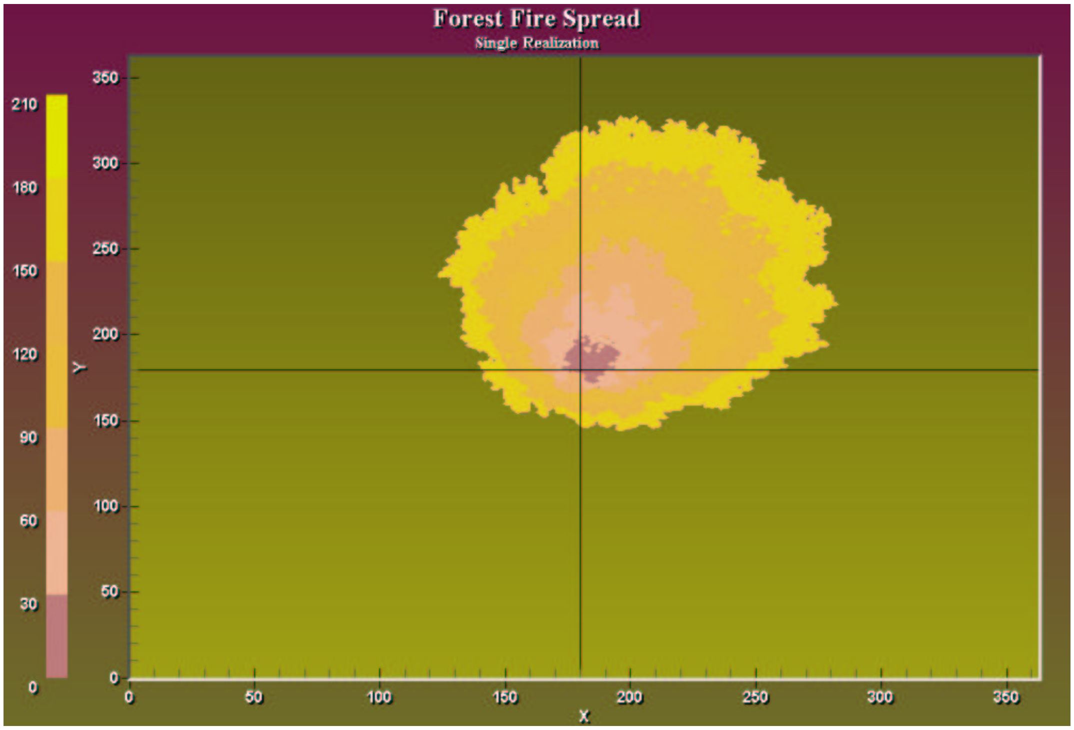

Figure 1: Fire start at cross hair. Single realization at time 180 min, wind direction 30 degrees

# Probability of burning contour plots

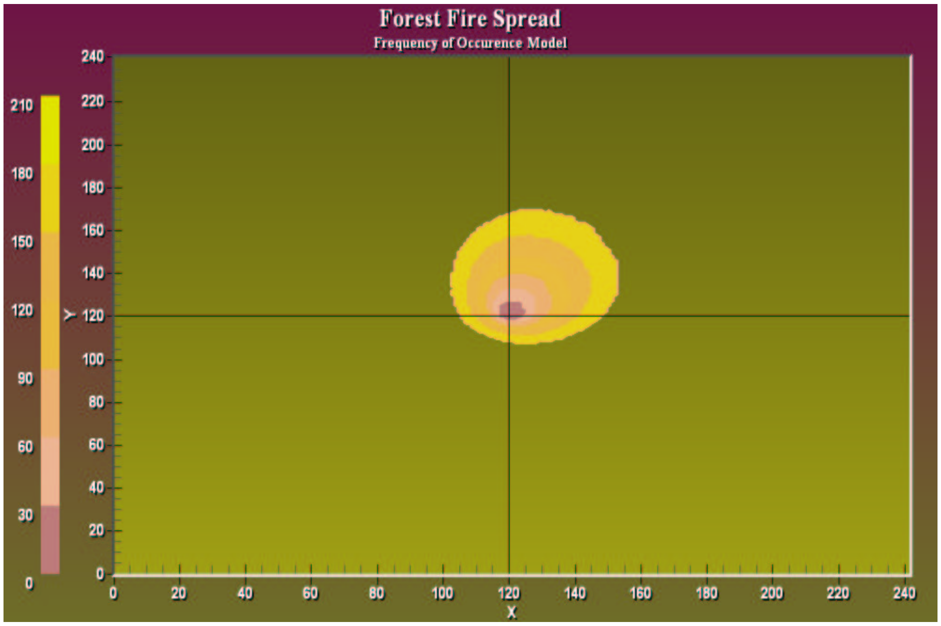

Figure 2: Forest Fire Spread, 50% probability contours, simulation time 180 min, wind direction 30 degrees

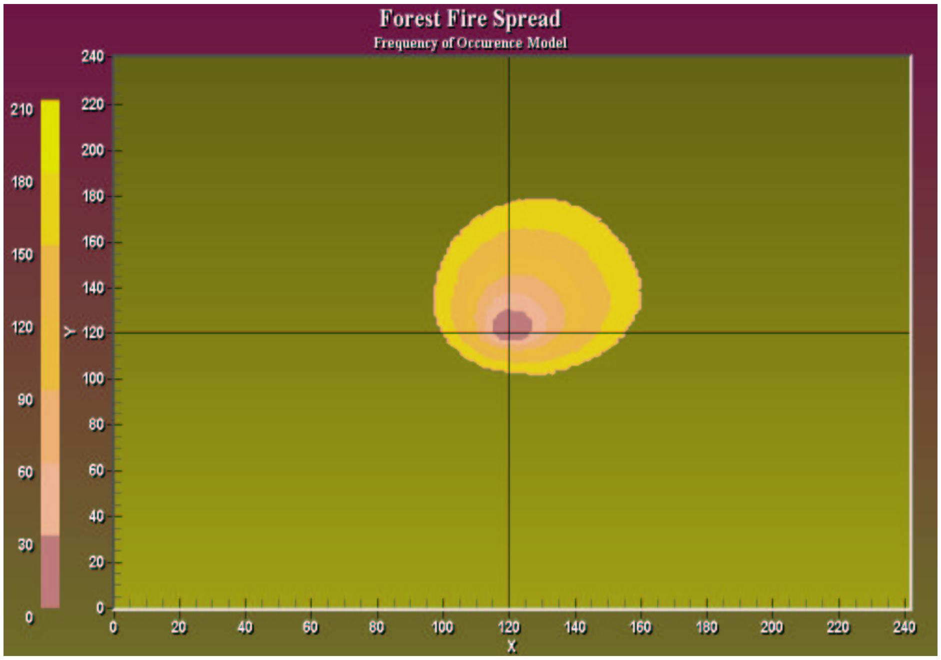

Figure 3: Forest Fire Spread, 10% probability contours, simulation time 180 min, wind direction 30 degrees

Spotting can be modelled. Calibration or fitting?

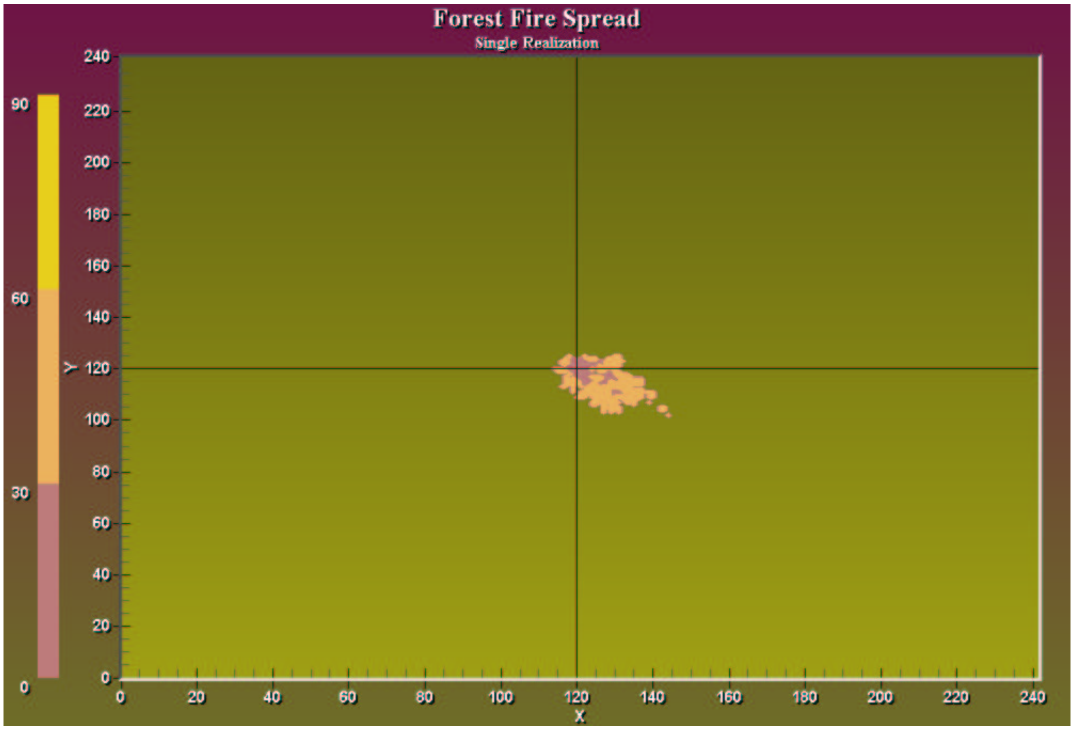

Figure 4: FS with Spotting, simulation time 60 min, wind direction 130 degrees

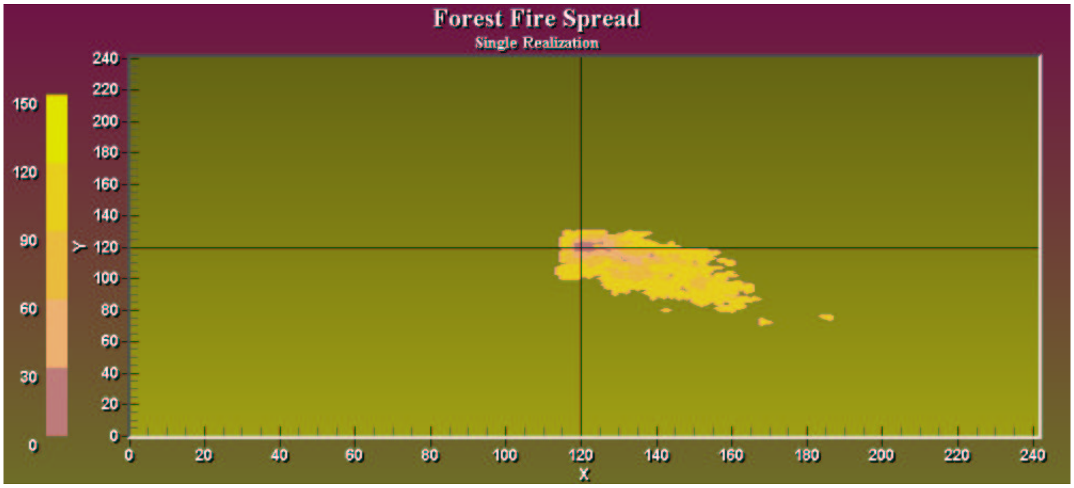

Figure 5: FS with Spotting, simulation time 120 min, wind direction 130 degrees

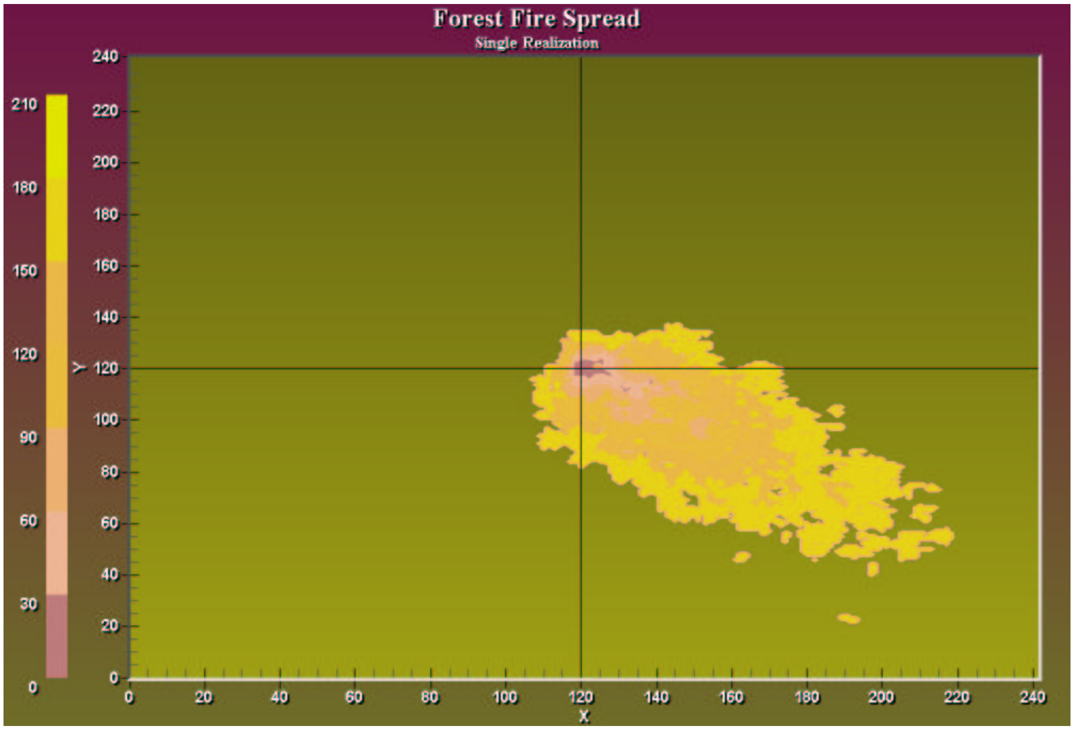

Figure 6: FS with Spotting, simulation time 180 min, wind direction 130 degrees

These simulations can be done on a lattice based on a real map.

Turkey Lakes water shed, northern Ontario

The fire spreads and spots around and over one small lake.

Figure 7: Fire Spotting Realization on the Turkey Lakes Region, simulation time 180 min

Is this model a useful exercise?

Farsite and others do a lot of useful things.

As we understand it :

random locations for start of fire, but deterministic spread thereafter

takes into account topographic information, slope and fuel type

Markov Model

- rates can in principle take into account topographic information and fuel type. We have done this to a limited extent in our little model.
- neighbourhood information uses nearest neighbours.

  Nearest neighbours may be the four immediate cardinal neighbours, the 8 nearest neighbours or some other definition.

  Spotting can be included as a special randomly chosen "neighbour" to be infected by a fire brand or shard
- Markov process has an associated DE obtained from the forward equations.

  In this way one may incorporate physical knowledge in a similar manner to DE deterministic models

  Generates random configuration evolution

  variability is a value added feature over any deterministic model while both can describe trends
- Useful as a random pattern generator as a test subject for "lab testing" of the sensitivity of environmental indices.

Canadian Forest Fire Behavior Prediction (CFFBP) System : construct *Rate of Spread* (ROS) on fire indices (eg DMC), wind velocity, various duff moisture and fuel codes, geographic location.

Idea is to incorporate these into the Markov rate functions.

$\lambda(i, j, t)$ is a function of the given current configuration at time $t$, weather indices, fuel and moisture indices. The time component depends on the season and the 24 hour day cycle.

The simplest model looks at a given season and ignores the diurnal cycle so that

$$\lambda(i, j, t) = \lambda(i, j) \quad \text{independent of } t$$

Model basics

Construct the Markov process on an $n$ by $m$ regular lattice.

- Lattice $\mathcal{L} = \{(i, j) : 0 < i < m, 0 < j \leq n\}$
- $\mathcal{S} = \{s_1, s_2, ..., s_r\}$ is the set of possible states of cell in the lattice.

  $\mathcal{S} = \{F, B, O, W, R\}$

  <u>F</u>ire, <u>B</u>urning, <u>O</u>ther = burnt out fuel, <u>W</u>ater, and <u>R</u>ocks/other
- Each cell in the lattice is given an initial state.
- At every time step, the lattice evolves to a new configuration
- The forest system $X := \{x(i, j) : (i, j) \in \mathcal{L}\}$.

  $X(t)$ = forest system at time $t$

  $x(i, j, t)$ = state of the system at location $(i, j)$ at time $t$

  Evolution over time of the state value $X(i, j)$ depends on its nearest neighbours $\mathcal{N}(i, j) = \mathcal{N} + (i, j) = \{(i, j), (i, j + 1), (i + 1, j), (i, j - 1), (i - 1, j)\}$.

  The process $X$ is a Markov process on the state space $\mathcal{S}^{\mathcal{L}}$.

- A lattice point is *active* if it is burning.
- $\mathcal{A}(t)$ = set of active lattice points at time $t$
- If $(i, j) \in \mathcal{A}(t)$

  Define rates of change $\lambda_{ijk}(t)$ as follows:

  $\lambda_{ij0}(t)$ = rate the cell burns out

  $\lambda_{ijk}(t), k = 1, 2, 3, 4$ = rates of spread to four cardinal neighbours

  $\lambda_{ij5}(t)$ = rate at which firebrands are generated

  (no spotting : $\lambda_{ij5} = 0$)
- $\Lambda_{ij}(t) = \sum_{k=0}^{5} \lambda_{ijk}(t)$

$$\Lambda(t) = \sum_{(i,j)\in\mathcal{L}} \Lambda_{ij}(t) = \sum_{(i,j)\in\mathcal{A}(t)} \Lambda_{ij}(t)$$

- Consequence: Process of state changes : non-homogeneous Poisson process

  ⇒ times between successive events not exponentially distributed.
- : Change to piecewise homogeneous Poisson :

  rates $\lambda_{ijk}(t)$ piecewise constant over a diurnal cycle

Update mechanism

- Generate $\tau \sim exp, \Lambda$
- Choose $(I, J)$ which causes change with prob

$$\frac{\Lambda_{i,j}}{\Lambda}$$

- Choose $K$ at cell (I,J) with prob
  $\lambda^l_{IJk}/\Lambda^l_{IJ}$
  $\Rightarrow$ very much prone to roundoff error for moderate size lattice
- Alternative direct method :
  Simulate $\tau_{i,j,k}$ and update at $\min\{\tau_{i,j,k}$ at event $(i^*, j^*, k^*) = \text{argmin}\{\tau_{i,j,k}$
  SLOWER

WIND EFFECTS

- $\lambda_{i,j,k}(t)$ is the ROS of the neighborhood's cells $(i, j)$ currently burning,

  $\lambda_{i,j,k}(t) = c(t) * \lambda^b(t)/(1.0 - (1.0 - \lambda^b(t)/\lambda^m(t) * cos(\theta_k - \theta^m(t)))$

  where $k = 1, 2, 3, 4$ corresponding to the four major compass directions N, E, S, W.

  ($b(t)$ : Xu and Lathrop)

  ($c(t)$ : J. Beck *et.al* , International Journal Of Wildland Fire, 2002, empirical time effect)

- $\lambda^b(t)$ is base rate of spread (ROS) without wind and slope at time $t$;

- $\lambda^m(t)$ is max ROS with given wind speed & slope @ t;

- $\theta^m(t)$ is direction of maximum ROS (wind direction) at time t;

  $\theta_k$ : constants to project direction onto the lattice coordinates

- $c(t)$ is the coefficient of fire intensity, depending on time $t$ within a day cycle

  Use 6th-order polynomial for diurnal fire intensity :

  $$\begin{aligned} c(t) &= -0.1668 + 0.4363t - 0.1453t^2 + 0.0187t^3 \\ &\quad -0.001t^4 + 2 * 10^{-5}t^5 - 2 * 10^{-7}t^6 \end{aligned}$$

  Maximum fire intensity is from 4 to 6 p.m : $c(t)$ is approximately equal to 1.0 for this period of time and c = 0.1125 for t = 6 a.m.

These can be chosen region or even lattice point specific

The model can be adjusted readily to allow for a bigger neighborhood.

## Stochastic Modelling of Fire Spotting

- ”spotting” of new fires is yet another factor our model considers.

  For certain fuel types such as birch, as fire consumes an area, firebrands can be carried aloft by wind.

- firebrand → lands → ignite fuel (possibly)

  Over time possibly several that may later merge

- problem of lofting and transport of burning brands in forest fires has received considerable attention

- little research has been done to quantify the transport of firebrands from burning structures; implement a stochastic mechanism of firebrand propagation.

- Our fire spotting mechanism : uses the current wind velocity to determine the amount of lofting that occurs.

  firebrands randomly lands → probability(fuel type, topography, moisture codes) starts fire

- Basic parameter for spotting model :

  the rate of firebrand spread

  the rate of firebrand burnout

  wind speed and wind direction (velocity)

  air time

  the probability that firebrand sets fire after landing

  landing location variability

Table 1: Simultaneous 10-minute wind speed values in m/min

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | 1.30 | 1.10 | 1.30 | 1.30 | 1.35 | 1.40 | 1.22 | 1.62 |
| 2 | 1.23 | 1.32 | 1.38 | 1.24 | 1.48 | 1.40 | 1.35 | 1.52 |
| 3 | 1.23 | 1.50 | 1.48 | 1.50 | 1.60 | 1.64 | 1.50 | 1.70 |
| 4 | 1.40 | 1.32 | 2.10 | 1.60 | 1.95 | 1.70 | 1.51 | 1.52 |
| 5 | 1.60 | 1.35 | 1.40 | 1.59 | 1.80 | 1.90 | 1.72 | 1.70 |
| 6 | 2.10 | 1.85 | 1.90 | 2.38 | 2.23 | 2.60 | 2.26 | 2.50 |
| 7 | 1.74 | 1.68 | 1.75 | 2.11 | 2.00 | 1.95 | 1.65 | 1.85 |
| 8 | 1.95 | 1.69 | 1.55 | 1.78 | 1.51 | 2.10 | 1.95 | 1.86 |

Table 2: Calculations of the basic rate of spread in cells/min

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| wind km/hour | 6 | 5 | 6 | 6 | 6 | 7 | 6 | 6 | 0 |
| wind speed x4 | 24 | 20 | 24 | 24 | 24 | 28 | 24 | 24 | 0 |
| ISI | 14 | 12 | 14 | 14 | 14 | 18 | 14 | 14 | 4 |
| ROS(m/min) | 22 | 18 | 22 | 22 | 22 | 31 | 22 | 22 | 4 |
| ROS(cell/min) | .733 | .600 | .733 | .733 | .733 | 1.033 | .733 | .733 | .133 |

## Simulation Details

- Cell dimension : 30 x 30 meters by default

  one (or several) ignition points exactly on the center of the lattice

  specify wind speed and direction

  OR variable wind velocity set for small periods

  - only from Table 1 at present; to reflect northern Ontario summer conditions

  Table 2 translates these into ROS for the cell dimensions

Simulation examples presented earlier : first are on a homogenous space

The initial stochastic conditions for spotting are the following: the firebrand ROS = 0.0133 $\mathrm{min}^{-1}$, the air time rate is 0.2 $\mathrm{min}^{-1}$, the firebrand burnout rate is 0.1 $\mathrm{min}^{-1}$, the probability that a landing firebrand leads to ignition is 0.7. The variation in the landing location is normally distributed $N(0, \sigma^2)$ with standard deviation $\sigma = 1$.

### Simulating Fire on an Actual Landscape

The effect of the spatial configuration of fuel classes on the spread of fire simulated on a 318 x 380 cell map (rows = 318, columns = 380) depicting a 6360 x 7600 m section (4833.6 ha) of Turkey Lakes in Ontario

The map is GIS

Spatial distribution of fuel classes is obtained from the Terrain Analysis System

All the simulations were run on the same landscape using a single ignition point (207, 223) in the hardwood fuel type near the south-east corner of the map. Cell resolution is 20 m, rate of spread, wind and other parameters are the same as described above for example presented

For both a single realization and a frequency of occurrence scenario, there is the possibility for simulations with different states of wind distribution - wind speed can be specified by a time series, wind speed can be constant, it can be normally distributed, or specified by other distributions.

The simulations reveal a common characteristic of fire spread:

fire spread contours : generally elliptical shape.

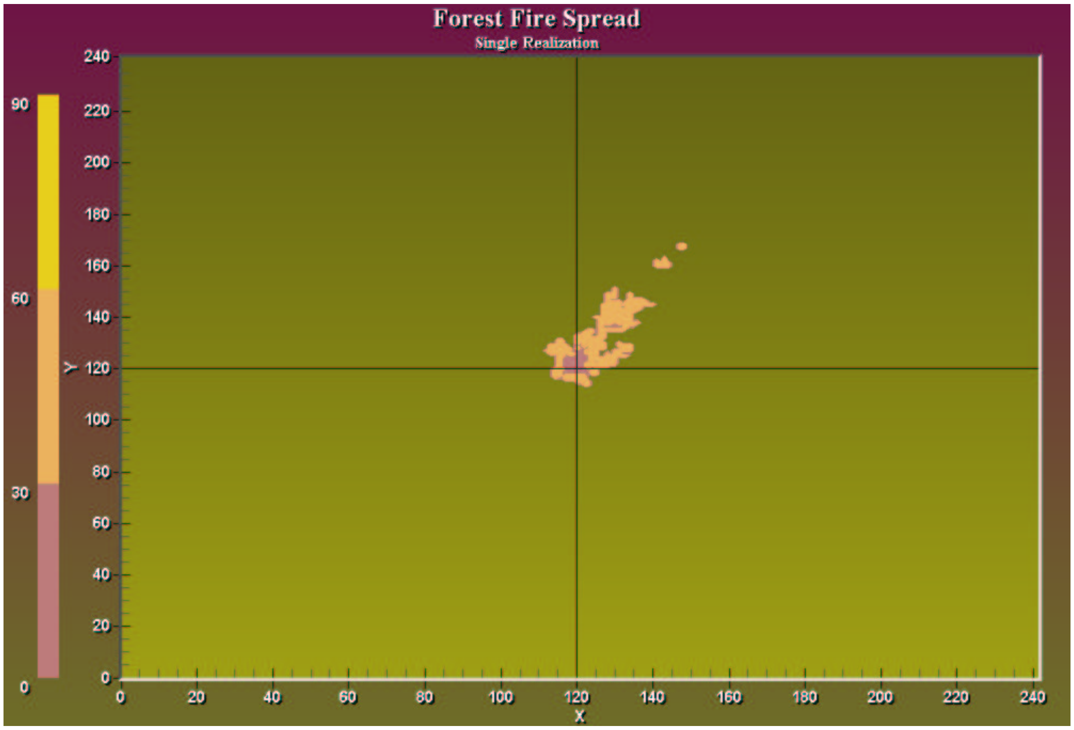

Figure 8: Forest Fire Spread with Spotting, simulation time 60 min, wind direction 30 degrees

Simulation examples presented in Fig. 11, 12 and 13 illustrate the fire spread with spotting over time after 180 min, 90%, 50%, and 10% probability contours accordingly (frequency of occurrence model scenarios)

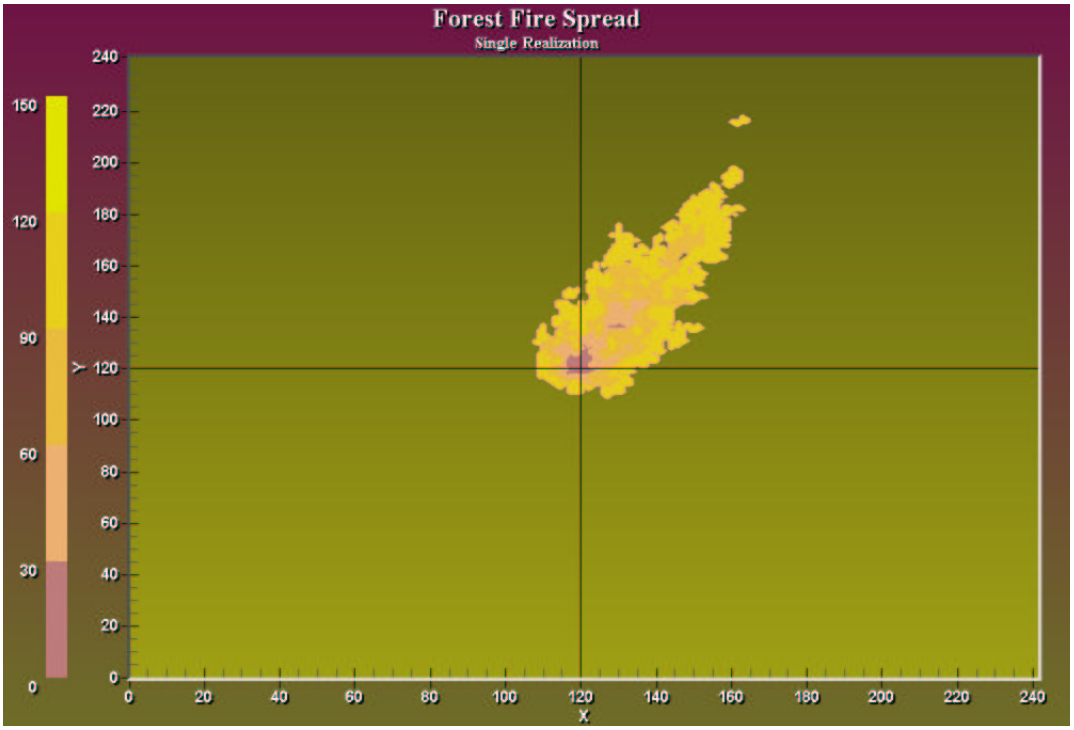

Figure 9: Forest Fire Spread with Spotting, simulation time 120 min, wind direction 30 degrees

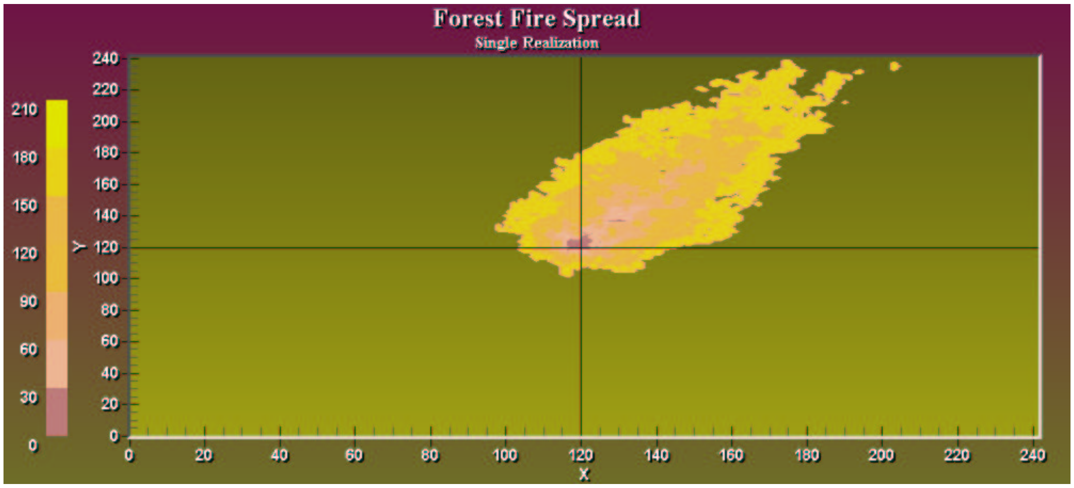

Figure 10: Forest Fire Spread with Spotting, simulation time 180 min, wind direction 30 degrees

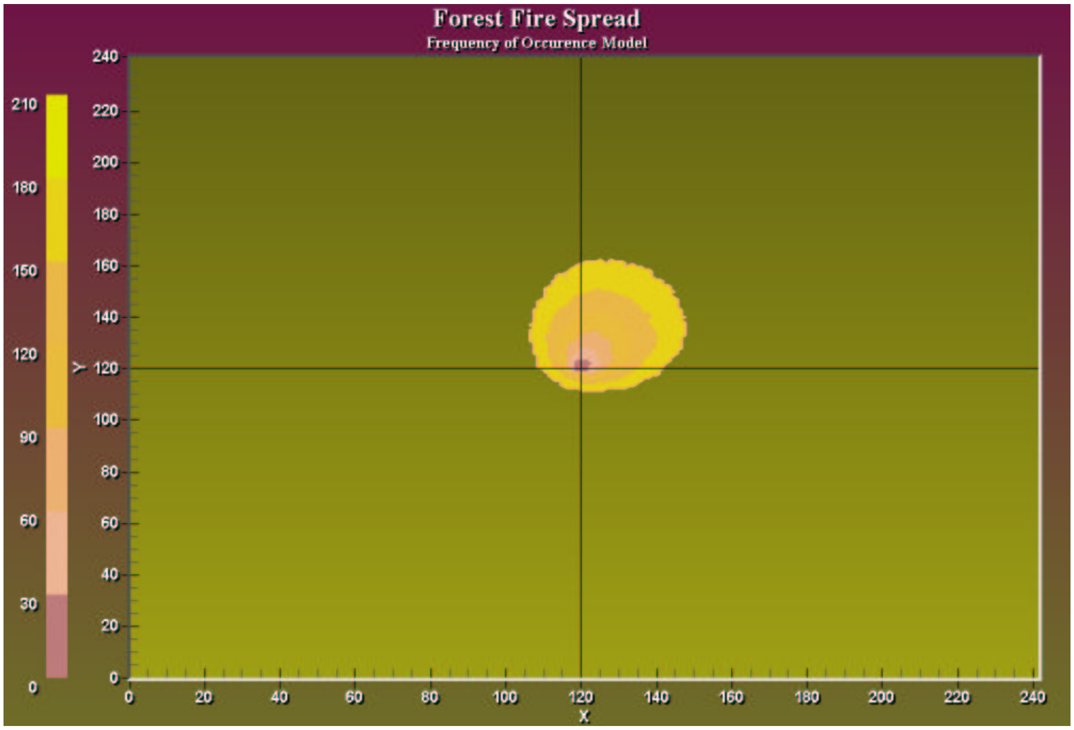

Figure 11: Forest Fire Spread, 90% probability contours, simulation time 180 min, wind direction 30 degrees

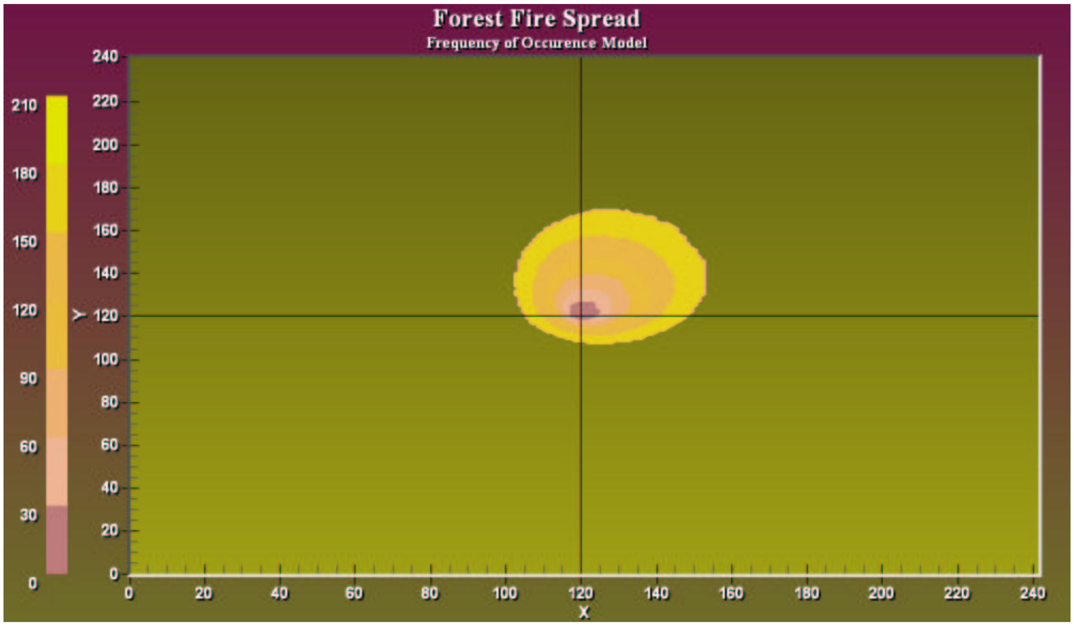

Figure 12: Forest Fire Spread, 50% probability contours, simulation time 180 min, wind direction 30 degrees

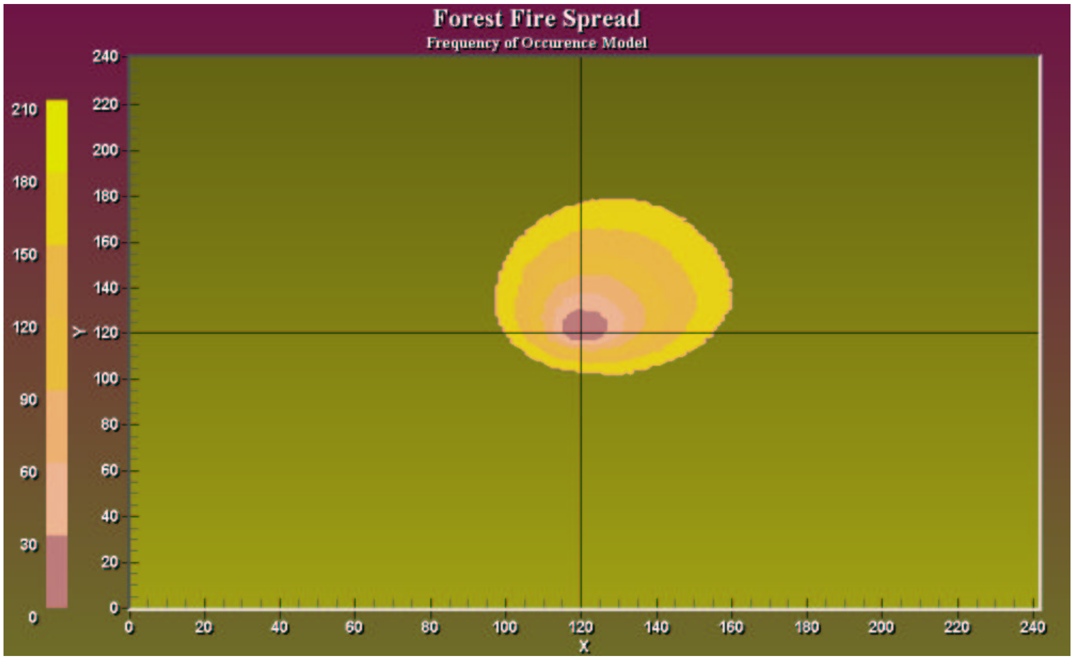

Figure 13: Forest Fire Spread, 10% probability contours, simulation time 180 min, wind direction 30 degrees

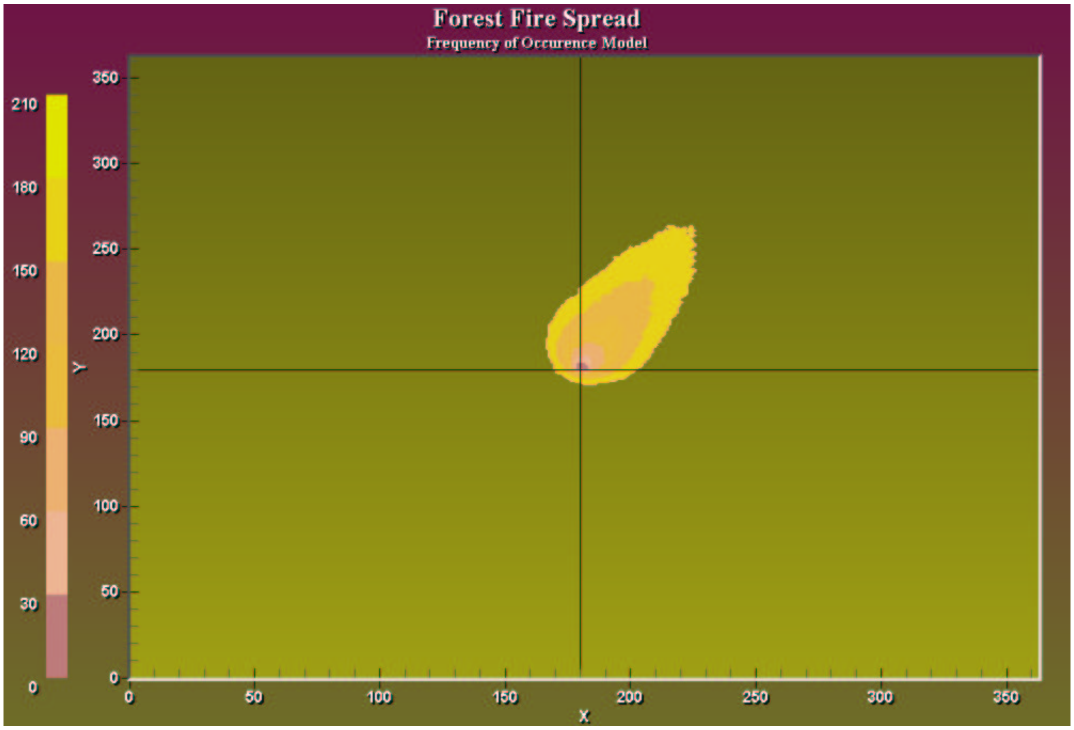

Figure 14: Forest Fire Spread with spotting, 90% probability contours, simulation time 180 min, wind direction 30 degrees

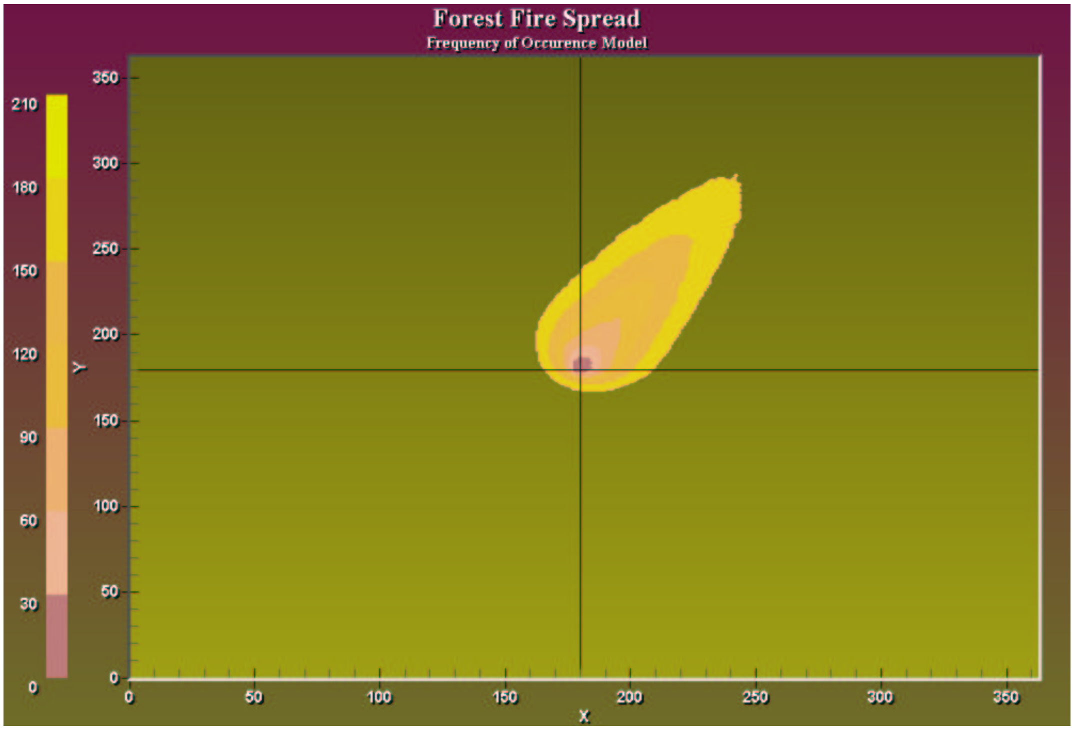

Figure 15: Forest Fire Spread with spotting, 50% probability contours, simulation time 180 min, wind direction 30 degrees

## Conclusions

The Stochastic Forest Fire Spread Model presented herein incorporates relations between cells as an effective approach to forest fire simulation and, we feel, has the advantage of being able to describe stochastic aspects not adequately addressed in deterministic models. Fire, as a natural phenomenon, has stochastic characteristics. Specific capabilities of the package include the following: a) All relevant variables can be changed at any step of simulation model. b) The model variables can include many forest fire indices and codes, and local topography information. c) The computer implementation allows real-time visualization of the evolving phenomena. d) Weather conditions and land topography can be easily incorporated in this model. The parameters in our model are functions of various underlying information such as wind speed and direction, Duff moisture code and fuel code and topographical or map information. Further work needs to be done on incorpo-

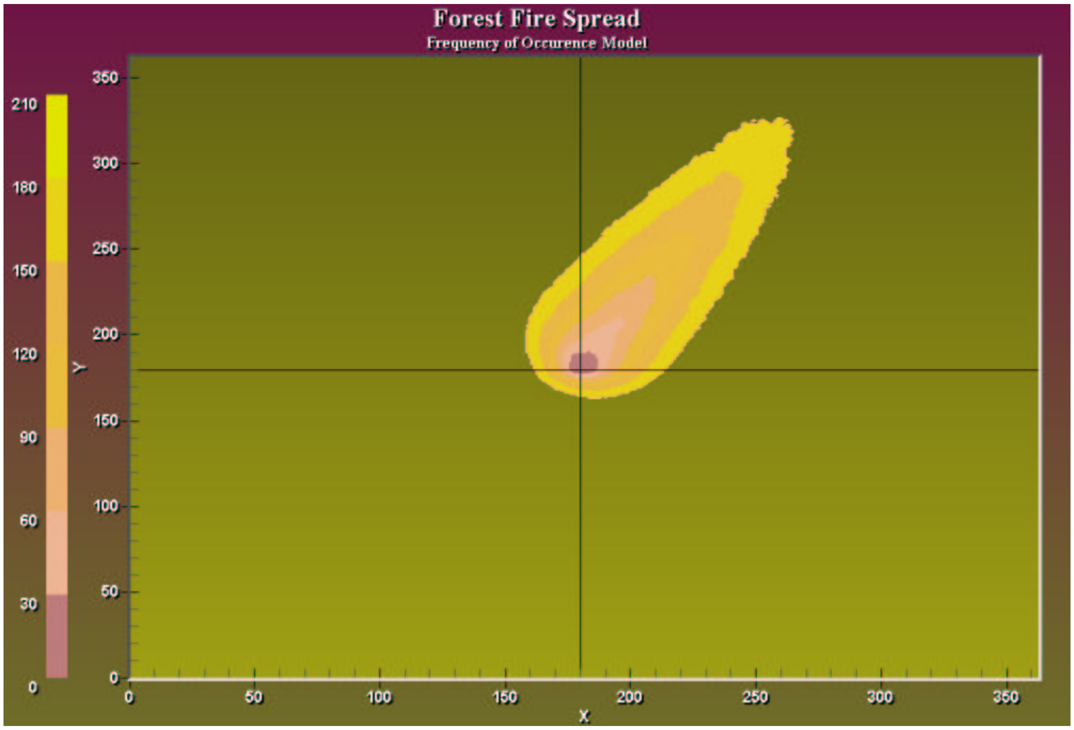

Figure 16: Forest Fire Spread with spotting, 10% probability contours, simulation time 180 min, wind direction 30 degrees

rating this information and estimating the relevant parameters.

The model as implemented can generate either a single realization or a composite of many realizations. A single realization allows one to view a growth pattern on a single forest or region and hence the variability in patterns. The composite can be used to generate probability contours, useful for average growth patterns, which do not give information on variability.

Our stochastic model can also be viewed as a random landscape generator. By its very nature, it can be made to interface with Geographic Information System (GIS) raster-based systems. The model stochastically generates disturbance patterns on the landscape based on the total area disturbed and the number of patches to be disturbed. This is the focus of the current development.

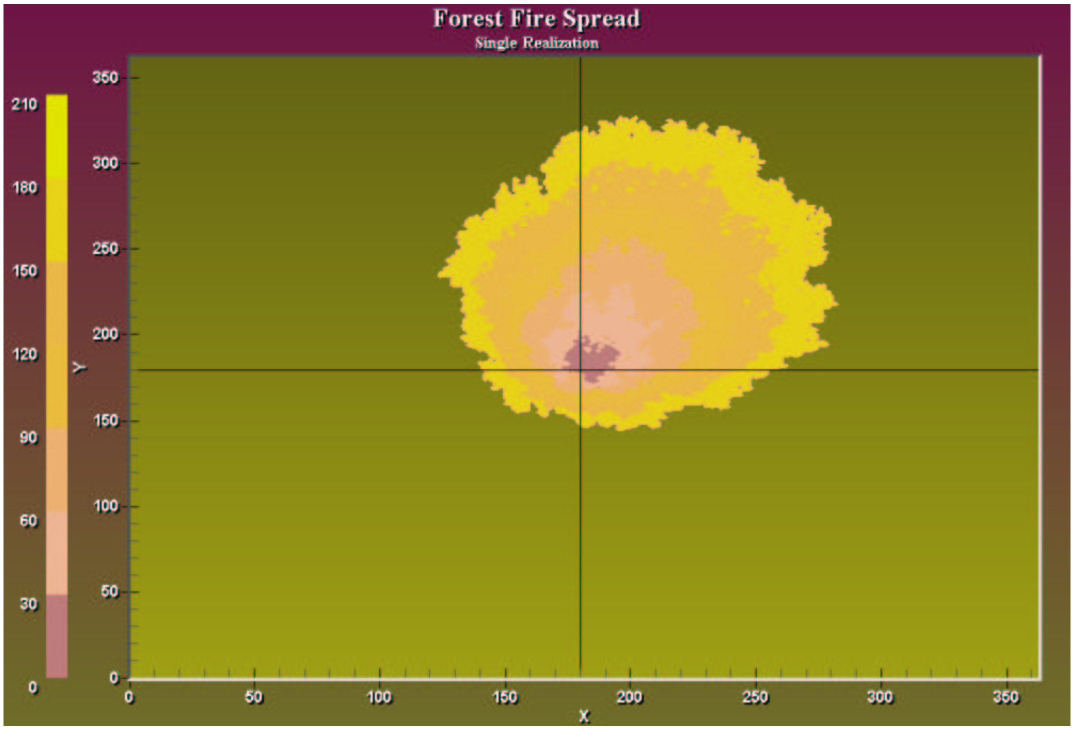

Figure 17: Forest Fire Spread, simulation time 180 min, wind direction 30 degrees, start simulation time 4 pm

## Acknowledgements

Thanks also to Dave Martell for several comments

## References

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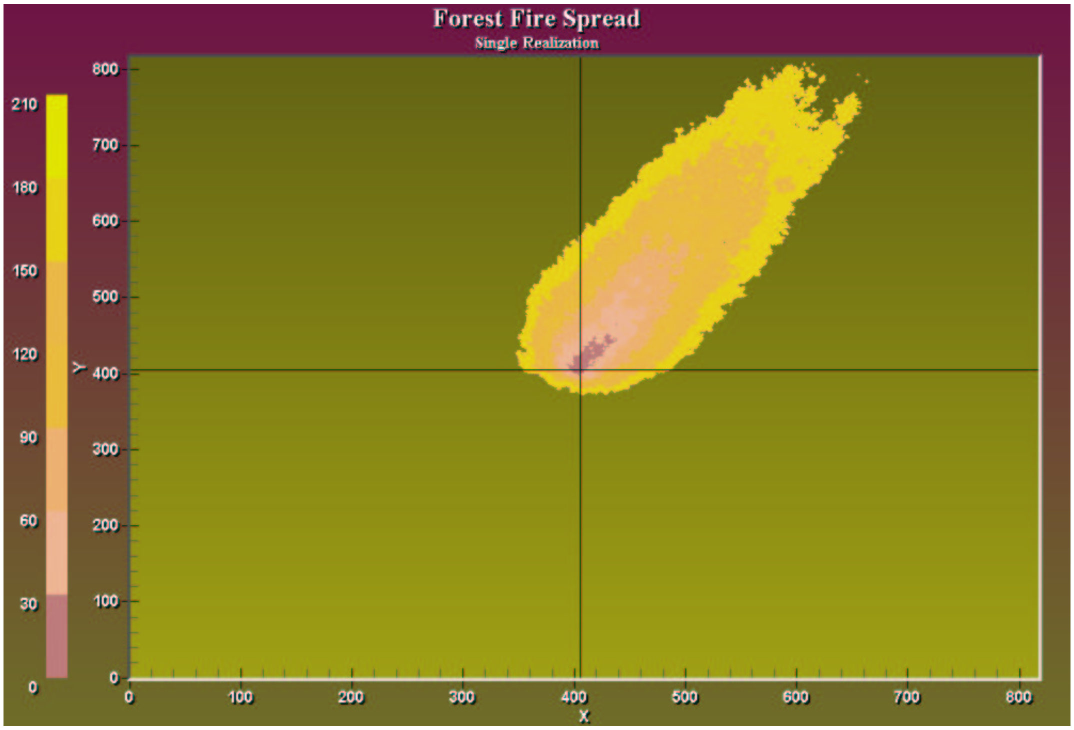

Figure 18: Forest Fire Spread with spotting, simulation time 180 min, wind direction 30 degrees, start simulation time 4 pm

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