Integrating Wildfire Risk and spread in a Cellular Forest harvesting Model. The static problem.

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Outline

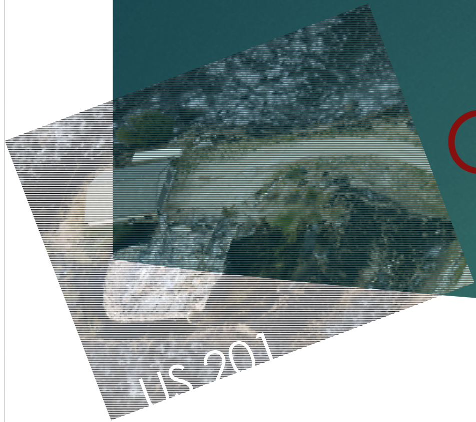
- Obejctive and Relation with other studies
- Modeling framework
- Calculating the probability that a stand will burn in a given period
- Some results…
- Conclusions
- Caveats

Objective

- The goal of the model is to use forest (timber) management to produce a sustainable supply of timber but taking into to account the flammability of the landscape.
- So, our objective function is to:
  - Maximize the present value of the expected economic return from the forest plus the expected ending value.

Relationship to Other Models

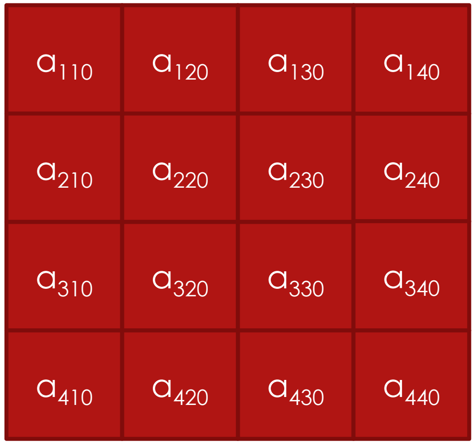
- Wei (2012) minimized fire loss as a function of the rate that fire can spread across a landscape.
- Our approach is more like that in Gonzalez et al. (2005) and Wei et al. (2008), who model the probability that the area in each cell will burn as a function of the cell's own flammability and the flammability of its adjacent cells.
- Unlike Wei et al. (2008), the treatments in our model are timber harvests.
- Like Gonzalez et al. (2005) we maximize the expected value of the forest.
- Like Wei et al. (2008), we directly model the probability that a cell will burn.

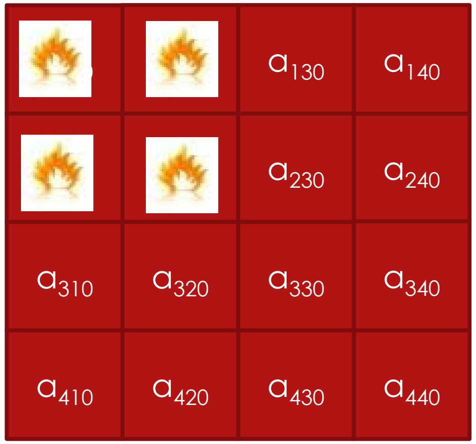


Contribution of this Work

- For the steady-state model, we maximize the forest value times one minus the probability that the cell will burn
- For the two-period model, we maximize the present value of the timber harvest plus the forest value of the ending state times one minus the probability that the cell will burn
- The way we calculate the probability that a cell will burn is different from Wei et al (2008) where they assumed that different burn path events are independent
- In our models, flammability is driven mainly by stand age, but other factors could easily be modeled as well
  - E.g., Marques et al 2012, Gonzalez et al 2005…

The State Space…

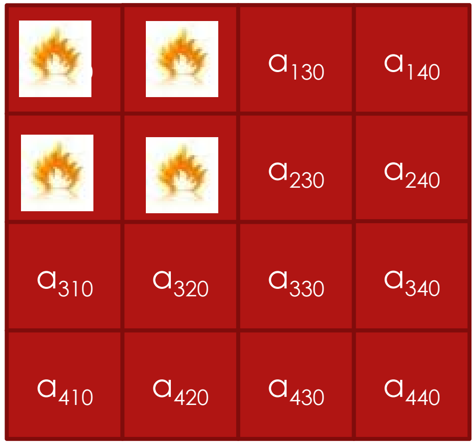




- We model our forest as an *m*×*n* grid, where each cell in the grid is a stand with an initial age at time 0 of a_{i0}.
  - For each age, we have a <u>timber yield</u>, y_a, and <u>flammability index</u>, f_a.
  - <u>Timber yield</u> is a monotonically increasing, concave function of stand age.

The State Space...

a_{110}	a_{120}	a_{130}	a_{140}
a_{210}	a_{220}	a_{230}	a_{240}
a_{310}	a_{320}	a_{330}	a_{340}
a_{410}	a_{420}	a_{430}	a_{440}



- The flammability index is low when stands are young and when they are old and highest when stands are of intermediate age.
- The probability that stand *i* will burn in period *t*, p_{it}, depends:
  - on ignition probability,
  - his own flammability and
  - The probability that adjacent stands will burn.

General Model Description

- The planning horizon consists of a set of T periods, t = 1, …, T, each τ years in length.
- Our decision variables determine whether and when to harvest management unit *i*.
  - X_{it} = 1 if stand *i* will be harvested in period *t*;
  - X_{it} = 0 if stand *i* won't be harvested in period t
    - Could also model fuel treatments or thinnings…

> We assume that a management unit can only be harvested once during the planning horizon; hence:

$$\sum_{t=0}^{T} X_{it} = 1 \quad \forall\, i$$

Objective: Economic Return

- Maximize the present value of the expected economic return from the forest…
  - For now, assume that none of the forest burns:

$$NPV = \sum_{i} \sum_{t=o}^{T} r_{it} X_{it}$$

  - r_{it} = the present value of the economic returns from stand *i* plus its ending value if it is harvested in period *t*;
    - i.e., $r_{it} = \delta^t \pi y_{a(it)} + \delta^T \varphi_{it}$, where δ is the discount term, π is the price of timber, a(it) is the age of stand *i* if it is harvested in period *t*, and φ_{it} is the ending value of stand *i* if it is harvested in period *t*.

Objective: Economic Return

- But…it's too unrealistic to model economic returns assuming that there is no fire.
- This can be addressed by multiplying each term in the economic objective function by the estimated probability that the stand will survive (not burn) up to that point.
- This would give the expected present value of the economic return from the forest.

Objective: Economic Return

- So the objective function can be rewritten as:

$$E(NPV) = \sum_{i}\sum_{t=0}^{T} p'_{it} r_{it} X_{it} + \sum_{i}\sum_{t=1}^{T} p_{it}\theta_{it}$$

  - where θ_{it} is the present value of stand *i* if it burns in period *t*.
  - Note that the value of the second term depends indirectly on the values of the decision variables because the p_{it}'s depend on the management decisions that are made.
- **Determining these probabilities is the key step in the model.**

Calculating the Probability that a Stand Will Burn: the p_{it}'s

- To simplify the model, we assume that a stand can only burn once during the planning horizon;
  - If a stand has already burned we assume that the probability that it will burn again is zero.
- For each period there are three possibilities:
  1. the stand burns because a fire starts in it,
  2. the stand burns because a fire in an adjacent cell spreads to it, or
  3. the stand does not burn.

Calculating the p_{it}'s

- The probability that a given stand will burn in a given period is a function of…
  1. the probability that a fire starts on that specific stand,
  2. the probability that each stand around it will burn, and
  3. the probability that a fire will spread from an adjacent stand.
- To make the model tractable, when we calculate p_{it} we assume that neither stand *i* nor any of the surrounding stands *k* have burned.
  - This tends to over-estimate the probability that a stand will burn, since if an adjacent stand has already burned then it is assumed to no longer be flammable.

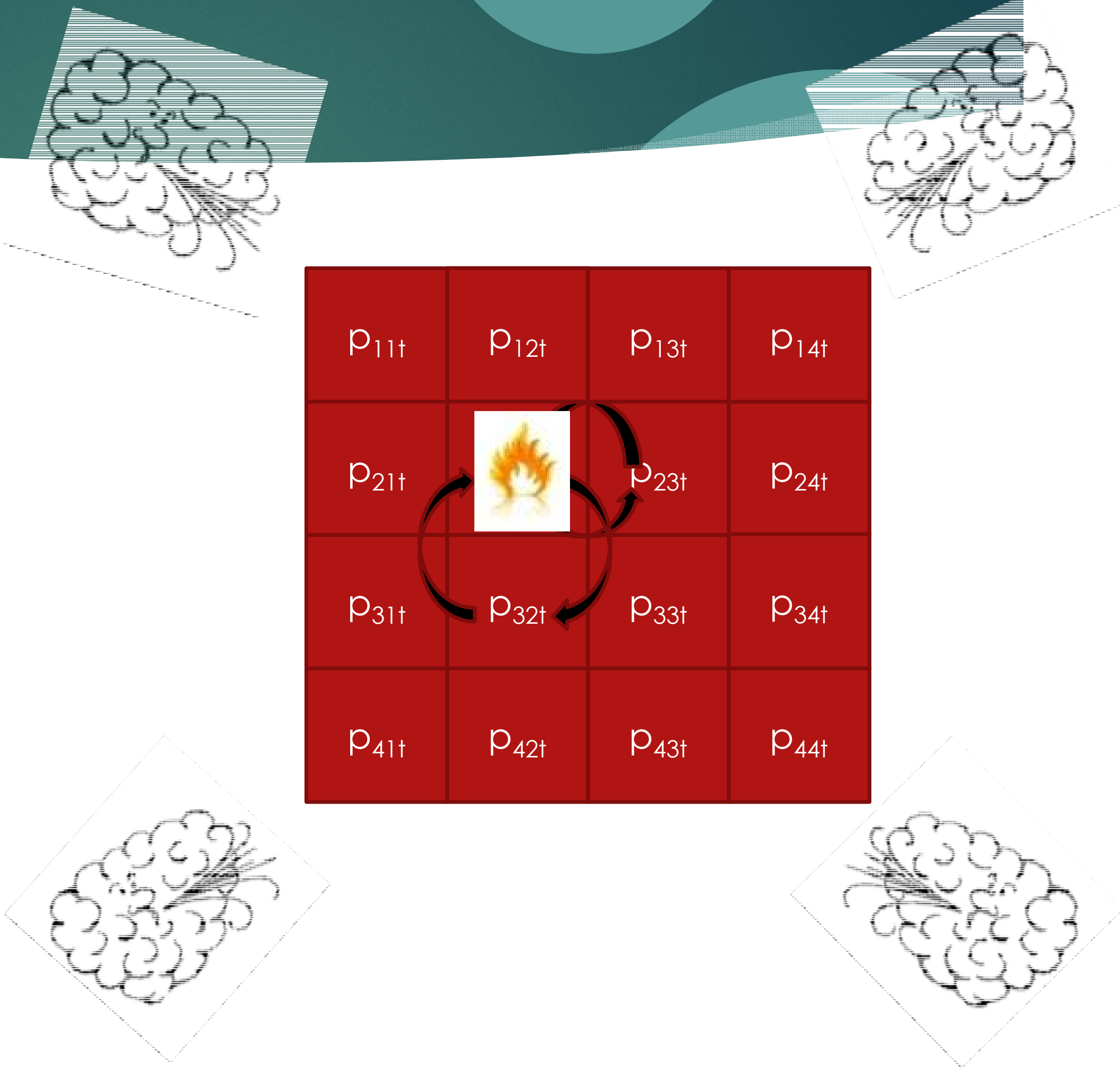
Calculating the p_{it}'s

- Even with the heroic simplifying assumptions we've already made, this is still a devilishly complicated problem.
- The probability of each stand burning is a function of the probability that every other stand will burn, which creates seemingly intractable circularities in the calculation of the probability that any one stand will burn.

Calculating the p_{it}'s

To deal with this, we separate the burn probabilities into <u>four independent cases based on wind direction</u>.

The cases are that the wind is from the NW, the NE, the SE, and the SW.



Calculating the p_{it}'s

- Let D be the set of wind directions: D = {NW, NE, SE, SW}.
- The probability that a stand i will burn in period t can be written:

$$p_{it}|d \cong p_{it}^{I} + (1 - p_{it}^{I}) \sum_{k \epsilon Adj_i^d} \left(\prod_{m \epsilon Adj_i^d m \neq k} (1 - p_{m_{adj}}|d)) \times p_{k_{adj}}|d \times p_{ki\ adj,t}^{S}|d \right.$$

- *Where:* p_{it}^{I} = the probability that a stand ignites and burns

  p_{it}^{S} = the probability that a fire spreads from an adjacent stand to i.

  Adj^{d}_{ik} = the set of stands that are adjacent and upwind from stand i, given that the wind is from direction d.

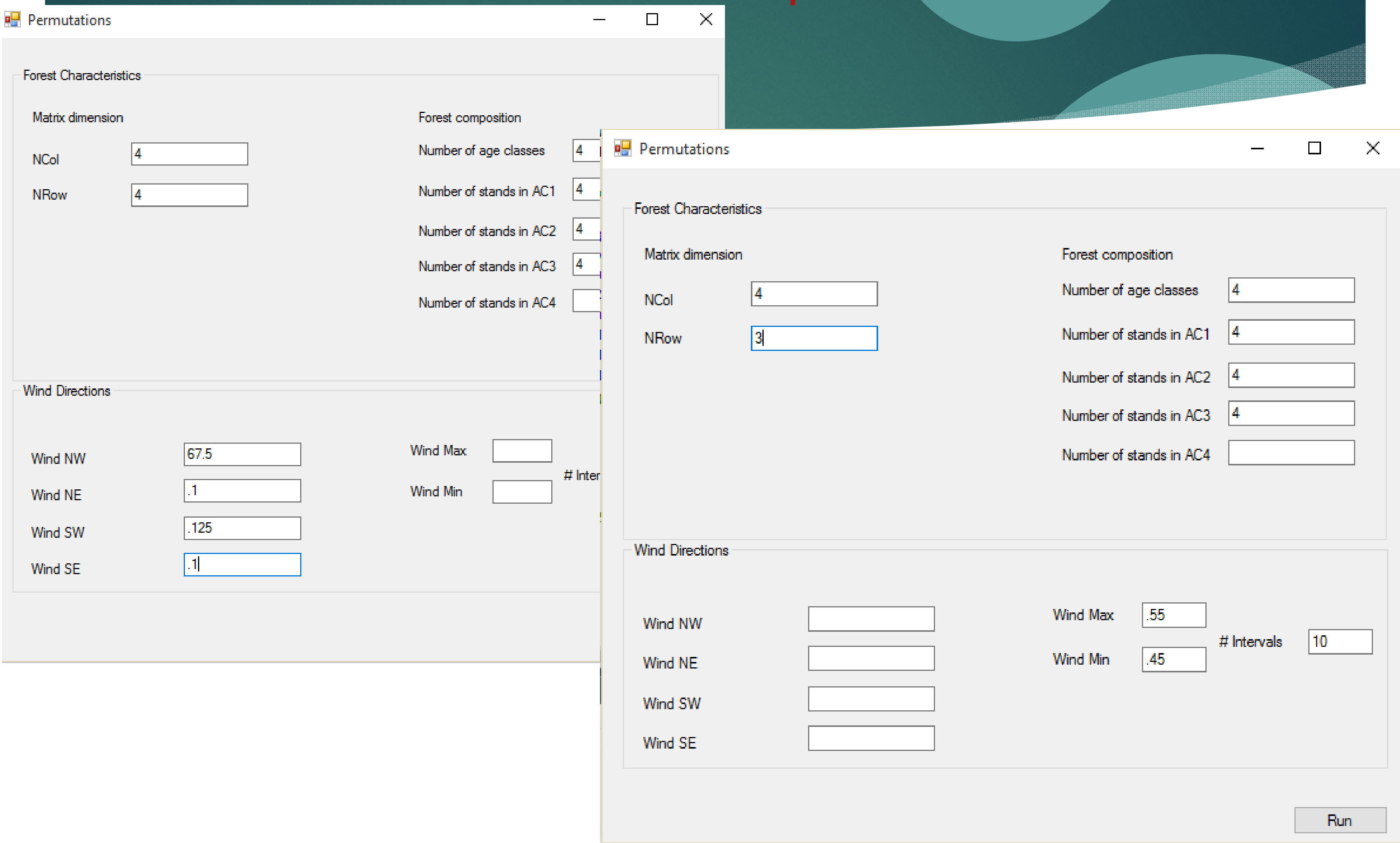
Calculating the p_{it}'s

- It seems reasonable to assume that the probability of the wind blowing from a given direction, p_d, does not change over time.
- It also seems reasonable to assume that the probability that a fire will start in stand *i* does not depend on the wind direction.

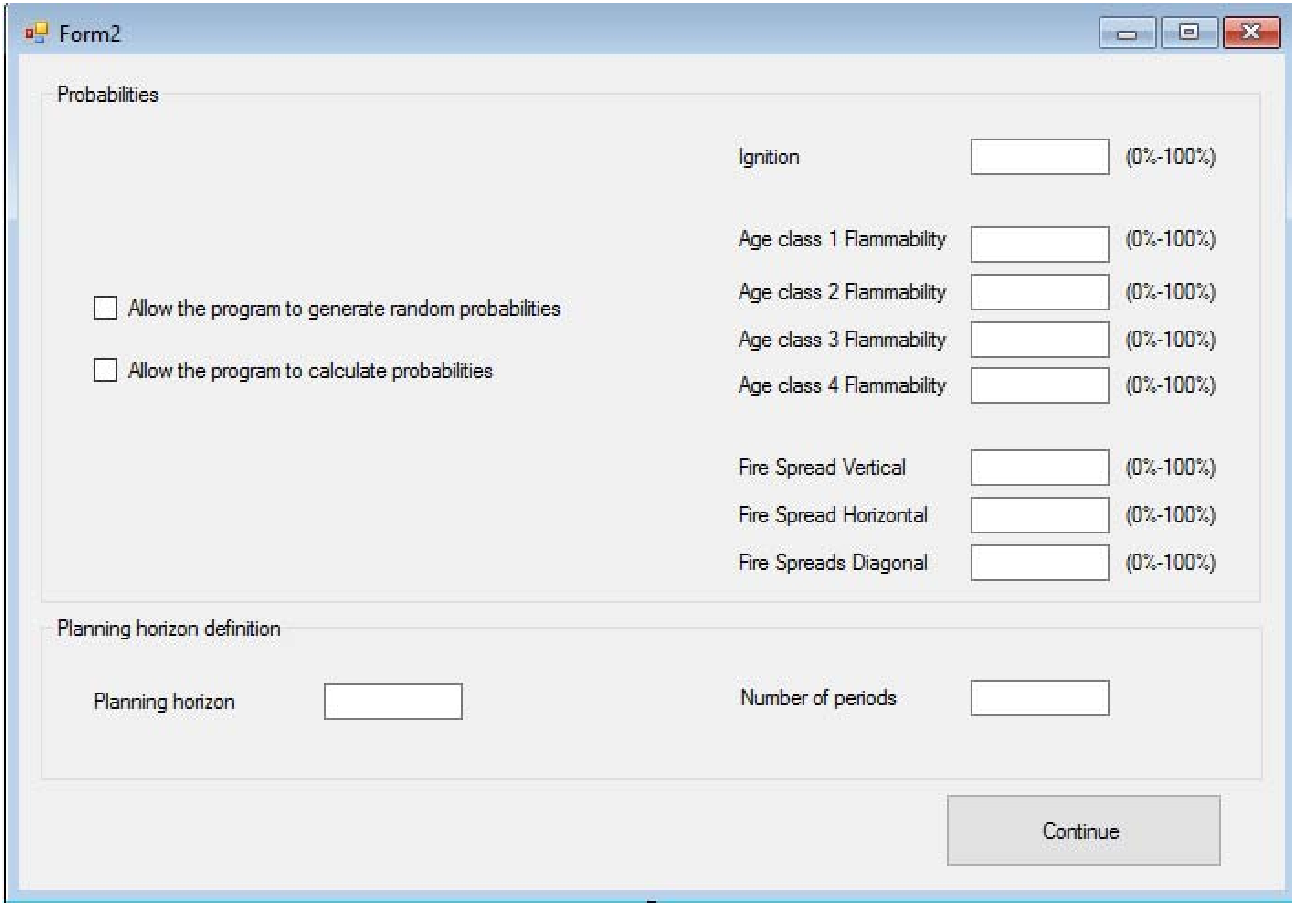
Calculating the p_{it}'s

- A key assumption here is that the probability of fire spreading upwind is zero.
  - This means that p_{it} only depends on the ignition probability and the flammability of stand *i* as well as the probabilities that an upwind stand will burn and that the fire will spread to stand *i*.
- Now the probability of each stand burning can be calculated by starting in the upwind corner of the forest and working downwind.
  - For example, if the wind is from the NW, processing would start in the upper left corner, proceed to the right through the top row; when the top row is done processing would continue with the second row, moving from left to right.

An example…


Permutations
Forest Characteristics
Matrix dimension
NCol 4
NRow 4
Forest composition
Number of age classes 4
Number of stands in AC1 4
Number of stands in AC2 4
Number of stands in AC3 4
Number of stands in AC4
Wind Directions
Wind NW 67.5
Wind NE .1
Wind SW .125
Wind SE .1
Wind Max
Wind Min
Permutations
Forest Characteristics
Matrix dimension
NCol 4
NRow 3
Forest composition
Number of age classes 4
Number of stands in AC1 4
Number of stands in AC2 4
Number of stands in AC3 4
Number of stands in AC4
Wind Directions
Wind NW
Wind NE
Wind SW
Wind SE
Wind Max .55
Wind Min .45
Intervals 10
Run

An example…


Form2
Probabilities
Ignition
(0%-100%)
Age class 1 Flammability
(0%-100%)
Age class 2 Flammability
(0%-100%)
Age class 3 Flammability
(0%-100%)
Age class 4 Flammability
(0%-100%)
Allow the program to generate random probabilities
Allow the program to calculate probabilities
Fire Spread Vertical
(0%-100%)
Fire Spread Horizontal
(0%-100%)
Fire Spreads Diagonal
(0%-100%)
Planning horizon definition
Planning horizon
Number of periods
Continue

Example: 4*4 matrix

Static model (just one period)

Regulated forest (4 age classes stands)

4 winds with equal probability

Using Complete enumeration…

Age	y(a)	f(a)	Ign(a)	0,02
0	0	0	0,000	
1	1	0,5	0,010	
2	3	0,8	0,016	
3	5	0,6	0,012	
4	6	0,3	0,006	

8 IDEAL SOLUTIONS

3	2	2	3
1	1	2	2
3	1	4	4
3	1	4	4

3	1	3	3
2	1	1	1
2	2	4	4
3	2	4	4

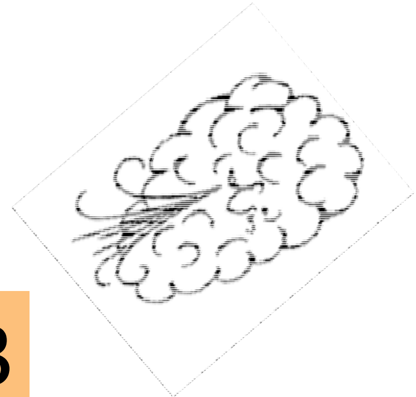
Example: 4*4 matrix

Static model (just one period)

Regulated forest (4 age classes stands)

Predominat winds from NW and NE…

3	2	2	3
1	1	1	1
3	2	2	3
4	4	4	4



Example: 3*3 matrix

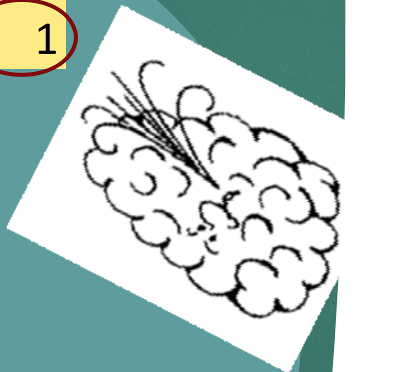
Dynamic model

Regulated forest (3 age classes stands)

Harvests (how many stands to harvest and each ones?(

Period 0

2	2	0
2	0	1
0	1	1



Example: 3*3 matrix

Dynamic model

Regulated forest (4 age classes stands)

Harvests (how many stands to harvest and each ones?

Period 0

2	2	0
2	0	1
0	1	1

Period 0 to period 1

Harv	Harv	0
Harv	0	0
0	0	0

Period 1

0	0	1
0	1	2
1	2	2

Non regulated forest

Dynamic Problem

3*3 landscape

Dominant wind NW (0,67)

NE (0,13)

SW(0,2)

Period 0

4	2	2
1	3	0
4	1	1

Harvesting plan

1	0	0
0	1	0
1	0	0

Period 1

0	3	3
2	0	1
0	2	2

Harvesting plan

0	1	1
0	0	0
0	1	0

Period 2

1	0	0
3	1	2
1	0	3

Conclusions…

- We now have a fully-specified harvest scheduling model that incorporates fire risk.
  - The problem is highly non-linear.
  - However, we could use any one of the many heuristic solution algorithms that have been developed for solving non-linear problems like this: simulated annealing, tabu search and genetic algorithms, etc.
  - It may be possible to develop unique heuristic algorithms specifically designed to solve this type of problem.
  - This will be the subject of our future research.

Caveats …

- A key assumption that a stand can burn only once.
  - This assumption was made to improve the tractability of the specification and calculation of the burn probabilities.
  - As long as the planning horizon is short or the probability of any given area burning is low, then this is probably a pretty good assumption.
  - If the probability that a stand will burn is high, then it probably makes sense not to have too long a planning horizon, as we will need to re-plan frequently as we learn which areas have actually burned.

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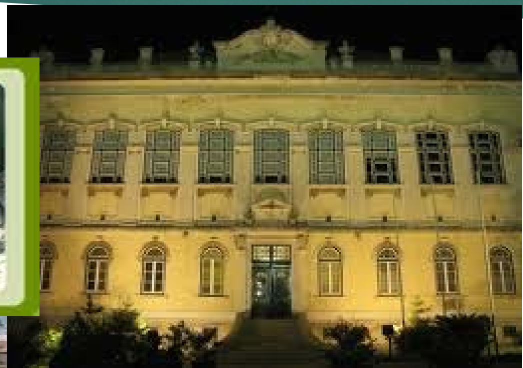
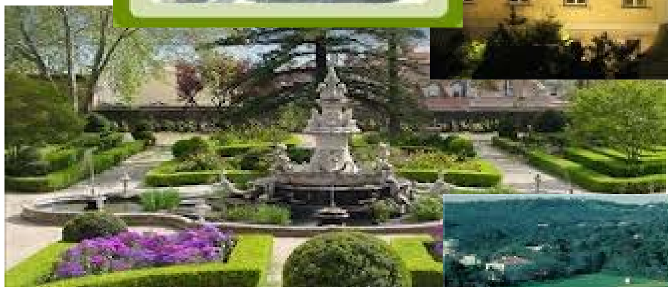
Thank you!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