A Forest Optimization Model to Minimize the Risk of Hurricane Damage

Eastern Nicaragua

Dr. Fernando J Mendoza Jara

National Agrarian University, Nicaragua
University of Texas at Dallas

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Introduction

- Nicaragua is *highly vulnerable to natural disasters* and is a the third most highly impacted country in the world in regards to the passage of tropical storms. Hurricanes are part of the life in eastern Nicaragua.

- North Atlantic has experienced a clear increase in the frequency of tropical storms and major hurricanes within the last three decades (Emanuel, K. 2005) .

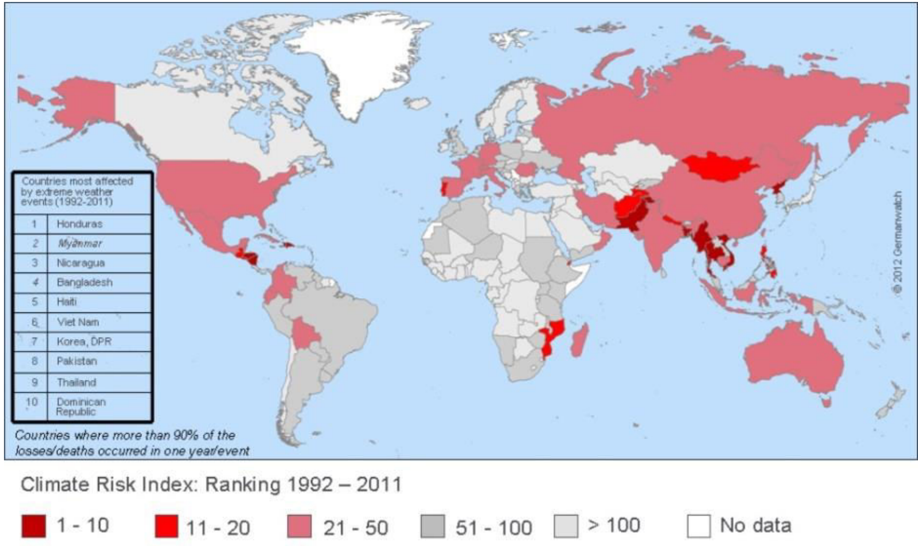
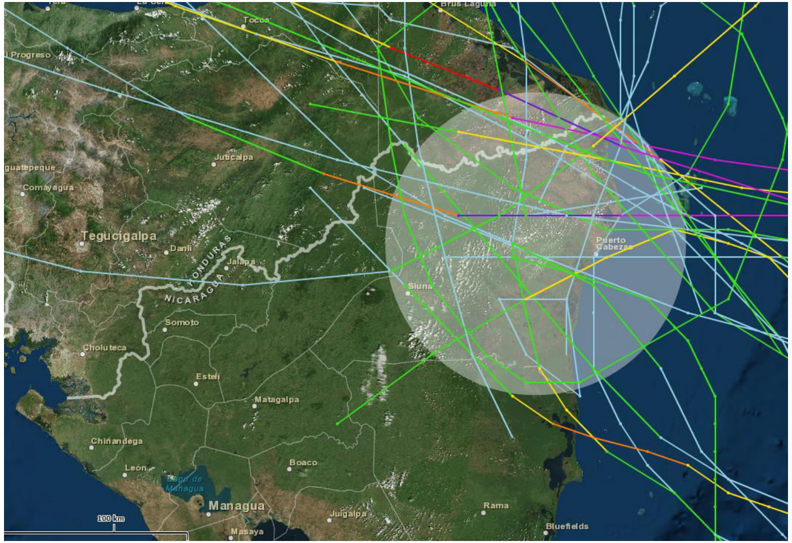


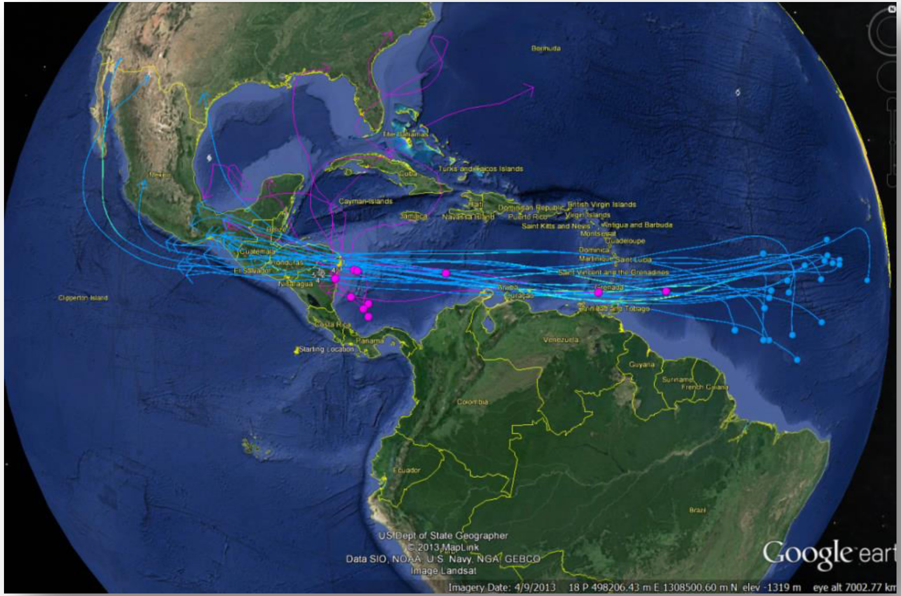
Figure 2: World Map of the Global Climate Risk Index 1992-2011

Source: Germanwatch and Munich Re NatCatSERVICE

Research question

- Based on damages from historic hurricanes and modeled synthetic hurricanes, could we successfully *propose a forest management plan* in order to *reduce the risks of impacts* from future hurricanes?



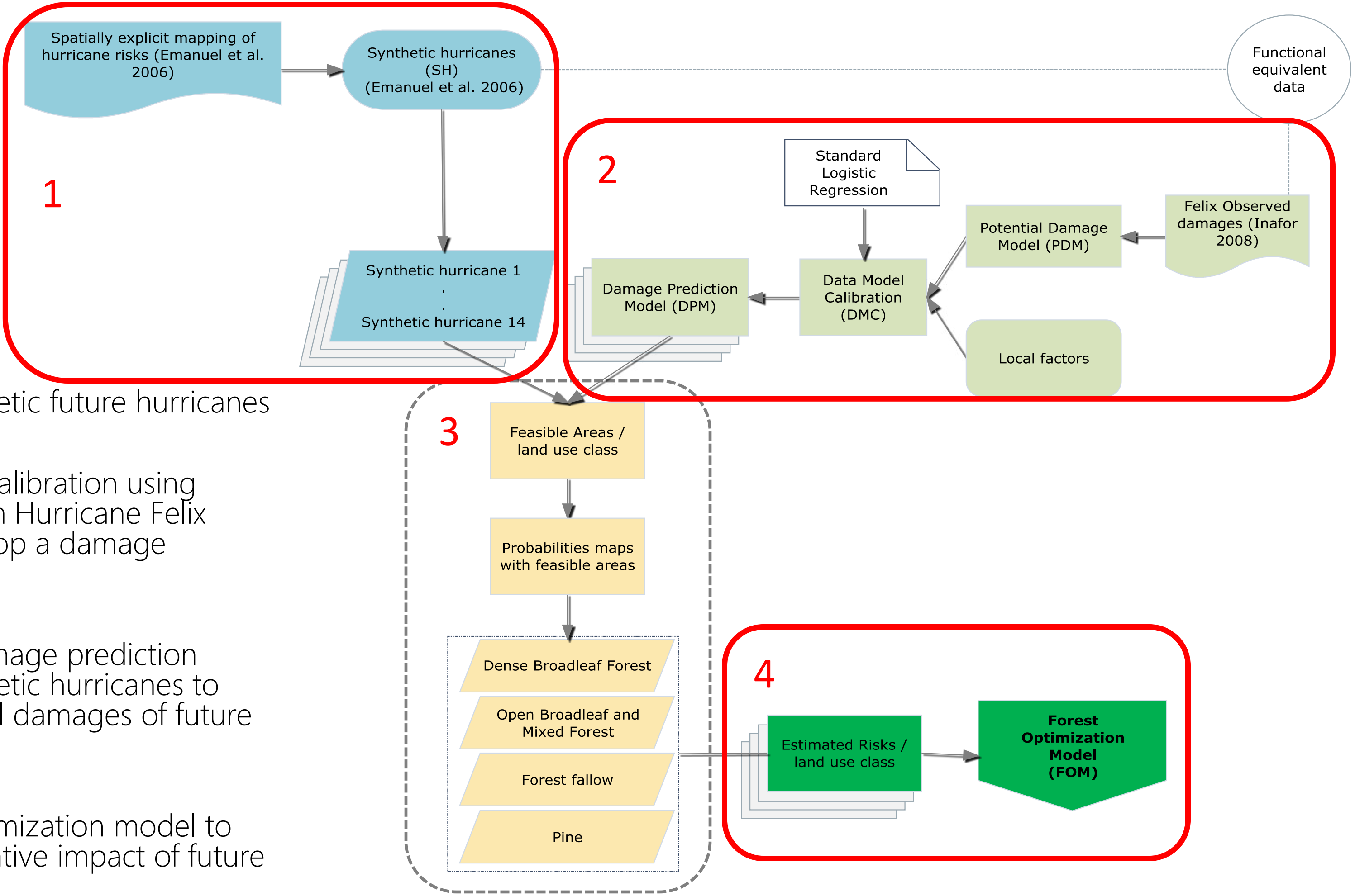


Research objective

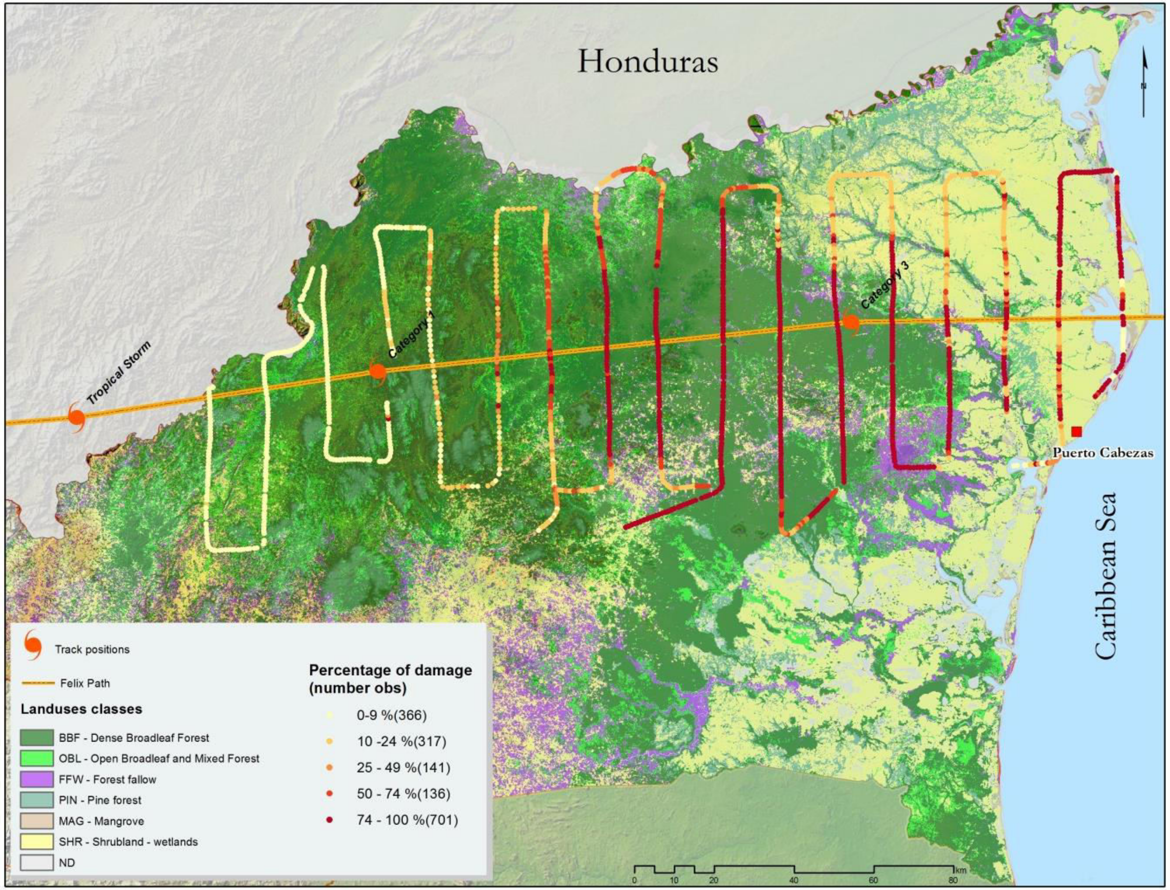
- To develop a forest optimization model that produces a land management plan that minimizes certain risks posed by hurricanes.

Outline

1. Generating synthetic future hurricanes
2. Damage model calibration using existing data from Hurricane Felix (2007) and develop a damage prediction model
3. Combine the damage prediction model with synthetic hurricanes to evaluate potential damages of future hurricanes.
4. Built a forest optimization model to mitigate the negative impact of future hurricanes



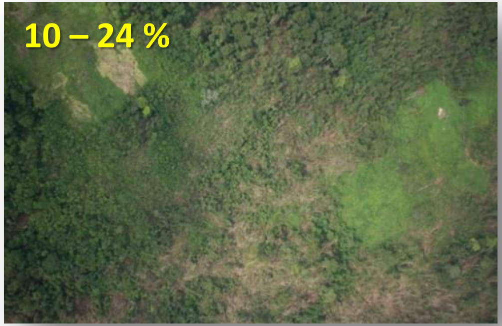
After Hurricane Felix

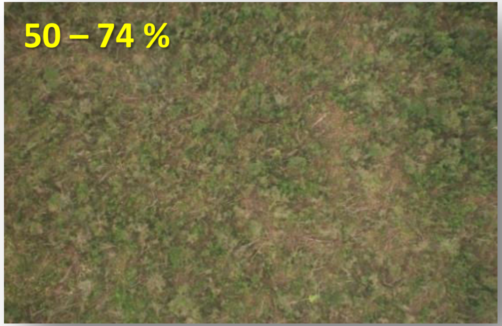


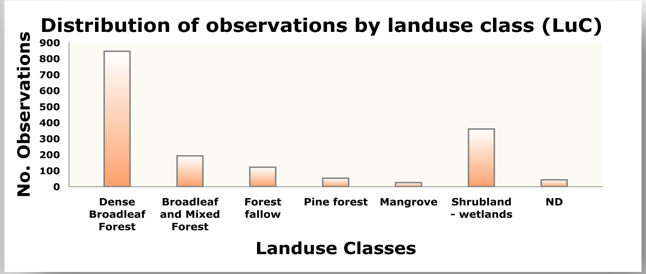
- Flight path around Felix's trajectory to evaluate forest damage: a systematic sample zigzagging along Felix's path.
- This sampling scheme did not control for land cover classes and, therefore, some classes over- or under-sampled.

After Hurricane Felix

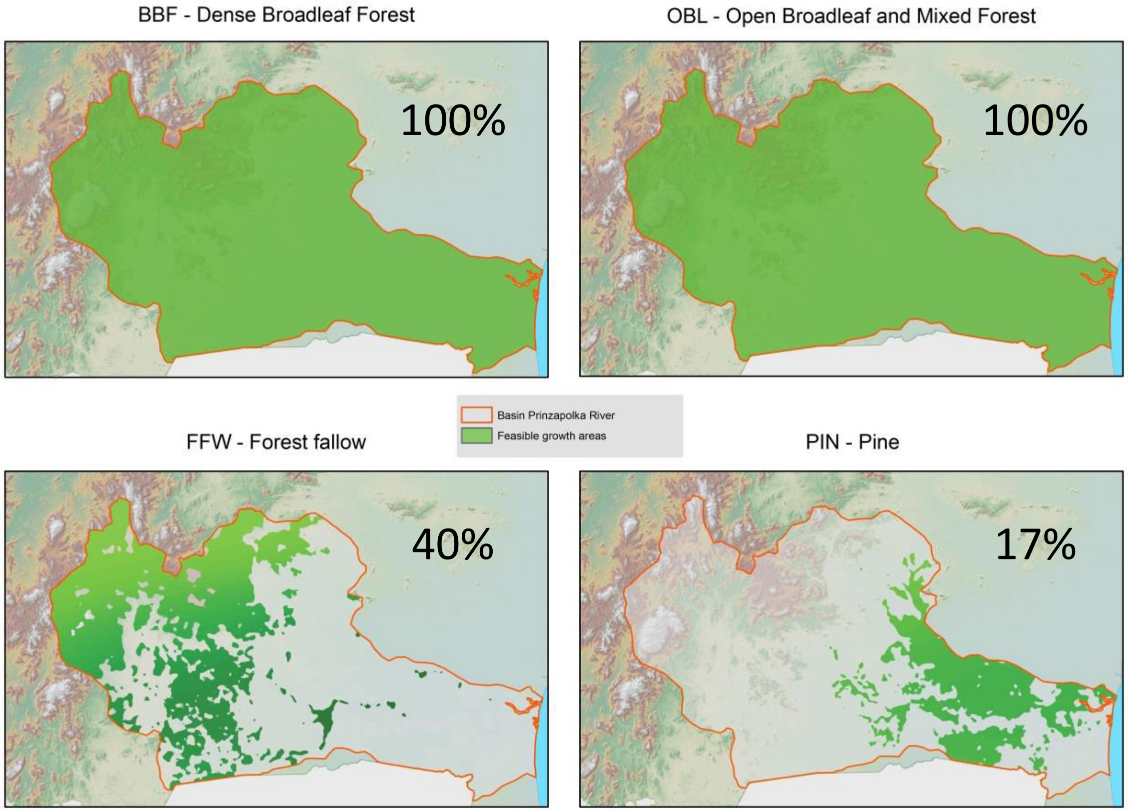
Level of damage







Feasible areas

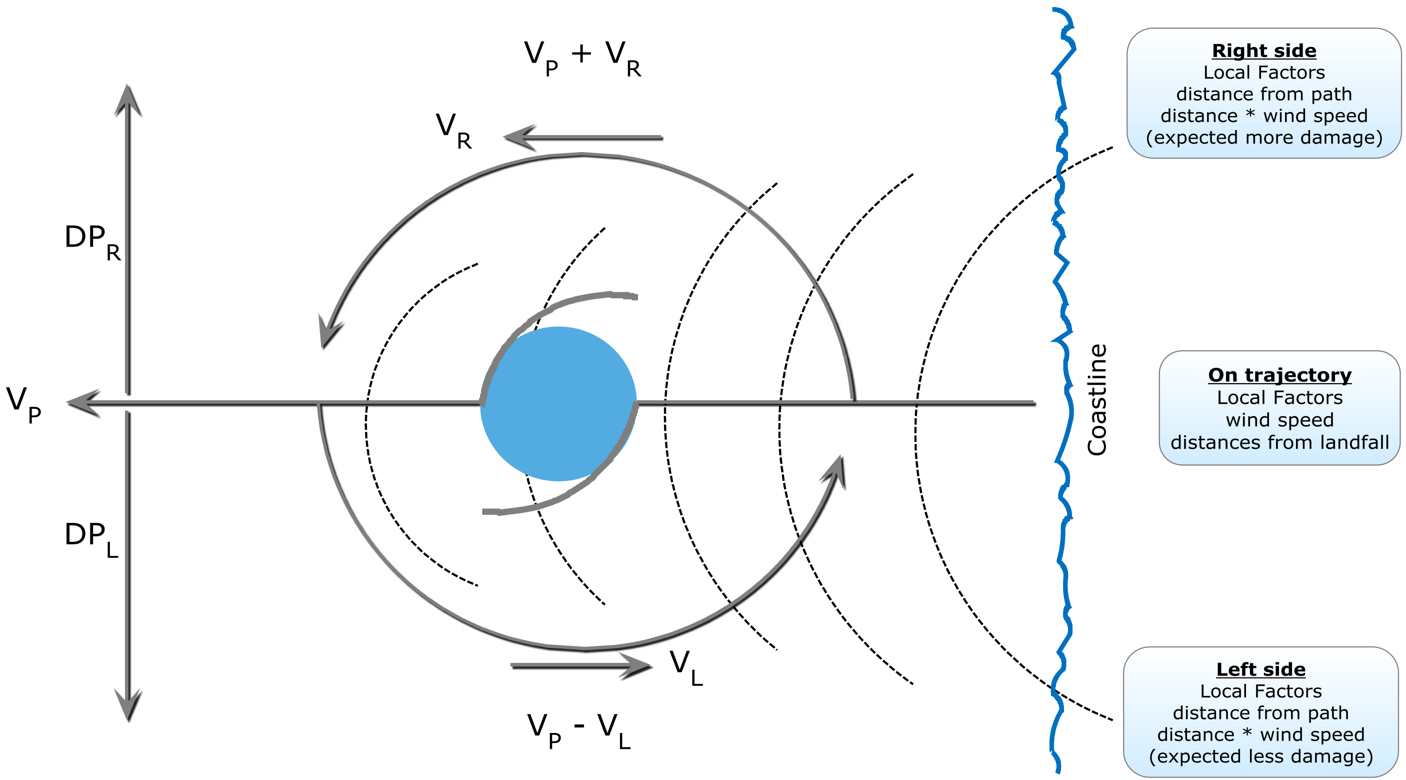


For prediction area:

Deterministic analysis to limit the *feasible growth areas* for each land cover class.

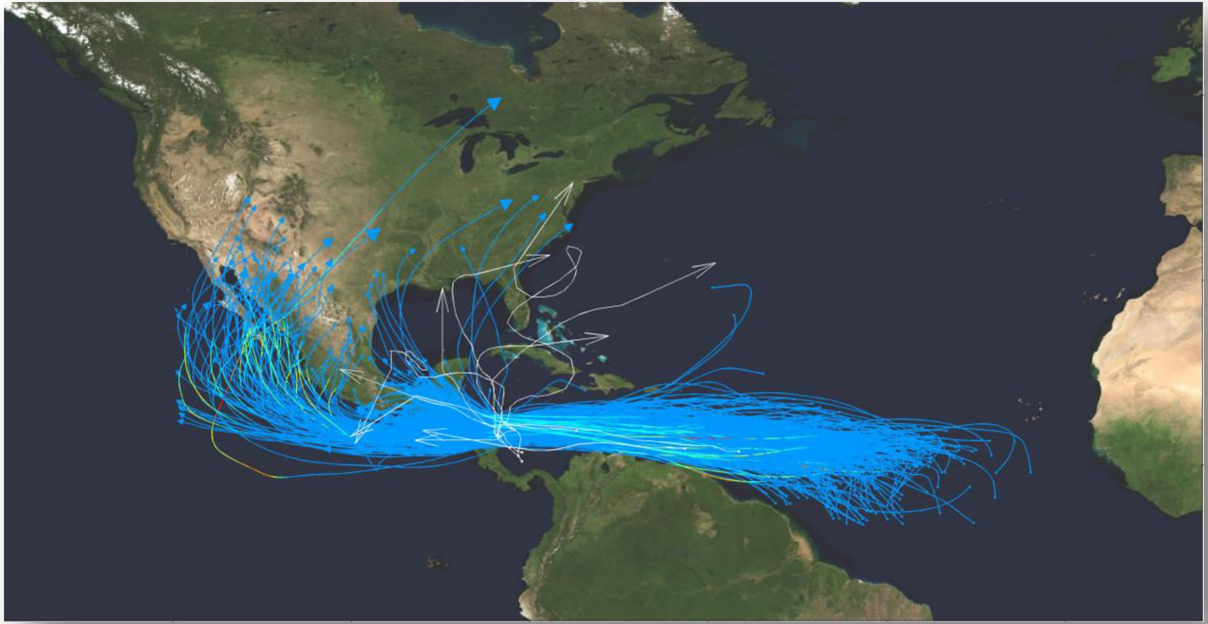
The subgroup soil map was overlayed with the terrain slope (%) to determine feasible growth areas for each land cover class

Components of Windspeed along Trajectory



Synthetic hurricanes

Statically deterministic approach to hurricane risk assessment” article published on American Meteorological Society, and developed by Emanuel (2006), who is a professor of Atmospheric Science of Massachusetts Institute of Technology (MIT)



Genesis points
Historical tracks
Surface temperature
Vertical shear of wind
6-h translation speed and direction

Damage model calibration

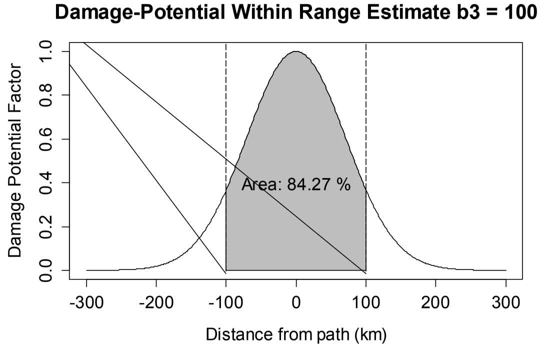
- Standard logistic regression has been used to model the level of damage within each landuse class (four main land cover classes)
- It is assume that wind speed, trajectory speed (duration) pressure, and precipitation (in), contribute to the level of damages.

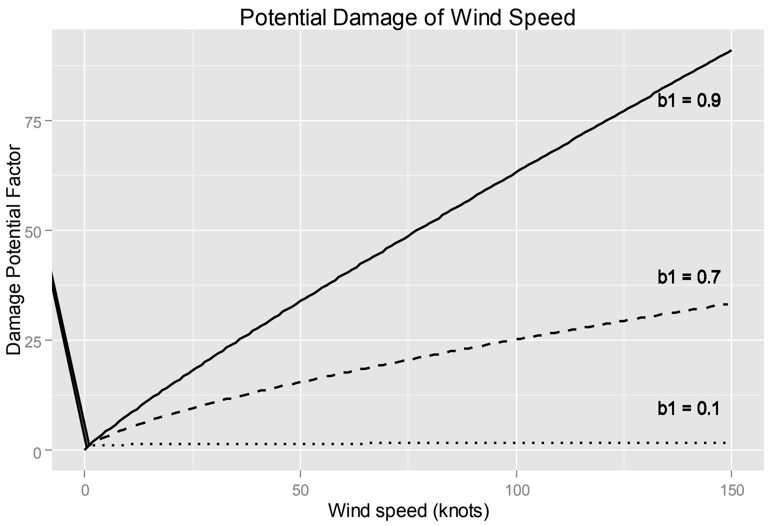
- This approach is two steps process:
  1. Estimate the *Potential Damage*: this is function solely based on the hurricane characteristics (distance from path and windspeed intensity on path)
  2. *Combine* the *Potential Damage* with *Terrain factors* (slope, aspect, etc) to predict actual damage within each land cover class.

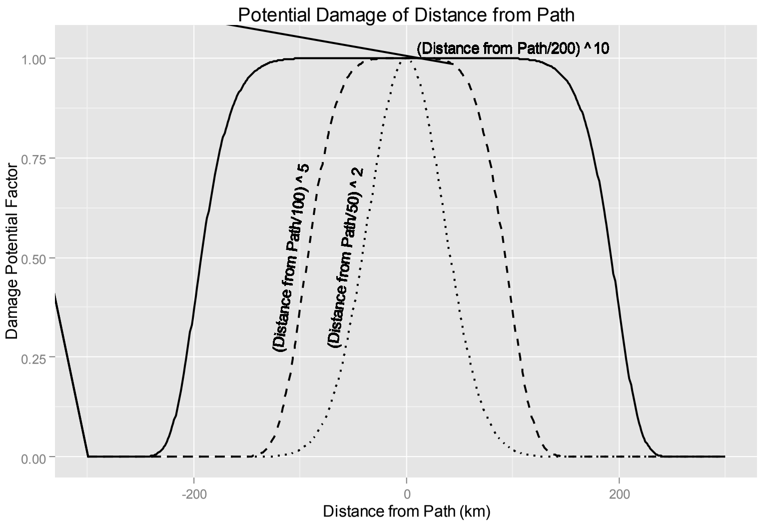
Damage model calibration

- Components of the Potential Damage:

$$Pot_{Damage} = WindSpeed^{\,b_1} \cdot \exp\left(-\left(\frac{DistPath}{b_3}\right)^{b_2}\right)$$

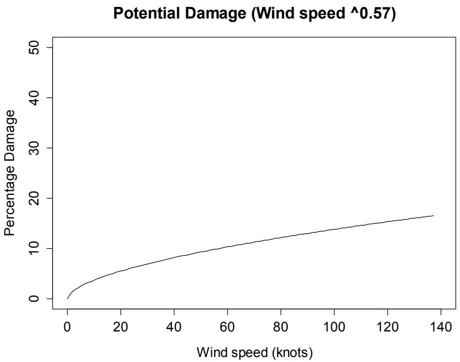


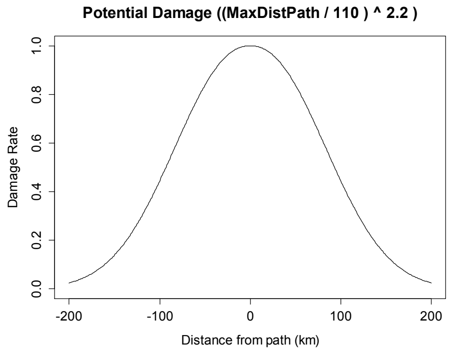


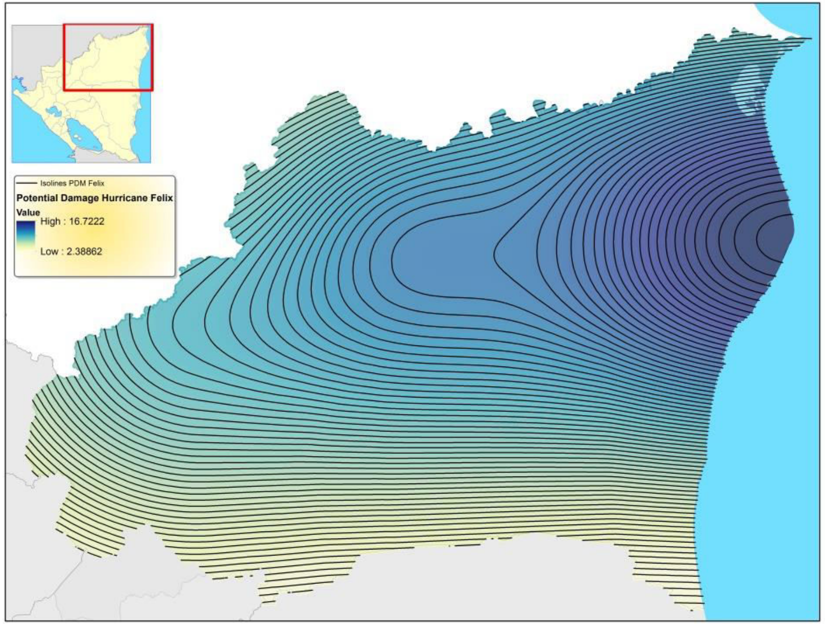


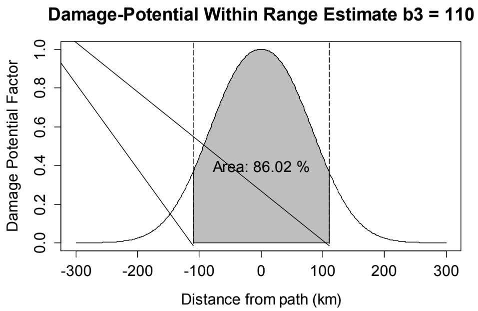
Damage model calibration – Results IV

$$Pot_{Damage} = WindSpeed^{\,0.57} \cdot \exp\left(-\left(\frac{DistPath}{110}\right)^{2.2}\right)$$

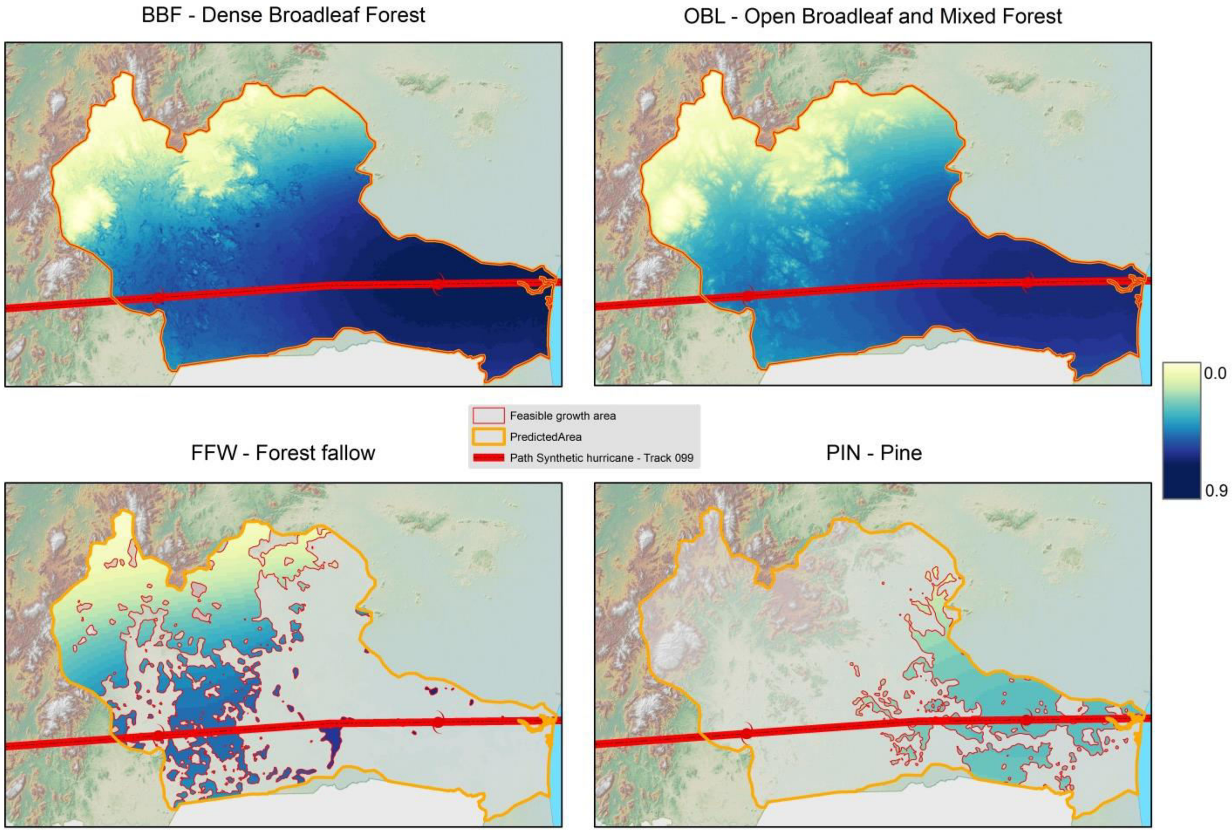








Damage Prediction Model



Implementing DMC (predicted damage probabilities, 0-1) in the predicted area (Prinzapolka river watershed) for each landuse class, using the synthetic hurricane track number 099

Forest Optimization Model

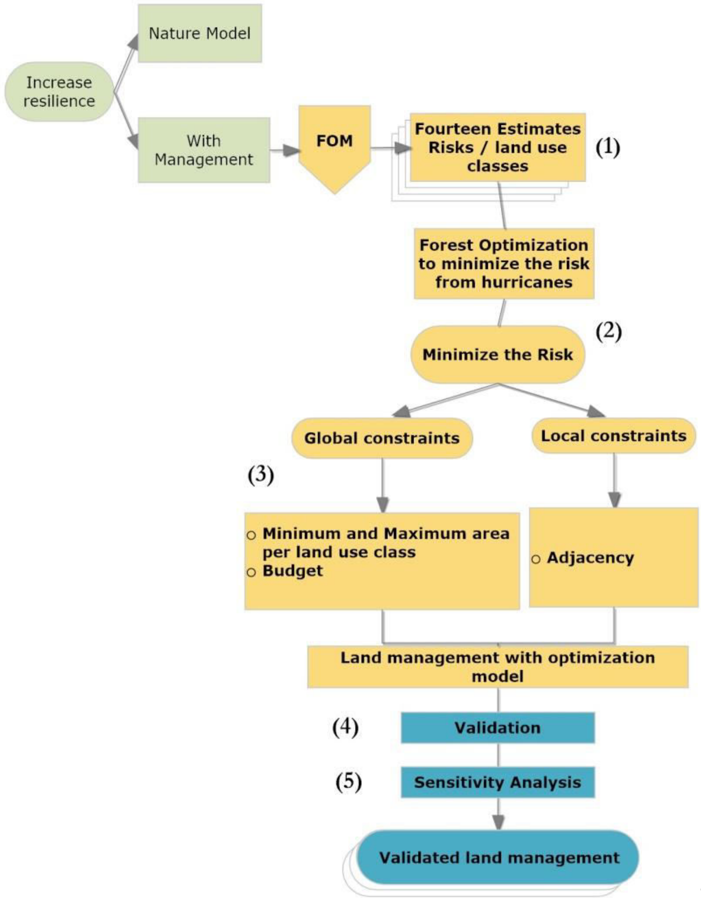
Objective function and constraints

Validation

Sensitivity analysis

Forest Optimization Model I

- A deterministic optimization method
- Spatial optimization problems in general consist of three components: an **objective function** with **constraining conditions** and **decisions** to be made.
- Constraints can be applied
  - Throughout the study area (global constraints)
  - Or on a pixel level (local constraints)



Forest Optimization Model Ⅱ

- Objective function
  - Minimize the impacts of hurricanes over the study area
  - Damage prediction model that is dependent upon landuses and synthetics hurricanes tracks and intensities

$$min \sum_{h=1}^{H} \cdot \sum_{k=1}^{L} \cdot \sum_{i=1}^{r} \cdot \sum_{j=1}^{c} D_{ijk} * R_{ijkh}$$

where:

i counter identifying the current row
j counter identifying the current column
k counter identifying the current landuse
H is the number of potential damage
D_{ijk} is the binary decision variable
$R_{ijkh'}$ represent the risk of hurricane damage

Forest Optimization Model III

- Constraints
  - Just one landuse class has to be assigned to each management unit

$$\sum_{k=1}^{L} D_{ijk} = 1 \qquad \forall_k$$

  - Adjacency constraint

$$D_{ijk} \leq D_{i+1,j,k} + D_{i-1,j,k} + D_{i,j+1,k} + D_{i,j-1,k} \qquad \forall_{ijk}$$

  - Minimum and maximum area constraints

$$\sum_{i=1}^{r} \cdot \sum_{j=1}^{c} D_{ijk} \geq min_{ij} \qquad \forall_k$$

$$\sum_{i=1}^{r} \cdot \sum_{j=1}^{c} D_{ijk} \leq max_{ij} \qquad \forall_k$$

  - Budget

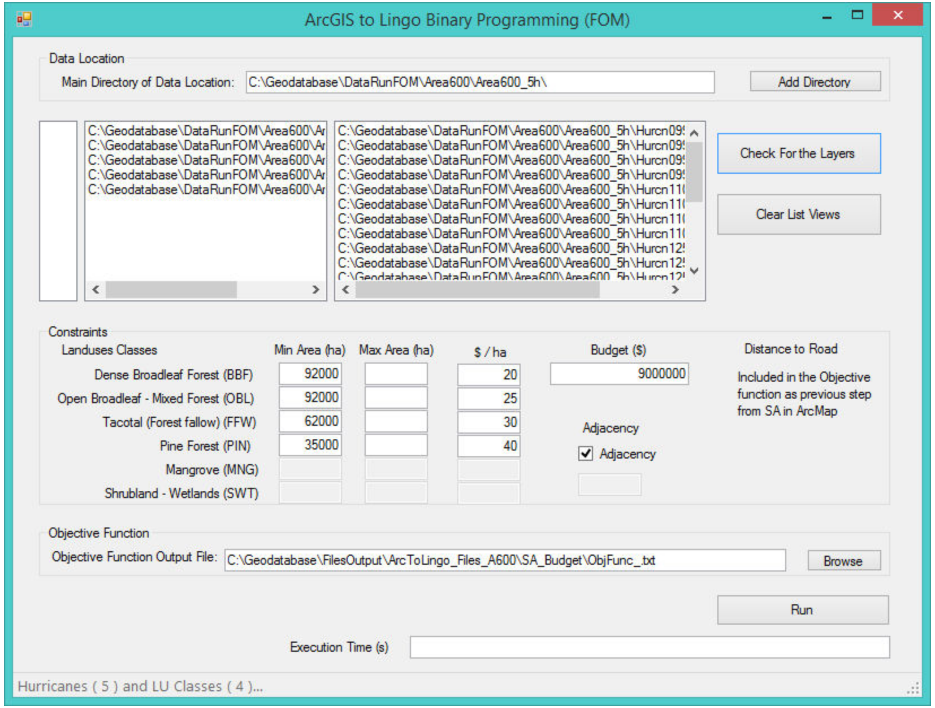
$$\sum_{k=1}^{L} C_{ijk} - M \leq 0 \qquad \forall_{ijk}$$

  - Decision variable

$$D_{ij} \in \{0,1\} \qquad \forall_{i,j}$$

Forest Optimization Model IV

Data Export Function in VB.NET: **ArcToLingo_FOM**



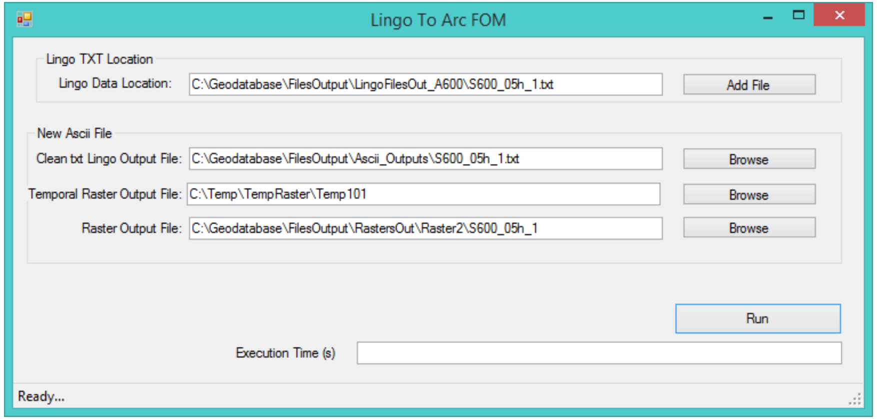

```
! This is the Objective Function of the FOM
MIN =
Hurricane 1
LU1_1_1 * 0.5 + LU2_1_1 * 0.3 + LU3_1_1 * 0.4 + LU4_1_1
LU1_1_2 * 0.4 + LU2_1_2 * 0.5 + LU3_1_2 * 0.3 + LU4_1_2
LU1_2_1 * 0.4 + LU2_2_1 * 0.3 + LU4_2_1 * 0.8 +
LU1_2_2 * 0.1 + LU2_2_2 * 0.2 + LU3_2_2 * 0.8 +

Hurricane 2
LU1_1_1 * 0.8 + LU2_1_1 * 0.4 + LU3_1_1 * 0.8 + LU4_1_1 * 0.1
LU1_1_2 * 0.8 + LU2_1_2 * 0.6 + LU3_1_2 * 0.3 + LU4_1_2 * 0.6 +
LU1_2_1 * 0.3 + LU2_2_1 * 0.8 + LU4_2_1 * 0.6 +
LU1_2_2 * 0.4 + LU2_2_2 * 0.8 + LU3_2_2 * 0.8 +

! Binary constraint: Just one landuse class has to be assigned to each pixel
LU1_1_1 + LU2_1_1 + LU3_1_1 + LU4_1_1 = 1;
LU1_1_2 + LU2_1_2 + LU3_1_2 + LU4_1_2 = 1;
LU1_2_1 + LU2_2_1 + LU4_2_1 = 1;
LU1_2_2 + LU2_2_2 + LU3_2_2 = 1;

! The ADJACENCY constraint to limit the number of Neighbors pixels
LU1_1_1 <= LU1_2_1 + LU1_1_2;
LU1_1_2 <= LU1_2_2 + LU1_1_1 + LU1_1_3;
LU1_2_1 <= LU1_1_1 + LU1_3_1 + LU1_2_2;

!The @BIN function restricts a variable to being binary (i.e., 0 or 1)
@BIN(LU1_1_1);
@BIN(LU2_1_1);
@BIN(LU3_1_1);
@BIN(LU4_1_1);
```

Forest Optimization Model V

Results Importation Function in VB.NET: **LingoToArc_FOM**

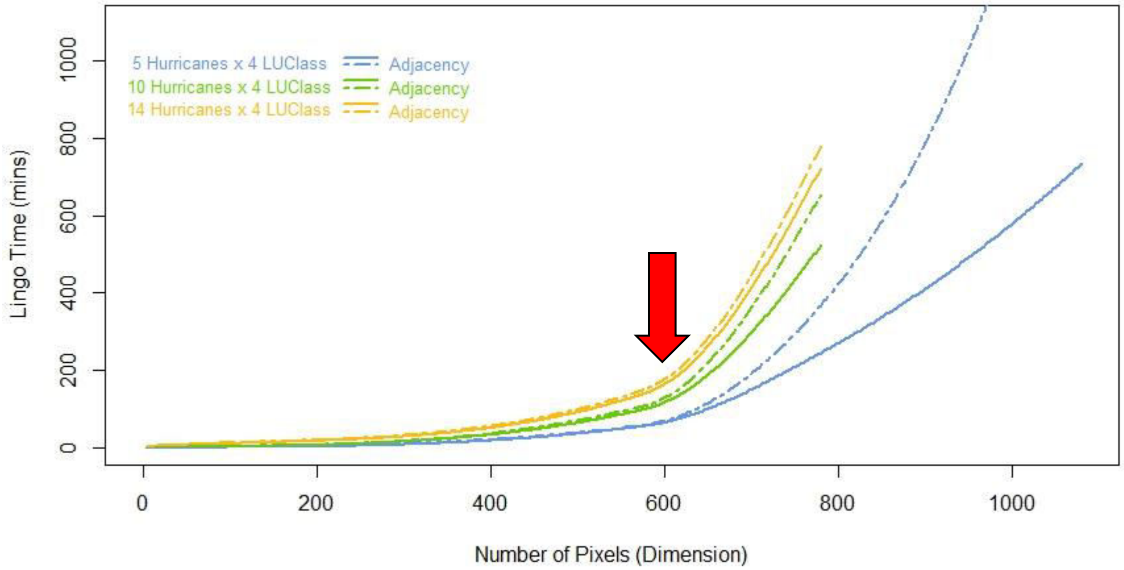
```
Global optimal solution found.
Objective value:                              5.200000
Elapsed runtime seconds:                          0.05
Model Class:                                      PILP

Total variables:                    48
Total constraints:                  10
Nonlinear constraints:               0
                              Variable           Value        Reduced Cost
                               LU1_1_1        0.000000            1.400000
                               LU2_1_1        0.000000           0.7000000
                               LU3_1_1        0.000000            1.200000
                               LU4_1_1        0.000000           0.7000000
                               LU5_1_1        1.000000           0.5000000
                               LU1_1_2        0.000000            1.300000
                               LU2_1_2        0.000000            1.200000
                               LU3_1_2        1.000000           0.6000000
                               LU4_1_2        0.000000            1.100000
                               LU6_1_2        0.000000            1.000000
                               LU1_1_3        0.000000            1.500000
                               LU3_1_3        1.000000           0.7000000
                               LU4_1_3        0.000000            1.000000
```

FFW to 1-2



Forest Optimization Model – Results

- System Performance



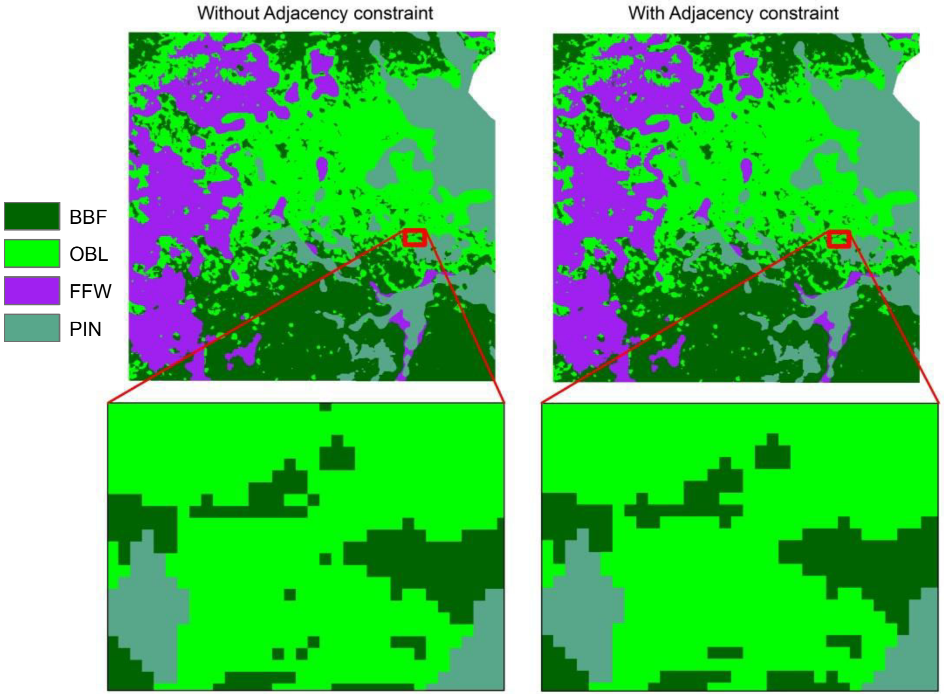
- The dimensionality of the problem increases proportionally to the number of hurricanes being evaluated

- Decision variables are binary, the result is a **perfect branch and bound scenario** where every single decision has two branches. These two branches are not only symmetric but also linear.

- Inflection point: limit of computer memory.

Forest Optimization Model – Results

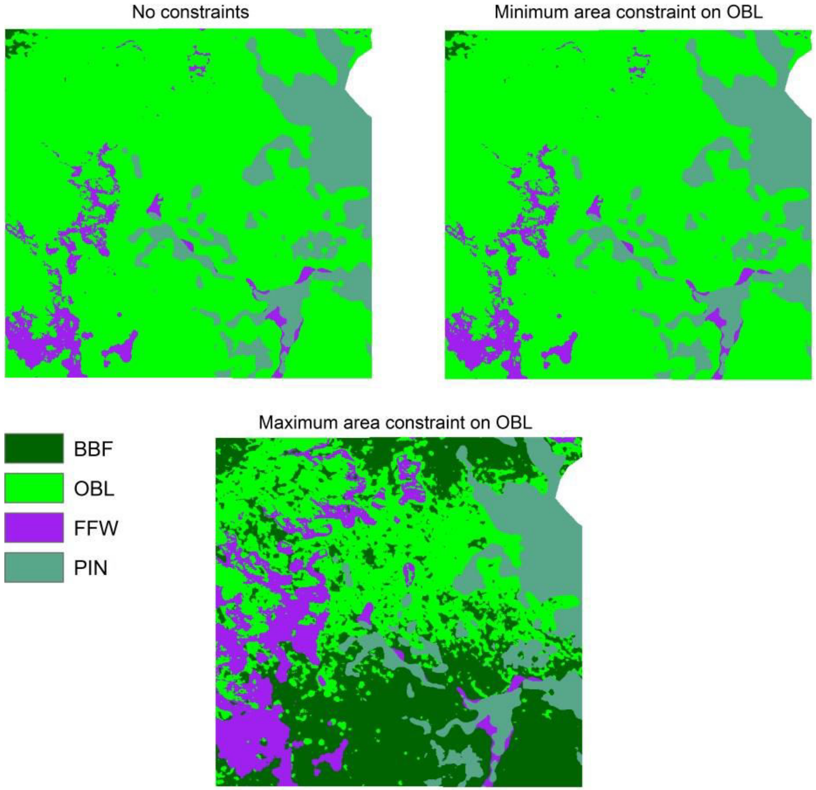
- Validation: Adjacency



- Implementation of Adjacency Constraints is standard practice in the management of public and private forests
- Including adjacency constraints will remove the "*salt–and–pepper*" effect and will make the value of objective function less optimal.

Forest Optimization Model – Results

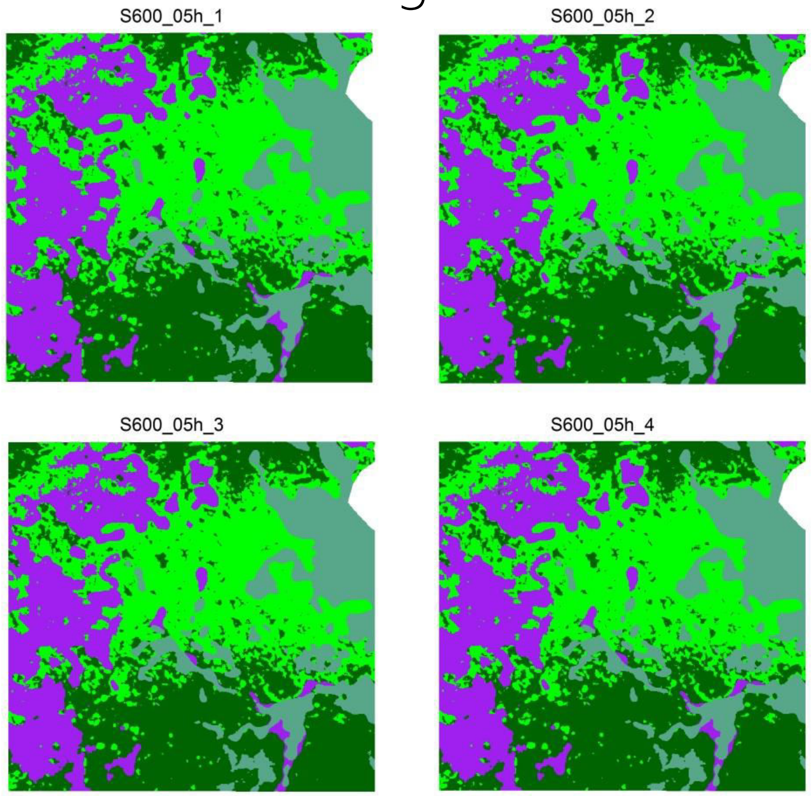
- Validation: Minimum and Maximum constraints



- Defines a specific number of hectares that must be assigned to each land use.
- Three models:
  1. No constraints
  2. Minimum area constraints
  3. Maximum area constraint

Forest Optimization Model – Results

- Validation: Budget 1

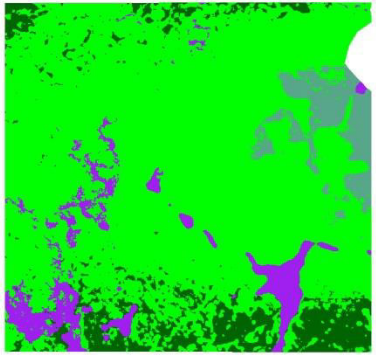


FOM implementing invariable minimum and maximum area and cost per hectare for each land use class					
Model Name	Min/Max Area	Cost / ha ($)	Percentage results (%)	Budget ($ MM)	Objective function value (e+9)
S600_05h_1	Min BBF: 92 Min OBL: 92 Min FFW: 62 Min PIN: 35	BBF 20 OBL 25 FFW 30 PIN 40	BBF 30.93 OBL 32.11 FFW 20.84 PIN 16.13	10	1.206027
S600_05h_2	Min BBF: 92 Min OBL: 92 Min FFW: 62 Min PIN: 35	BBF 20 OBL 25 FFW 30 PIN 40	BBF 30.93 OBL 32.11 FFW 20.84 PIN 16.13	9	1.206027
S600_05h_3	Min BBF: 92 Min OBL: 92 Min FFW: 62 Min PIN: 35	BBF 20 OBL 25 FFW 30 PIN 40	BBF 30.93 OBL 32.11 FFW 20.84 PIN 16.13	8.5	1.206027
S600_05h_4	Min BBF: 92 Min OBL: 92 Min FFW: 62 Min PIN: 35	BBF 20 OBL 25 FFW 30 PIN 40	BBF 31.36 OBL 31.68 FFW 20.84 PIN 16.12	8	1.206346
S600_05h_5	Min BBF: 92 Min OBL: 92 Min FFW: 62 Min PIN: 35	BBF 20 OBL 25 FFW 30 PIN 40		7	Infeasible

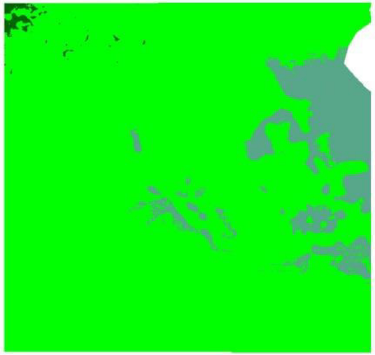
Forest Optimization Model – Results

- Validation: Budget 2

S600_05h_6



S600_05h_7



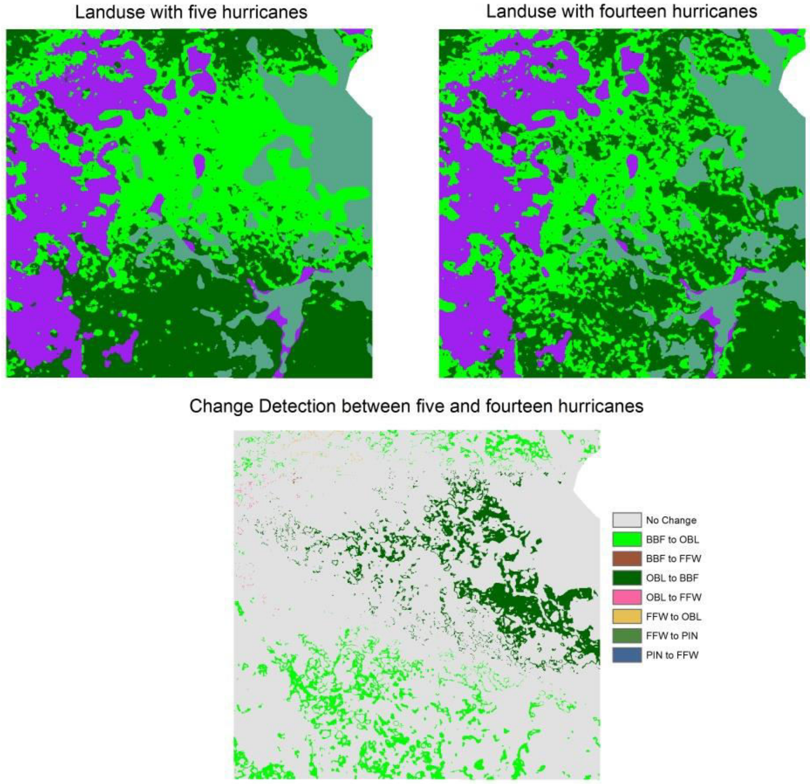
S600_05h_8

S600_05h_9

FOM implementing invariable minimum and maximum area and cost per hectare for each land use class					
Model Name	Min/Max Area	Cost / ha ($)	Percentage results (%)	Budget ($ MM)	Objective function value (e+9)
S600_05h_6	Min BBF: 30 Min OBL: 30 Min FFW: 20 Min PIN: 10	BBF 1 OBL 5 FFW 100 PIN 120	BBF 10.1 OBL 78.12 FFW 6.72 PIN 5.06	5	1.249815
S600_05h_7	No minimum /maximum	BBF 1 OBL 5 FFW 100 PIN 120	BBF 0.50 OBL 89.21 FFW 0 PIN 10.28	5	1.21313
S600_05h_8	No minimum /maximum	BBF 20 OBL 25 FFW 30 PIN 40	BBF 78.89 OBL 7.27 FFW 0.00 PIN 15.84	7	1.239120
S600_05h_9	No minimum /maximum	BBF 1 OBL 5 FFW 100 PIN 120	BBF 0.29 OBL 77.7 FFW 5.88 PIN 16.12	10	1.17546

Forest Optimization Model – Results

- Pooling Synthetic Hurricanes together: Storm frequency and intensity



- Single hurricane, its output would reflect the spatial patterns seen in that hurricane's predicted potential damage map
- Increasing the number of hurricanes, the output would exhibit an increasingly diversified spatial structure.
- Five hurricanes: relatively simple pattern of land uses OBL in the central region and bands of the other three land uses to the north, south, east and west of this central region.
- Fourteen hurricanes the pattern is much less pronounced; the BBF landuse has encroached on many of the areas formally assigned to OBL

Forest Optimization Model – Results IX

- Sensitivity analysis:

Constraints	S600_05h_SA1		S600_05h_SA2		S600_05h_SA3	
Budget ($)	9MM	10MM	9MM	10MM	9MM	10MM
Cost per landuse	BBF 20 OBL 25 FFW 30 PIN 40	BBF 20 OBL 25 FFW 30 PIN 40	BBF 20 OBL 50 FFW 60 PIN 80	BBF 20 OBL 50 FFW 60 PIN 80	BBF 20 OBL 35 FFW 45 PIN 60	BBF 20 OBL 35 FFW 45 PIN 60
Min area (thousand/ha)	BBF 92 OBL 92 FFW 62 PIN 35	BBF 92 OBL 92 FFW 62 PIN 35	BBF 92 OBL 92 FFW 62 PIN 35	BBF 92 OBL 92 FFW 62 PIN 35	BBF 92 OBL 92 FFW 62 PIN 35	BBF 92 OBL 92 FFW 62 PIN 35
Solution	Feasible Solution	Feasible Solution	Infeasible Solution	Infeasible Solution	Infeasible Solution	Infeasible Solution
Objective Value (e+9)	1.206027	1.206027	--	--	--	--
Min area (thousand/ha)	BBF 30 OBL 30 FFW 20 PIN 10	BBF 30 OBL 30 FFW 20 PIN 10	BBF 30 OBL 30 FFW 20 PIN 10	BBF 30 OBL 30 FFW 20 PIN 10	BBF 30 OBL 30 FFW 20 PIN 10	BBF 30 OBL 30 FFW 20 PIN 10
Solution	Feasible Solution	Feasible Solution	Feasible Solution	Feasible Solution	Feasible Solution	Feasible Solution
Objective Value (e+9)	1.18022	1.18022	1.285537	1.24553	1.220881	1.200808

Forest Optimization Model – Results XI

- Sensitivity analysis suggests that feasible solutions are strongly regulated by the interaction of four factors:
  1. the feasible area assigned to each landuse,
  2. the minimum and maximum area constraints for each landuse,
  3. landuse implementation costs, and
  4. the available budget.
- Adjusting these factors largely determines the feasibility of the model's results

Conclusions

1. A simple but efficient approach has been developed to model the potential damage of hurricanes in different tropical land cover classes.

   Residual analysis helped uncover initial data problems

Forest Optimization Model.

2. The FOM is flexible. The use of feasible areas allows the model to take into account the environmental and geographic realities in the study region.

3. The inclusion of adjacency constraint in the FOM has the greatest impact on execution time of any of the components of the model. This factor is exponentially related to time required to solve the optimization model

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To strengthen the capacity of registered Masters and PhD students in universities in Latin America

IDRC CRDI

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Thank you!