# Measuring the consequences of wildfires in a Bayesian Network with vulnerability and exposure indicators

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## Aim of the Study

Development of a wildfire consequences assessment system at the meso scale, i.e. at a 1 km ² spatial resolution. The system is based on a Bayesian Network model, which facilitates the explicit modeling of the relevant parameters, their causal relationships and the associated uncertainties. Vulnerability and exposure indicators and their interrelations are included as random variables in the model.

## Methods

Wildfire risk can be estimated as a function of occurrence probability and consequences. Wildfire consequences are a function of vulnerability and exposure of the affected biotic and abiotic systems (e.g. human lives and properties, infrastructure, soil and air quality).

**Vulnerability** describes the degree of expected damage as a function of hazard intensity (Thywissen 2006).

**Exposure** refers to the items at risk, such as people and property.

Risk $R$ can be formulated as a function of the hazard $H$, the resulting damages $D$ and the consequences $C$ as,

$$R = \mathrm{E}_{H,D}[C] = \int_H \Pr(H) \int_D \Pr(D|H) C(D,H) dD\, dH$$

$\mathrm{E}_{H,D}$ denotes the expected value with respect to $H$ and $D$.

$\Pr(D|H)$ is the probability of damage $D$ conditional on the hazard $H$ and $C(D, H)$ is the cost as a function of damage and hazard.

In the above equation, the inner integral,

$$\mathrm{E}_D[C \mid H] = \int_D \Pr(D|H)\, C(D,H) dD$$

describes the expected consequences $C$ for given hazard $H$.

**Bayesian Networks** (BN) are directed acyclic graphs and consist of nodes, arcs and probability tables attached to the nodes (Jensen, Nielsen 2007). In a discrete BN considered here, each node represents a discrete random variable, i.e. its sample space consists of a finite set of mutually exclusive states. The arcs describe the assumed dependence structure among the random variables.

A conditional probability table (CPT) is attached to each of the nodes, giving the probability of the variable to be in one of its states conditional on the states of its parents. If we consider a BN with discrete random variables $\mathbf{X} = [\boldsymbol{X_1}, \dots, \boldsymbol{X_n}]$ then the full (joint) probability model of these variables is the joint Probability Mass Function (PMF), $\boldsymbol{p}(\mathbf{x}) = \boldsymbol{p}(\boldsymbol{x_1}, \dots, \boldsymbol{x_n})$ which can be specified with the help of the chain rule:

$$p(\mathbf{x}) = p(x_n|x_{n-1}, \dots, x_1) p(x_{n-1}|x_{n-2}, \dots, x_1) \dots p(x_2|x_1) p(x_1)$$

By making use of the independence assumptions encoded in the graphical structure of the BN, this chain rule reduces to:

$$p(\mathbf{x}) = \prod_{i=1}^{n} p(x_i|pa(x_i))$$

wherein $pa(x_i)$, are realizations of the parents of $X_i$. In other words, the joint probability mass function (PMF) of all random variables in the BN is the product of the conditional PMFs of each individual random variable given its parents.

When one or several variables are observed or fixed, this information (evidence $\mathbf{e}$) is propagated through the network and the joint prior probability of all nodes is updated to its posterior. The posterior joint probability of a set of variables $\mathbf{y}$ in the network given the evidence is:

$$p(\mathbf{y}|\mathbf{e}) = \frac{p(\mathbf{y}, \mathbf{e})}{p(\mathbf{e})}$$

The constructed **Bayesian Network** model for estimation of wildfire building damage cost is shown in Figure 1. The BN includes variables that correspond to hazard, exposure, vulnerability and costs. Connecting arcs show the causal relationships among the variables.

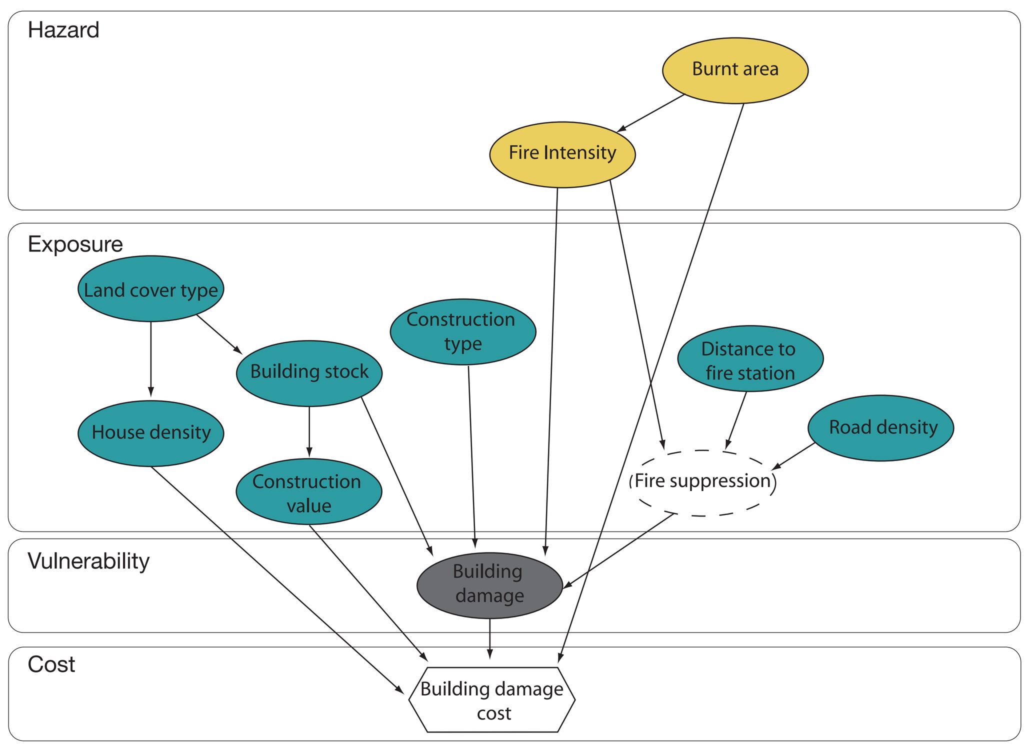


Figure 1. BN for building damage cost caused by wildfire. The frames indicate hazard, exposure, vulnerability and cost variables. Connecting arcs show the causal relationships among the variables.

## Case Study

Data from Cyprus are used to learn the CPTs of the hazard and exposure variables of the model. Additionally, expert knowledge is incorporated for CPTs of hazard and vulnerability variables. Cyprus is chosen to serve as study area, due to the Mediterranean climate conditions that favor fire occurrences (Figure 2). Spatial data with 1 km² resolution are stored and managed in a Geodatabase (Figure 3).

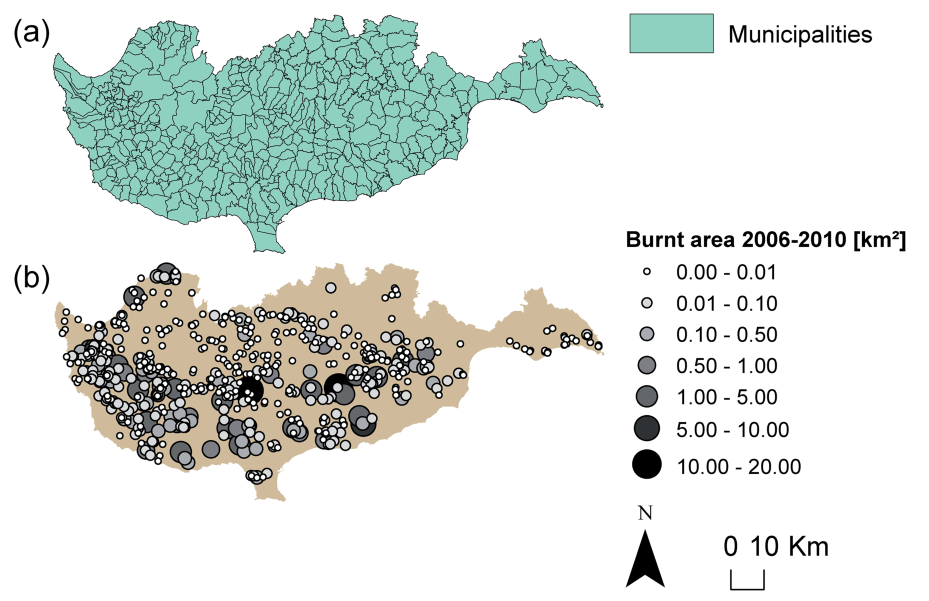


Figure 2. (a) Municipality administrative borders of case study. (b) Historical fire events (2006-2010) classified in terms of their resulting burnt area (Data source: Ministry of Agriculture, Cyprus)

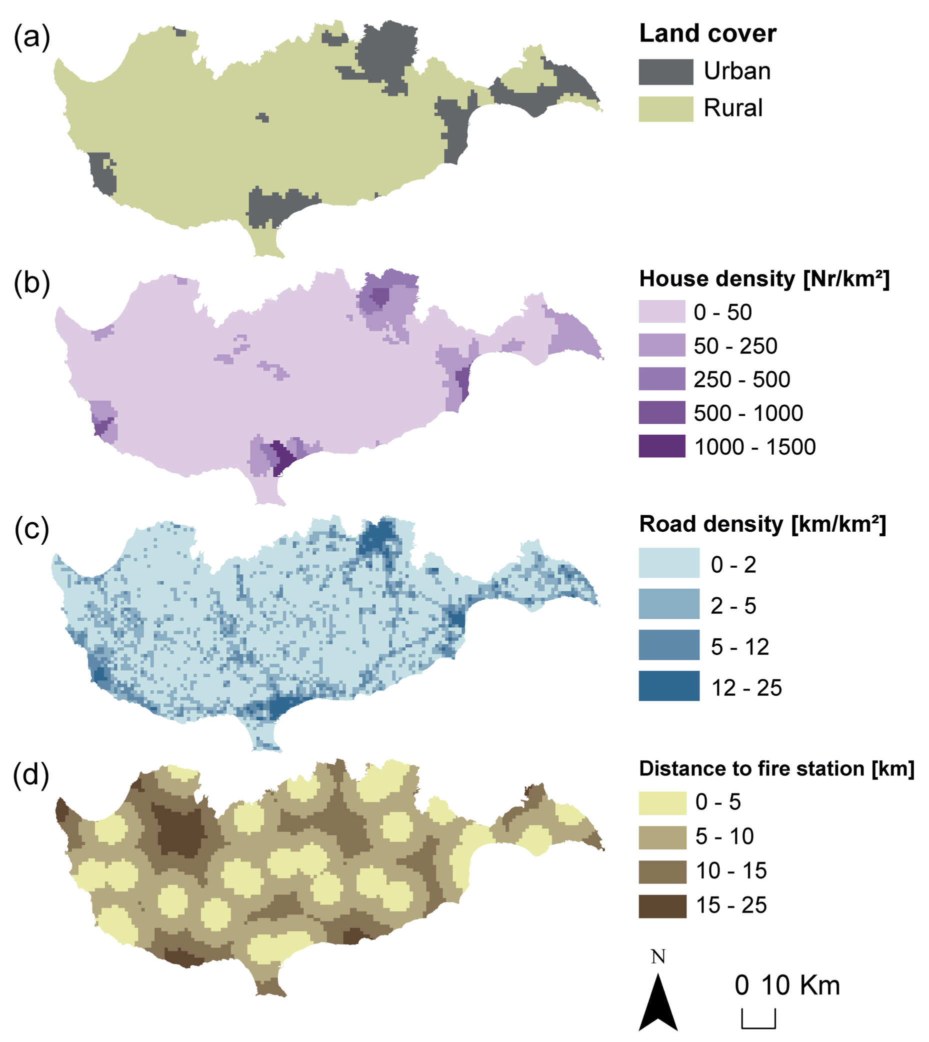


Figure 3. (a) Land cover type (Source: Cyprus Statistical Service), (b) House (Dwelling) density (Nr Dwellings/km²) (Source: Cyprus Statistical Service), (c) Street density (km/km²) (Source: OpenStreetMap), (d) Distance to fire station (Source: Cyprus Fire Service)

Table 1. BN variables, states and data sources

| Node | #states | States | Source of probability distribution* |
|---|---|---|---|
| Fire intensity [kW/m] | 4 | 0-346<br>346-1730<br>1730-4000<br>>4000 | Classification based on literature |
| Burnt area [km²] | 7 | 0-0.01<br>0.01-0.1<br>0.1-0.5<br>0.5-1<br>1-5<br>5-10<br>10-20 | Historical fire events (2006-2010)<br><br>Data source: Department of Forest, Ministry of Agriculture Cyprus |
| Road density [km/km²] | 3 | 0-2<br>2-5<br>5-15 | Edited from road map<br><br>Data source: Open Street Map |
| Distance to next fire station [km] | 3 | 0-5<br>5-10<br>10-30 | Edited from fire station locations<br><br>Data source: Cyprus Fire Service |
| Fire suppression | 3 | poor<br>medium<br>Effective | Conditional on fire intensity based on literature |
| Land cover | 2 | Urban/Rural | Edited from Corine Land Cover map (version 13)<br>Data source: European Environmental Agency |
| Building Stock | 2 | 40s_25r_35a<br>70s_20r_10a | s: single houses<br>r: row houses<br>a: apartments<br>(% percentage)<br><br>Edited from data from Cyprus Statistical Service 2010 |
| Construction Type | 2 | 5t_15s_80i<br>10t_25s_65i | t: traditional houses, stone/mud wall<br>s: single brick wall/flat roof houses<br>i: insulated brick/inclined roof<br><br>(% percentage)<br>Edited from Statistical Service Cyprus 2012 and literature |
| Dwelling density [Nr.dwelings/km²] | 5 | 0-50<br>50-250<br>250-500<br>500-1000<br>>10000 | Based on Nr.Houses statistics and minicipality borders<br><br>Data source:<br>Statistical Service Cyprus |
| Building damage | 2 | minor<br>major | minor: 20%<br>major: 80%<br>Based on fire severity evaluation of different fire intensities<br>assumed minor for fire intensities<346 kW/m<br>Conditional on construction type and building stock (defensible space)<br>based on scorings systems from literature |
| Construction value [x 10³ €] | 4 | 0-100<br>100-200<br>200-500<br>500-1500 | Customized to Building Stock based on mean value and range for each building type<br><br>Data from: Cyprus Statistical Service 2010 |

* Literature references used for CPTs listed in Papakosta & Straub 2013

** In this example Building damage refers to House (Dwelling) damage

## Results

Figure 4 shows the computed expected building damage cost conditional on fire occurrrence in 1 km², for given evidence on burnt area (Figure 4a) and dwelling density (Figure 4b). As expected, the cost increases with increasing burnt area. For burnt area 10-20 km² the cost reaches 2.28 ·10⁸ €.

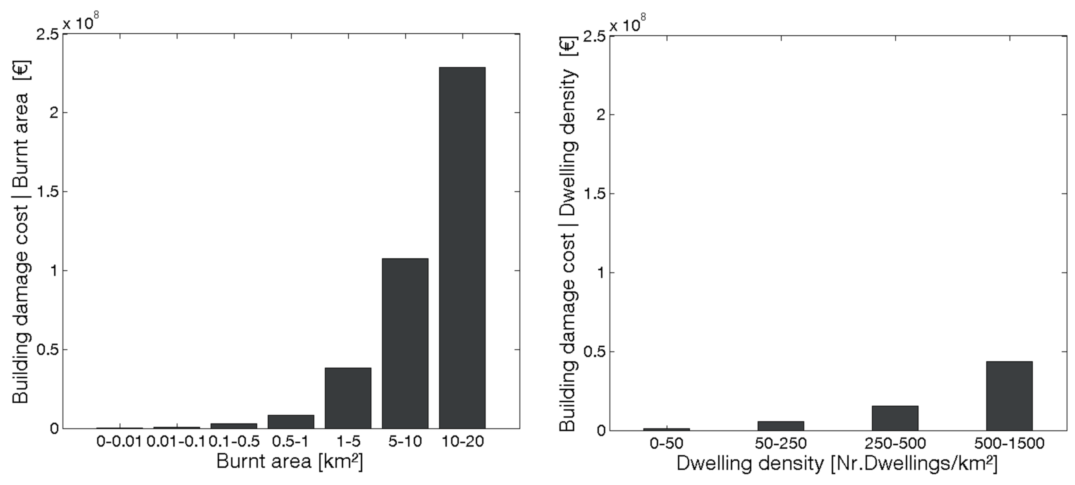


Figure 4. Building damage cost [€] calculated for different states of (a) burnt area, (b) dwelling density on Cyprus

Figure 5 illustrates the calculated expected building damage cost for given conditions of a wildfire hazard event (burnt area and fire intensity), with 1 km² resolution on the study area.

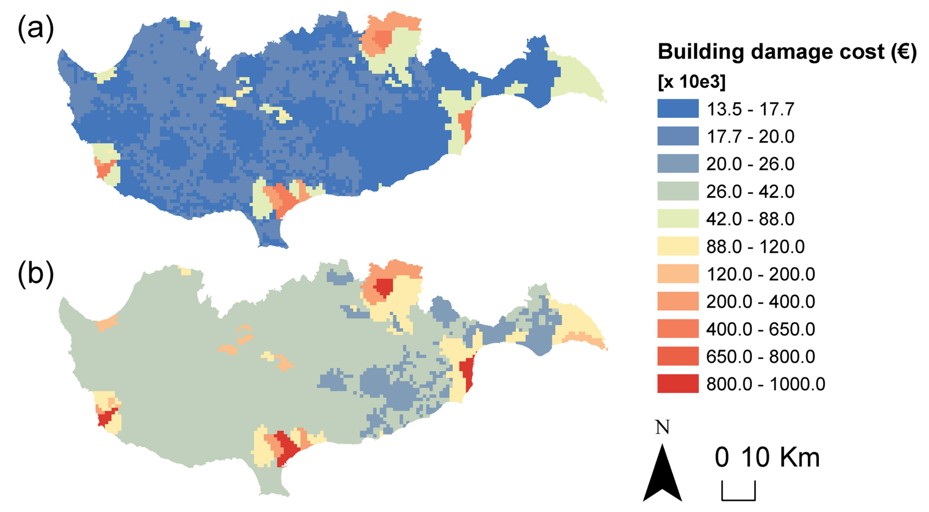


Figure 5. Building damage cost [€] for (a) burnt area being in the stated 0-0.01 km² and (a) fire intensity 0-346 kW/m, (b) fire intensity 346-1730 kW/m

## References

Thywissen, K. (2006): Core terminology of disaster reduction: A comparative glossary. In: Birkmann, J. (Ed.): Measuring vulnerability to natural hazards. Towards disaster resilient societies. Tokyo, Japan: United Nations University Press, pp. 448–496.

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