Bayesian Modeling of Ecosystem Services in Human-Environment Systems

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The adaptive management of ecosystem services requires knowledge about the interdependence of land use decision-making and the ecosystem features in a given landscape; and how this coupled humanenvironment system is influenced by drivers of global change. The problem in this context is, that both decision-making processes and the ecosystem changes are subject to large uncertainties and incomplete information. Furthermore, trade-offs between different ecosystem services and biodiversity exist and actors tend to maximize only one feature. The adaptive management of an entire system thus needs to find a solution, which optimizes all ecosystem services given uncertain information.
For this purpose, we develop a Bayesian Network BN of the human-environment system allowing evaluating simultaneously the effect of different decision-making processes on ecosystem responses and updating the results when better information becomes available.
We test the approach in a case study in the Swiss Alps, where we focus on integrating the value of different ecosystem services as a support for landscape planning. Results show that if uncertainties are not explicitly integrated into the modeling framework, the information provided to the decision-makers might be misleading.
For a case study in a Costa Rican watershed, we expand the BN with exogenous drivers from market (e.g., change in price for crops), policy (e.g., change in national park border) and climate (e.g., change in frequency of heavy rainfall). Policy instruments like command and control, park zoning and payments for cosystem services can help reaching a more balanced management of a watershed. For the planning of those instruments, however, it is helpful to have a model which shows how the manager of individual land units, takes policy measures, together with expected market changes and climate change into account in his land use decision-making. For each management unit, the prior probability of a specific land use and cover is updated with a posterior probability, when additional information about the management unit (e.g., slope, soil type, governance) is available.
This type of model can be used to plan and simulate new policy measures like payments for ecosystem services, because it simultaneously takes the ecosystem, socio-economic system and the policy system into account. The model allows identifying management units with high and low values for each ecosystem services and thus the targeting of available financial funds can be optimized. First working steps show that such a BN provides a robust modeling environment, useful for better informed and participatory decision-making.

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Swiss Federal Institute of Technology Zurich

DUWIS Department of Environmental Sciences

NSSI Natural and Social Science Interface

Research Group Ecosystem Services

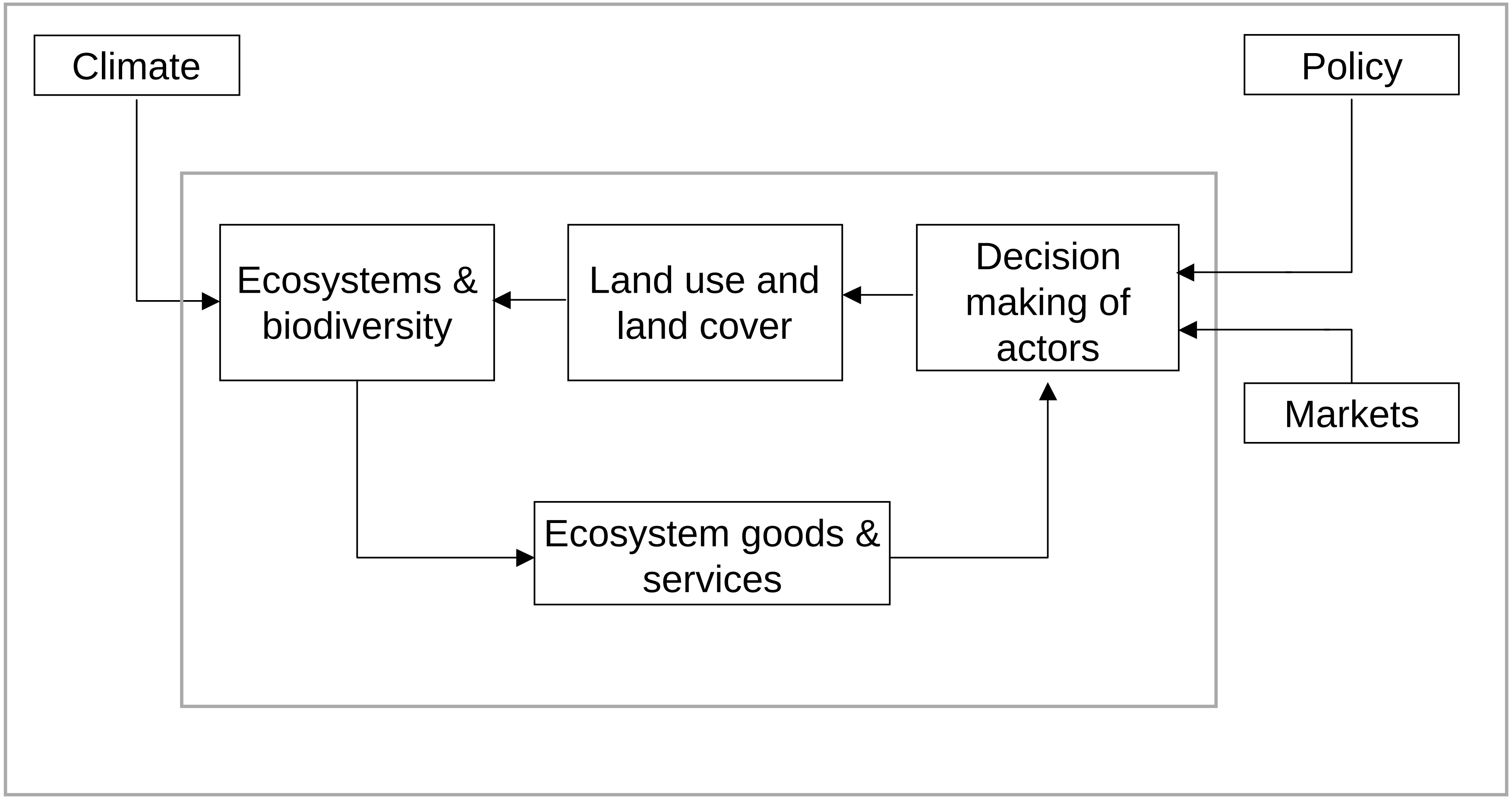
Bayesian Modeling of Ecosystem Services in Human-Environment Systems

Thomas Koellner[1], Adrienne Grét-Regamey[1], Miguel Marchamalo[2], and Raffaele Vignola[3]

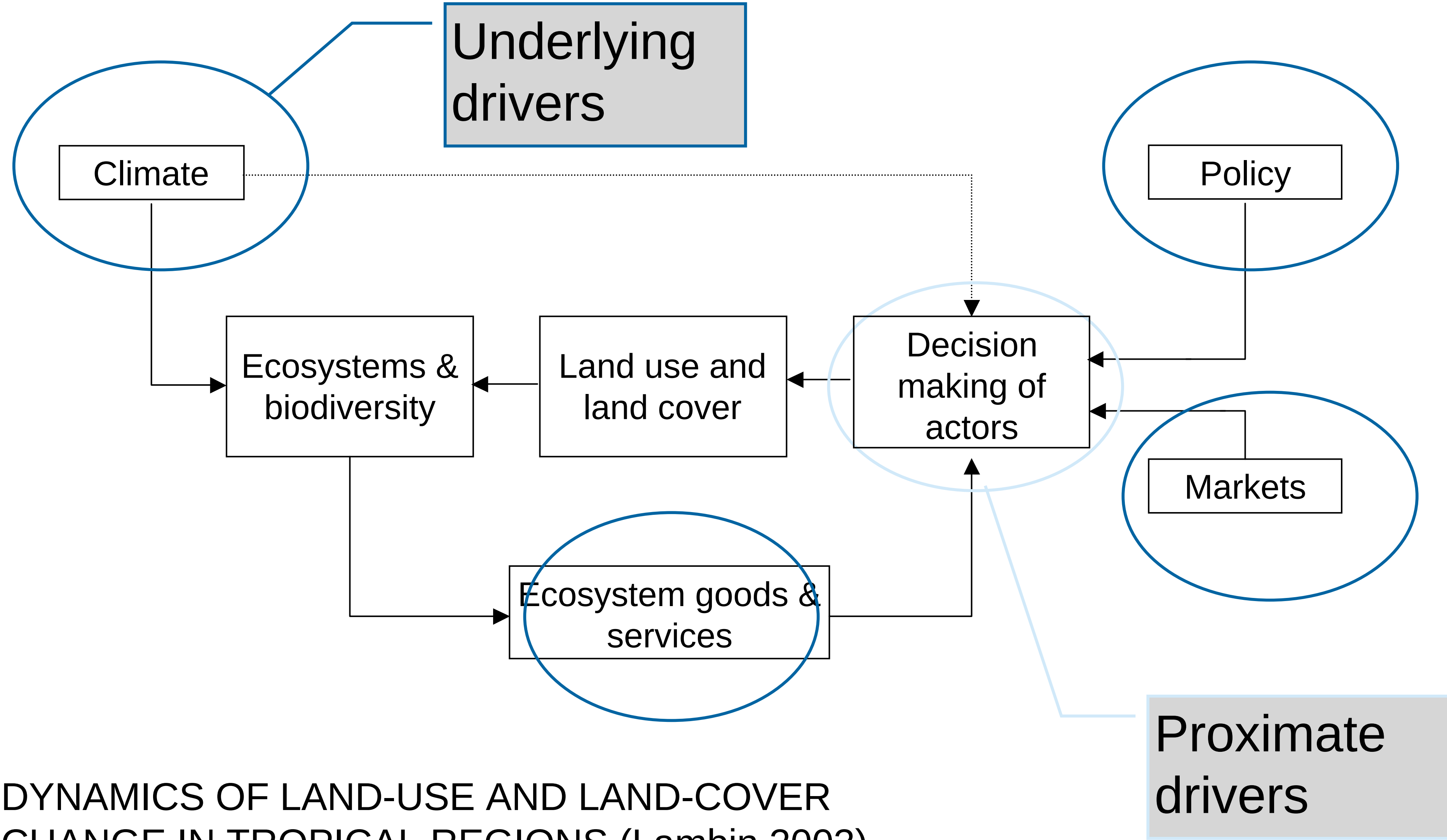
Our concept of human-environment systems

Environmental System

Socio-economic System



Our concept of human-environment systems



DYNAMICS OF LAND-USE AND LAND-COVER CHANGE IN TROPICAL REGIONS (Lambin 2003)

The problem

- Modeling ecosystem services in Human-Environment Systems for decision support ...

- ... under uncertainty and incomplete information.

Model types for Human-Environment System

- **System dynamics**
  - Voinov, A., Costanza, R., Wainger, L., Boumans, R.M.J., Ferdinando, V., Maxwell, T. and Voinov, H., 1999. Patuxent landscape model: integrated ecological economic modeling of a watershed. Environmental Modelling & Software 14: 473-491.
- **Geostatistical Analysis**
  - Coxhead, I., Rola, A. and Kim, K., 2001. How Do National Markets and Price Policies Affect Land Use at the Forest Margin? Evidence from the Philippines. Land Economics 77: 250-267.
- **Agent-based modeling**
  - Mathews, R., 2006. The People and Landscape Model (PALM): Towards full integration of human decision-making and biophysical simulation models. Ecological Modelling 194: 329-343.
- **Markov Chain**
  - Balzter, H., 2000. Markov chain models for vegetation dynamics. Ecological Modelling 126: 139-154.
- **Bayesian Networks**
  - Gret-Regamey, A., Bebi, P., Ian D. Bishop, I.D. and Willy Schmid, W., in press. Linking GIS-based models to value ecosystem services in an Alpine region. Journal of Environmental Management.

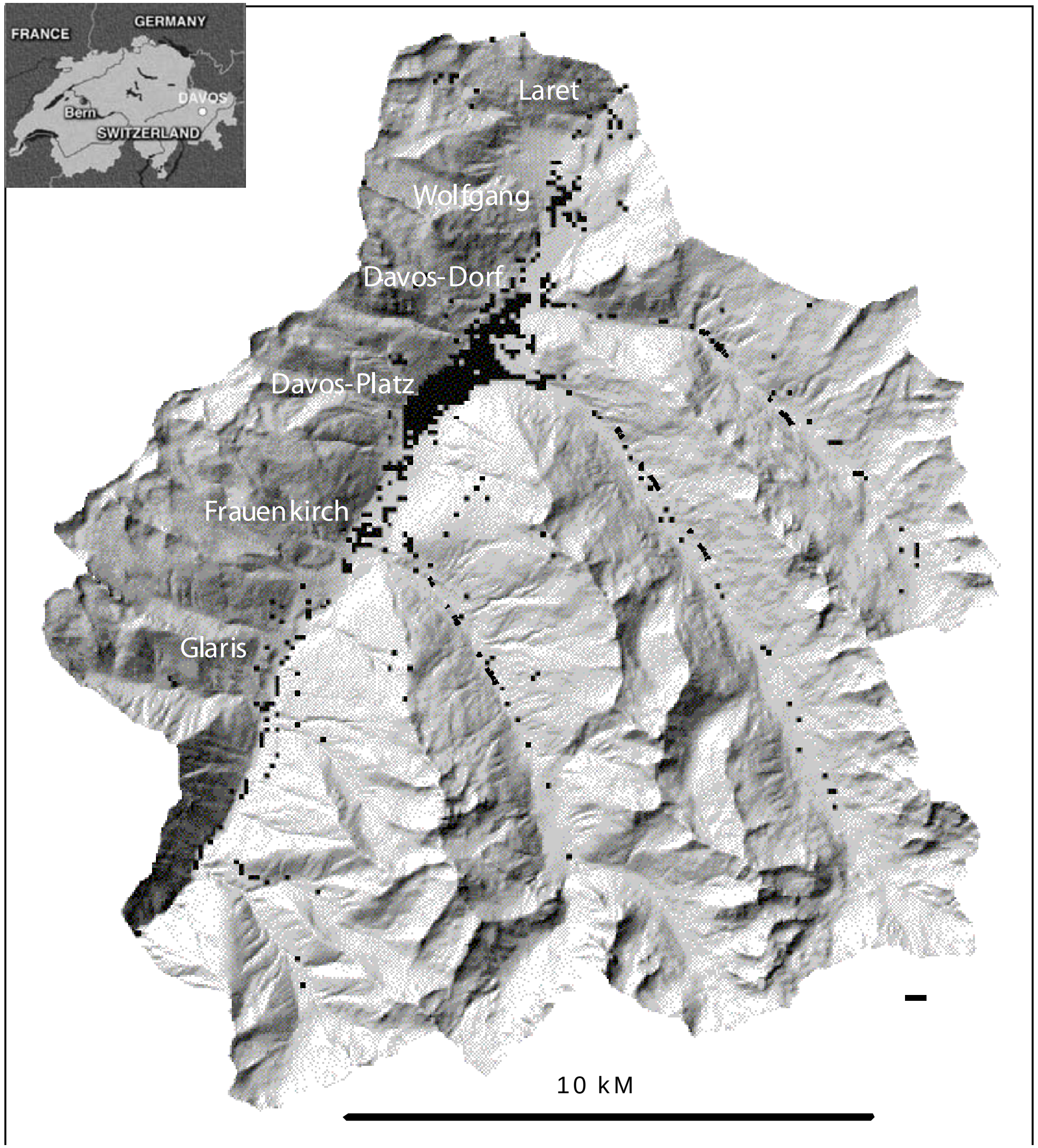
Case study Switzerland

Practical Problem: Spatial planning in Davos must take ecosystem services into account (avalanche protection, habitat protection, scenic beauty, carbon sequestration)

Decision Problem: Where in the valley of Davos is settlement expansion ecologically and economically feasible?

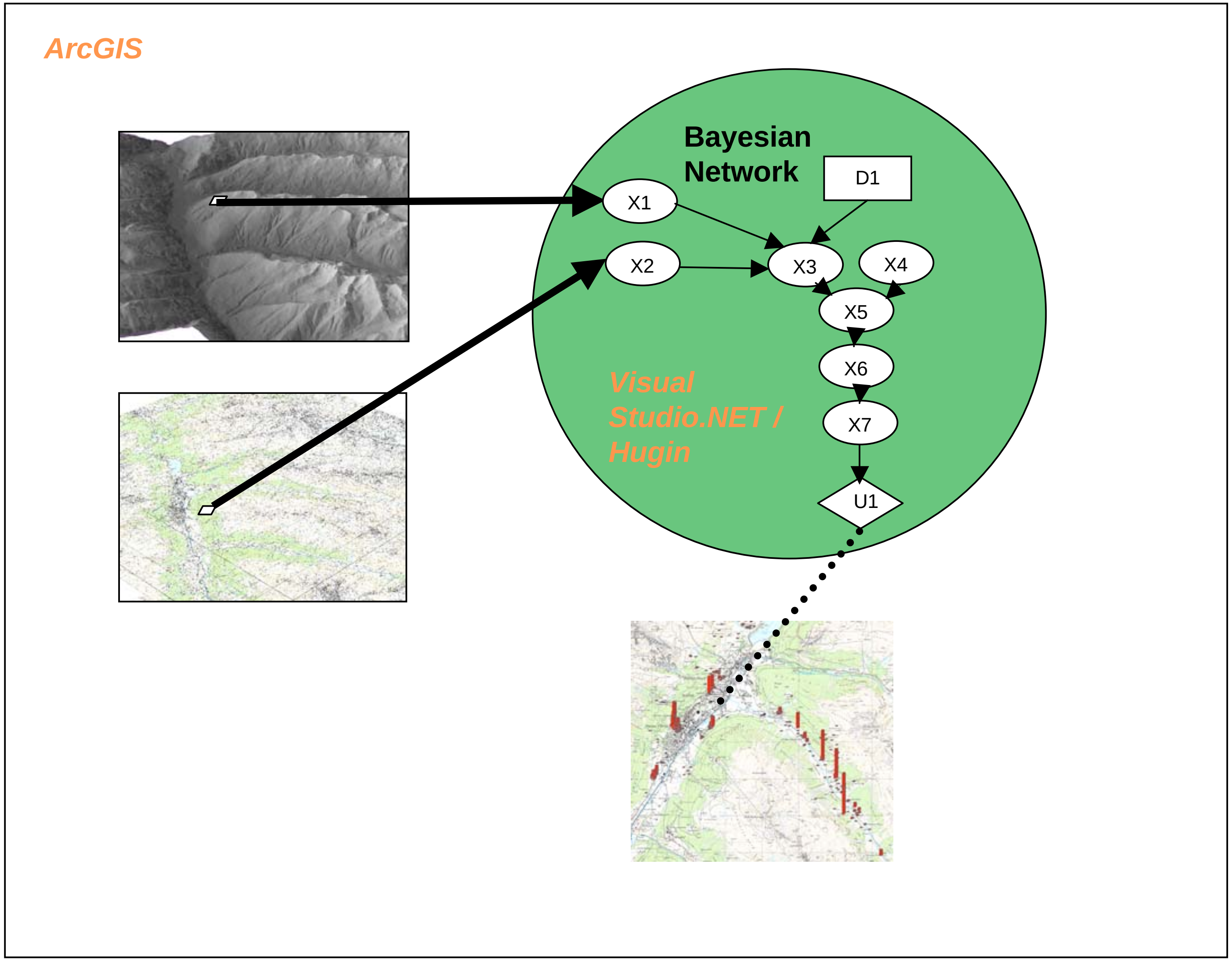
Solution: Assessing direct economic benefit and ecosystem services values with spatial Bayesian Networks

VALUE OF ES INTO SPATIAL PLANNING

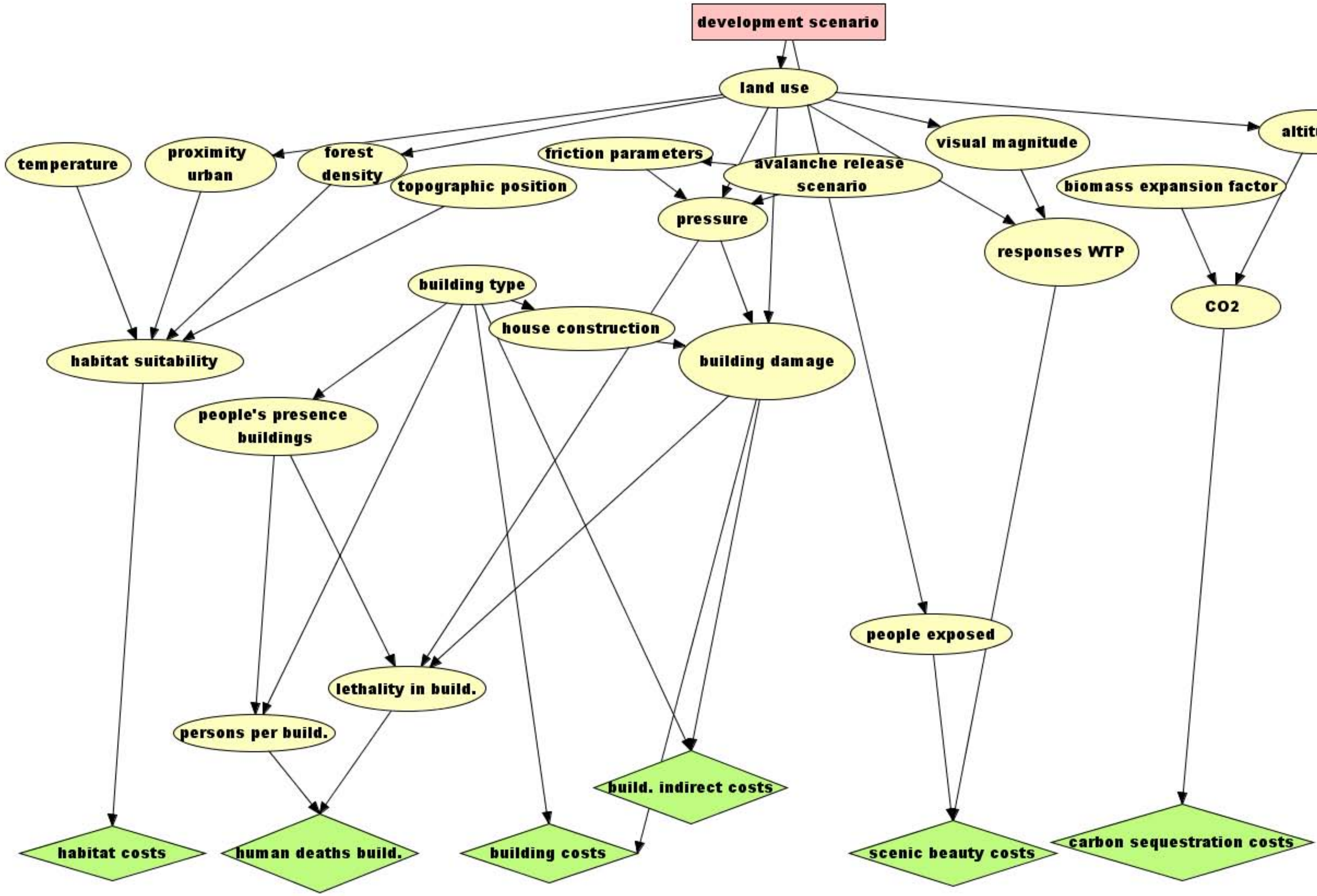


LINKING BAYESIAN NETWORK TO A GIS

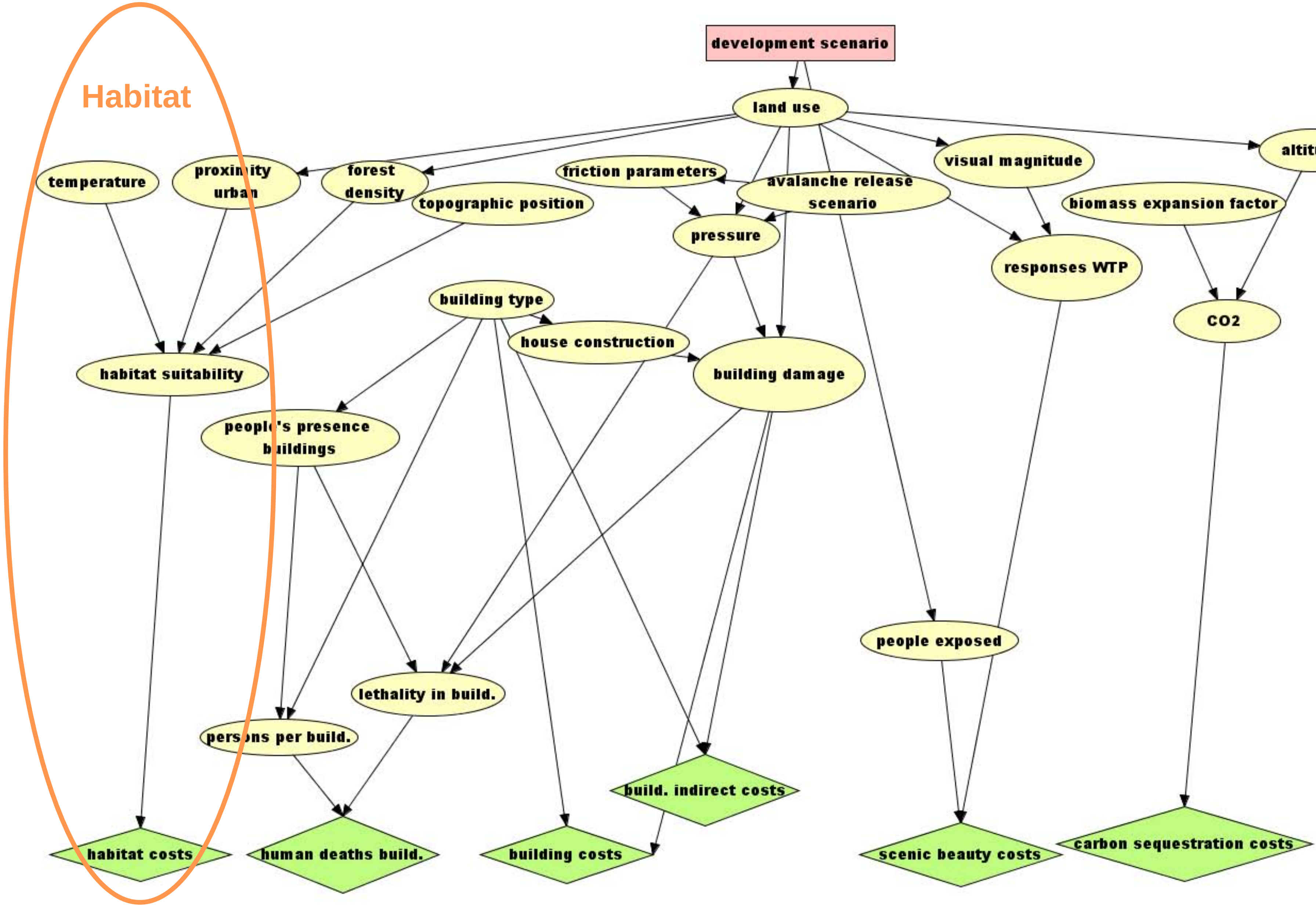
► Value of ES into planning for settlement expansion



BAYESIAN NETWORK FOR ES VALUATION



BAYESIAN NETWORK FOR ES VALUATION



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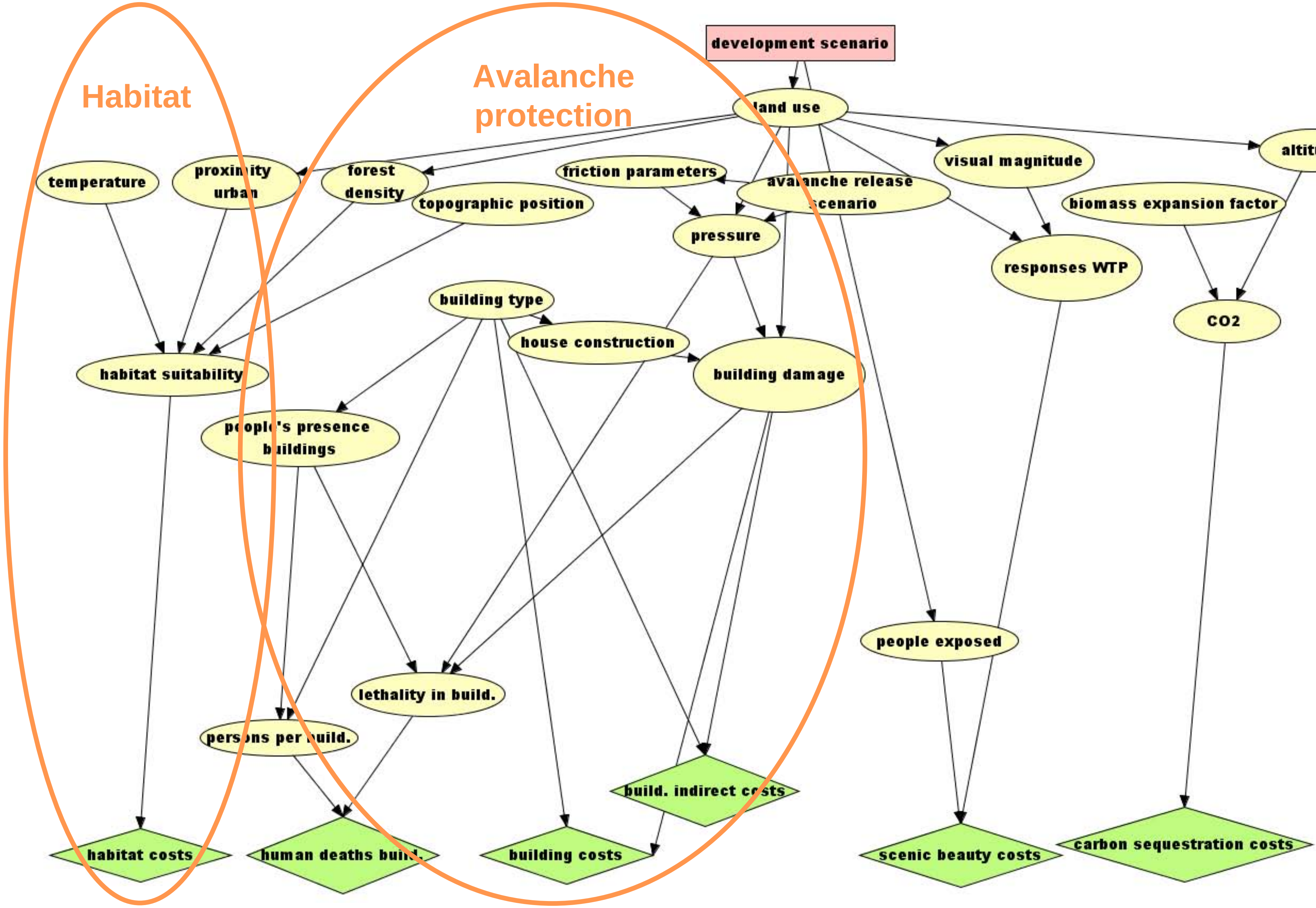

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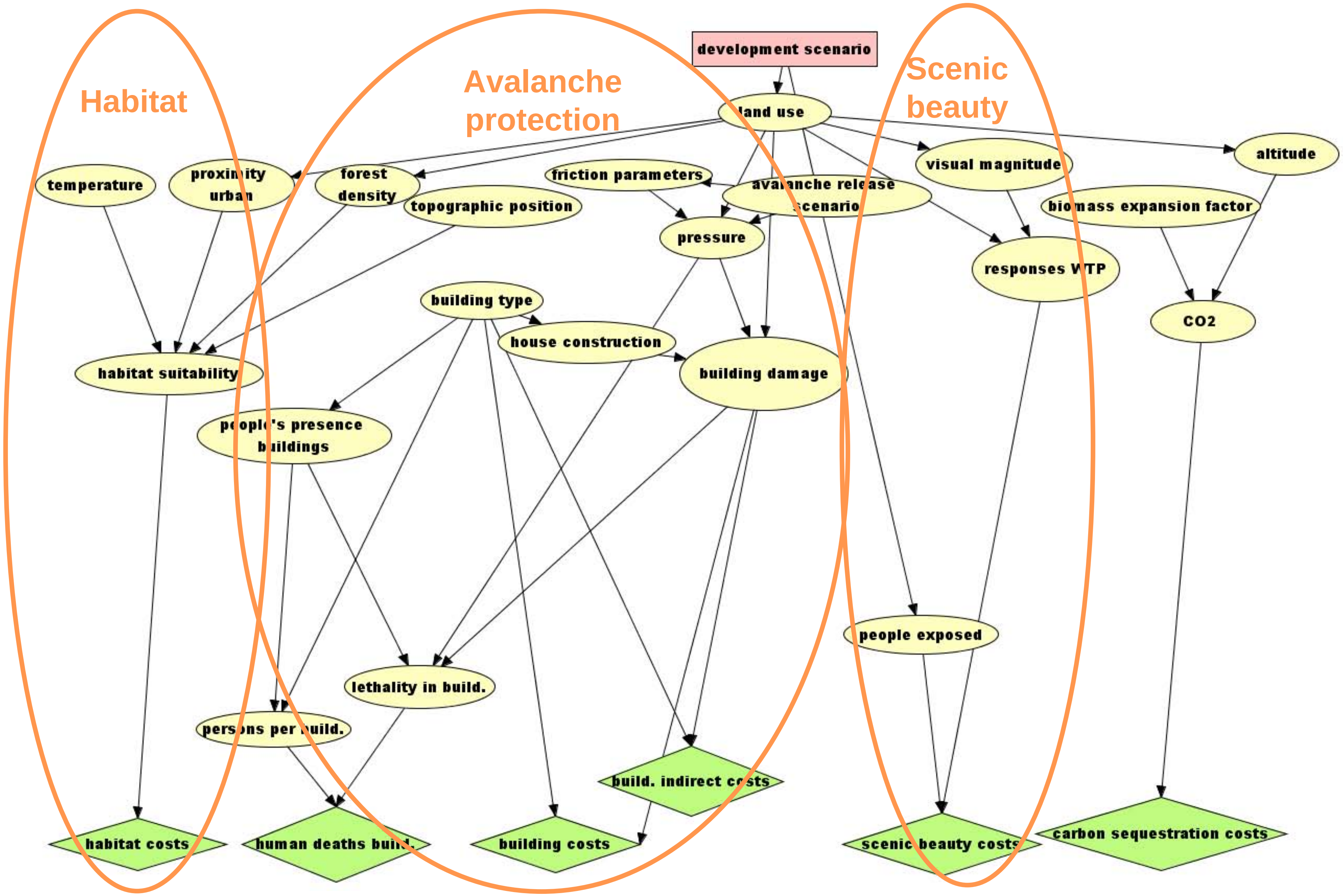
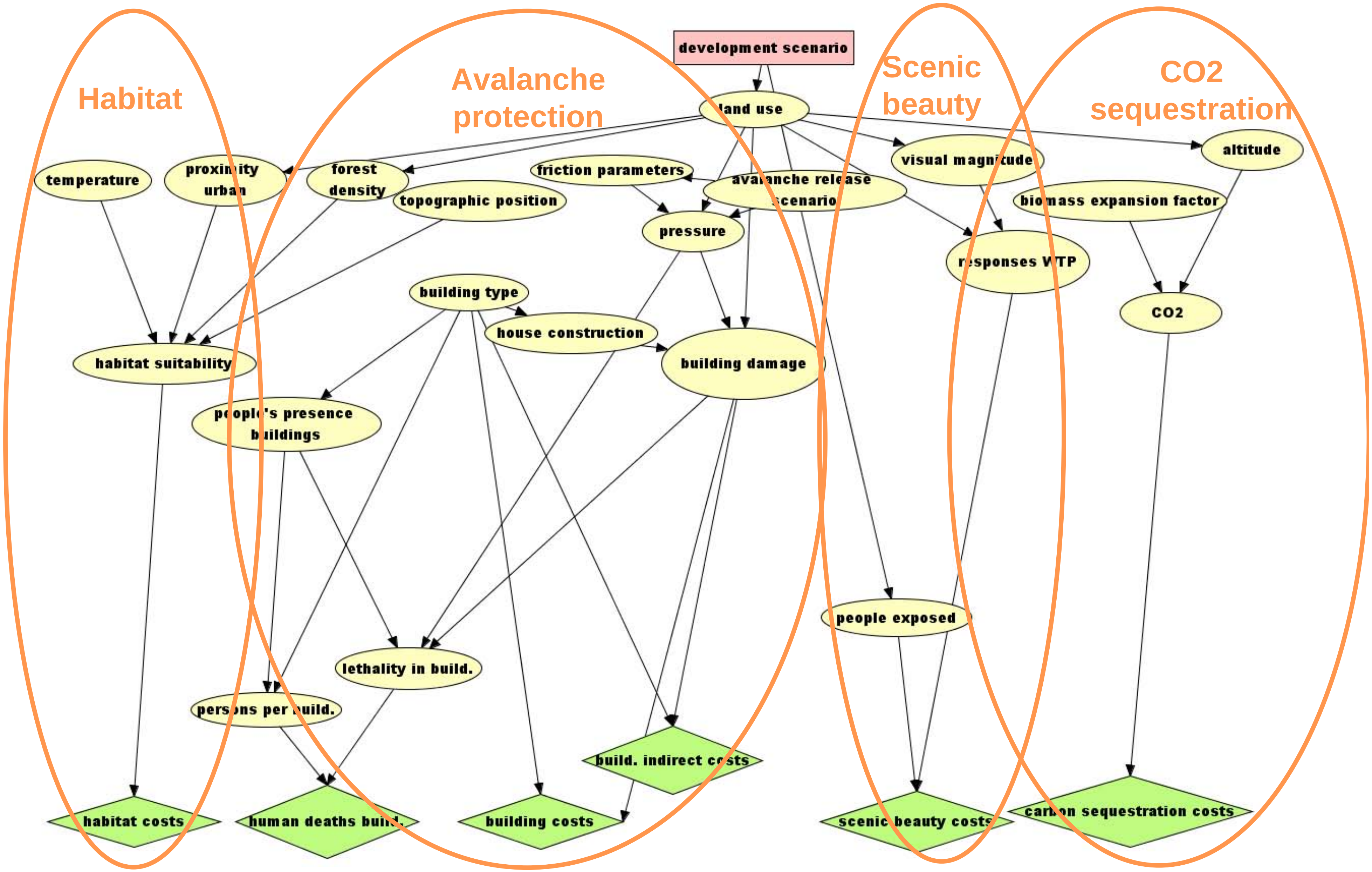
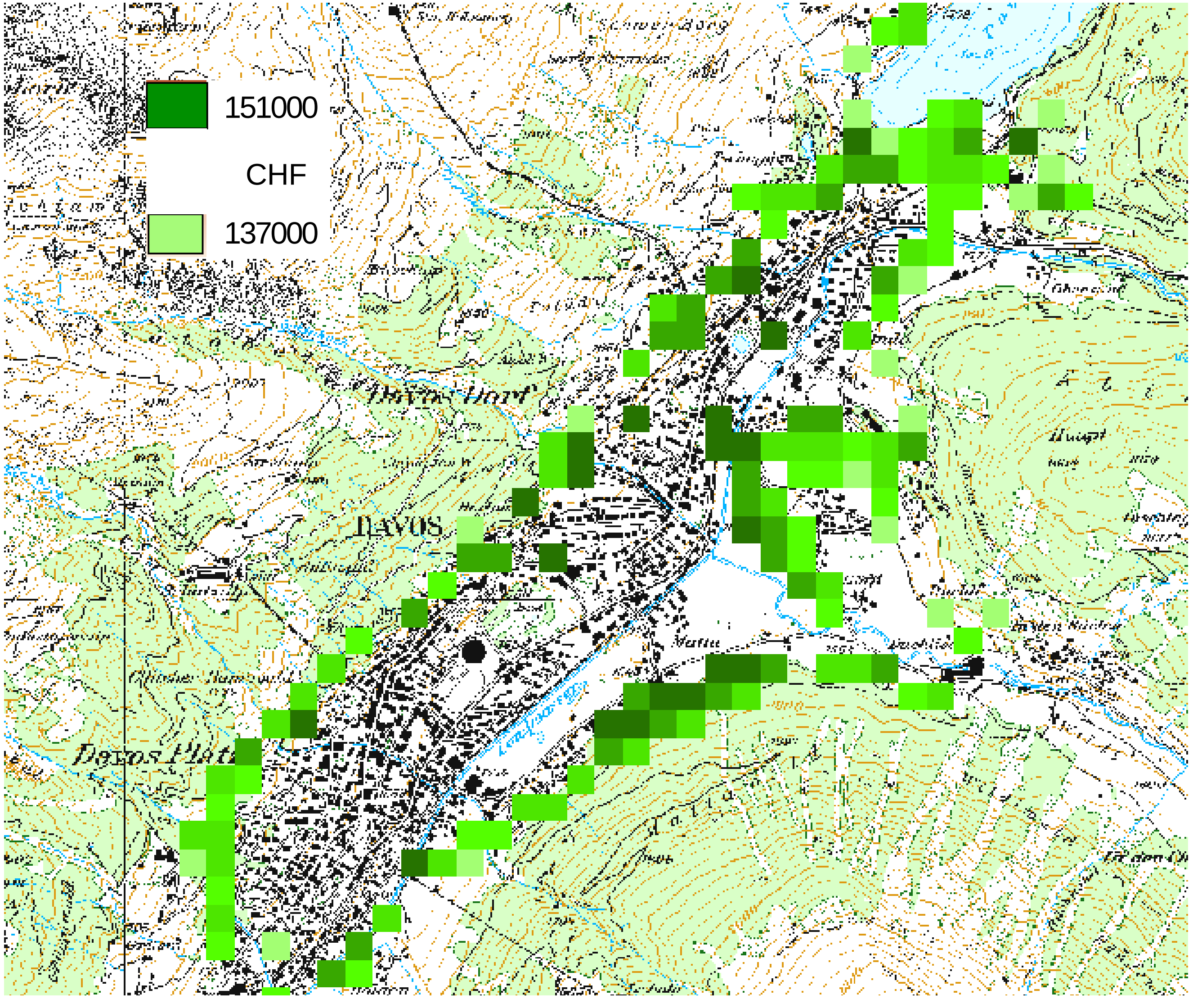


BAYESIAN NETWORK FOR ES VALUATION



Economic benefits provided by vacation rentals



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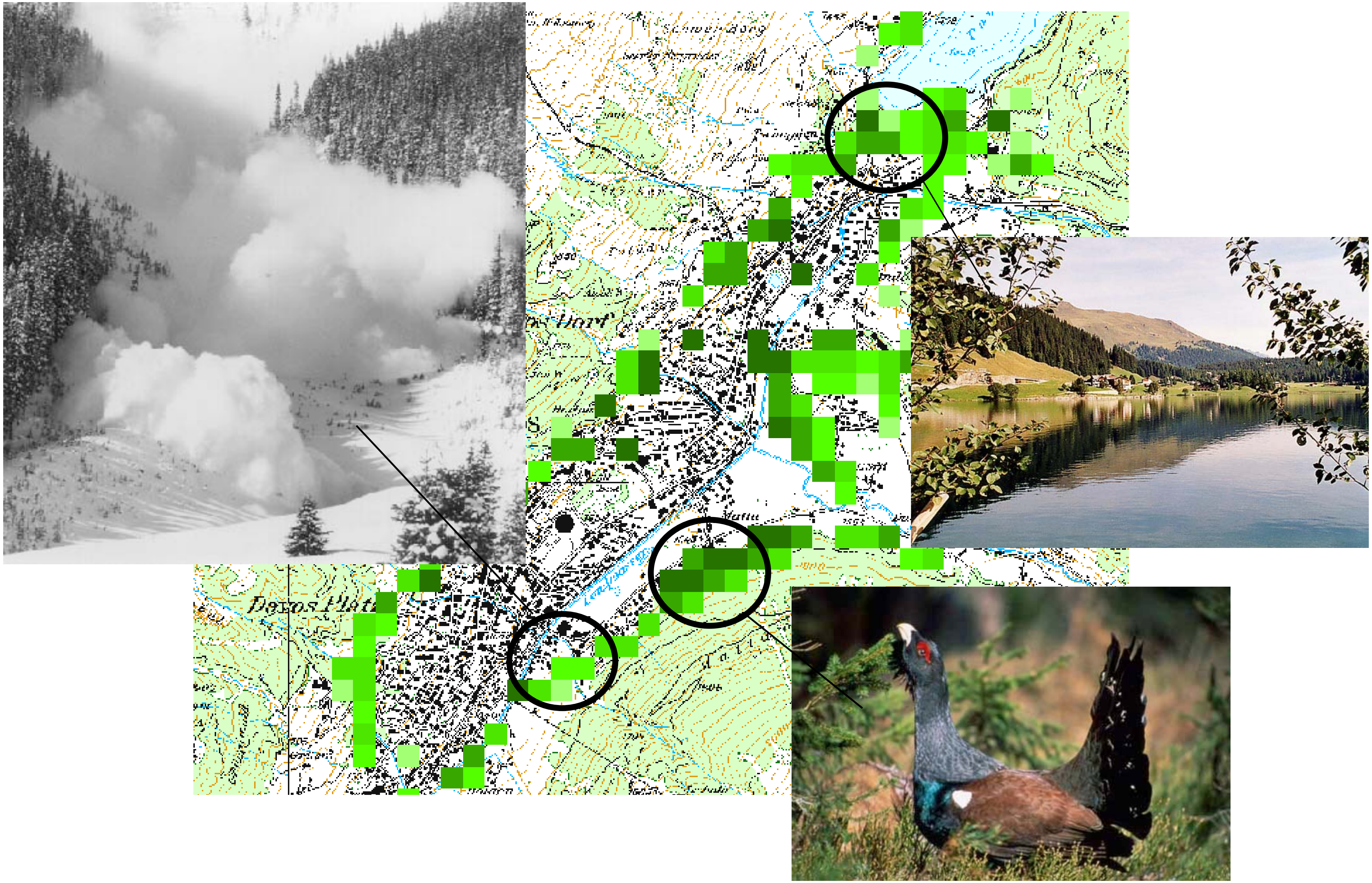
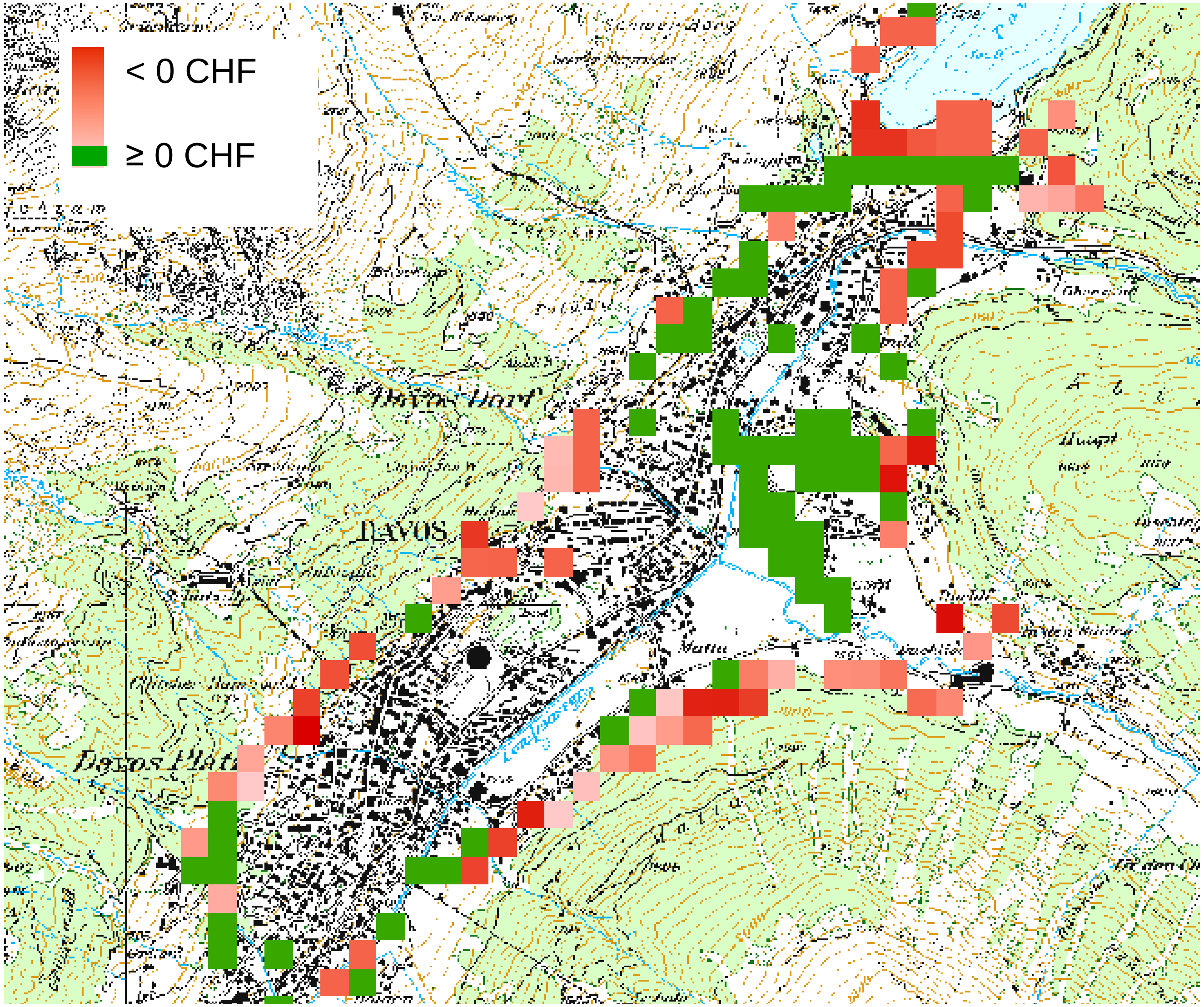


Direct economic benefits minus ecosystem services value



ES benefits from 1997 to 2045 without and with BN

	Without Bayesian Network	With Bayesian Network
Scenic Beauty	-96	- 13,358
Habitat	- 808	- 822
Carbon sequestration	- 658,941	- 124,182
Avalanche protection	-14,112,408	-9,408,272
Total ES	**-14,772,253**	**-9,546,634**

[1] *Values are in CHF. No discount rates are applied*

Literature: Grêt-Regamey et al. (2008) Valuing Ecosystem Services for Sustainable Landscape Planning in Alpine Regions. *Mountain Research and Development* 28: 156-165

Case study Costa Rica

Practical problem: Upstream farmers produce sediments and downstream hydropower producers have economic damage

Decision problem: Design of payments for ecosystem services for improved soil erosion regulation

Solution: Linking erosion model with farmers decision model in spatial Bayesian Networks

Erosion regulation by natural ecosystems

- Reduced erosion regulation service
- Production of sediments in the Birris Watershed upstream

- Costs of additional sediments downstream in the Angostura Dam
  - Cost of dredging the dam in $ per year
  - Reduced lifetime of dam

Erosion model

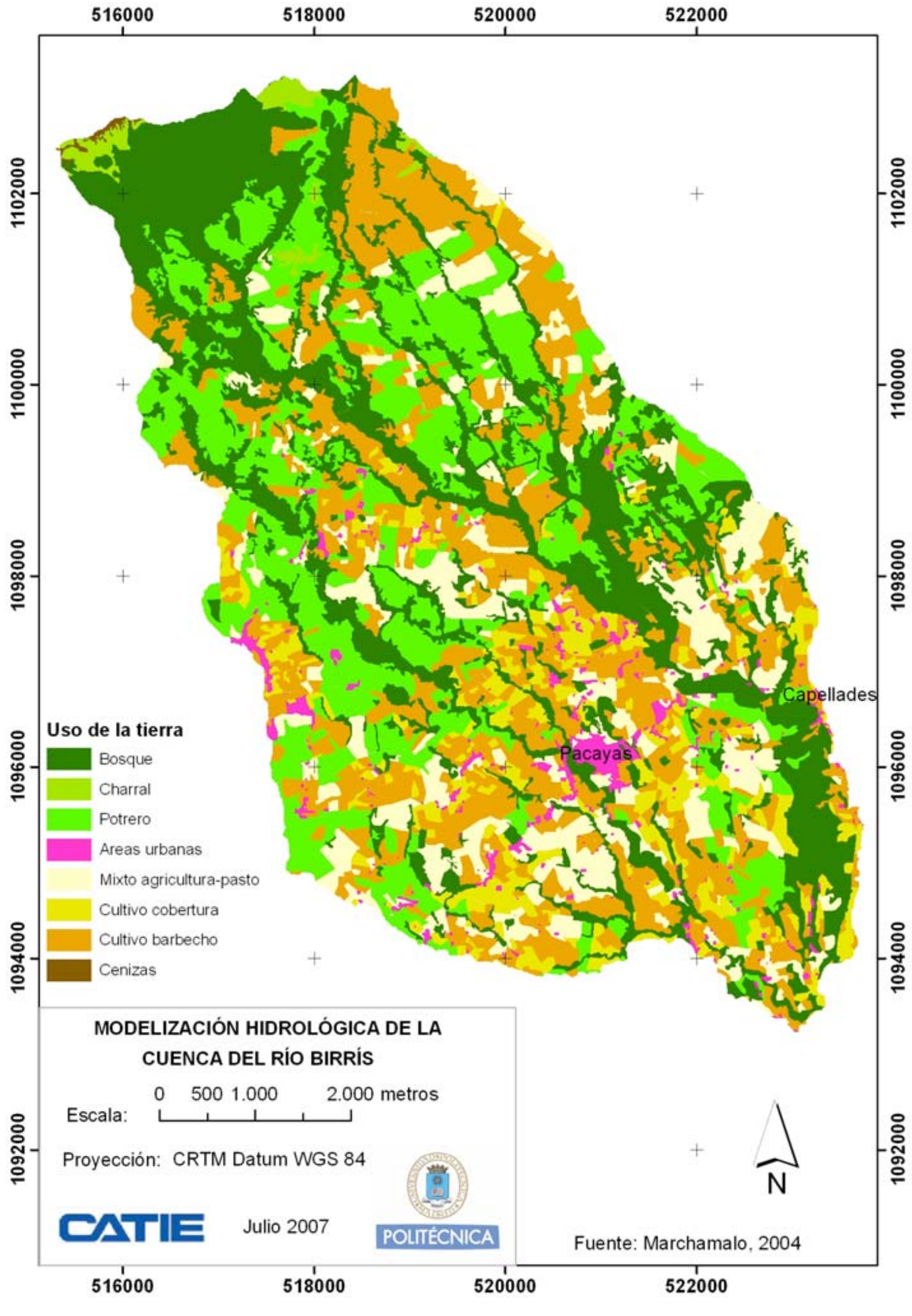
- **RUSLE model (Revised Universal Soil Loss Equation)** (*Wischmeier y Smith, 1978; Renard et al. 1997)*

  - **SE = R, K, LS, CP**

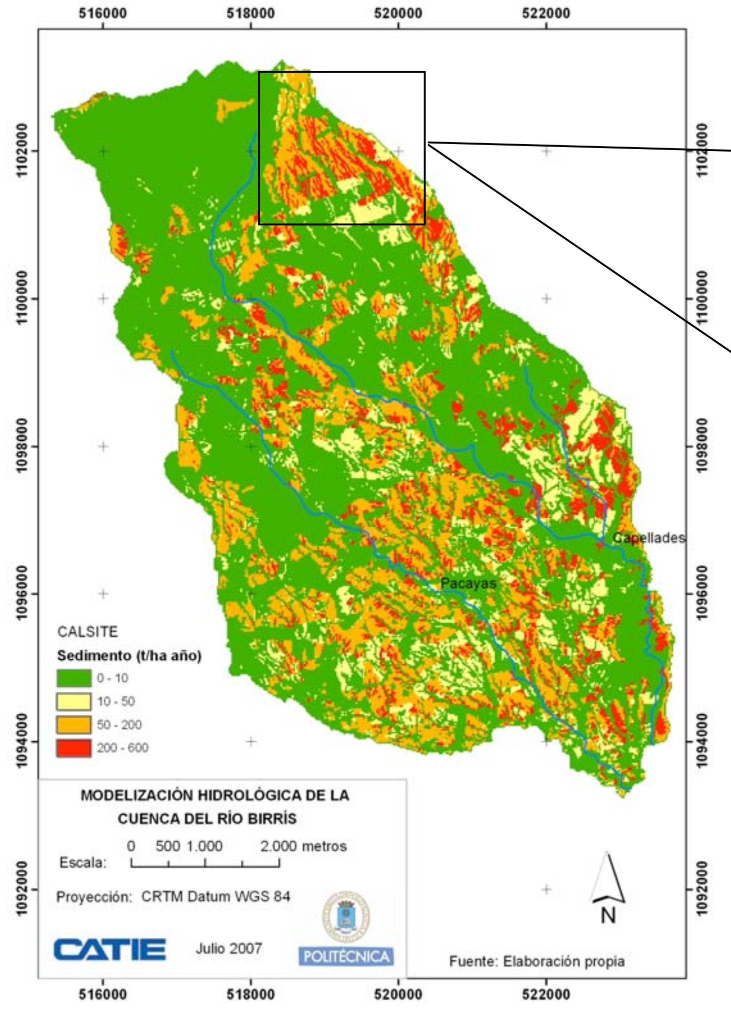
- **SE:** Soil erosion **(ton/ha/yr)**
- **R:** Precipitation erosivity [MJ mm / (ha hr año)]
- **K:** Soil erodability [ton ha hr / (ha MJ mm)]
- **LS:** Length of slope (adimensional)
- **C:** Soil cover (adimensional)
- **P:** Soil management practices (adimensional)

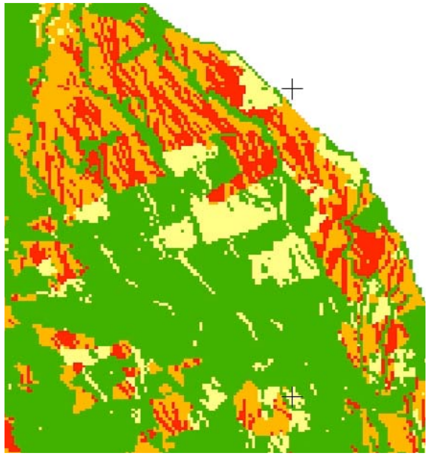
Factor CP

- Accounts for vegetation cover comparing actual vs "natural" vegetation cover effect, and conservation practices
- Typically used in modelling effect of conservation options
- Expresses average value of soil cover over the year
- Existing data for C in Costa Rica have been used combined with data collected by the project (Lianes, 2007)

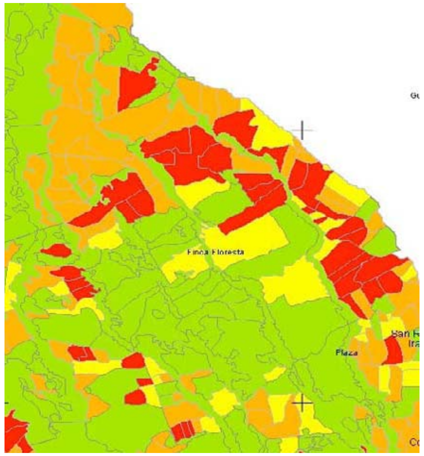


Payment for ecosystem services in high risk areas





Pixel



Management unit

51,67 t/ha/año


explorer

Factors influencing the land-use decision

- **Knowledge and belief system**
  - Signals from climate, policy and markets

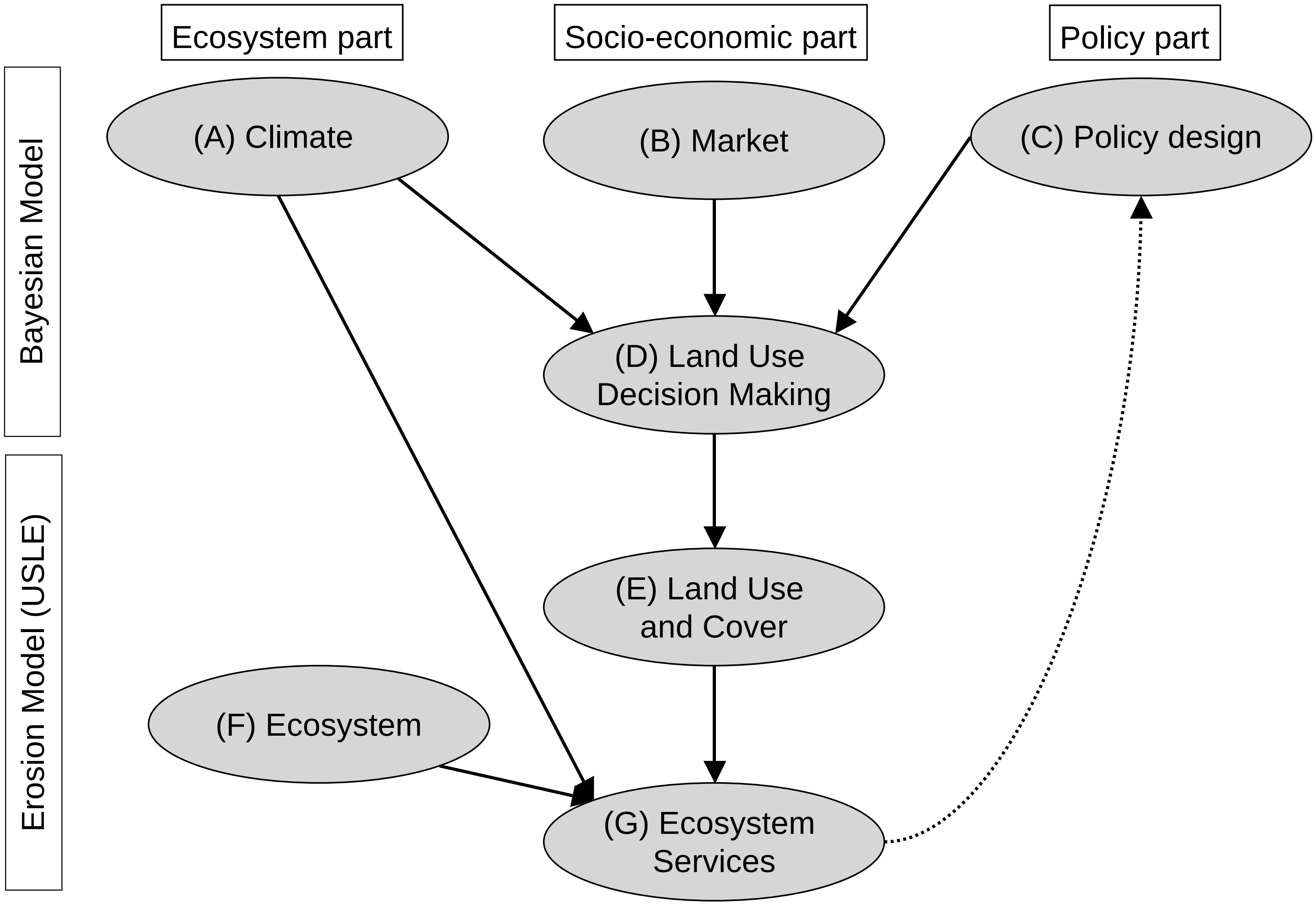
- **Subjective Norms**

- **Cost-benefit expectations** (Attitude)
  - Financial benefits and costs
  - Non-financial benefit and costs

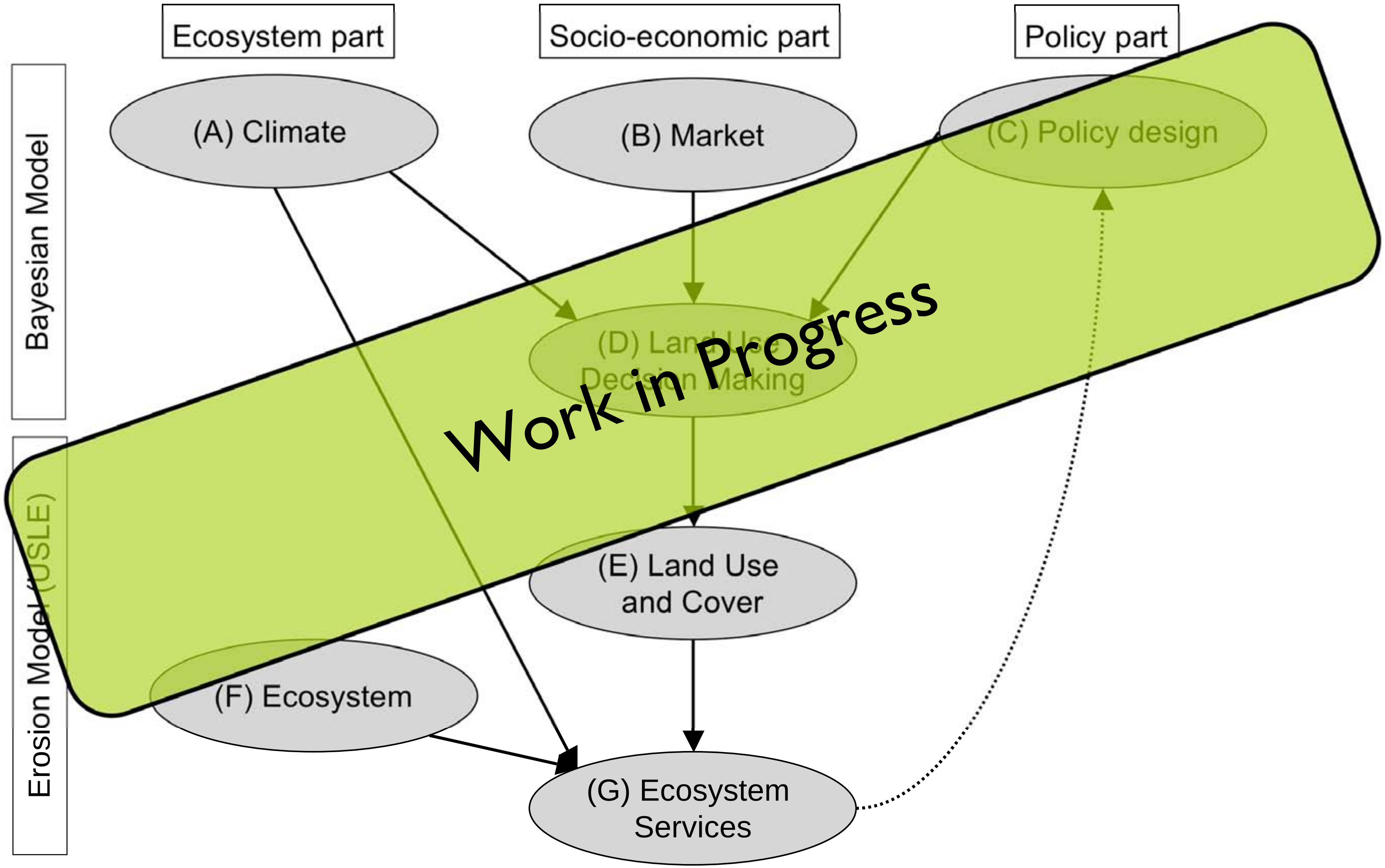
- **Perceived behavioral control** (+/-)
  - Environmental constraints
  - Legal constraints
  - Technical constraints
  - Financial constraints

Based on
** Ajzen 1991 Theory of Planned Behavior*
** Von Neumann and Morgenstern 1944 Expected Utility Theory*

Bayesian model + process models



Bayesian model + process models



Conclusion - Modeling Ecosystem Services with Bayesian Networks BN

Disadvantage

1. No continuous functions -> proxy by discontinuous ones
2. No feedback loops -> output of BN for time step 1 is input for BN for time step 2

Advantage

1. Uncertainties: Probability distribution for all variables in the model; calculation of joint probabilities
2. Incomplete information: Input data from expert assessment, survey data, data from process models, remote sensed data etc.
3. Design of cost-effective models: Assessment of costs and benefits of additional information as input into the model