



# Qualitative Modelling and Bayesian Belief Networks

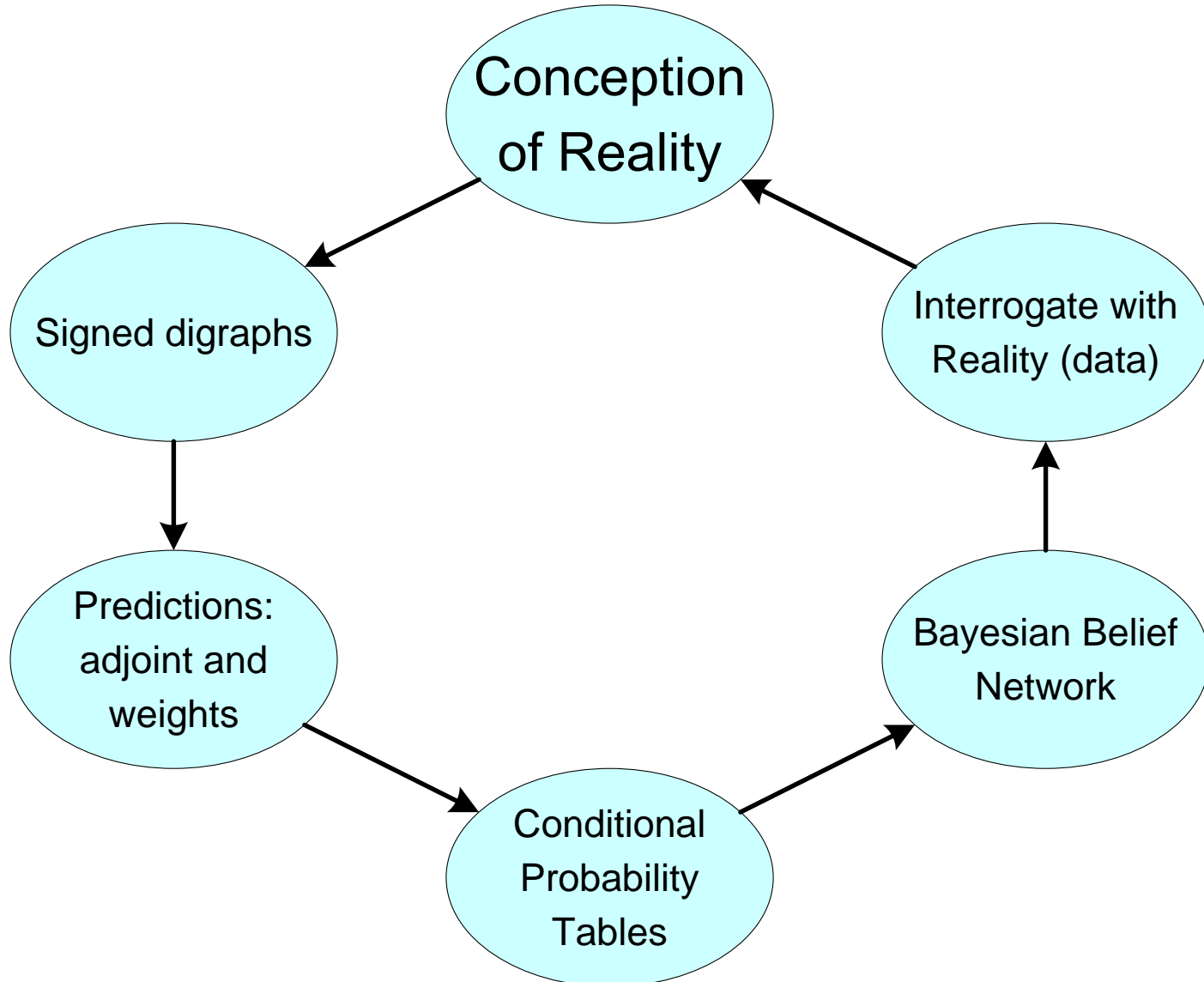
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CSIRO Marine and Atmospheric Research

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# What does Qualitative Modelling offer BBN's?





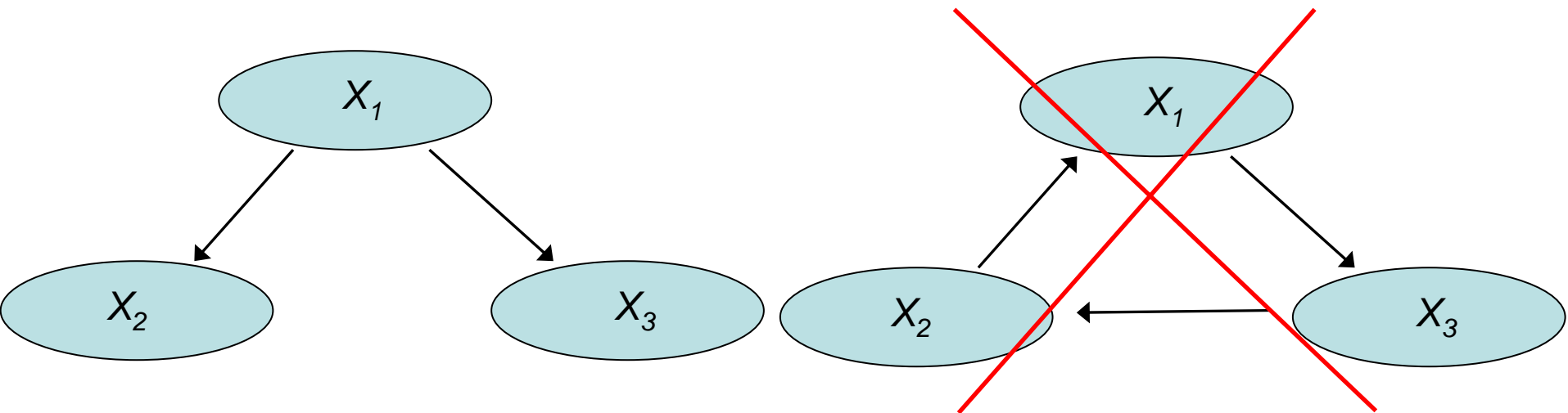
# Bayesian Belief Networks in Risk Analysis

## **Bayesian Belief Networks (BBNs) applied to ecological risk assessment**

- Prediction (Borusk et al 2004)
- Synthesis of ecological data and expert knowledge (Pollino et al 2006, Stiber et al 2004)
- Optimal decision-making (Varis 1998)

## Bayesian Belief Network

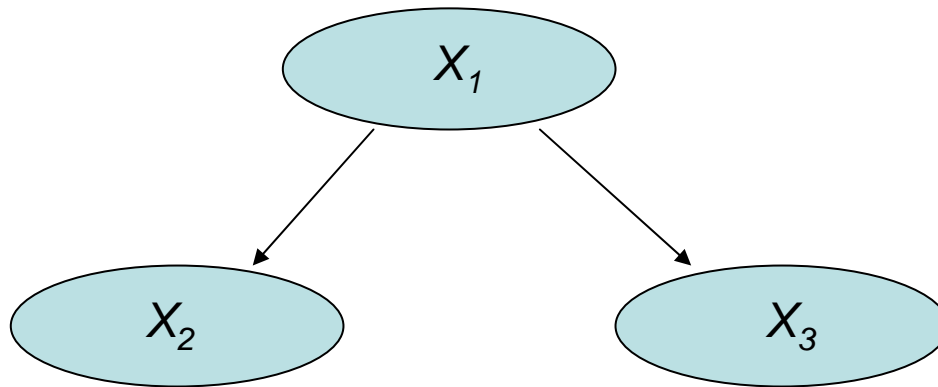
- a group of nodes connected by directed arrows such that there are no cycles (loops)



- “Child” nodes with incoming arrows are probabilistically dependent on “parents” values

# Bayesian Belief Networks

- The directed graph represents conditional dependency among nodes

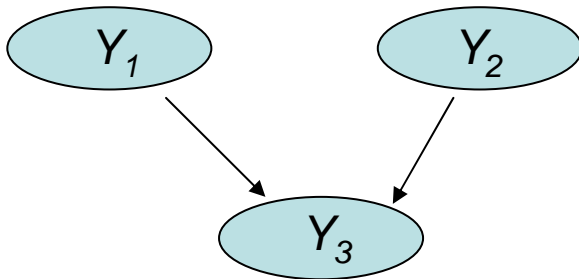


$$\begin{aligned} &P(X_1 \cap X_2 \cap X_3) \\ &= P(X_2 | X_1) \times P(X_3 | X_1) \times P(X_1) \end{aligned}$$

- Joint probability recovered from Bayesian network
- Answer any query

# An expert-informed BBN

- Ecological risk assessment starting to utilize expert opinion within BBN framework
  - Allows inference in absence of case-specific measurements
  - Well-suited for variety of ecological problems
- Set probabilities for every possible contingency in Conditional Probability Table (CPT)



**CPT**

$Y_1$	$Y_2$	$P(Y_3 = T   Y_1, Y_2)$
<b>T</b>	<b>T</b>	<b>.20</b>
<b>T</b>	<b>F</b>	<b>.15</b>
<b>F</b>	<b>T</b>	<b>.40</b>
<b>F</b>	<b>F</b>	<b>.25</b>



# Conditional Probability:

Condition 1



“Given a fish population in ‘poor’ health, a day in which bottom water oxygen concentrations average 0.5 mg/l at mid-channel locations, and the strength and direction of winds are such that the bottom water is being brought to the surface along the windward shore, *what is the probability of more than 100,000 fish being trapped and dying?*”

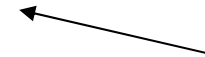
Condition 2



Condition 3



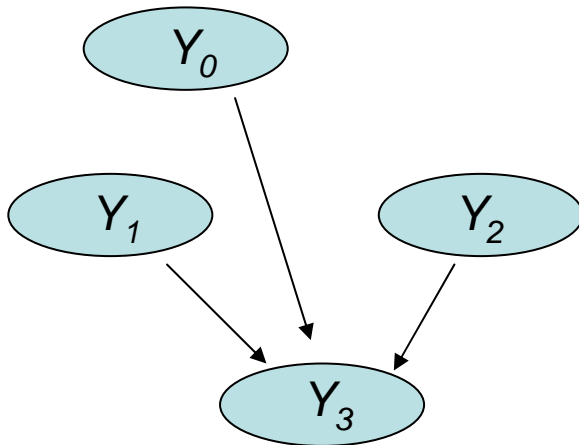
Probability statement



- Borusk et al 2004

# Determining Conditional Probability Tables (CPT's)

Example: Adding one dichotomous variable,  $Y_0$

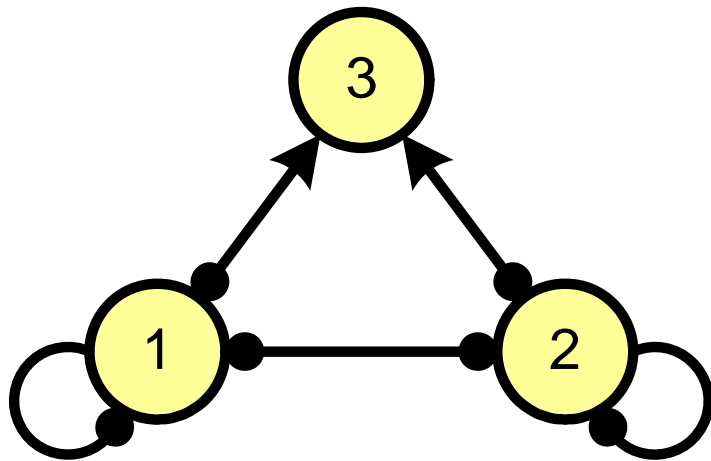


$Y_0$	$Y_1$	$Y_2$	$P(Y_3 = T \mid Y_0, Y_1, Y_2)$
T	T	T	<b>.08</b>
T	T	F	<b>.38</b>
T	F	T	<b>.04</b>
T	F	F	<b>.09</b>
F	T	T	<b>.16</b>
F	T	F	<b>.17</b>
F	F	T	<b>.06</b>
F	F	F	<b>.10</b>

- BBN's have difficulty incorporating unobserved or unmeasured variables since CPT becomes very large with additional contingencies (Elye-Datubo et al 2006)

# Qualitative Modelling Advantages: Inclusion of feedback cycles

- Acyclic representation of BBNs disallow the incorporation of ecologically significant feedback cycles (Borusk et al. 2004)
- Qualitative models utilize feedback cycles to make predictions:



$$\text{adj}(-A) =$$

Input

	$V_1$	$V_2$	$V_3$
$V_1$	-	+	+/-
$V_2$	+	-	+/-
$V_3$	+/-	+/-	0

Response

# Example: Hare and Lynx

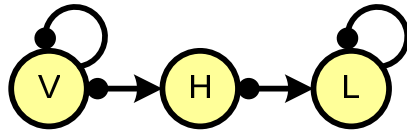
- Simple trophic chain: Vegetation – Hare – Lynx
- Krebs et al. (1995) observed non-intuitive indirect effect: experimental increase of vegetation did not significantly increase the density of hares



Experimental  
positive input  
to vegetation

# Hare – Lynx alternative model predictions

## Model A1



Symbolic adjoints:

$$\begin{bmatrix} a_{2,3} & a_{3,2} & -a_{1,2} & a_{3,3} & a_{1,2} & a_{2,3} \\ a_{2,1} & a_{3,3} & a_{1,1} & a_{3,3} & -a_{1,1} & a_{2,3} \\ a_{2,1} & a_{3,2} & a_{1,1} & a_{3,2} & a_{1,2} & a_{2,1} \end{bmatrix}$$

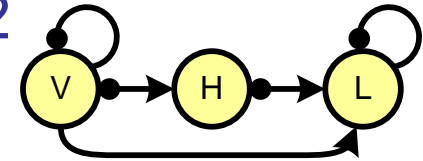
Numeric Adjoints:

$$\begin{bmatrix} 1 & -1 & 1 \\ 1 & 1 & -1 \\ 1 & 1 & 1 \end{bmatrix}$$

Prediction Weights:

$$\begin{bmatrix} 1. & 1. & 1. \\ 1. & 1. & 1. \\ 1. & 1. & 1. \end{bmatrix}$$

## Model A2



$$\begin{bmatrix} a_{2,3} & a_{3,2} & -a_{1,2} & a_{3,3} & a_{1,2} & a_{2,3} \\ a_{2,1} & a_{3,3} - a_{2,3} & a_{3,1} & a_{1,1} & a_{3,3} & -a_{1,1} & a_{2,3} \\ a_{2,1} & a_{3,2} & a_{1,1} & a_{3,2} - a_{1,2} & a_{3,1} & a_{1,2} & a_{2,1} \end{bmatrix}$$

$$\begin{bmatrix} 1 & -1 & 1 \\ 0 & 1 & -1 \\ 1 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 1. & 1. & 1. \\ 0. & 1. & 1. \\ 1. & 0. & 1. \end{bmatrix}$$

## Fully connected community matrix:

Symbolic Adjoint:

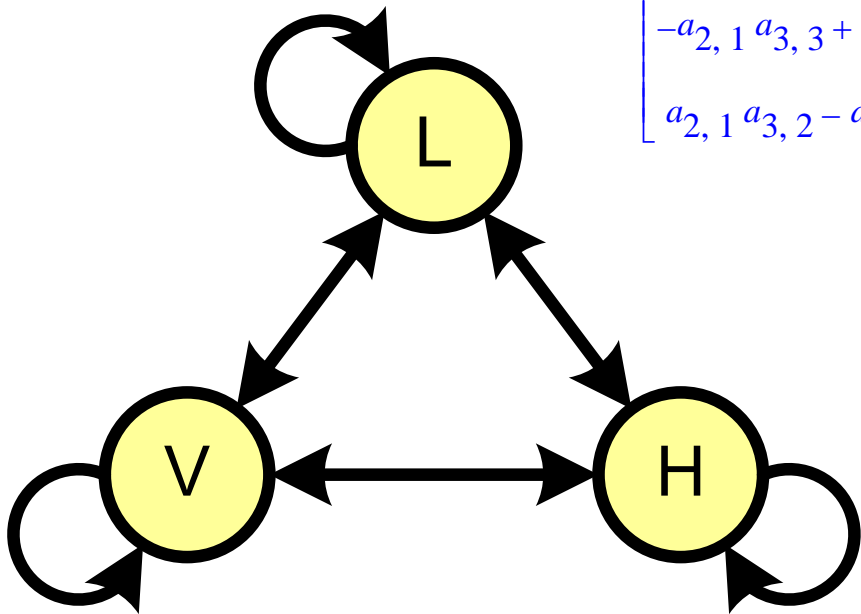
$$\begin{bmatrix} a_{2,2} a_{3,3} - a_{2,3} a_{3,2} & -a_{1,2} a_{3,3} + a_{1,3} a_{3,2} & a_{1,2} a_{2,3} - a_{1,3} a_{2,2} \\ -a_{2,1} a_{3,3} + a_{2,3} a_{3,1} & a_{1,1} a_{3,3} - a_{1,3} a_{3,1} & -a_{1,1} a_{2,3} + a_{1,3} a_{2,1} \\ a_{2,1} a_{3,2} - a_{2,2} a_{3,1} & -a_{1,1} a_{3,2} + a_{1,2} a_{3,1} & a_{1,1} a_{2,2} - a_{1,2} a_{2,1} \end{bmatrix}$$

Numeric Adjoint:

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

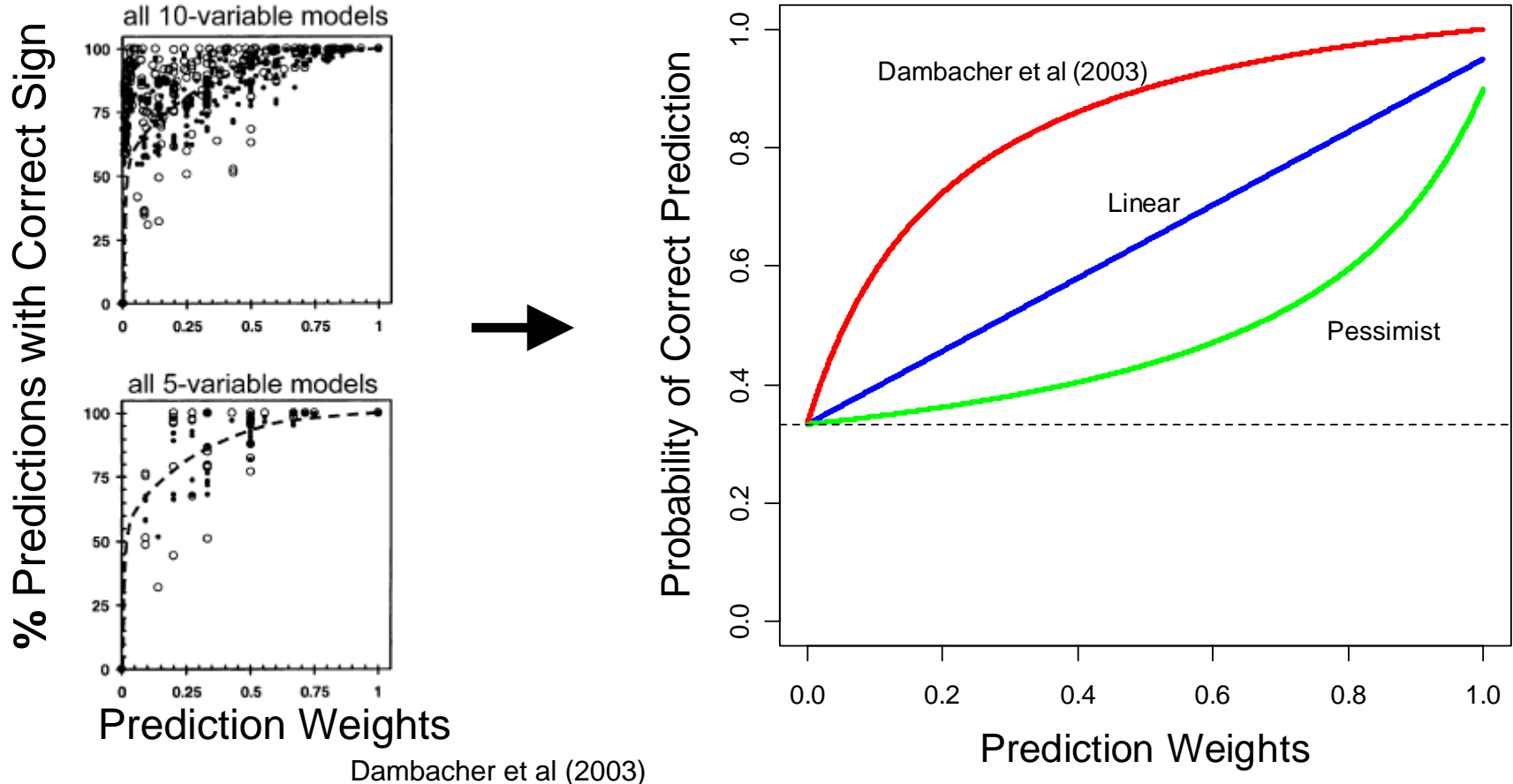
Prediction Weights:

$$\begin{bmatrix} 0. & 0. & 0. \\ 0. & 0. & 0. \\ 0. & 0. & 0. \end{bmatrix}$$



# Transforming weighted predictions to probabilities of increase and decrease

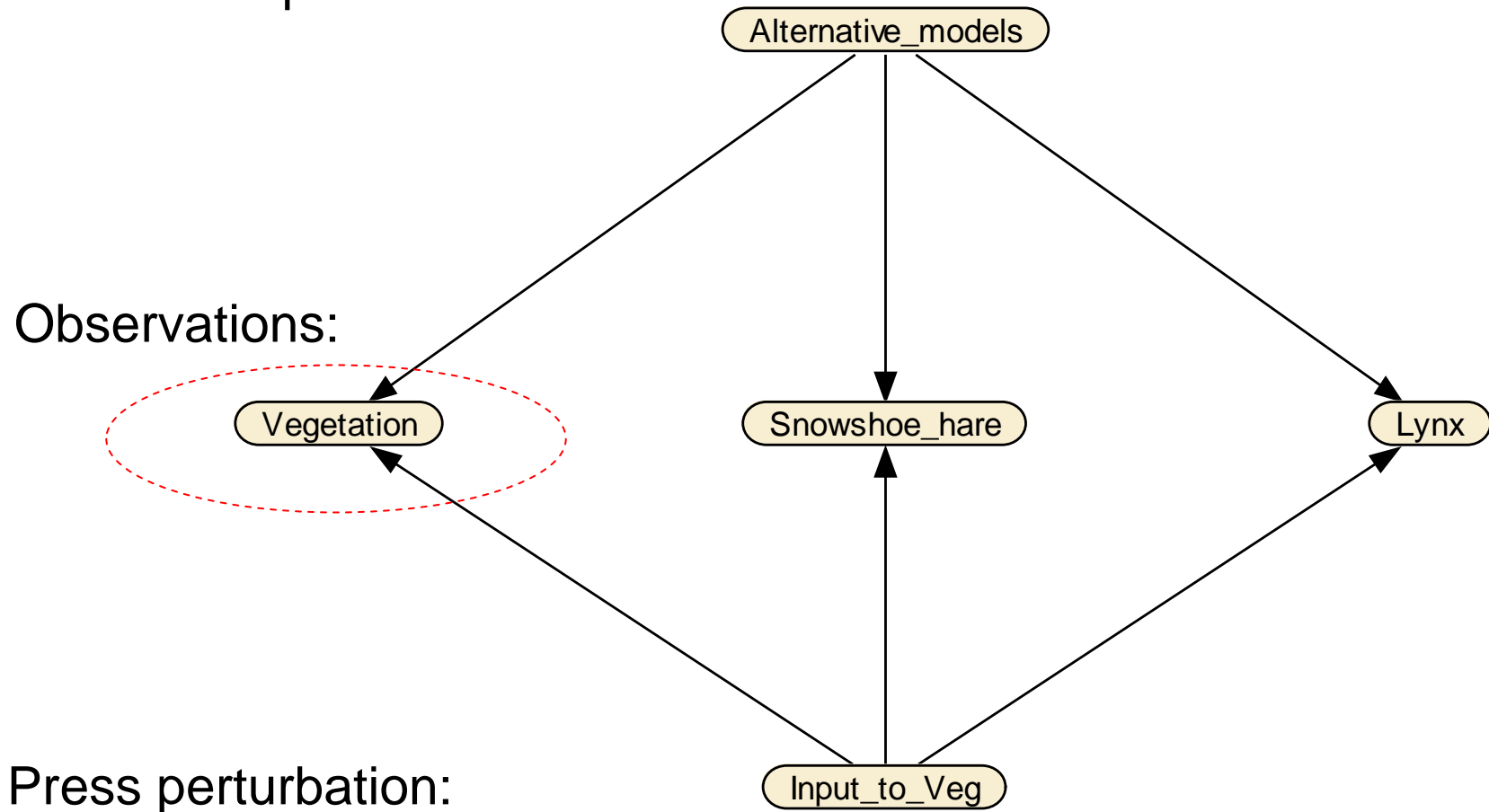
- Simulations suggest weights  $> 0.5$  have better than 90% chance of sign determinacy
- Functions translate predicted weights to probabilities



# Example: Hare Lynx BBN

Model comparisons:

Observations:



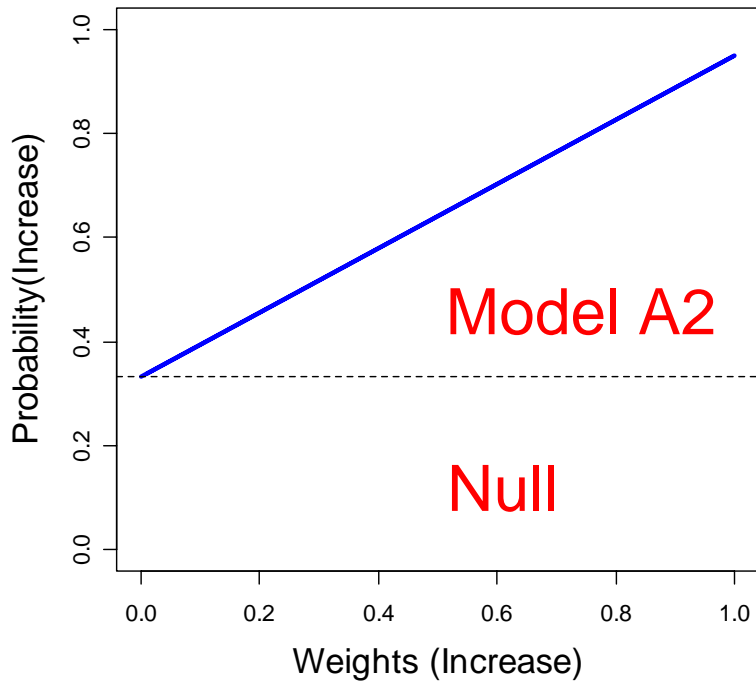
Press perturbation:



# Conditional Probability Table: Vegetation

Linear transformation:

Model A1



Model	Input(Veg)	Increase	Unchanged	Decrease
1	Incr	0.950	0.025	0.025
1	Unch	0.025	0.950	0.025
1	Decr	0.025	0.025	0.950
2	Incr	0.950	0.025	0.025
2	Unch	0.025	0.950	0.025
2	Decr	0.025	0.025	0.950
Null	Incr	0.333	0.333	0.333
Null	Unch	0.333	0.333	0.333
Null	Decr	0.333	0.333	0.333

Model comparisons:

Alternative_models		
A1	33.3	█
A2	33.3	█
Null	33.3	█

Observations:

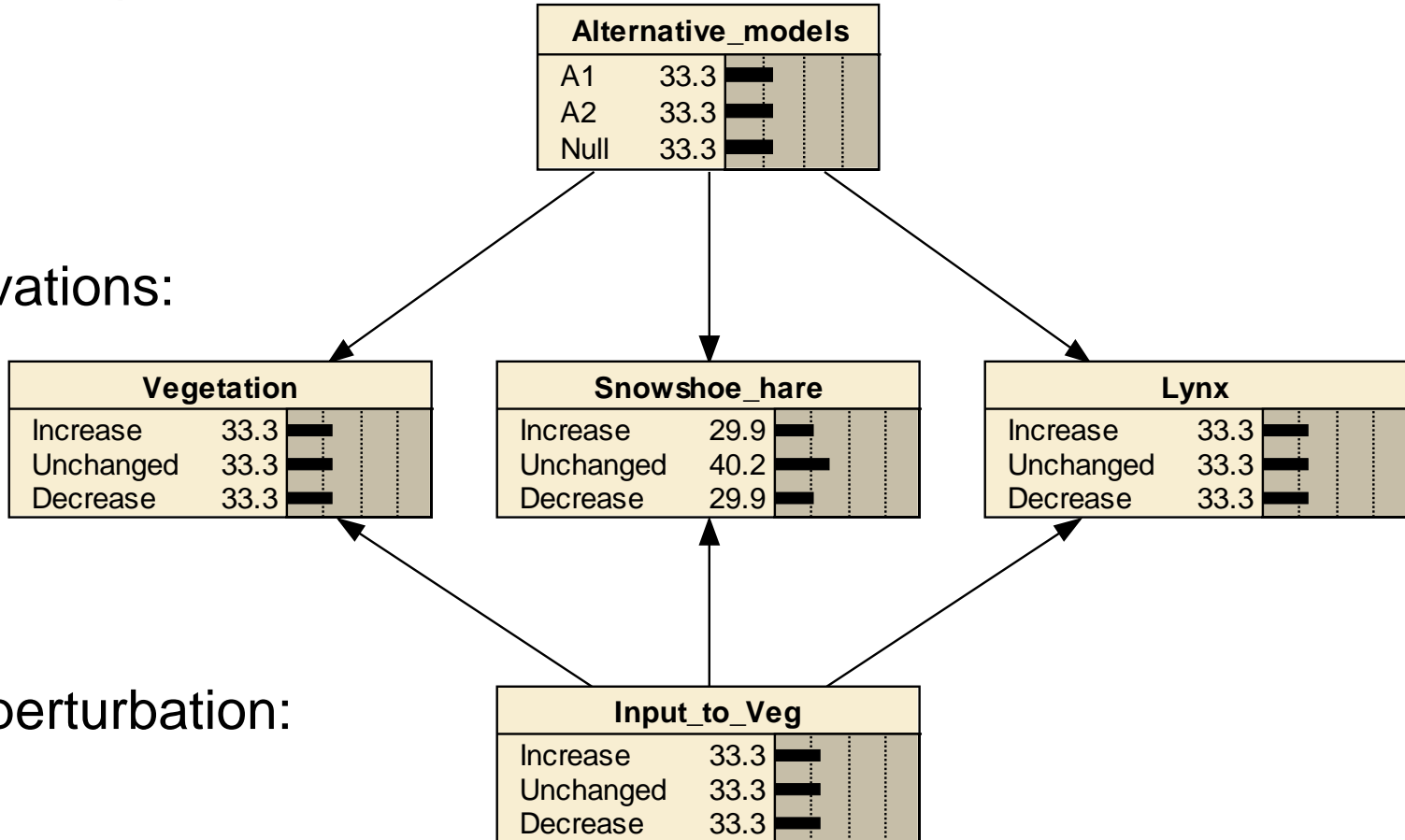
Vegetation		
Increase	33.3	█
Unchanged	33.3	█
Decrease	33.3	█

Snowshoe_hare		
Increase	29.9	█
Unchanged	40.2	█
Decrease	29.9	█

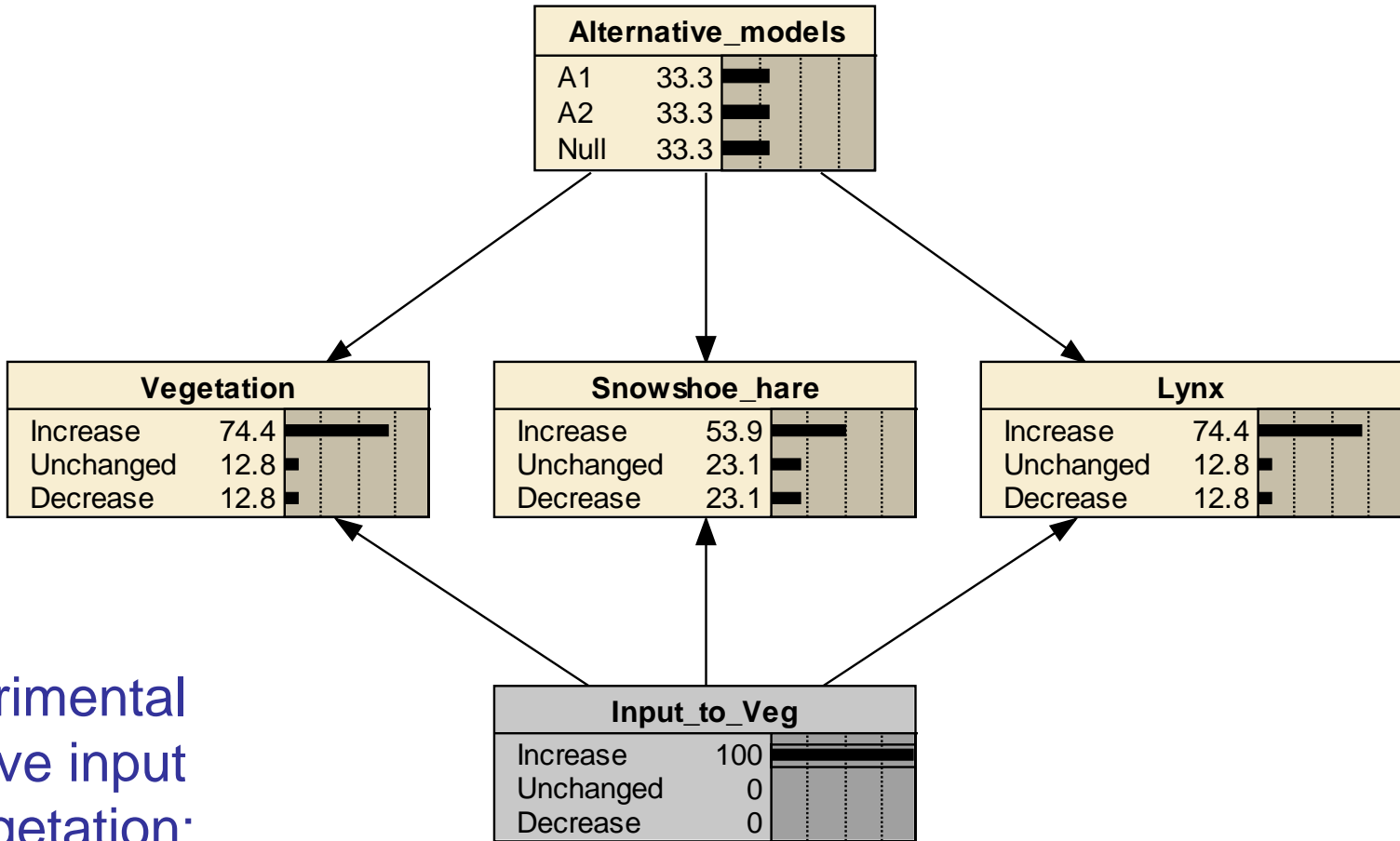
Lynx		
Increase	33.3	█
Unchanged	33.3	█
Decrease	33.3	█

Press perturbation:

Input_to_Veg		
Increase	33.3	█
Unchanged	33.3	█
Decrease	33.3	█



# Hare Lynx BBN



Experimental  
positive input  
to vegetation:

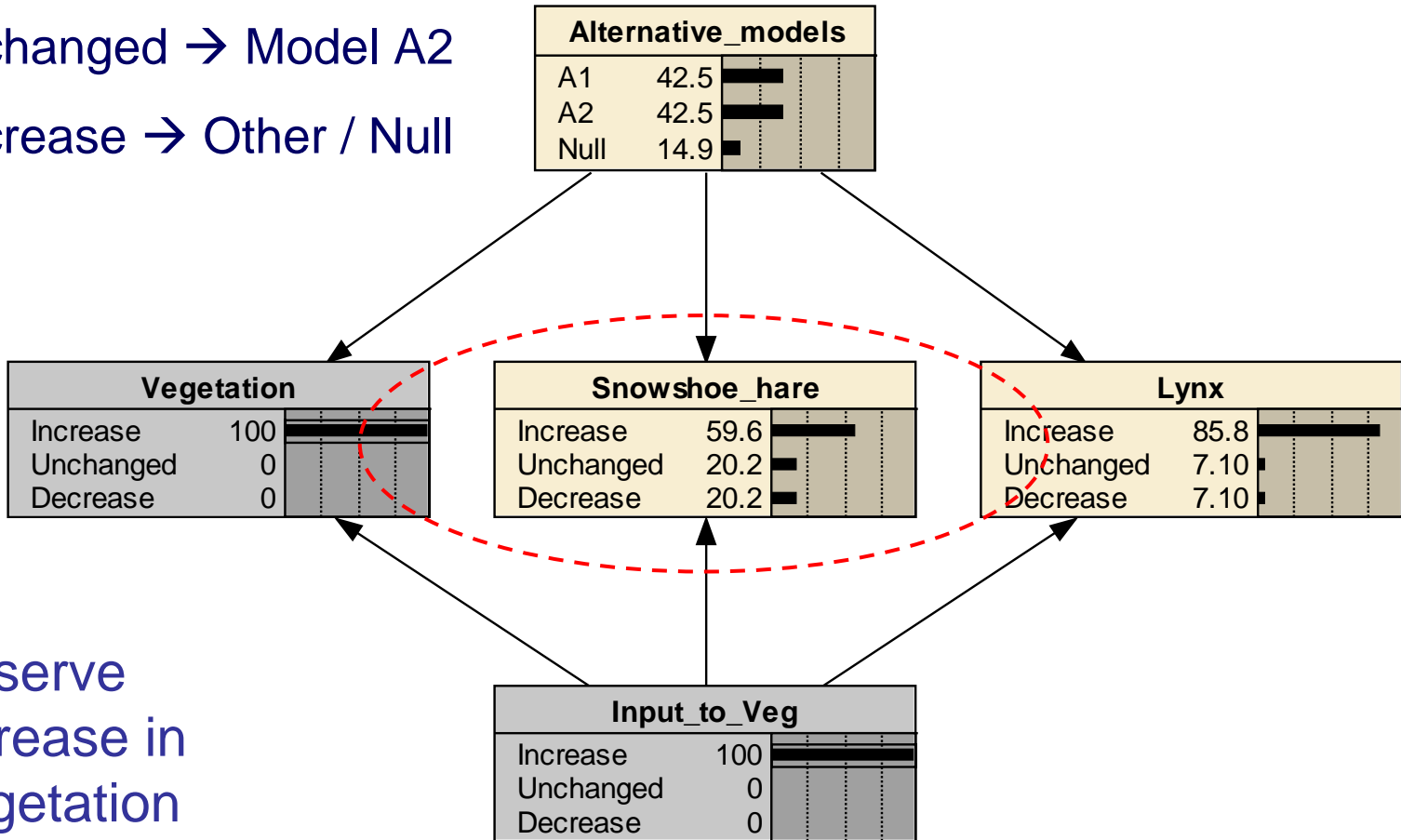


# Hare Lynx BBN

Hare Increase → Model A1

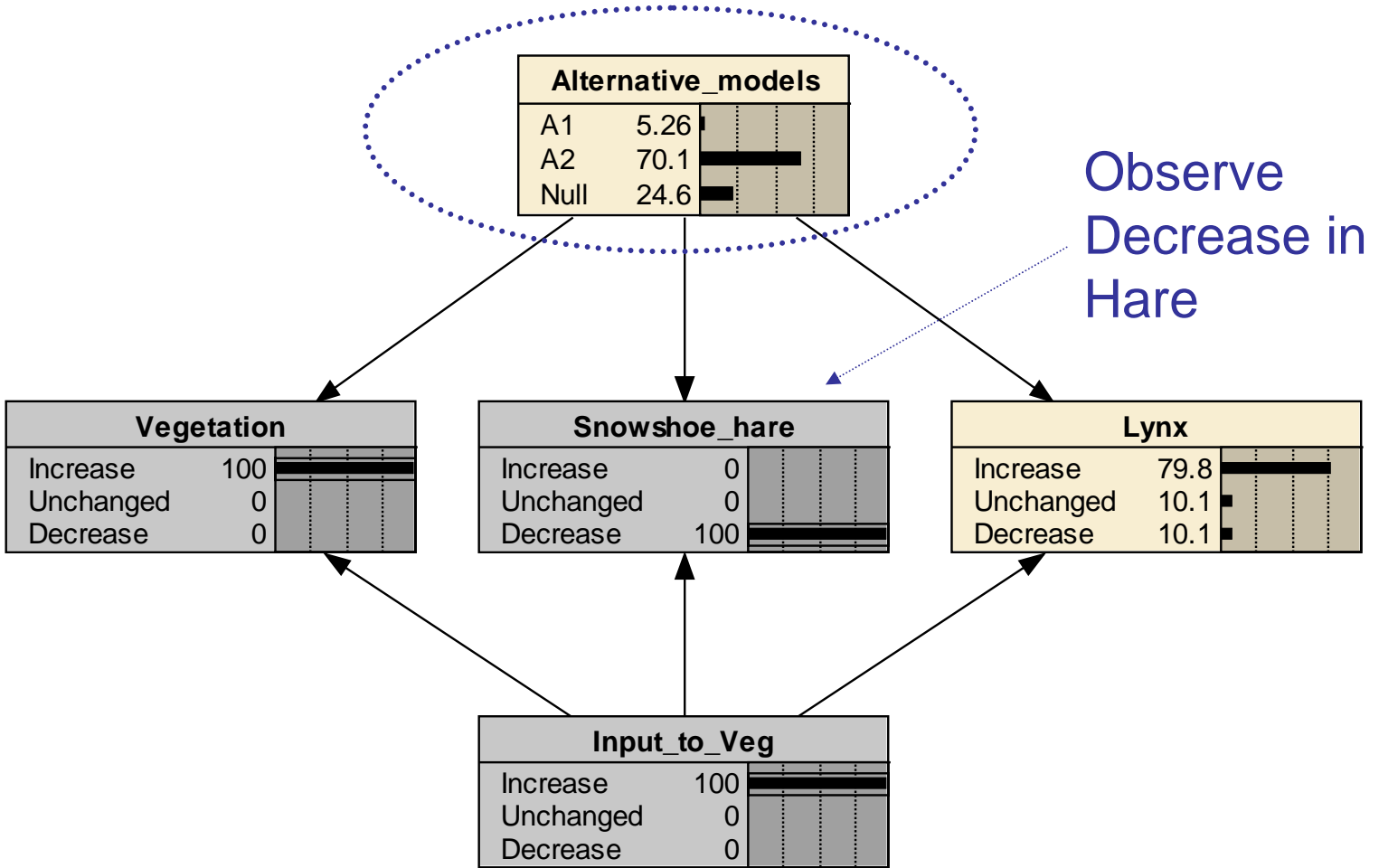
Hare Unchanged → Model A2

Hare Decrease → Other / Null



Observe  
Increase in  
Vegetation

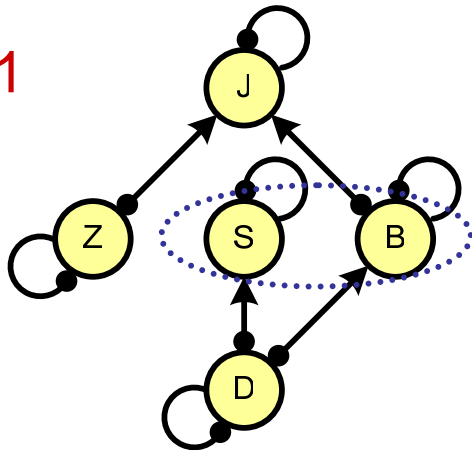
# Hare Lynx BBN



## Variables of interest:

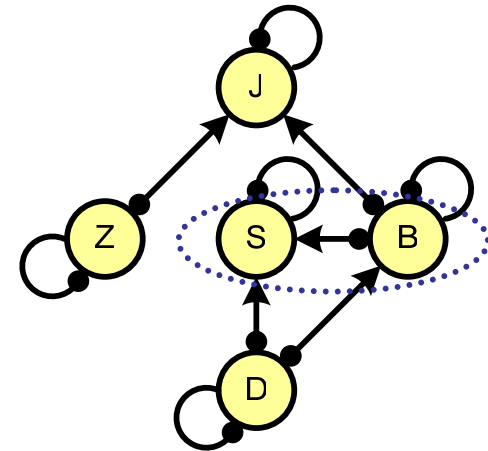
- Shrimp – Detritus – Zooplankton – Juvenile Fish – Benthic invertebrates

Model B1



Shrimp do not consume  
Benthic invertebrates

Model B2



Shrimp consume  
Benthic invertebrates



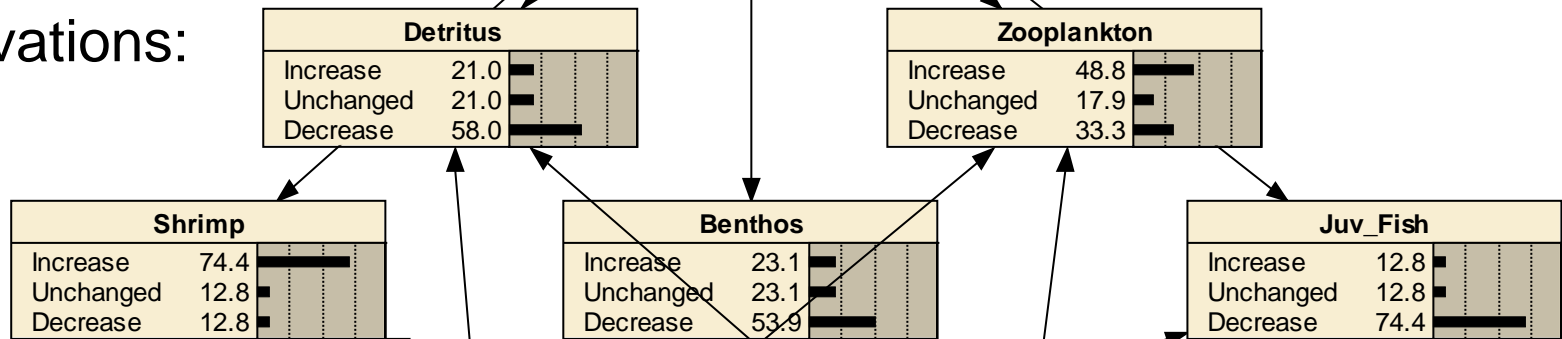
# Which variable best differentiates between models?

- If only have resources to monitor one variable, which should it be?

Model comparisons:

Alternative_Models		
B1	33.3	█
B2	33.3	█
Null	33.3	█

Observations:



Press perturbations:

Input_to_Detritus		
Increase	0	█
Unchanged	100	█
Decrease	0	█

Input_to_Shrimp		
Increase	100	█
Unchanged	0	█
Decrease	0	█



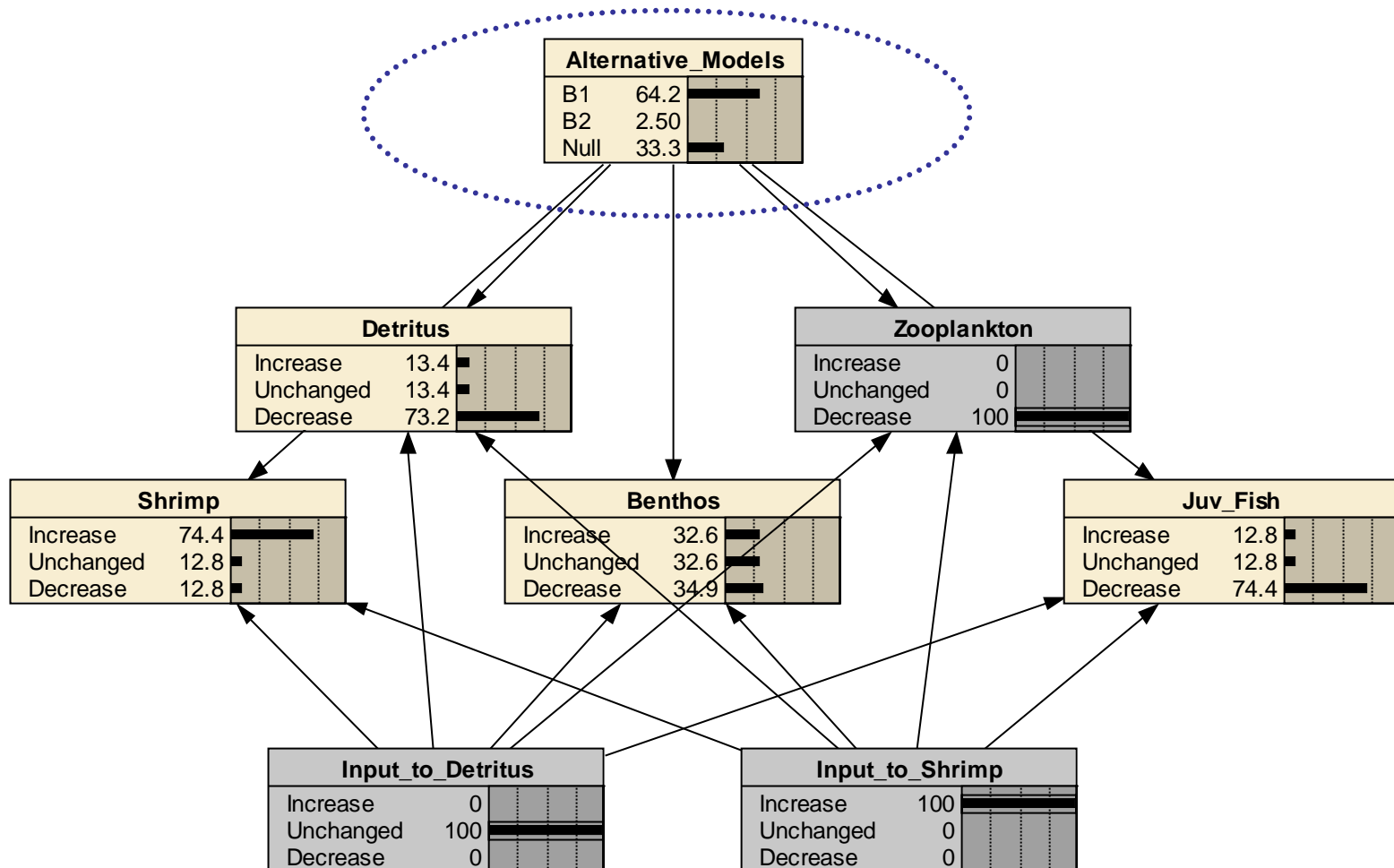
# Sensitivity Analysis of BBN Informs Monitoring Strategy

- **Sensitivity findings suggest zooplankton best discriminates between competing models:**
  - Model B1: Shrimp do not prey on benthic invertebrates
  - Model B2: Shrimp consume benthic invertebrates
  - Null Model: Uniform probabilities of increase or decrease

<b>Node</b>	<b>Mutual Information</b>
<b>Zooplankton</b>	<b>.404</b>
<b>Shrimp</b>	<b>.323</b>
<b>Juvenile Fish</b>	<b>.323</b>
<b>Benthic Invertebrates</b>	<b>.288</b>
<b>Detritus</b>	<b>.248</b>

# Observing a decrease in zooplankton suggests model B2 is incorrect

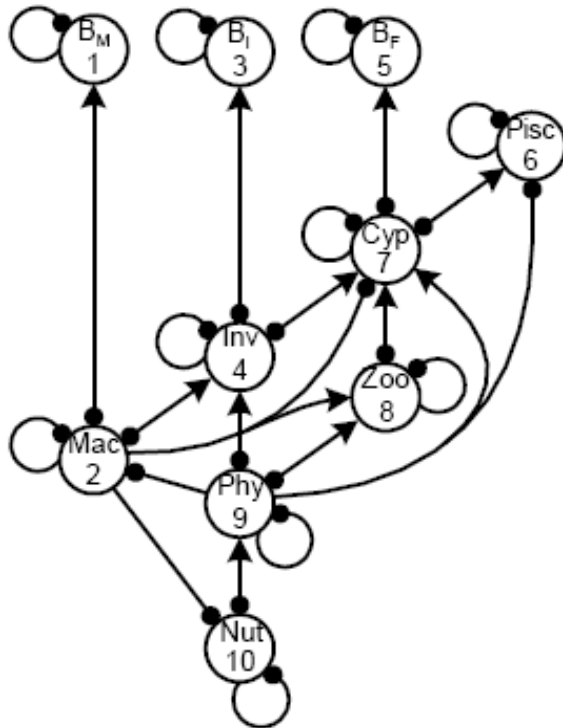
- Observation consistent with shrimp not preying on benthic invertebrates:



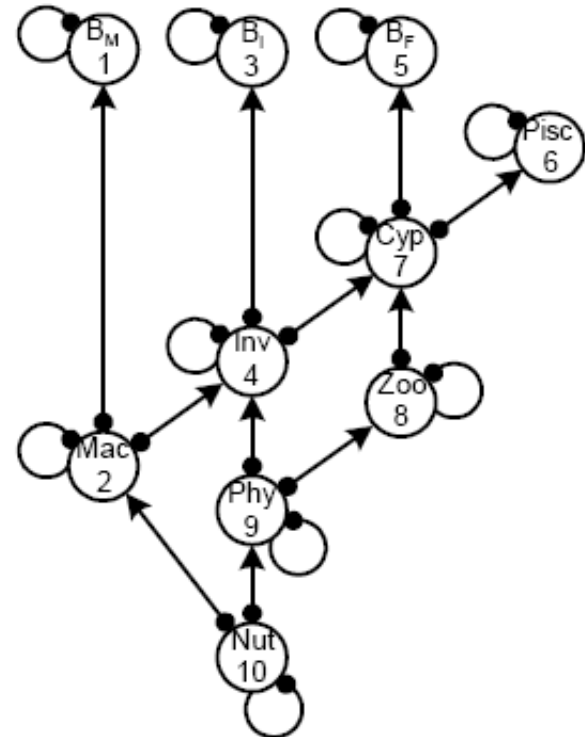
# More Qualitative Modelling advantages: Alternative model falsification

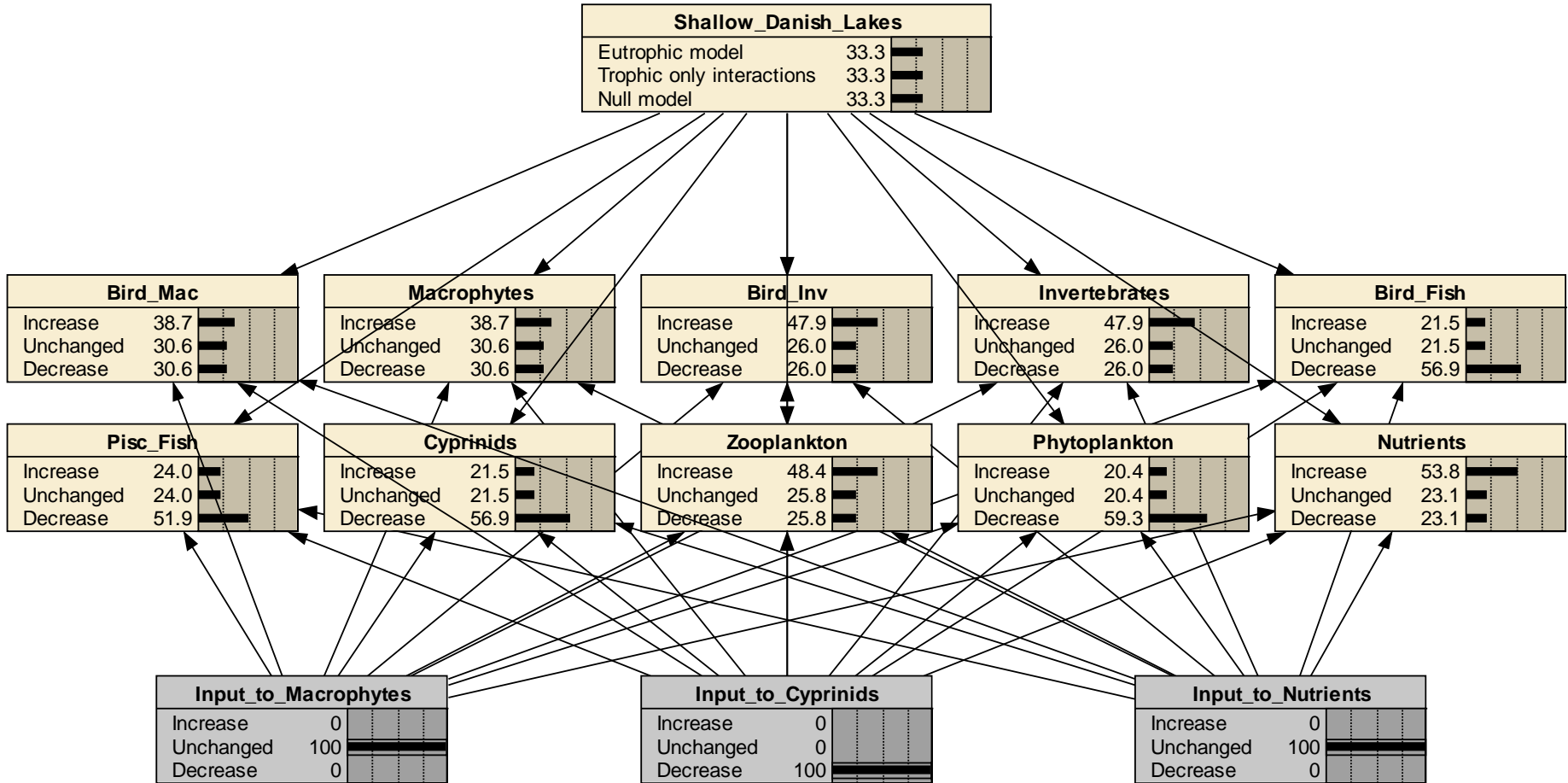
- BBN's sensitive to structural uncertainty with important impacts on intervention strategy (Varis and Kuikka 1999)

Eutrophic Lake



Trophic Interactions only



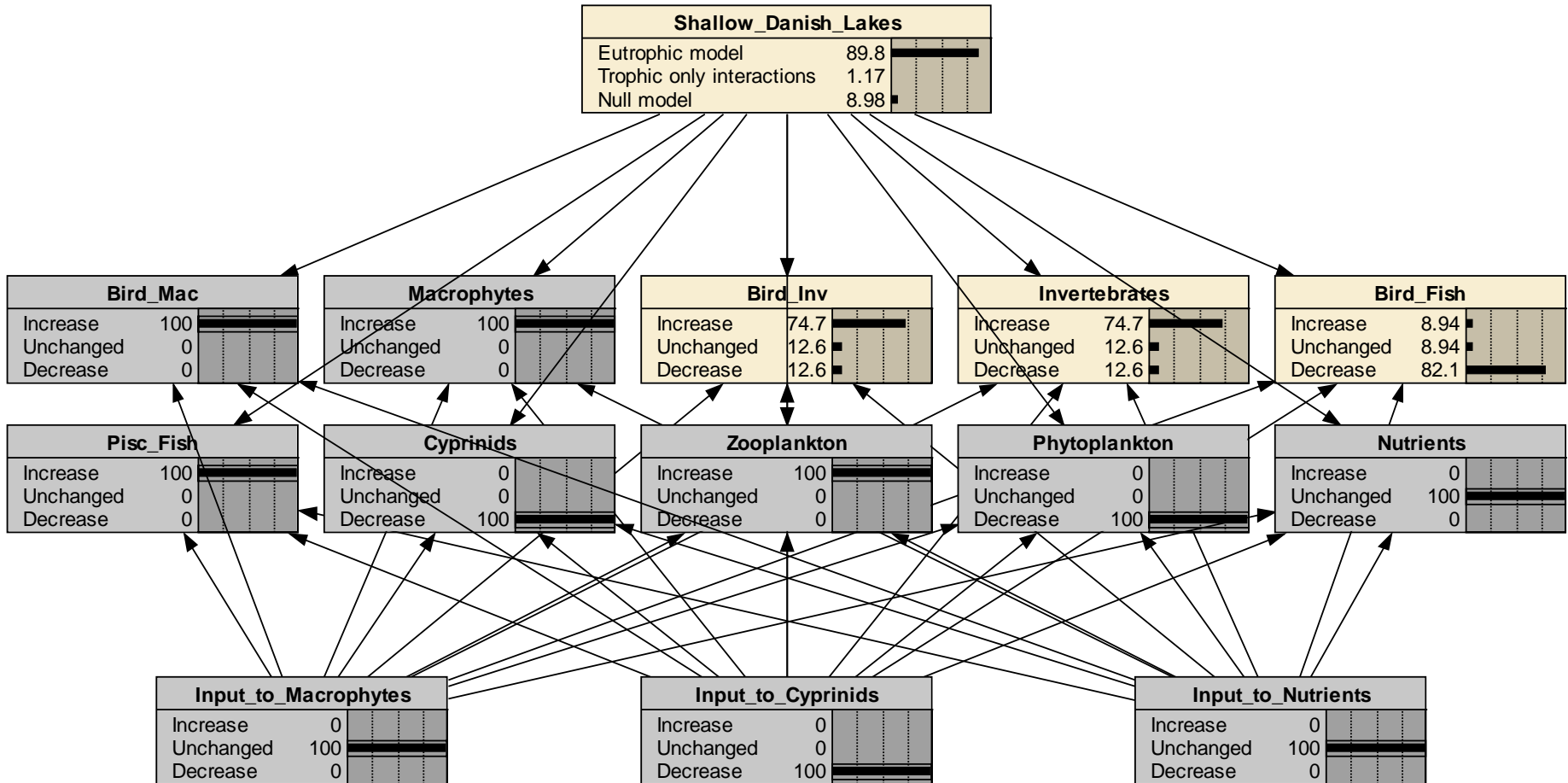


Cyprinid removal



# Danish Lake BBN

## “Optimistic” transformation:



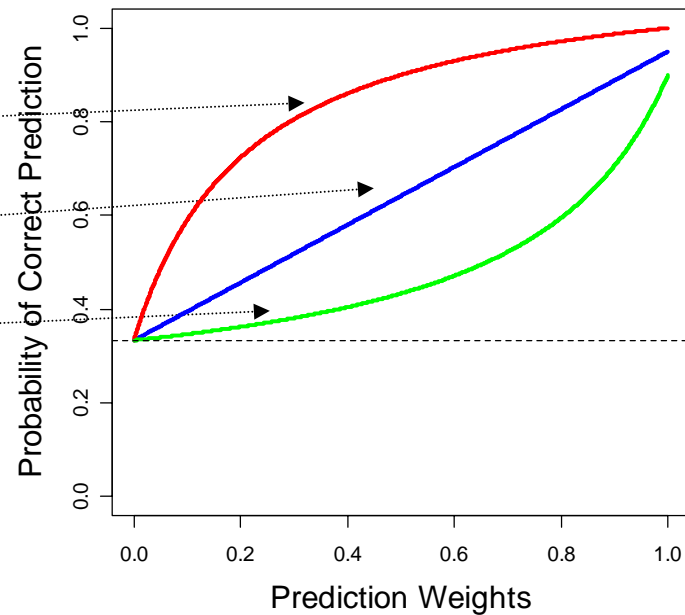
# Alternate models and transformations

- Observations from published studies of cyprinid removal
- Eutrophic and trophic models have predictions of same sign but different weights
- Tested three different weight-to-probability transformations:

“Optimistic”

“Linear”

“Pessimistic”



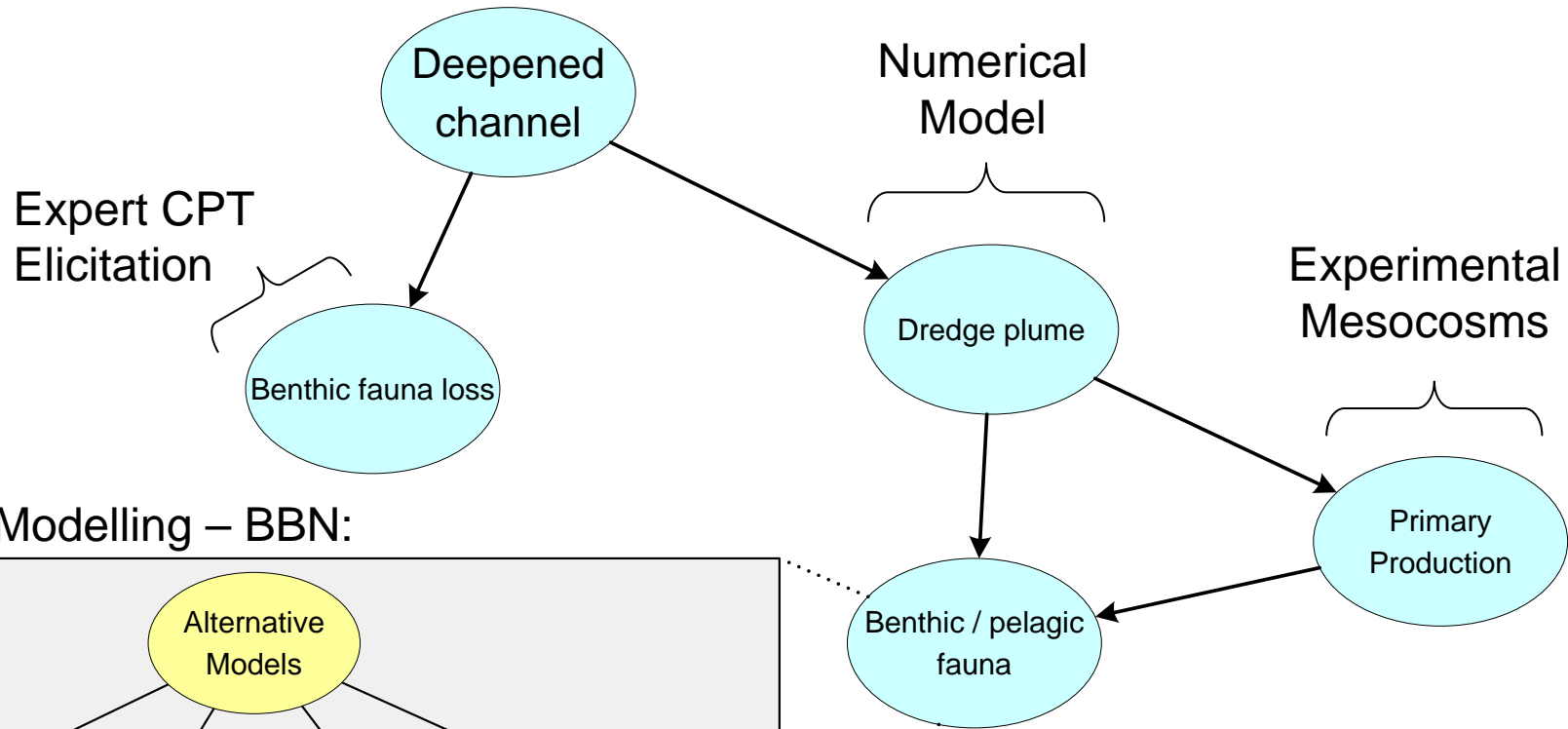


# Transformations influence ability to falsify alternative models

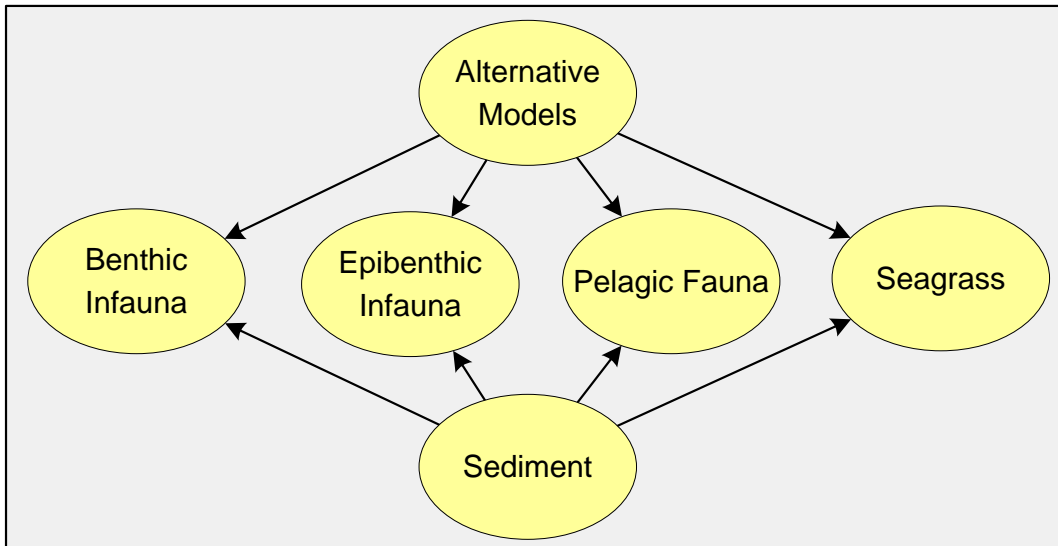
## Transformation:

Model	Optimistic	Linear	Pessimistic
Eutrophic	.90	.66	.41
Trophic	.01	.21	.38
Null	.09	.13	.22

- Eutrophic and trophic model predictions of same sign but different weights
- Each transformation suggested observations consistent with “eutrophic” model
- Optimistic transformations allow better model discrimination
  - Difficult to falsify under pessimistic transformation



## Qualitative Modelling – BBN:



## Advantages:

- Informed construction of large multi-conditional BBN's
- Explicit inclusion of important feedback cycles
- Represent multiple alternative models

## Why important?

**Incorporate both observations and model structure uncertainty in Bayesian framework to predict community response following perturbation**

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# Thank You

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