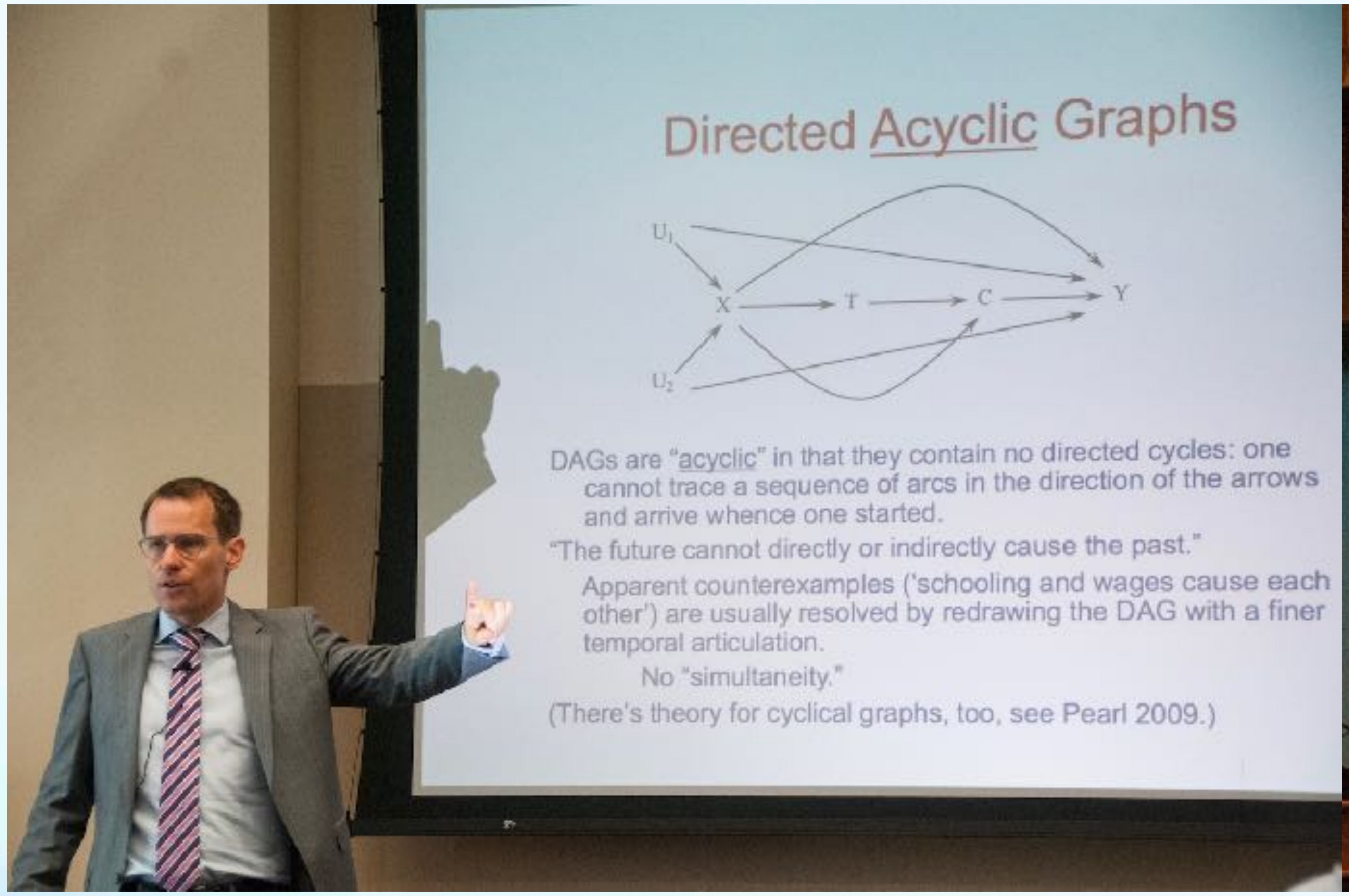
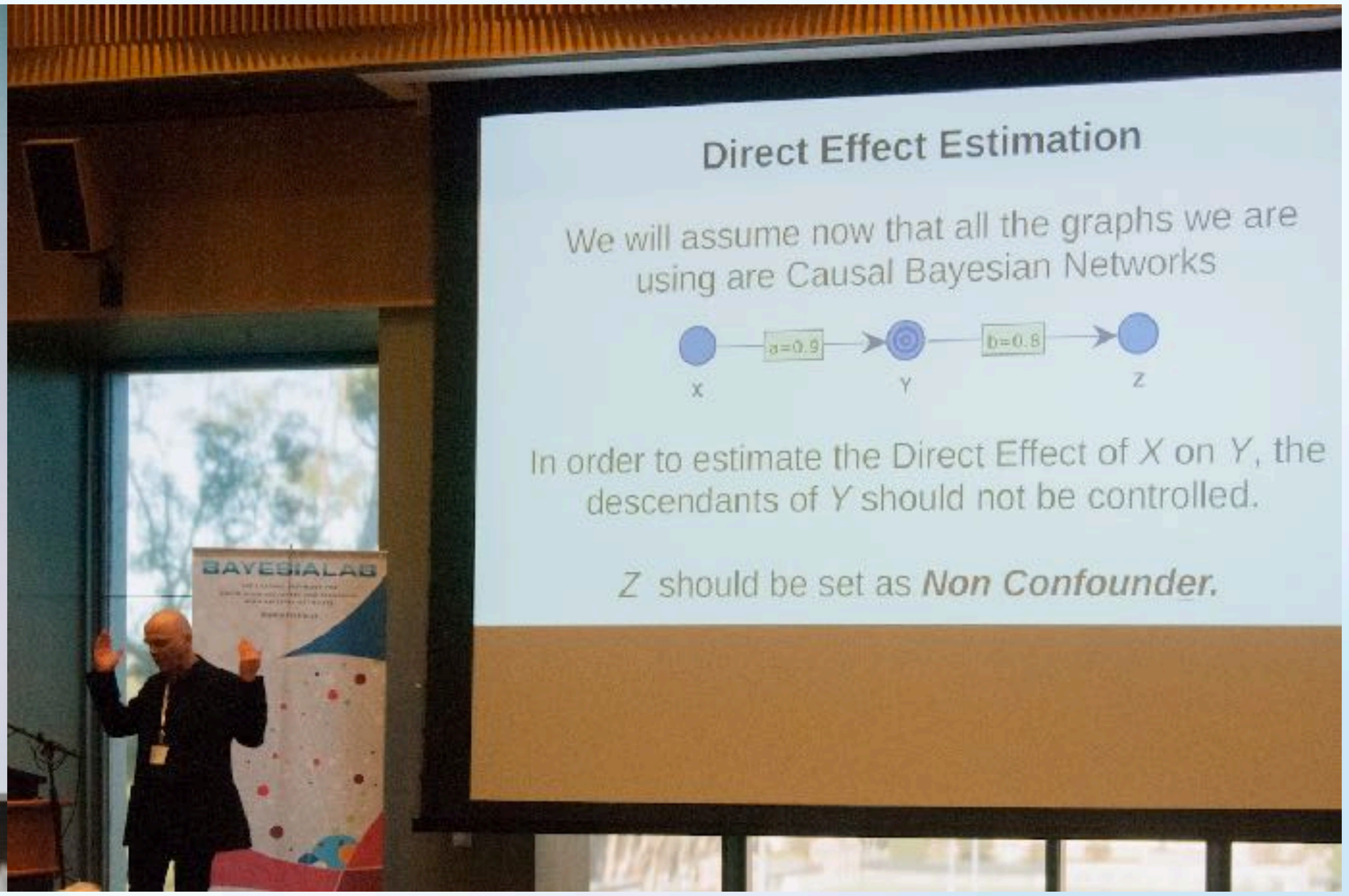
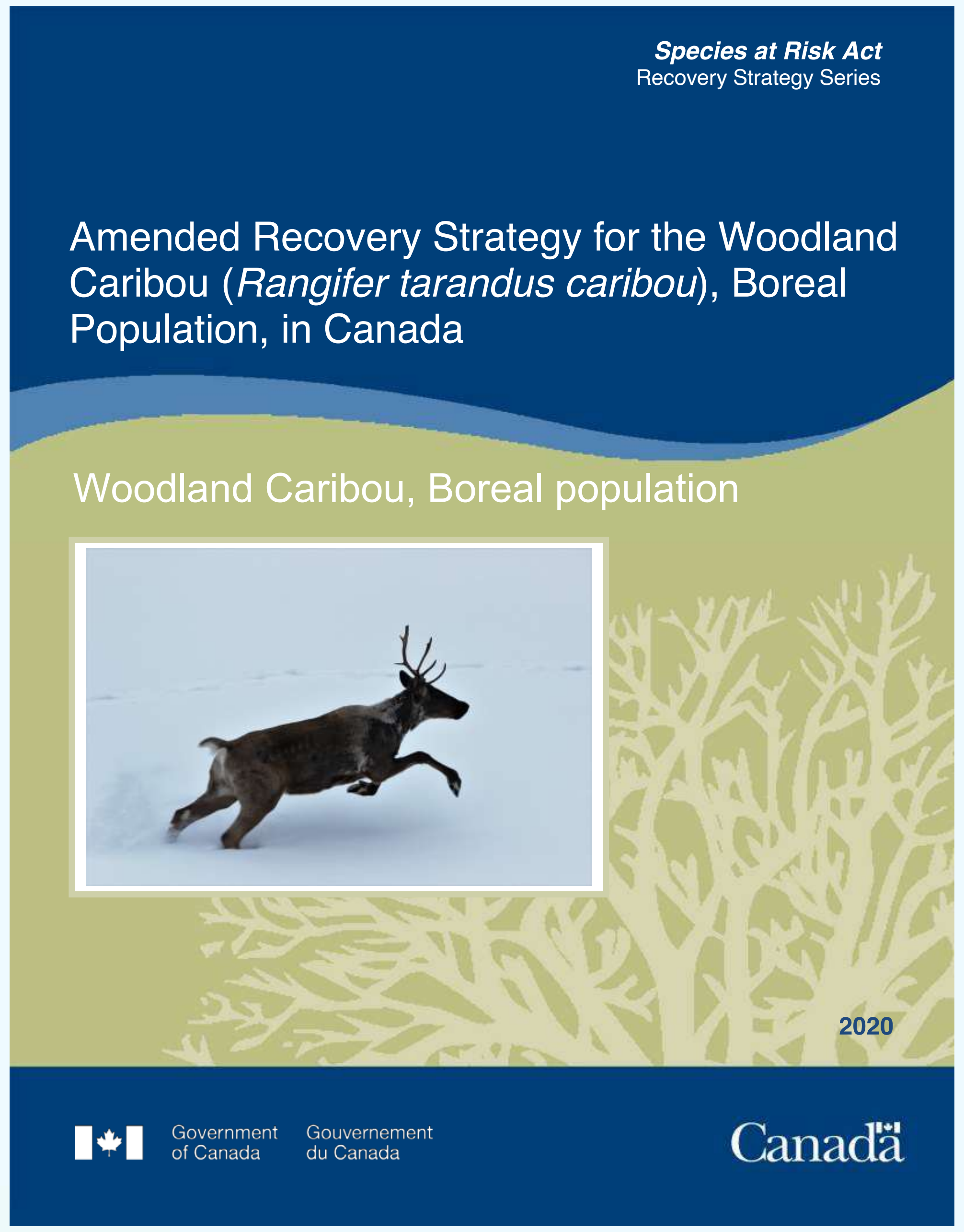
Counterfactual Reasoning Using Bayesian Networks for Environmental Policy Analysis

A Case Study of Woodland Caribou in Northern Canada

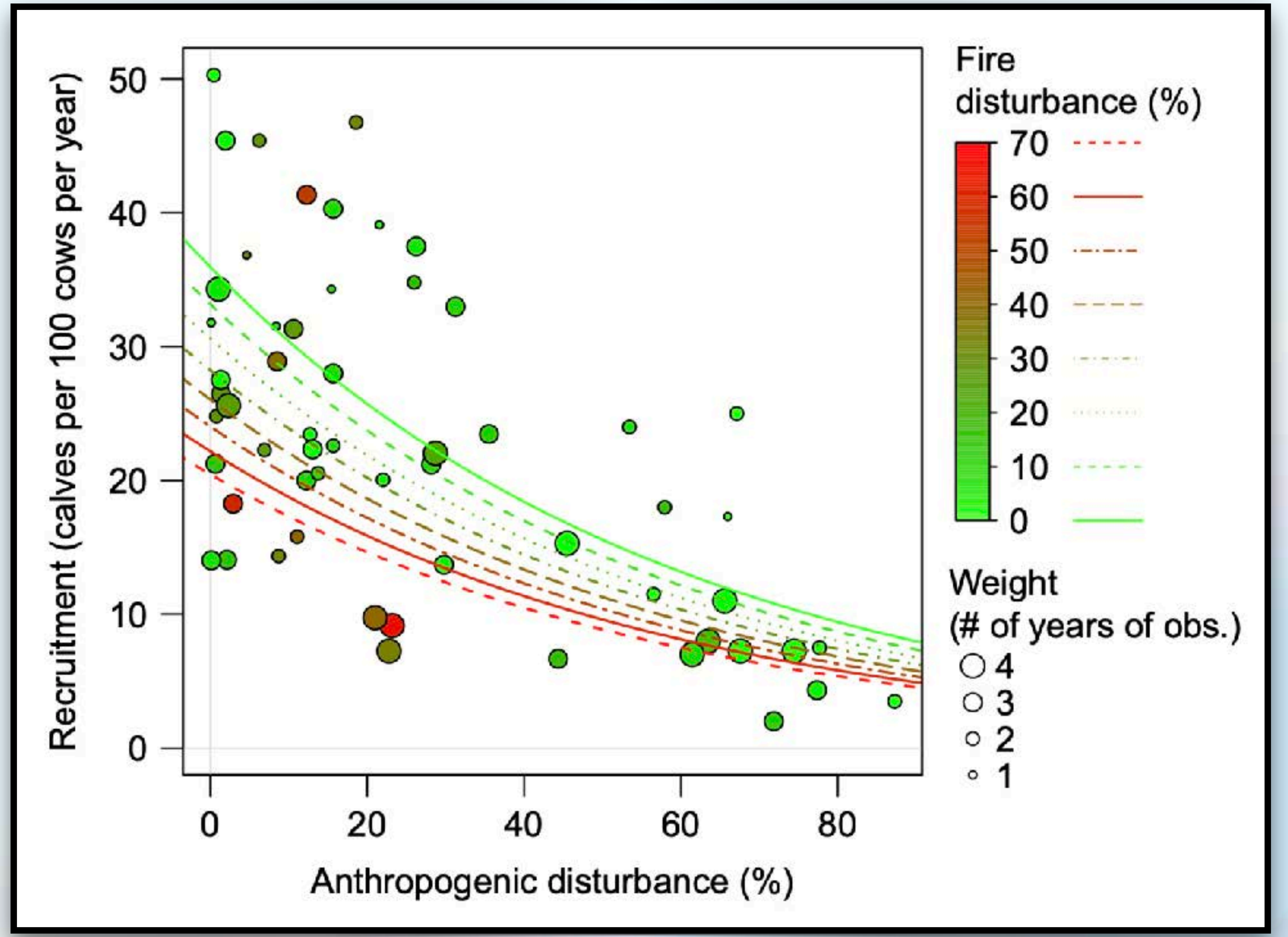
Steven F. Wilson, Ph.D., EcoLogic Research


Directed Acyclic Graphs
U1
X
T
C
Y
U2
DAGs are "acyclic" in that they contain no directed cycles: one cannot trace a sequence of arcs in the direction of the arrows and arrive whence one started.
"The future cannot directly or indirectly cause the past."
Apparent counterexamples ('schooling and wages cause each other') are usually resolved by redrawing the DAG with a finer temporal articulation.
No "simultaneity."
(There's theory for cyclical graphs, too, see Pearl 2009.)


BAYESIALAB
Direct Effect Estimation
We will assume now that all the graphs we are using are Causal Bayesian Networks
X
Y
Z
In order to estimate the Direct Effect of X on Y, the descendants of Y should not be controlled.
Z should be set as Non Confounder.



"Restoration of disturbed habitat to a minimum 65% undisturbed habitat will be necessary."



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Perspective

A causal modelling approach to informing woodland caribou conservation policy from observational studies

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ABSTRACT

As global conservation actions become more urgent, informed decision-making requires robust analyses of the costs and benefits of policy options, based on available evidence. Recovery planning for threatened or endangered species must assume a cause-and-effect relationship between proposed management interventions and population responses. However, a significant portion of current knowledge about threatened or endangered species is derived from observational studies because experiments that fully meet random and controlled design criteria are largely infeasible or unethical. Large-scale field experiments are becoming more common, yet the greater uncertainty generated by what remain fundamentally observational studies can lead researchers to weak inferences about causal mechanisms, creating debate and confusion among decision-makers, planners and stakeholders. This has been an acute problem facing conservationists and governments as they struggle with the successful recovery of species in decline. In other domains where experimental evidence is difficult to collect, causal modelling has been adopted to identify causal relationships from observational data, based on a set of strong assumptions and identification rules. In Canada, significant and ongoing efforts have had limited success in reversing the population decline of woodland caribou (*Rangifer tarandus caribou*). We examine the scientific framework for woodland caribou recovery efforts through the lens of causal modelling, highlighting feasible steps that could be taken to improve the rigour of causal inferences.

1. Introduction

Successful conservation of species and ecosystems requires forecasts of the future benefits of management interventions to ensure sound decision making; however, most assessments rely on retrospective evaluations of observational data that may not generate reliable predictions (Oliver and Roy, 2015; Law et al., 2017). This issue is particularly acute for wide-ranging species on multiple-use landscapes where experimental studies that can fully satisfy random and controlled design criteria are infeasible, and/or where management interventions are associated with significant economic, social or ethical implications. As Druzdzel and Simon (1993:4) noted, "*the effect of a structural change in a system cannot be induced from a model that does not contain causal information. Having the causality right is crucial for any policy making.*"

Caribou and reindeer (*Rangifer tarandus*) are in general decline throughout their global range, despite ongoing conservation efforts (Vors and Boyce, 2009; Gunn, 2016). Woodland caribou (*R. tarandus caribou*) are legally classified as *Threatened* throughout most of Canada, but subpopulations continue to decline, fragment, and disappear, particularly along the southern extent of their range (Environment Canada, 2014; Environment and Climate Change Canada, 2020). While caribou ecology varies among regions, the primary cause of decline is considered to be apparent competition (Holt, 1977; DeCesare et al., 2009), whereby abundant "primary" prey species such as moose (*Alces alces*), white-tailed deer (*Odocoileus virginianus*), and elk (*Cervus canadensis*) support increased predator populations (primarily wolves, *Canis lupus,* but also cougars, *Puma concolor,* coyotes, *Canis latrans*, and bears, *Ursus spp.*), which consequently prey on caribou. Because caribou have a lower reproductive potential than the primary prey, these species fare better and appear to out-compete declining caribou. Because anthropogenic landscape change and wildfire are argued to be causing the increase in primary prey, the mechanism has been described as "habitat-mediated" apparent competition (Frenette et al., 2020; Neufeld et al., 2021).

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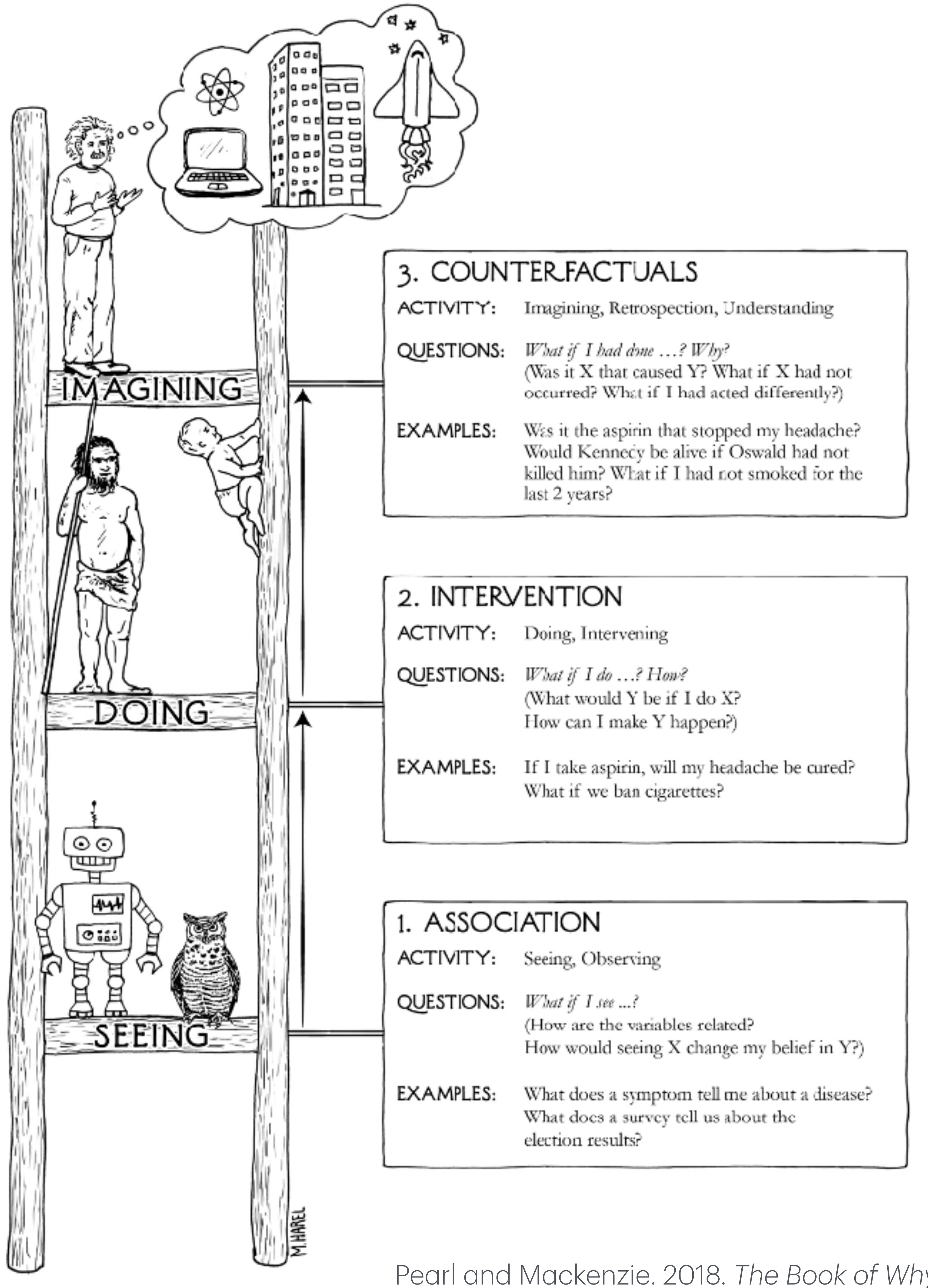


Pearl and Mackenzie. 2018. *The Book of Why*

"Policy analysis is an exercise in counterfactual reasoning" Pearl (2009)

Policy option: if you have a headache, take an aspirin

1. "If I have a headache, will taking an aspirin cause it to go away?"

What is the effect (headache goes away) of a cause (taking an aspirin)?

2. "My headache went away; is it because I took an aspirin?"

What is the cause (taking an aspirin?) of the effect (headache goes away)?

Counterfactual: If I hadn't taken the aspirin, would my headache not have gone away?

Necessary and Sufficient Causation

- **Necessary causation:** probability that an outcome would not have occurred in the absence of an event (given that they both did occur)
- **Sufficient causation:** probability that an outcome would have occurred in the presence of an event (given that they both did not occur)
- **Necessary and sufficient causation:** probability that the outcome would have occurred in the presence of the event and would not have occurred in its absence

From Rung 2 to Rung 3

Interventions → Counterfactuals

Exogenous and monotonic

Causal Effects from Observational Data

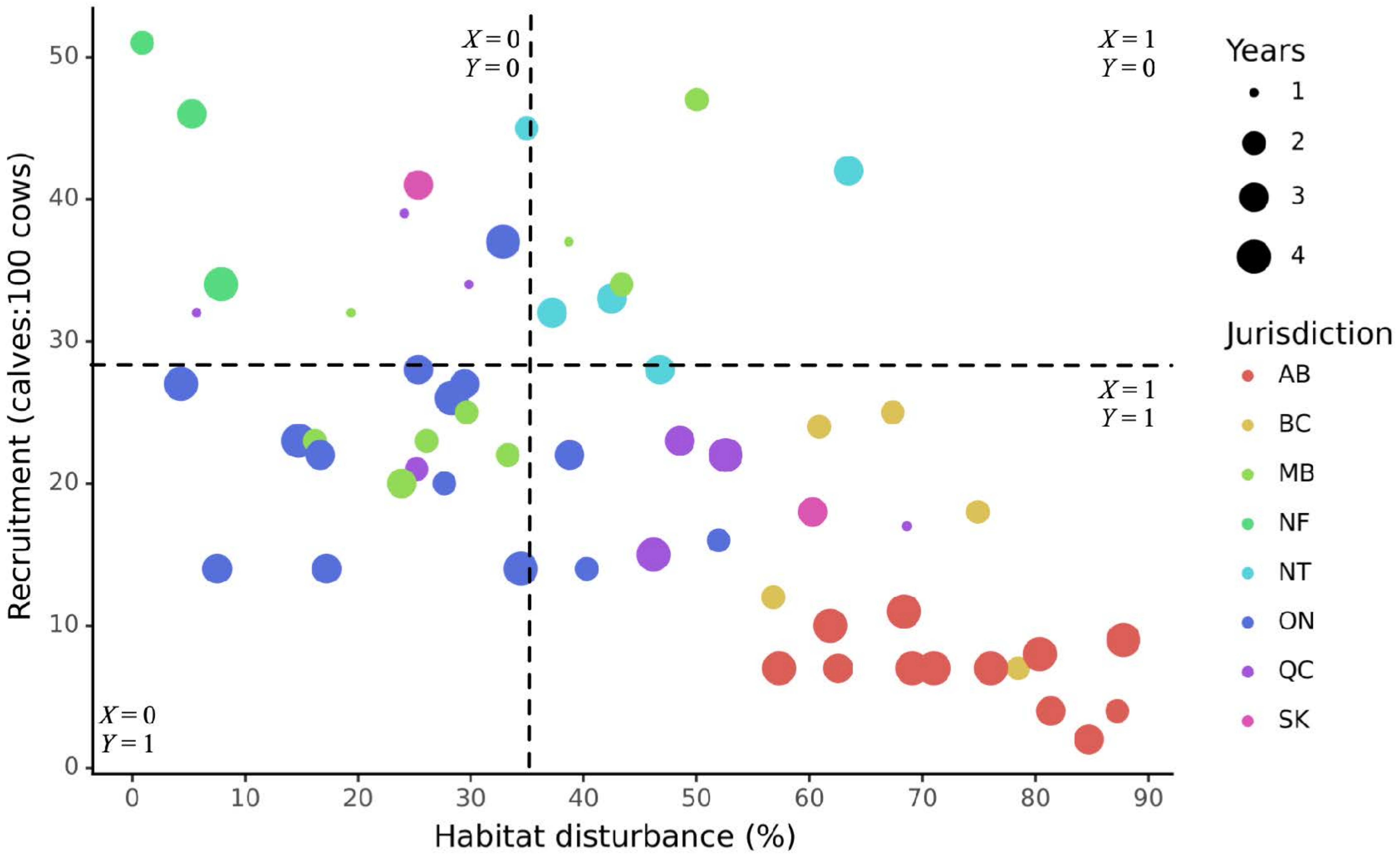
- **Observations → Interventions →Counterfactuals** increases the information required about a system and/or the assumptions that need to be made
- Using Bayesian causal networks for counterfactual reasoning with observational data assumes an exogenous exposure and a monotonic effect

Cambridge Bay
Kugluktuk
Gjoa Haven
Kugaaruk
YUKON
NUNAVUT
NORTHWEST TERRITORIES
Whitehorse
Baker Lake
Yellowknife
Rankin Inlet
Skagway
Maxhamish
Sitka
Ketchikan
Canada
ALBERTA
BRITISH COLUMBIA
MANITOBA
Edmonton
SASKATCHEWAN
Calgary
Vancouver
Winnipeg
Seattle
Spokane
WASHINGTON
Portland
NORTH DAKOTA


2017-05-27 06:25:02 M 2/5 5°C
PC900 PROFESSIONAL

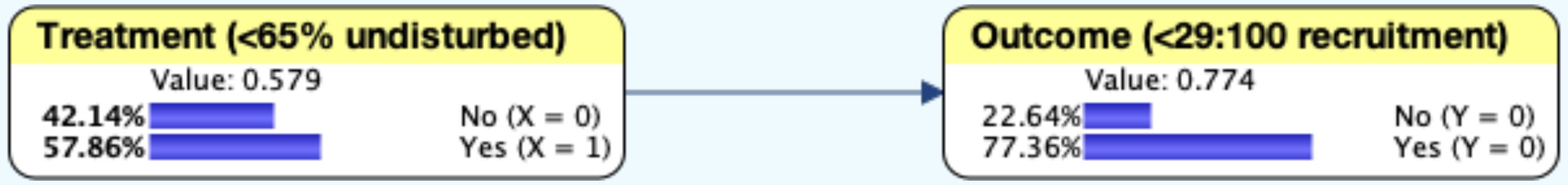

2017-05-13 19:34:22 M 1/5 5°C
PC900 PROFESSIONAL





Recruitment (calves:100 cows)
Habitat disturbance (%)
X = 0
Y = 0
X = 1
Y = 0
X = 1
Y = 1
X = 0
Y = 1
Years
1
2
3
4
Jurisdiction
AB
BC
MB
NF
NT
ON
QC
SK
0
10
20
30
40
50
60
70
80
90

Implied Causal Model

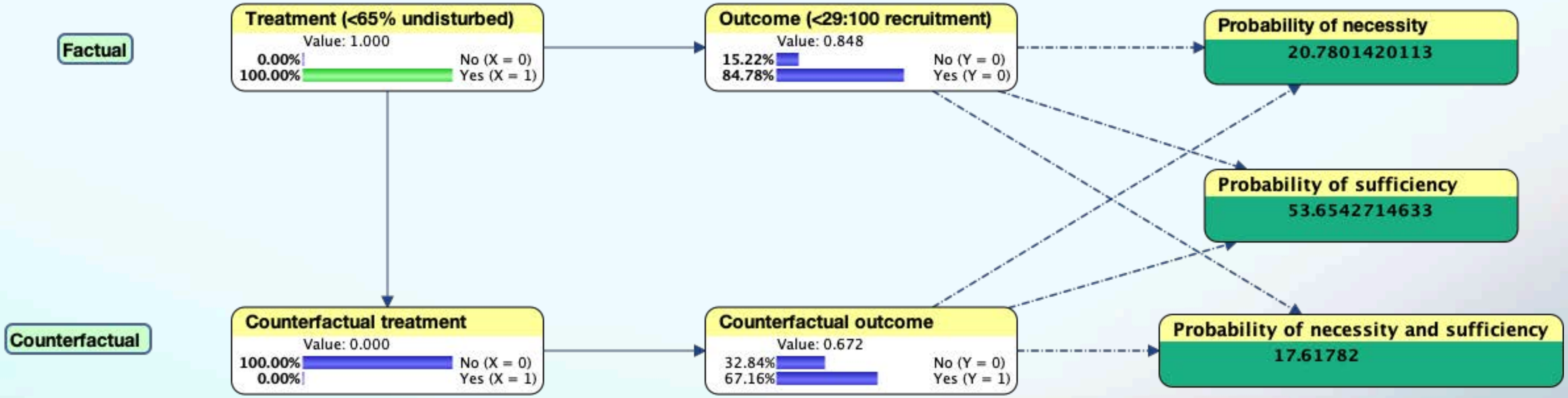


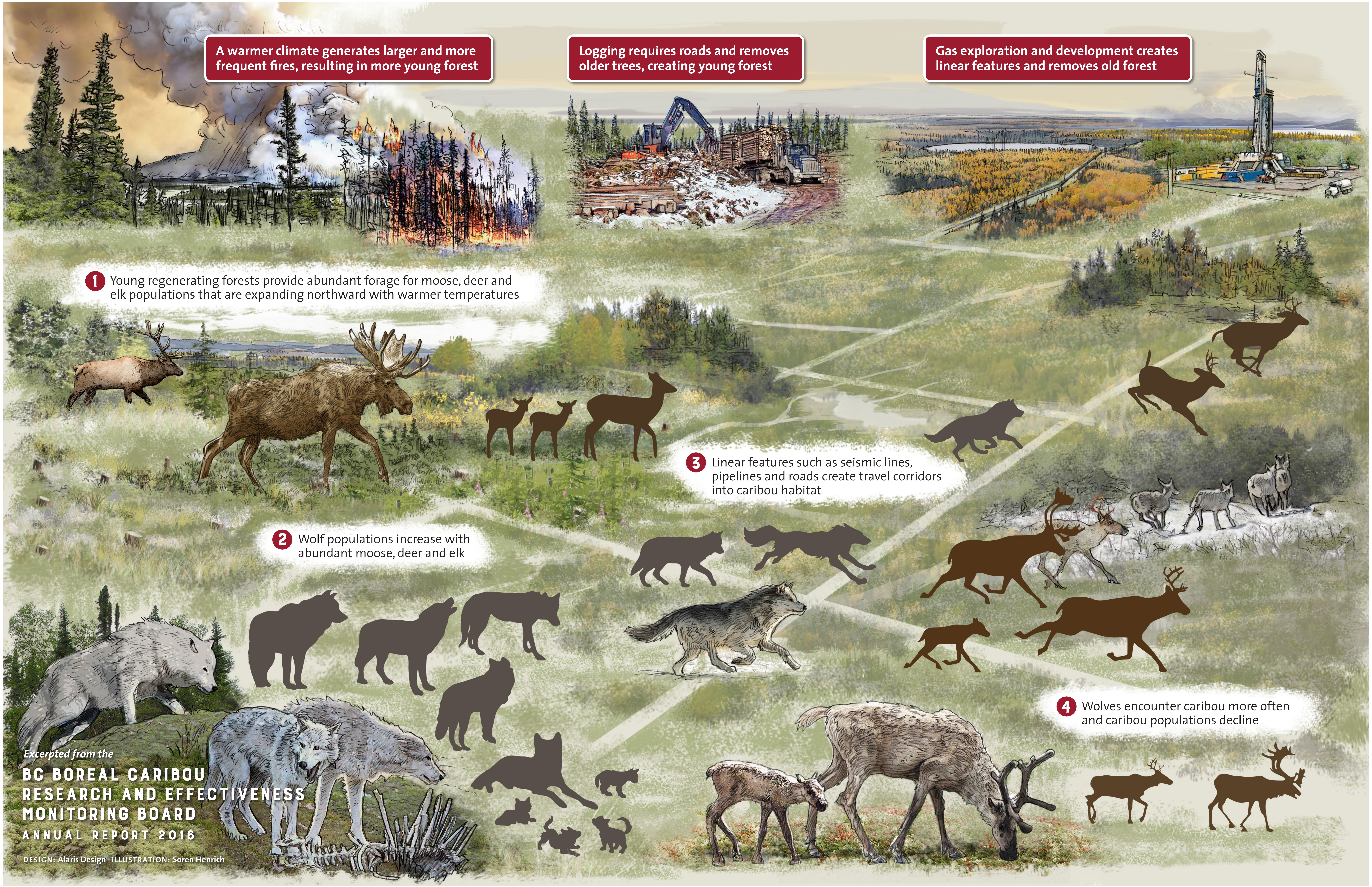
Factual: $p_1 = P(Y = 1|X = 1)$

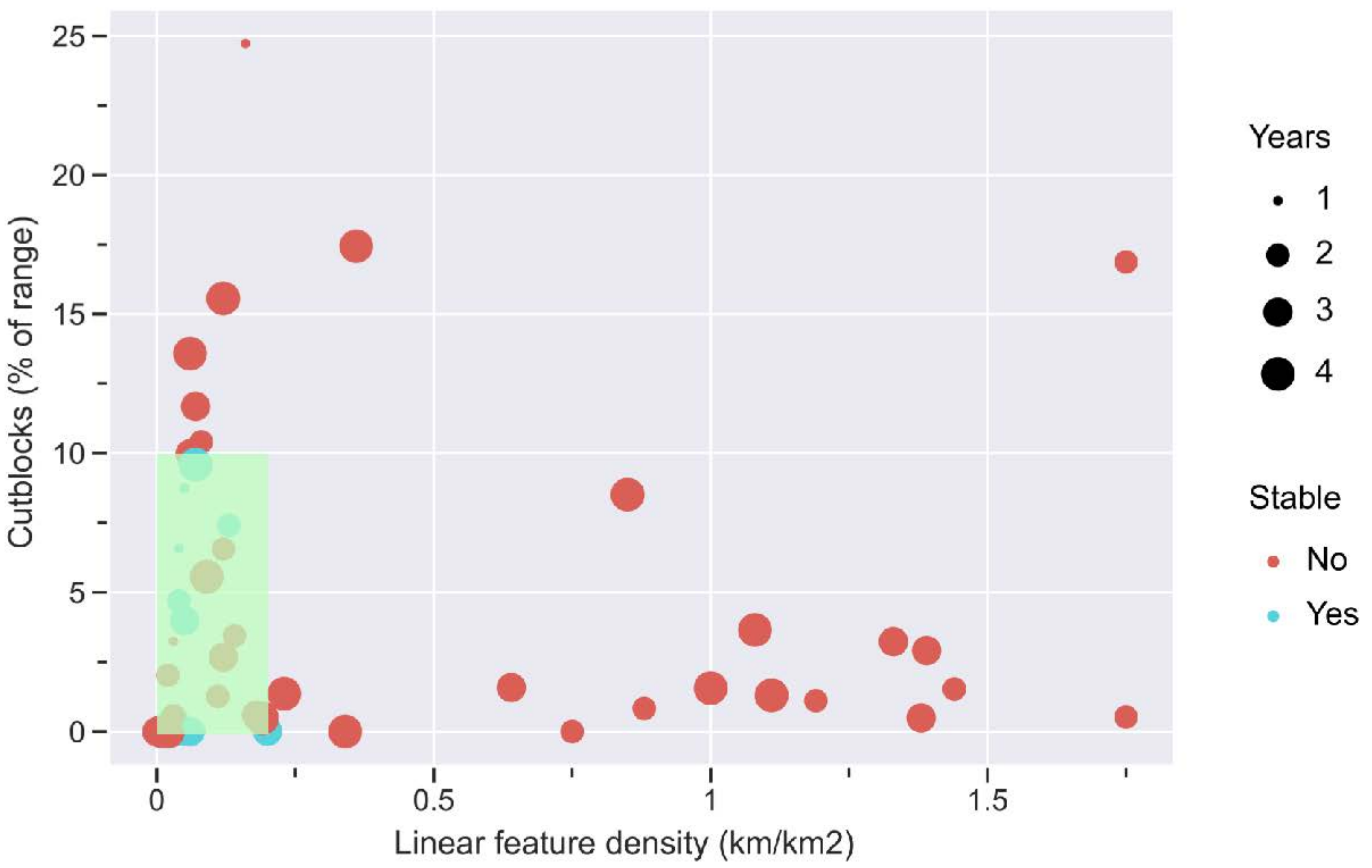
Counterfactual: $p_0 = P(Y = 1|X = 0)$

$$PN = max\left\{1 - \frac{p_0}{p_1}, 0\right\} \qquad PS = max\left\{1 - \frac{1 - p_1}{1 - p_0}, 0\right\} \qquad PNS = max\left\{p_1 - p_0, 0\right\}$$

Assuming exposure is exogenous and has a monotonic effect

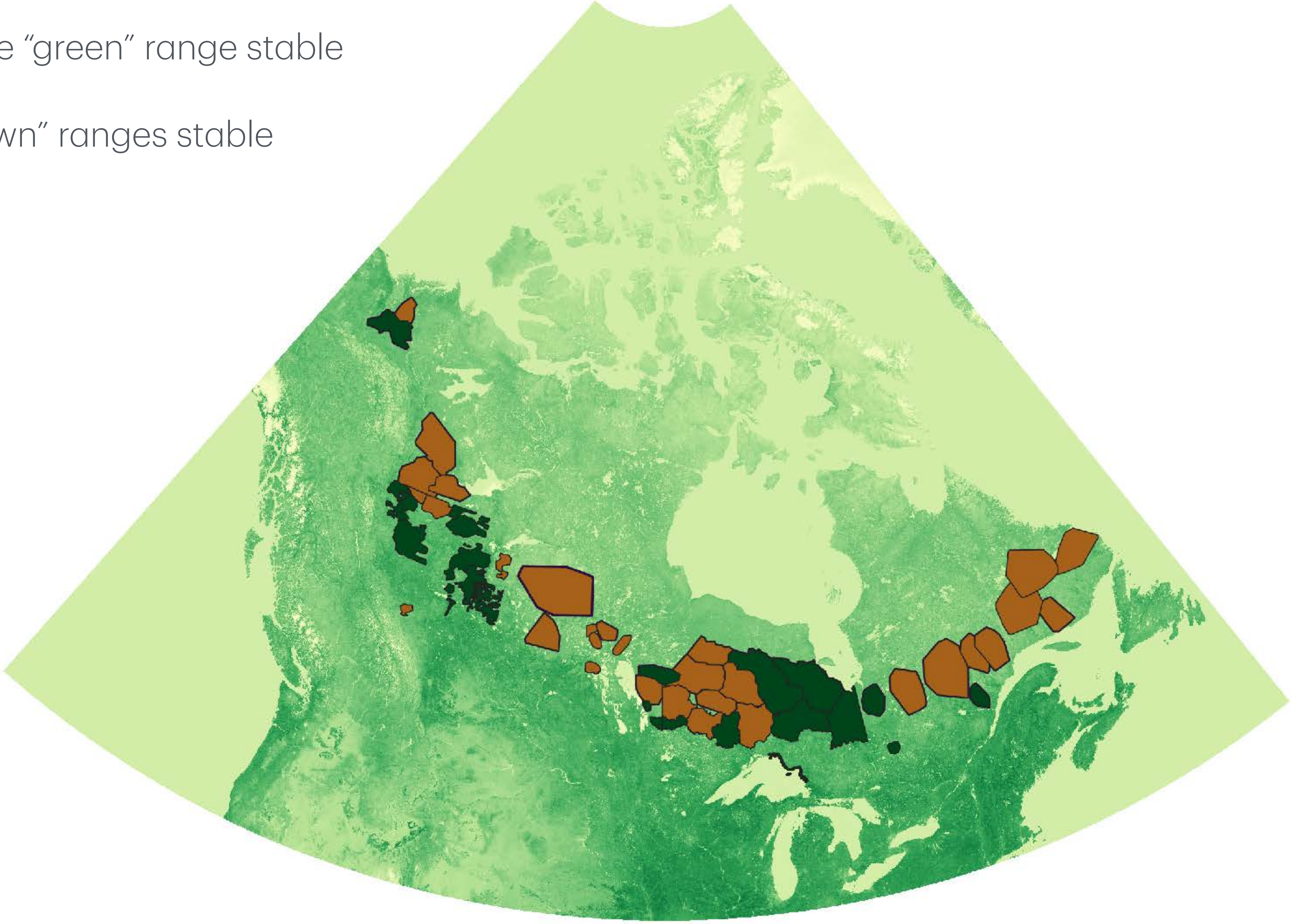

Factual
Counterfactual
Treatment (<65% undisturbed)
Value: 1.000
0.00% No (X = 0)
100.00% Yes (X = 1)
Outcome (<29:100 recruitment)
Value: 0.848
15.22% No (Y = 0)
84.78% Yes (Y = 0)
Counterfactual treatment
Value: 0.000
100.00% No (X = 0)
0.00% Yes (X = 1)
Counterfactual outcome
Value: 0.672
32.84% No (Y = 0)
67.16% Yes (Y = 1)
Probability of necessity
20.7801420113
Probability of sufficiency
53.6542714633
Probability of necessity and sufficiency
17.61782

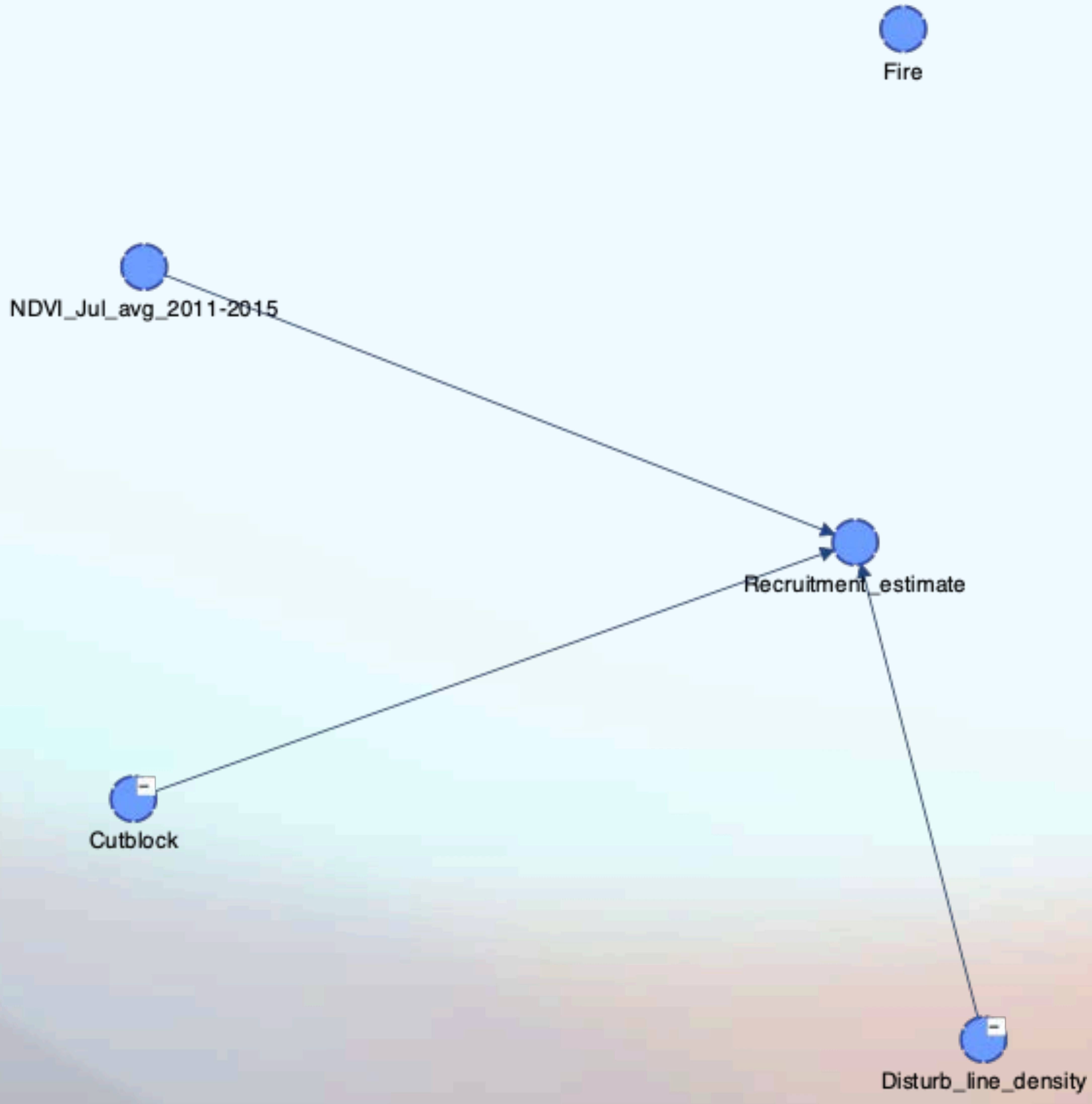

A warmer climate generates larger and more frequent fires, resulting in more young forest
Logging requires roads and removes older trees, creating young forest
Gas exploration and development creates linear features and removes old forest
1 Young regenerating forests provide abundant forage for moose, deer and elk populations that are expanding northward with warmer temperatures
2 Wolf populations increase with abundant moose, deer and elk
3 Linear features such as seismic lines, pipelines and roads create travel corridors into caribou habitat
4 Wolves encounter caribou more often and caribou populations decline
Excerpted from the
BC BOREAL CARIBOU RESEARCH AND EFFECTIVENESS MONITORING BOARD
ANNUAL REPORT 2016
DESIGN: Alaris Design ILLUSTRATION: Soren Henrich



Fire is a third source of disturbance (no under management control)

- Only one “green” range stable
- 1/3 “brown” ranges stable





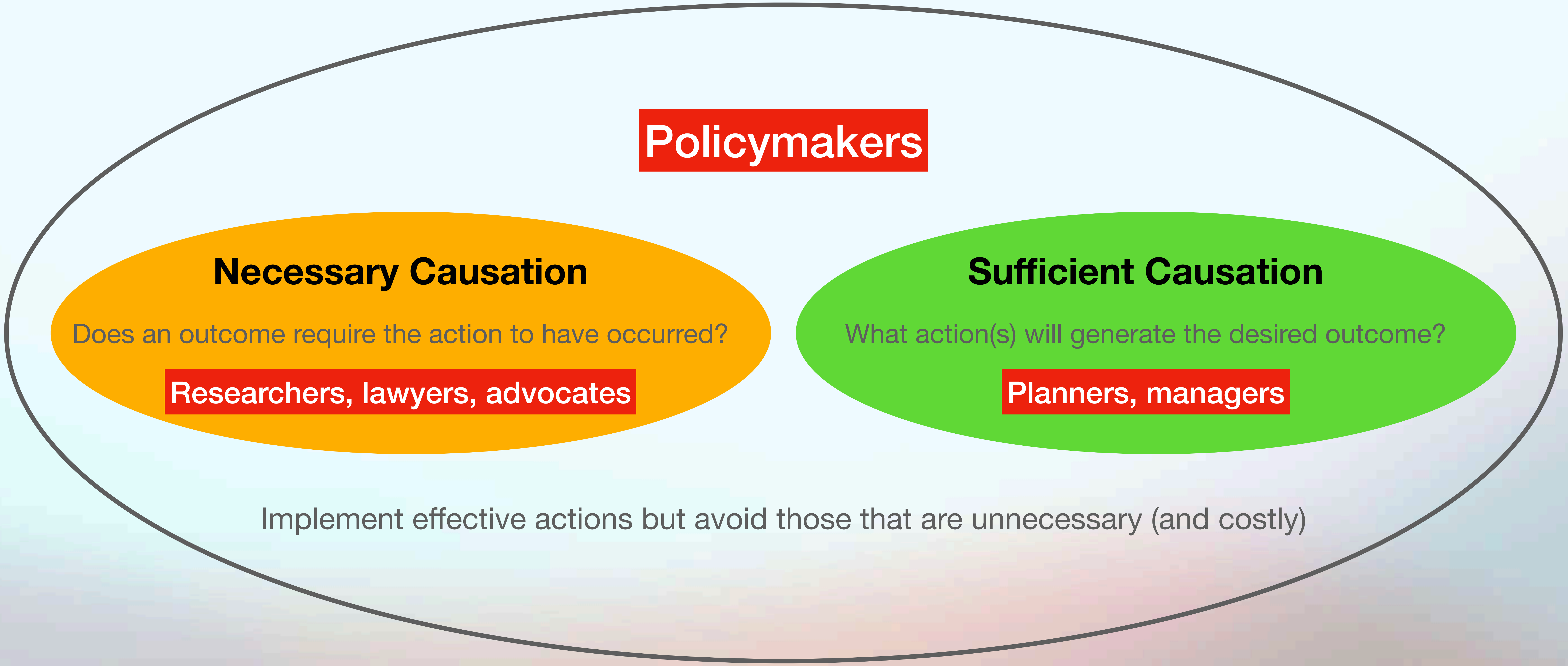
- Assume no unobserved variables
- Set temporal indices
- Learn network
- Delete/reorient edges and relearn, if necessary

Model	Conditioning	Exposure	p_1	p_0	PN (%)	PS (%)	PNS (%)
Aggregate disturbance	**None**	**<65% undisturbed**	0.8483	0.6722	20.8	53.7	17.6
Separate disturbance	**None**	**Linear >0.02**	1.0000	0.7418	25.8	100.0	25.8
		Cutblock >10%	1.0000	0.8030	19.7	100.0	19.7
		Cutblocks >10%, Linear >0.02	1.0000	0.7049	29.5	100.0	29.5
	High EVI	**Linear >0.02**	1.0000	0.9701	3.0	100.0	3.0
		Cutblock >10%	1.0000	0.9772	2.3	100.0	2.3
		Cutblocks >10%, Linear >0.02	1.0000	0.9659	3.4	100.0	3.4
	Low EVI	**Linear >0.02**	1.0000	0.5154	48.5	100.0	48.5
		Cutblock >10%	1.0000	0.6307	36.9	100.0	36.9
		Cutblocks >10%, Linear >0.02	1.0000	0.4462	55.4	100.0	55.4

Implications for Caribou Management

- Current model has low causal attribution → poor restoration outcomes based on average causal effect

- Separating habitat disturbance by pathway and setting different thresholds improves attribution → better restoration results, particularly if targeted in low productivity ranges


Policymakers
Necessary Causation
Does an outcome require the action to have occurred?
Researchers, lawyers, advocates
Sufficient Causation
What action(s) will generate the desired outcome?
Planners, managers
Implement effective actions but avoid those that are unnecessary (and costly)

Intervention → Counterfactual Analysis

- Important when interventions are costly
- Enables targeted policies: moving from average to individual effects
- Requires additional knowledge and/or assumptions about a system