Synoptic Modeling of Animal Locations Combining Animal Movements, Home Range and Resource Selection

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Presentation Outline

- Demonstrate a new approach to analysis based on synoptic models
- A 12 step program based on a new philosophy for analysis of animal locations
- Examples with white rhinos, mountain goats, cougar, ocelots and Alaskan caribou
- After lunch: Demonstration of Windows and R software

Goal: A New Philosophy

Rather than simply drawing a boundary around an animal's locations, let's ask interesting ecological questions!

Modeling Animal Locations

3 Alternatives?

Home Range

The area used by an animal as it goes about its business reproducing, eating, and not getting eaten

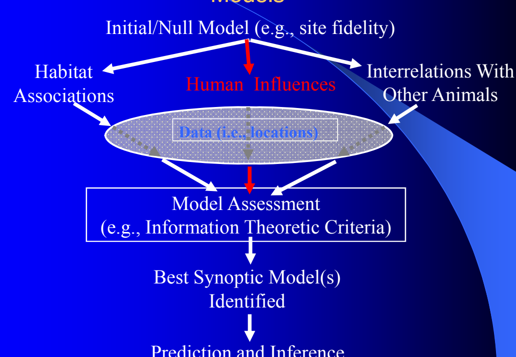
Movement Model

Describe fine-scale patterns of movement and spatial locations utilized

Resource Selection

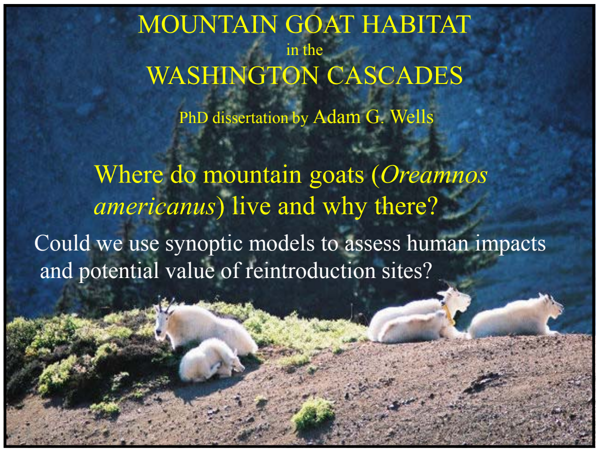
The disproportionate use of some areas over others when compared to what was "available"

Synoptic Approach… Multiple Competing Models

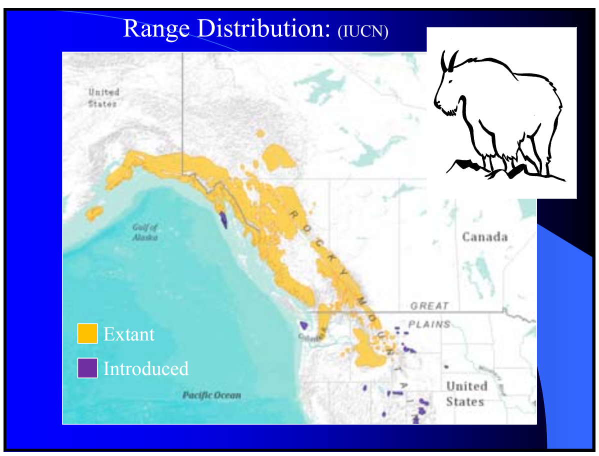


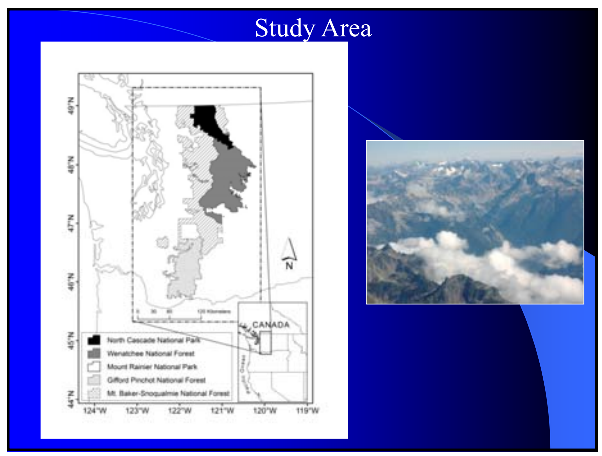
A New Philosophy in 12 Steps

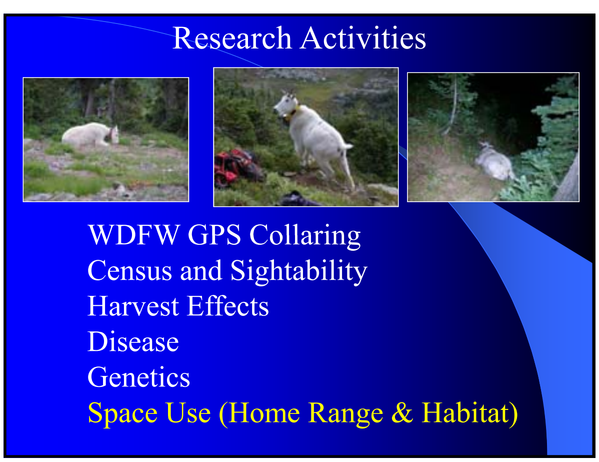
- 1. State research question clearly with details of why location data are required to answer it.
- Specifically: what type of data necessary (scale/order) and how will it be used to answer the key question(s).

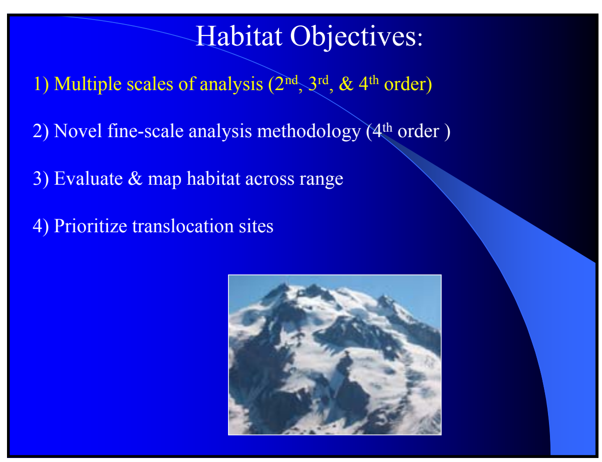

MOUNTAIN GOAT HABITAT
in the
WASHINGTON CASCADES
PhD dissertation by Adam G. Wells
Where do mountain goats (*Oreamnos americanus*) live and why there?
Could we use synoptic models to assess human impacts and potential value of reintroduction sites?


Taxonomy: Mountain Goats
(*Oreamnos americanus*)
Subfamily: Caprinae
Rupicaprinea Tribe
Rupicapra rupicapra)
Naemorhedus spp.)


Range Distribution: (IUCN)
United States
Gulf of Alaska
Canada
GREAT PLAINS
Pacific Ocean
United States
Extant
Introduced

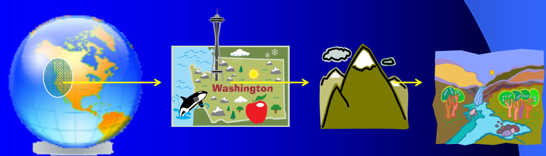

Study Area
CANADA
N
North Cascade National Park
Wenatchee National Forest
Mount Rainier National Park
Gifford Pinchot National Forest
Mt. Baker-Snoqualmie National Forest
124°W 123°W 122°W 121°W 120°W 119°W


Research Activities
WDFW GPS Collaring
Census and Sightability
Harvest Effects
Disease
Genetics
Space Use (Home Range & Habitat)


Habitat Objectives:
1) Multiple scales of analysis (2nd, 3rd, & 4th order)
2) Novel fine-scale analysis methodology (4th order)
3) Evaluate & map habitat across range
4) Prioritize translocation sites

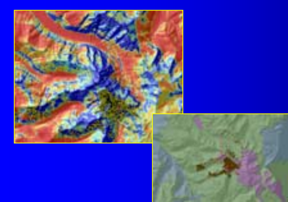
Orders of Selection (Johnson 1980)

- 1st order: Physical or Geographic Range
- 2nd order: Home Ranges within geographic range
- 3rd order: Within Home Range habitat components
- 4th order: Fine-scale; actual items or resources



Objective 1: Population level (2nd order)

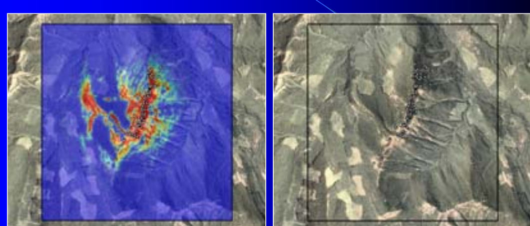
- Availability: Random sample across entire study area
- Two years of data
- Annual
- Seasonal (Summer & Winter)
- Western Cascades


Washington GAP (2004)

Wells et al. (2011)

Objective 1: Home-Range level (3rd order)

Synoptic model of habitat selection and space use



- Mountain goats are selecting high elevation ridges in early summer

New Philosophy

- 2. Define animal population of interest and sampling approach providing inference to it.
- Ideally draw samples randomly but more typically we must use stratified random samples (see below).

New Philosophy

- 3. Identify potentially important strata:
  - Age-sex-behavior classes of animals (males vs females, residents vs migrants)
  - Temporal seasons
    - Breeding
    - Summer
    - Fall
    - Migration to winter range
    - Winter
    - Migration to summer range

Tests for Male-Female Differences in Resource Selection

MODEL	Statistic	Value	F Value	df	Pr >F
Logistic	Wilks' λ	0.95342	0.67	4,55	0.6142
BBSM	Wilks' λ	0.9701	0.42	4,55	0.7913
Synoptic BVN	Wilks' λ	0.6414	6.85	4,49	0.0002
Synoptic EXP	Wilks' λ	0.6946	5.06	4,46	0.0018

Sex Differences in Selection

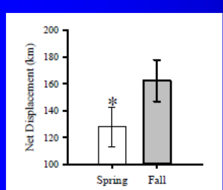
GOATS	Statistic	D2ET
ALL	Average	-3.92
	SE	2.53
	Upper CI	1.14
	Lower CI	-8.98
MALE	Average	9.79*
	SE	4.11
	Upper CI	18.04*
	Lower CI	1.55*
FEMALE	Average	-19.48**
	SE	4.9
	Upper CI	-9.65**
	Lower CI	-29.31**

Caribou Space Use and Alaskan North Slope Oil Development

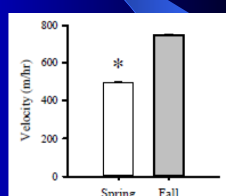
- Using caribou locations gathered with 54 GPS collared cows over 5 years (1993-1997) to assess the impacts of oil developments on the North Slope, Alaska

Central Arctic Caribou Migration
Movement Patterns Differ Between Spring and Fall

Net Displacement by Season



Velocity by Season



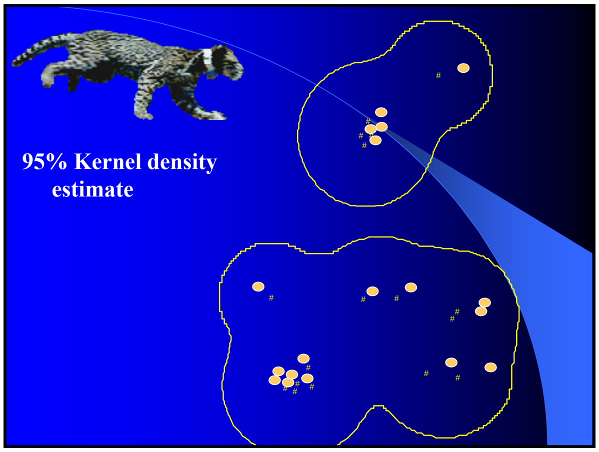
New Philosophy

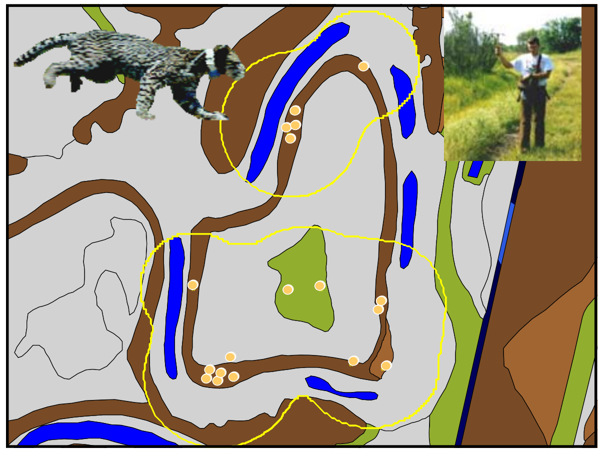
- 4. Select type of spatial analysis:
  - Model space use with a synoptic model combining home range with resource (habitat) selection
  - Model movements similarly with a synoptic model combining a movement model with resource (habitat) selection
  - Illustrate this approach after step 5 but an alternative exists and dominates analysis now!

Alternate Approaches

- Choose to leave this approach:
  - Delineate sharp boundary (Minimum Convex Polygon or Convex Hulls, Getz et al. 2007)
  - Spatial density estimator (kernels)
- Polygon or non-parametric density approaches make further modeling difficult and they are weak at detecting effects.
- Illustrate their key problem

Problems with polygon or kernel density estimators



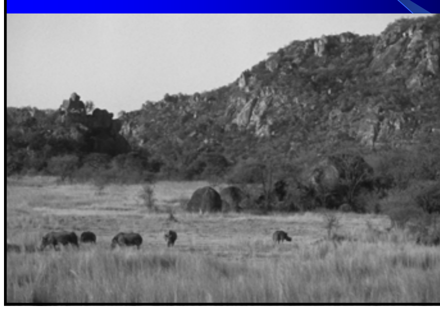


New Philosophy

- 5. List interesting ideas (hypotheses) about ecological factors, processes or drivers determining patterns of space use: e.g.,
  - Probability of encountering potential mates
  - Need to provision a nest or den
  - Movements to water or salt licks
  - Food resources or cover requirements
  - Energetic demands of movement
  - Density of intraspecific or interspecific competitors
  - Probability of encountering predators/hunters/poachers

Example: Space Use of Male White Rhinos

- Location Data: 3 Adult Males, Matobo National Park, Zimbabwe



Habitat:
-Topography flat with granite outcrops
-Prefer grass forage
-Boundary fence encloses NP

Social behavior:
-Adult males territorial
-Females often in groups where grass is most lush

Example: Space Use of Male White Rhinos

- Location Data: 3 Adult Males, Matobo National Park, Zimbabwe
- Rhinos in Zimbabwe
  - Topography: flat with granite outcrops
  - Prefer grass for foraging
- Social Behavior
  - Adult males: territorial around female concentrations

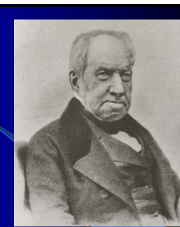
Ecological Questions:

- Since males defend territories to ensure breeding opportunities, must forage on grass in flat areas and are kept within the boundary fence:
- Do males choose areas with high female densities?
- Or flat areas with forage?
- Or both?

New Philosophy

- 6. Select a null model for space use:
  - Need to provision a nest or den
  - Need to defend a territory against conspecifics

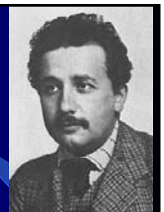
Brownian Motion



Robert Brown (1773 – 1858)

- 1827: examined pollen grains in water
- "Jittery motion"
- Phenomenon named in his honor

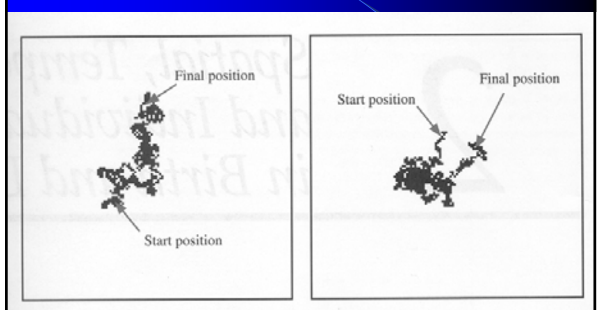
Brownian Motion Explained



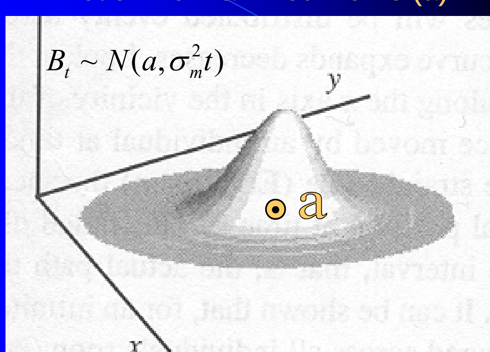
Albert Einstein 1905

- 1905: "On the Motion-Required by the Molecular Kinetic Theory of Heat
- Explained Brownian Motion
- Provided Evidence for the Existence of Atoms

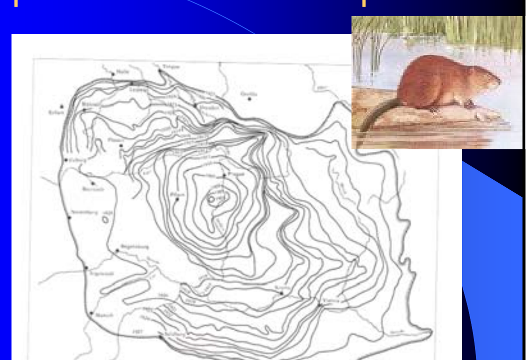
Brownian Motion = Random Walk



Distribution of Locations from Brownian Motion from a Fixed Home (a)



Spread of Introduced Species



(a) After Elton (1958)

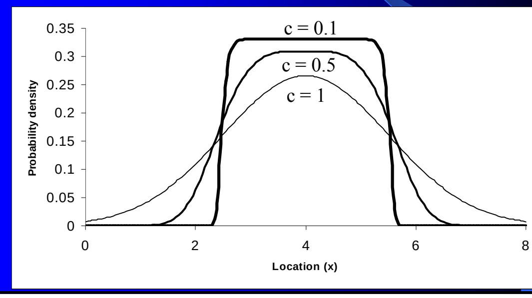
Applying Selection Criteria to Null Home Range Models

- Can we calculate likelihood?
  - Yes, if home range models estimate the utilization distribution
  - No for minimum convex polygon (MCP) nor for kernel density estimators
- New model based on random to uniform distributions
  - Exponential Power Function

Exponential Power Function

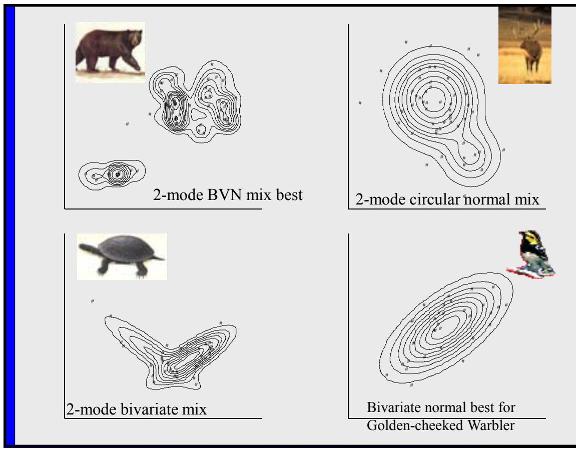
Circular Uniform and Normal are Particular Cases

3 parameters: location, scale, shape (c)



Example:
Information Theoretic Model Selection

- Used location data from a variety of species
- Used 4 home range models:
  - Bivariate normal
  - Exponential power
  - 2-mode circular normal mix
  - 2-mode bivariate normal mix
- Calculated AIC



Application of Model Selection
AIC for parametric models

Model	bobcat (20)	warbler (32)	turtle (35)	elk (51)	black bear (64)	hawk (102)
	ΔAIC_c					
CU (4)	0.0	16.9	23.0	8.4	100.4	130.1
BVN (6)	3.3	0.0	12.8	0.0	53.2	20.3
2CN (7)	9.5	10.8	16.2	4.4	9.2	32.0
2BVN(11)	28.5	13.2	0.0	12.4	0.0	0.0

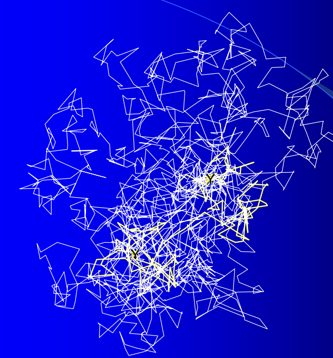
See Horne and Garton, 2006 *Ecology*

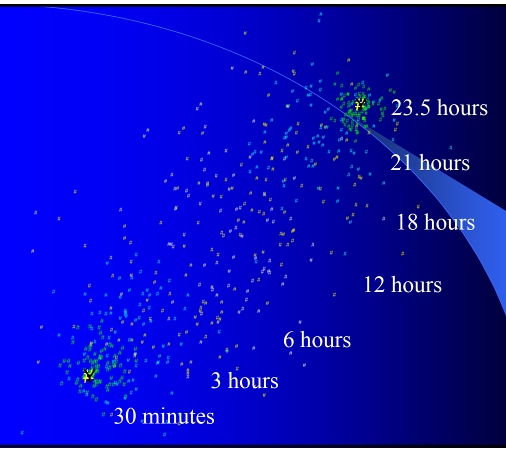
A Movement Model Based on Brownian Motion

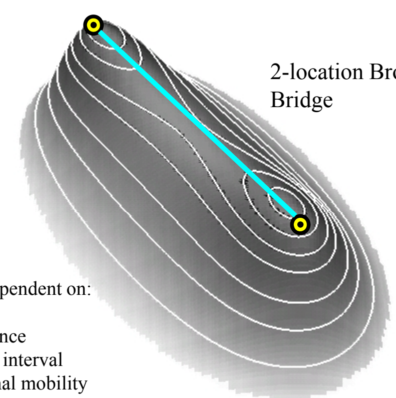
- Floyd Bullard (1999)
  - "Estimating the Home Range of an Animal: A Brownian Bridge Approach"
- Brownian Motion Conditioned On…
  - A starting AND ending location (location data divided into successive pairs)
    - Distance
    - Time
    - Animal mobility

Building on Bullard’s Work

- We derived a Brownian bridge model assuming normally distributed location error
- We developed a maximum likelihood approach for parameter estimation

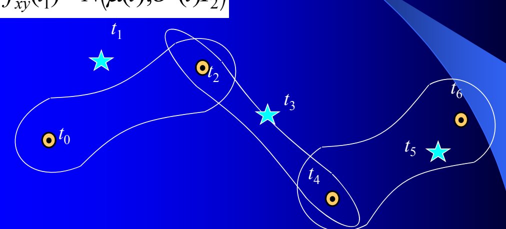






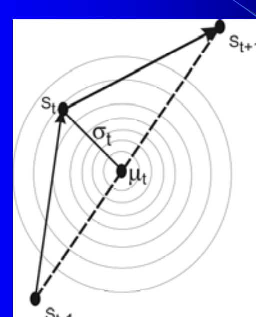
Estimating the Brownian Motion Variance

$f_{xy}(t_1) \sim N(\mu(t), \sigma^2(t) I_2)$



Maximum likelihood used to estimate final parameter

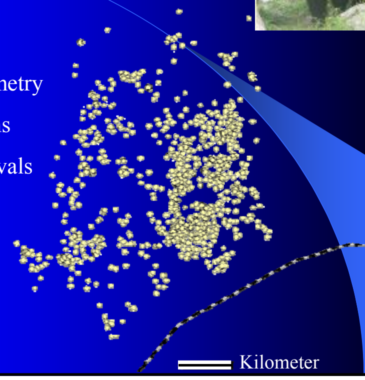
Estimating the Brownian Motion Variance from Each Triplet



Brownian Bridge Applications

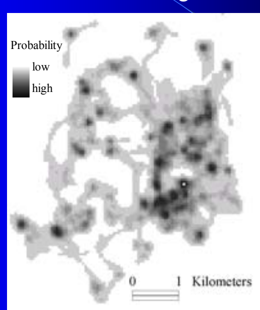
- Estimate movement paths
  - Fine-scale estimation of home range
  - Migration routes
  - Resource utilization/selection at fine scale (Johnson's fourth order)

- Black bear
- Satellite telemetry
- 1470 locations
- 20-min. intervals
- ~1 month



Movement model for a male black bear

Brownian bridge



Advantages of Brownian Bridge Movement Model as Null Model

- ASSUMES serially correlated data
- Models the movement path
- Location error explicitly incorporated

Brownian Bridge Movement Model

$$f_{xy}(t) \sim N(\mu(t), \sigma^2(t))$$

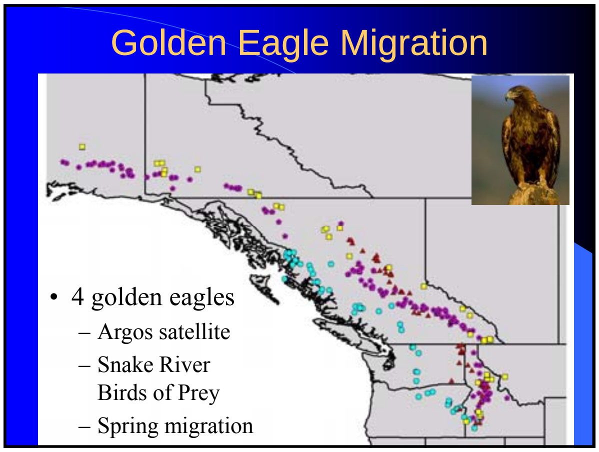
$$\sigma^2(t) = T\alpha(1-\alpha)\sigma_m^2 + (1-\alpha)^2\sigma_a^2 + \alpha\sigma_b^2$$

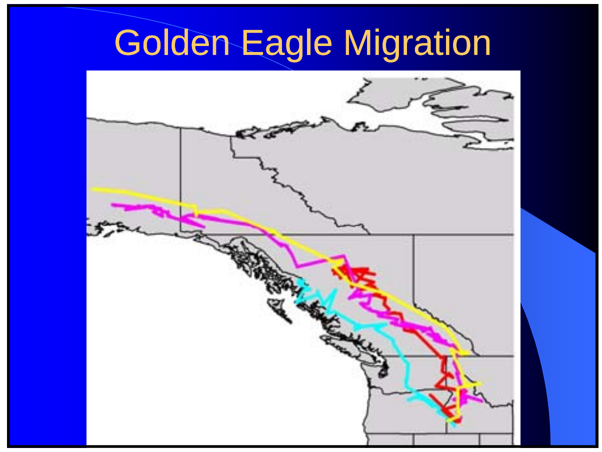
Brownian motion variance

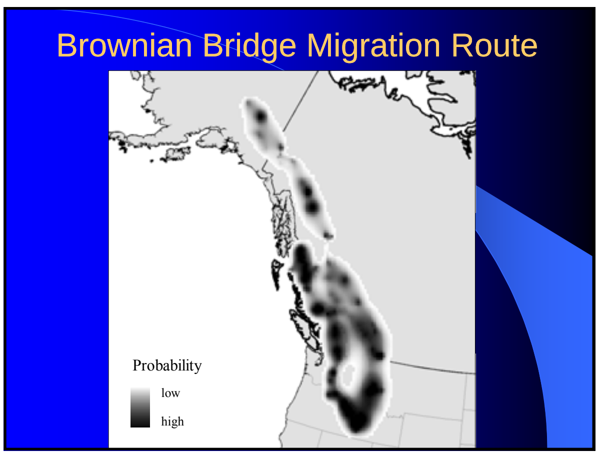
Variance of normally distributed location error

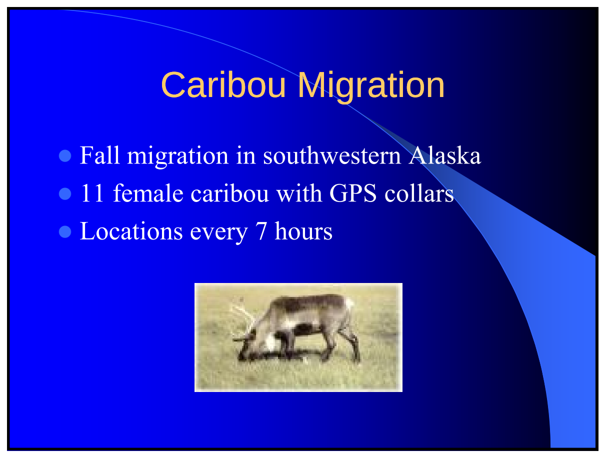
Estimated using maximum likelihood

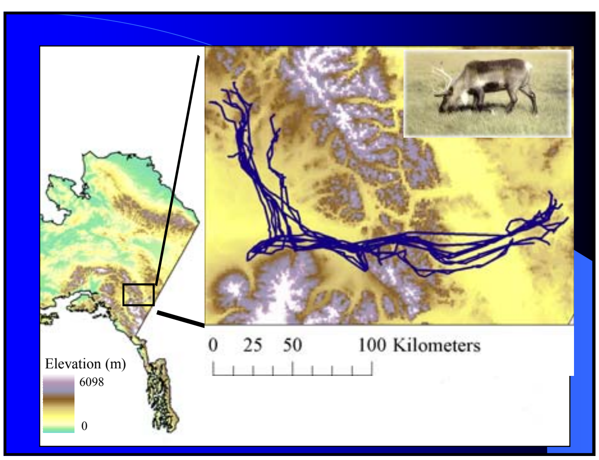
Animal Migration Routes

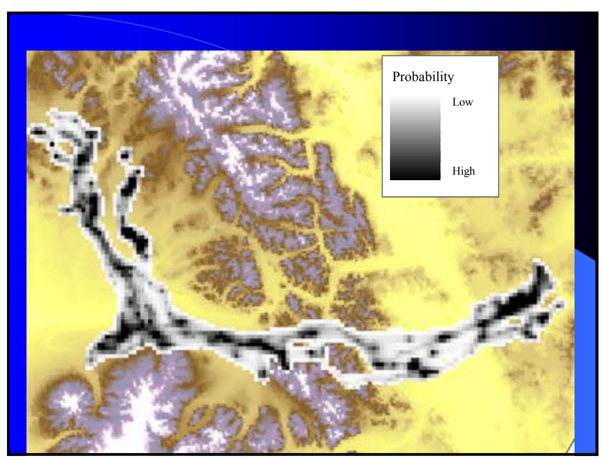

Golden Eagle Migration
• 4 golden eagles
– Argos satellite
– Snake River Birds of Prey
– Spring migration


Golden Eagle Migration


Brownian Bridge Migration Route
Probability
low
high


Caribou Migration
• Fall migration in southwestern Alaska
• 11 female caribou with GPS collars
• Locations every 7 hours


Elevation (m)
6098
0
0 25 50 100 Kilometers


Probability
Low
High

New Philosophy

- 7. State the ideas (hypotheses) in form of multiple parametric (synoptic) models where parameters express effects of key ecological factors or processes, are feasible to estimate with maximum likelihood methods and these competing models can be compared using information theoretic methods.

Example: 3rd Order Space Use of Male White Rhinos

- Location Data: 3 Adult Males, Matobo National Park, Zimbabwe

Habitat:
-Topography flat with granite outcrops
-Prefer grass forage
-Boundary fence encloses NP

Social behavior:
-Adult males territorial
-Females often in groups where grass is most lush

Interesting Questions (Hypotheses)

- Males defend fixed territories within boundary fence
  - Exponential power model within boundary
- Steep terrain energetically demanding
- Preferred forage in grassland or open forest
- Males optimize breeding opportunities by spending most time where females concentrate

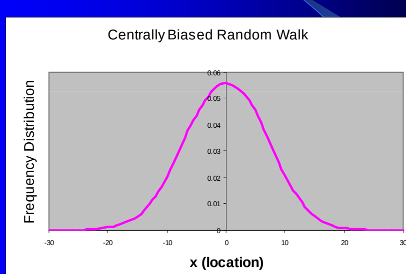
Candidate Models… Hypotheses

- Null model: no environmental covariates
  - Exponential Power + Park boundary
- Habitat model:
  - Null + open covertype + percent slope
- Social model:
  - Null + female density
- Combined model:
  - Null + habitat + social

AIC Model Selection

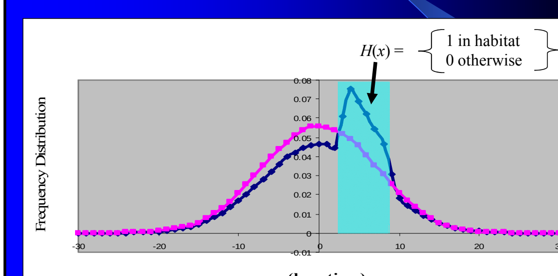
A Proposed Model

1st Simulated a Centrally-biased random walk…



Synoptic model **= null model + proportional change**

$f_u(x) \quad = \quad f_0(x) \quad \times \; \mathrm{Exp}[\beta^* H(x)]$



Model Fitting and Selection

- Parameters governing both the null model and the selection coefficients (Betas) are estimated by maximizing likelihood of observed locations
- Information-theoretic approaches are used for both model construction and selection

Synoptic Model

- Probability of use based on weighted distributions

$$f_u(x) = \frac{f_a(x)w(x)}{\int_x f_a(x)w(x)}$$

"use" distribution

f_a = available (null) distribution

$w(x)$ = weighting or resource selection function

= "link" function

Lele and Keim 2006 *Ecology*

Model for *i* = 1 to *k* covariates and general *H*(*x*)

Proportional change

$$s(x) = \frac{f_0(x)w(x)}{\int_x f_0(x)w(x)},$$

$$w(x) = 1 + B_x H(x)$$

Synoptic Model

- Probability of use based on weighted distributions

$$f_u(x) = \frac{f_a(x)w(x)}{\int_x f_a(x)w(x)}$$

"use" distribution

f_a = available (null) distribution

$w(x)$ = weighting or resource selection function

=*exp(β'H(x))*

Synoptic Model with Exponential Link

Home range — Null model — Proportional change

$$f_u(x) = \frac{f_a(x)\exp(\beta' H(x))}{\int_x f_a(x)\exp(\beta' H(x))}$$

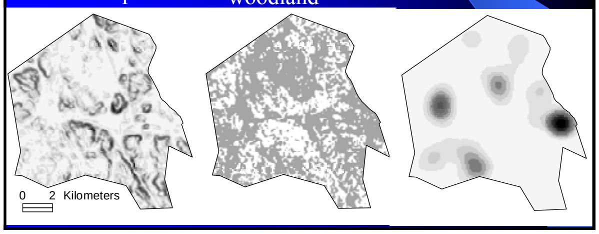
New Philosophy

- 8. Assemble potentially predictive covariate maps.

Candidate Models… Covariates

- Park boundary
- 3 Environmental Covariates $H(x)$

Percent slope | Grassland/open woodland | Female Density



New Philosophy

- 9. Fit multiple competing synoptic models for each stratum.

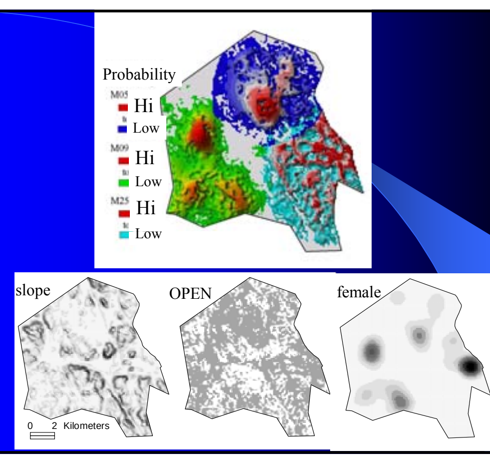
Model Selection Results

Rhino ID	Model	K	-2*ln(L)	AIC_c	ΔAIC_c	w_i
M05 (n = 36)	ExpPower	4	1237.52	1246.81	12.28	0.002
	ExpPower*PB	4	1237.18	1246.81	11.94	0.003
	ExpPower*PB*FemDens	5	1226.83	1246.47	4.30	0.098
	ExpPower*PB*OPEN*PS	6	1225.15	1238.83	5.53	0.053
	ExpPower*PB*FemDens*OPEN*PS	7	1216.53	1230.05	0	0.844

Rhino ID	Model	K	-2*ln(L)	AIC_c	ΔAIC_c	w_i
M05 (n = -36)	ExpPower	4	1237.52	1246.81	12.28	0.002
	ExpPower*PB	4	1237.18	1246.81	11.94	0.003
	ExpPower*PB*FemDens	5	1226.83	1246.47	4.30	0.098
	ExpPower*PB*OPEN*PS	6	1225.15	1238.83	5.53	0.053
	ExpPower*PB*FemDens*OPEN*PS	7	1216.53	1230.05	0	0.844
M09 (n =44)	ExpPower	4	1559.08	1568.10	74.58	0.000
	ExpPower*PB	4	1540.78	1549.80	56.28	0.000
	ExpPower*PB*FemDens	5	1487.09	1498.67	5.14	0.071
	ExpPower*PB*OPEN*PS	6	1516.91	1531.18	37.66	0.000
	ExpPower*PB*FemDens*OPEN*PS	7	1476.41	1493.53	0	0.929
M25 (n = 57)	ExpPower	4	2016.55	2025.31	52.46	0.000
	ExpPower*PB	4	1983.31	1992.08	19.22	0.000
	ExpPower*PB*FemDens	5	1976.51	1987.69	14.83	0.000
	ExpPower*PB*OPEN*PS	6	1959.24	1972.92	0.06	0.492
	ExpPower*PB*FemDens*OPEN*PS	7	1956.57	1972.88	0	0.507

Covariate Associations

	Parameter Estimate (β)		
Male ID	**Female Density**	**Percent Slope**	**OPEN**
M05	**8.77**	**-0.99**	**2.00**
M09	**47.58**	**-0.53**	**1.36**
M25 – gained territory	**1.48**	**-0.98**	**0.66**



Candidate Models… Hypotheses

- Null model: no environmental covariates
  - Exponential Power + Park boundary
- Habitat model:
  - Null + open covertype + percent slope
- Social model:
  - Null + female density
- Combined model:
  - Null + habitat + social

Best Model

AIC Model Selection

Parameter Estimates

Rhino ID	μ_x	μ_y	a	c	PS[b]	OPEN[b]	FD[b]
M05	646309	7729348	2831	.53	0.010	3.02	6.78
M09	638919	7722865	6184	.63	0.468	2.36	41.38
M25	649985	7724209	4292	.10	0.023	1.58	2.48

Example:

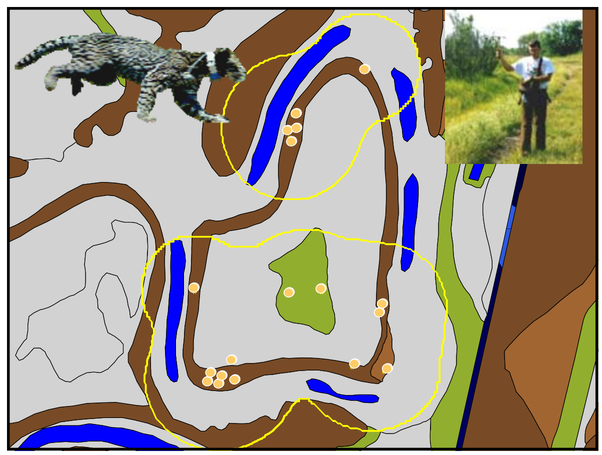
M05 is ~3 times as likely to be in an area with…

2% slope, 0.5 relative female density, and in the open covertype
versus
10% slope, 0.7 relative female density, and not in the open

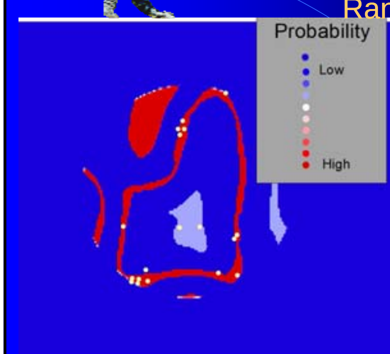
[b] Probability ratios representing the proportional change in the utilization distribution attributable to each variable.

Interpretation of Best Model

- Best Model Can Be Used to:
  - Estimate space use as a pdf
  - Define home range
  - Determine factors affecting space use
  - Infer importance of these factors
- Answers not only "Where?" but "Why?"



Ocelot Synoptic Home Range



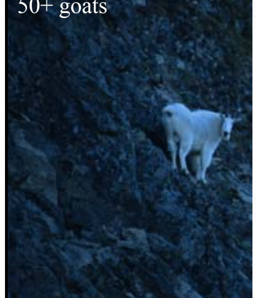
Beta estimates

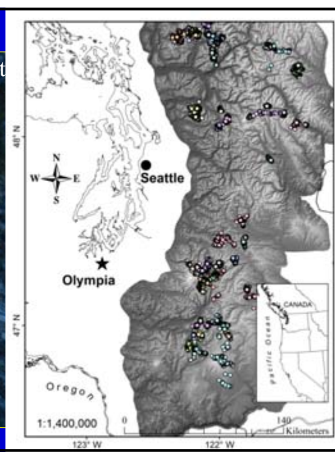
54 times dense thornshrub

20 times mixed covertype

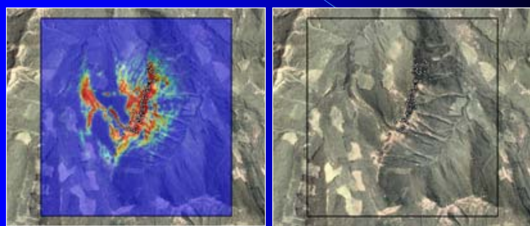
GPS Data:

Thousands of locations at 6 hour intervals for 50+ goats





Synoptic model of space use (3rd order)



•Summer use concentrates along high elevation ridges

Recreation Impacts?

Do the presence of backcountry recreation routes influence patterns of selection?

Interesting Ideas (Hypotheses)

- During late summer (July & August) mountain goats select high elevations but are steeper slopes and locations of escape terrain (steep ridges) and hiking trails important?
- Are patterns same for males and females?
  - Note males are hunted from trails in fall

Synoptic Model Selection Coefficients for 32 Mountain Goats in Late Summer

Sex	Statistic	Dist to Escape Terrain	Slope	Elevation	Distance to Trails
Male	Average	9.8*	5.3**	6.4**	20.3*
	SE	4.1	1.0	1.5	10.0
Female	Average	-19.5**	-3.1**	-2.2	-20.6
	SE	4.9	1.2	1.8	11.9

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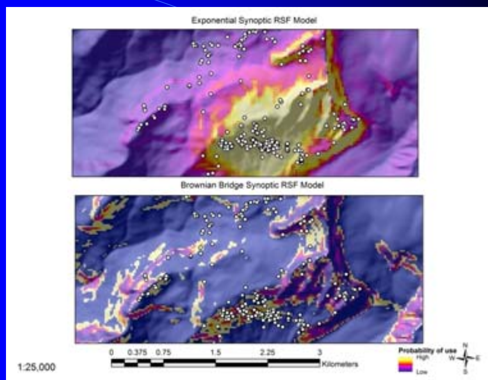
Multiple Scales; 3rd and 4th order



4th Order Selection (Brownian Bridge Synoptic Model)

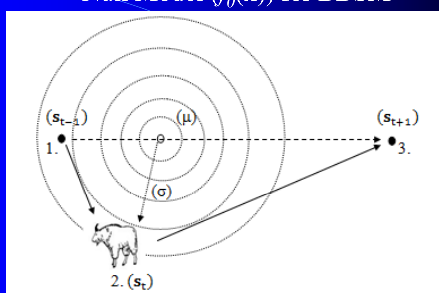
Probability of use is model as weighted distribution of availability times selection

$$f_u(\mathrm{x}) = K^{-1} w(\mathrm{x}) f_a(\mathrm{x})$$

Johnson et al. (2008) & Horne et al. (2008)

$f_a(\mathrm{x})$ = null model (random movement is derived from Brownian bridge

Null Model ($f_0(\mathrm{x})$) for BBSM



- (s_t) is location of animal at time t
- (σ) is spatial variance
- (μ) expected position; center of Circular Normal Distribution

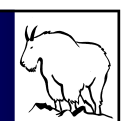
Impacts of Recreation

- Overall: Slope, Elevation & D2et were significant
- Significant differences by sex (Synoptic) including distance to trails
- Females; flatter areas closer to trails and escape terrain
- Males; steeper areas further from trails & escape terrain

New Philosophy

- 10. Re-evaluate original strata by evaluating /testing differences and collapsing strata where feasible.

Cascade Mountain Goats



MODEL	Wilks' λ	F	df	Probability
Logistic	0.95342	0.67	4,55	0.6142
BBSM	0.9701	0.42	4,55	0.7913
BVN Synoptic	0.6414	6.85	4,49	0.0002
EXP Synoptic	0.6946	5.06	4,46	0.0018

New Philosophy

- 11. Refit models, if necessary, with collapsed strata.

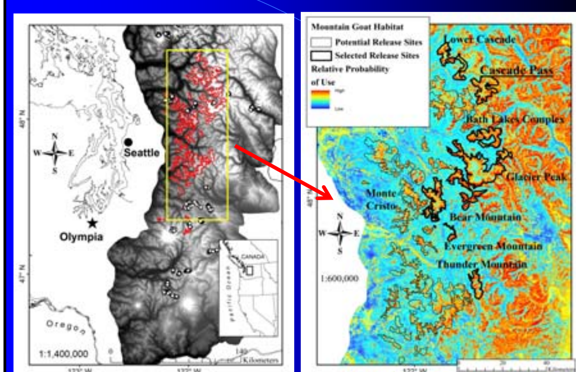
Selecting the Best Model

- What Is the "Best" Model?
  - Closest to true distribution
  - Smallest Kullback-Leibler distance
- Selection Criteria
  - Akaike's Information Criteria (AIC)
    - Equals: model log likelihood + 2 * number of parameters
- Begin by selecting the best null model and then use this approach for best synoptic models

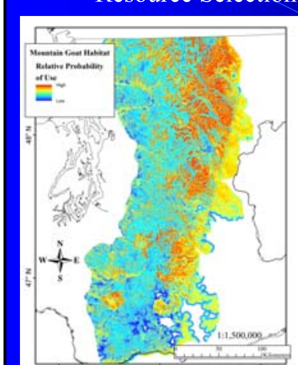
New Philosophy

- 12. Write it up, present it, use it and start validating and improving it through adaptive management.

POTENTIAL POPULATION AUGMENTATION OR NEW TRAILS/ROADS?



Brownian Bridge Synoptic Model Resource Selection Function (BBSM RSF):



K-fold cross validation

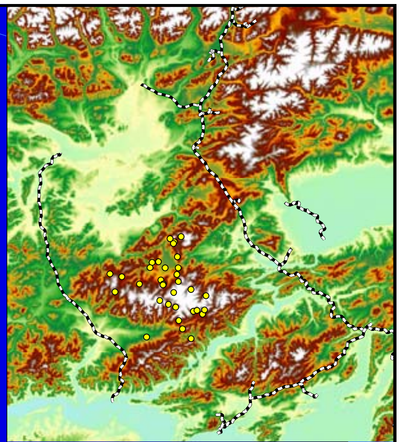
k	*Spearman r*	*P*
1	0.86	< 0.001
2	0.81	< 0.001
3	0.50	< 0.07
4	0.56	< 0.05
5	0.52	< 0.06
Average	0.65	< 0.02

Caribou Space Use and Alaskan North Slope Oil Transportation

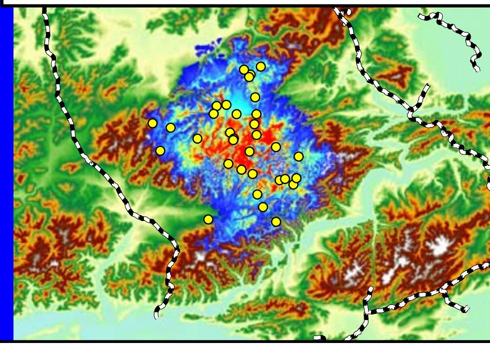
- Using caribou locations gathered with VHF collars irregularly over 4 years to assess the impacts of the oil transportation corridor from North Slope, Alaska

Caribou in central Alaska

Covariates, **H**(x):
- Elevation
- Slope
- Vegetation type(s)
- Roads



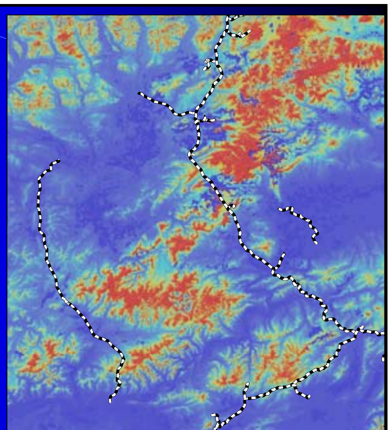
$S(x)$ =BVN*(elevation, distroads, slope, shrub cover)



Population-level

Prob. of use = $\frac{Exp(\boldsymbol{\beta}'\mathbf{H}(x))}{\int Exp(\boldsymbol{\beta}'\mathbf{H}(x))}$

where β'H(x) =
19.2 Elev
- 22.7 Elev2
+ 2.2 DistRoad
+ 1.4 LandNonVeg
- 12.0 WetCover



Telemetry Data and Model Covariates

- Location Data (VHF)
  - 36 adults
  - 1987 – 1994; 1998 – 2005

- Environmental Covariates: **H**(x)
  - Wolf use
  - Elk use
  - Forest cover (3)
  - Topography (5)
  - Snow*

Temporally Varying Covariates

The probability density of being at location x at time t is…

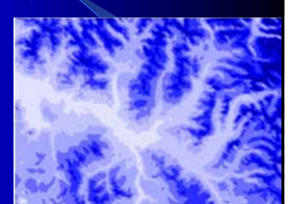
Relationship is constant → $\boldsymbol{\beta}'$

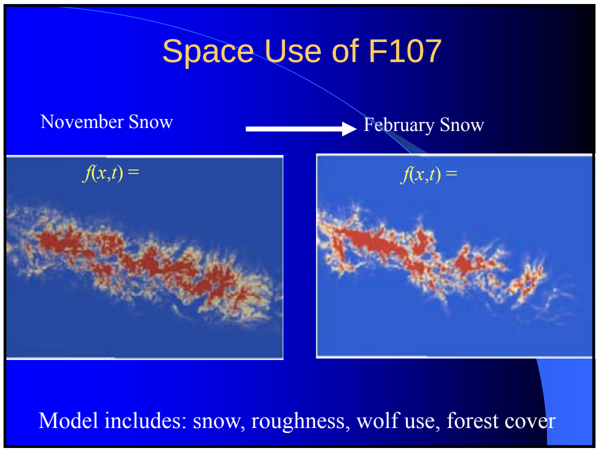
Value can change → $\mathbf{H}(x_t)$

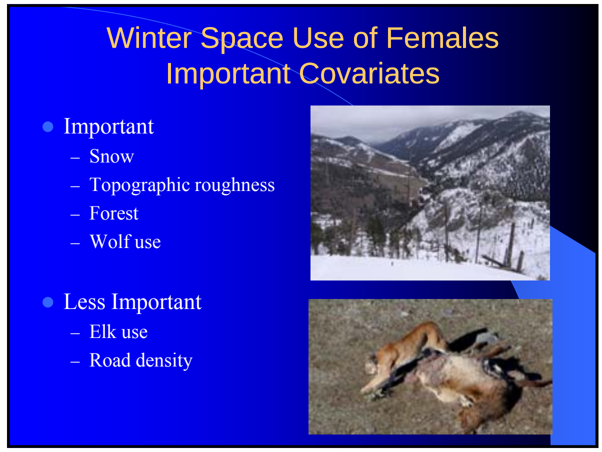
$$f_u(x_t) = \frac{f_0(x)\times Exp(\boldsymbol{\beta}'\mathbf{H}(x_t))}{\dots}$$

Within Season Change in Snow

November Snow → February Snow




Space Use of F107
November Snow
February Snow
f(x,t) =
f(x,t) =
Model includes: snow, roughness, wolf use, forest cover


Winter Space Use of Females
Important Covariates
Important
– Snow
– Topographic roughness
– Forest
– Wolf use
Less Important
– Elk use
– Road density


Questions?
Software available at my web site:
http://www.cnr.uidaho.edu/population_ecology