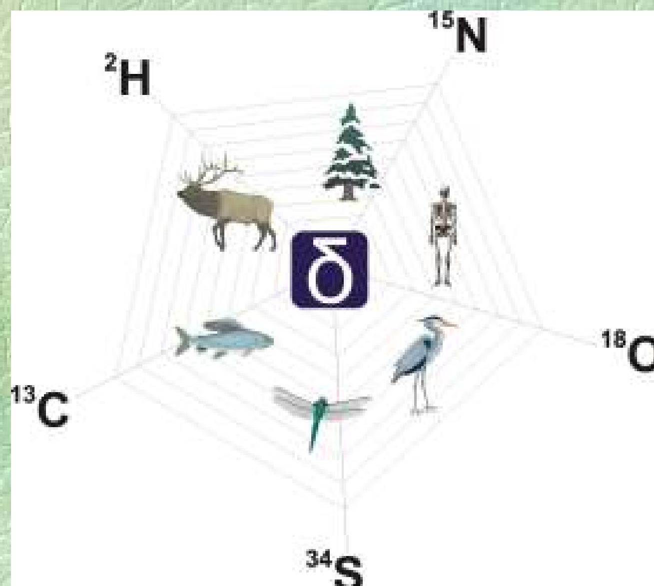
Tracking animal movements using stable isotopes

Keith A. Hobson



Isotopes as endogenous markers

^{12}C

^{13}C — $\delta^{13}C$ (‰)

^{14}N

^{15}N — $\delta^{15}N$ (‰)

^{32}S

^{34}S — $\delta^{34}S$ (‰)

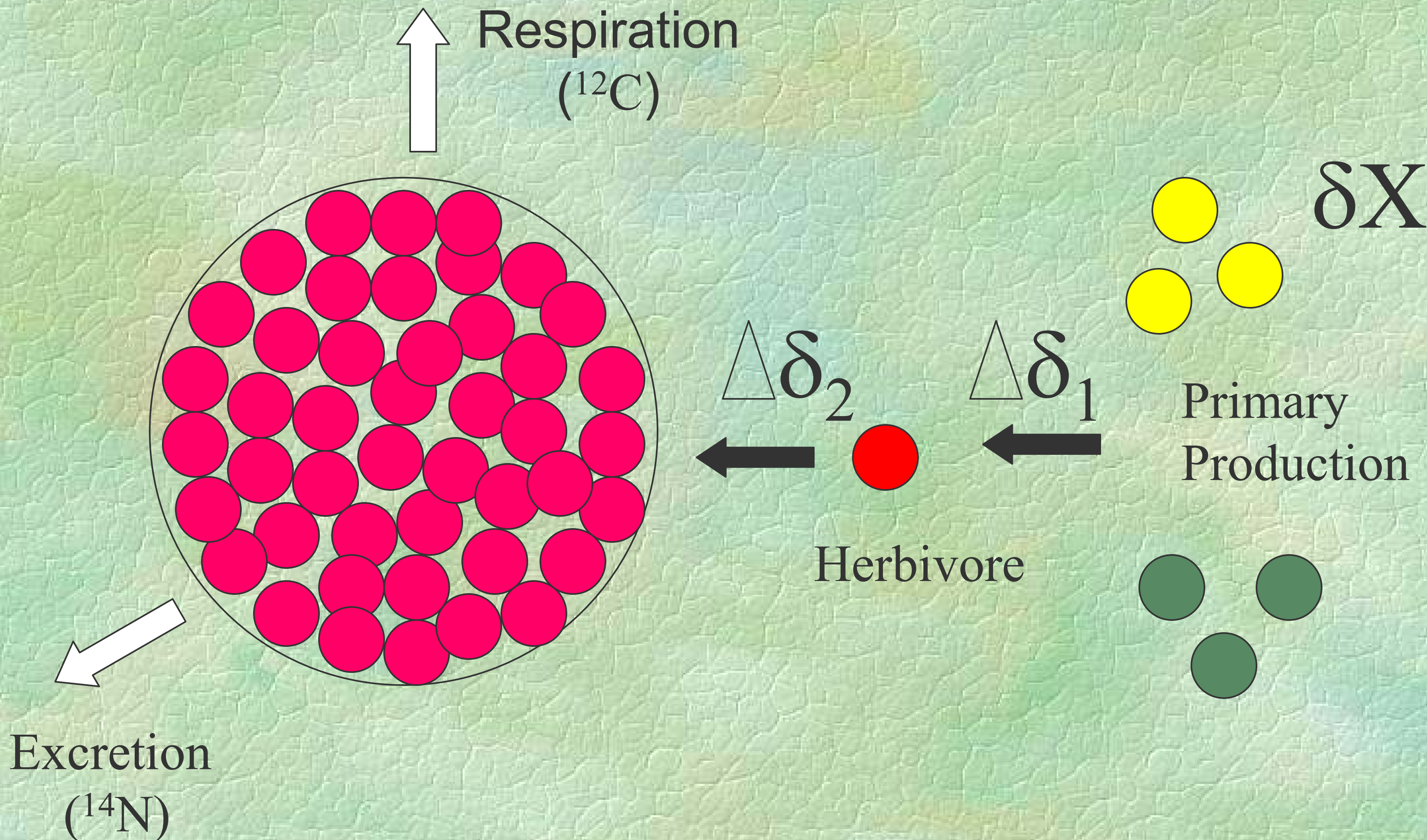
^{16}O

^{18}O — $\delta^{18}O$ (‰)

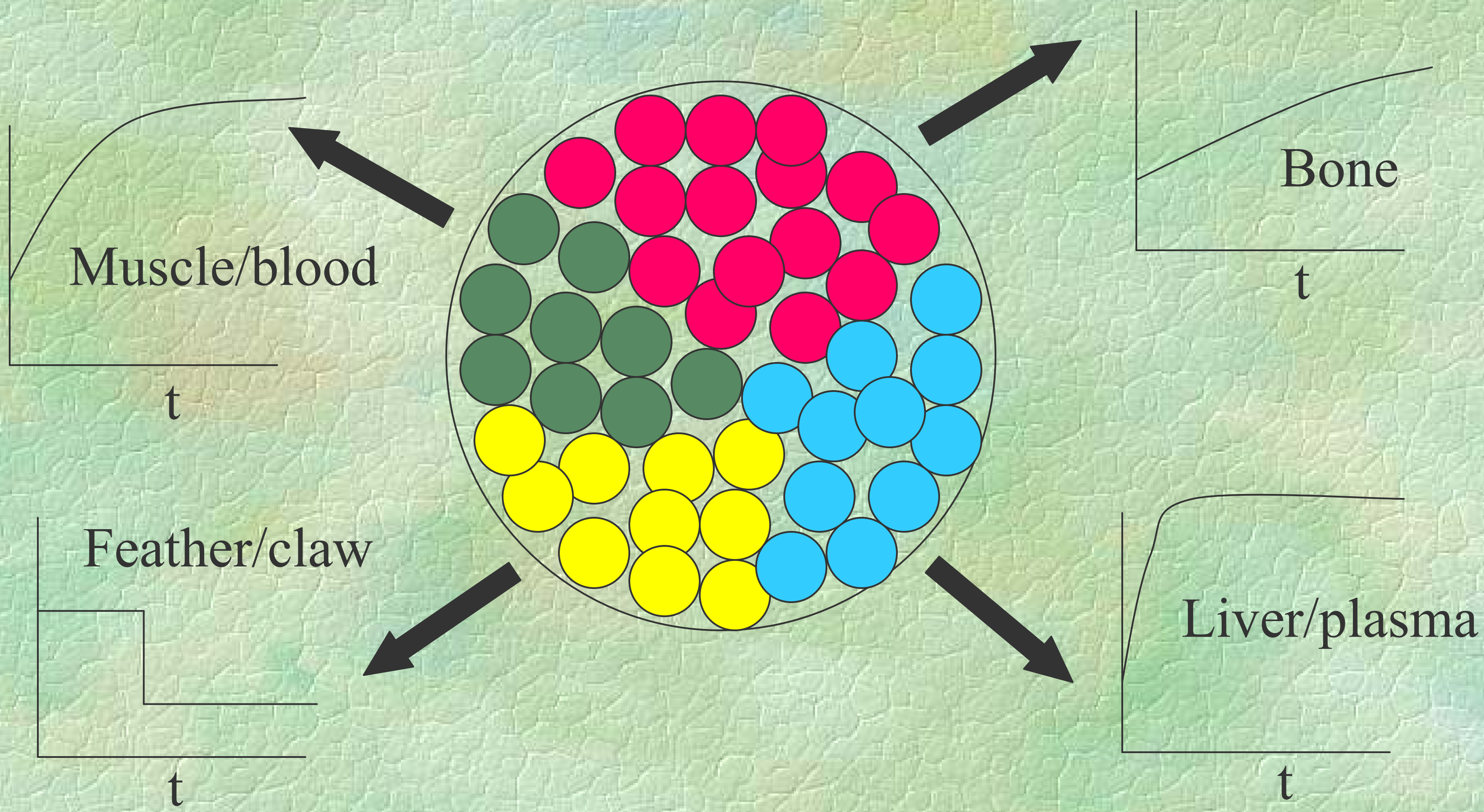
^{1}H

^{2}H — δD (‰)

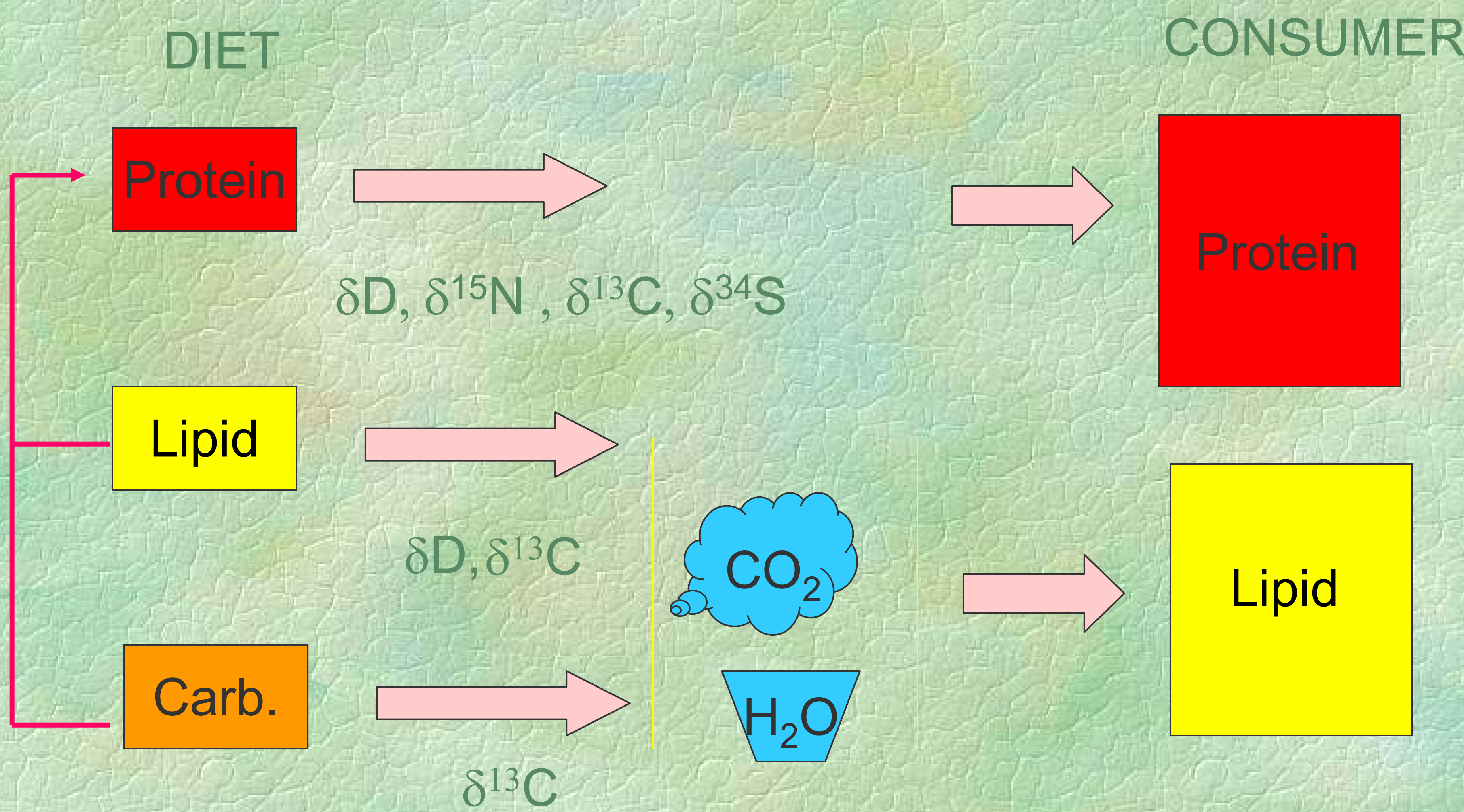
The basic principles of trophic level and source determinaitons



Choice of tissue …..



Metabolic routing: where does the element come from in your isotopic measurements?….

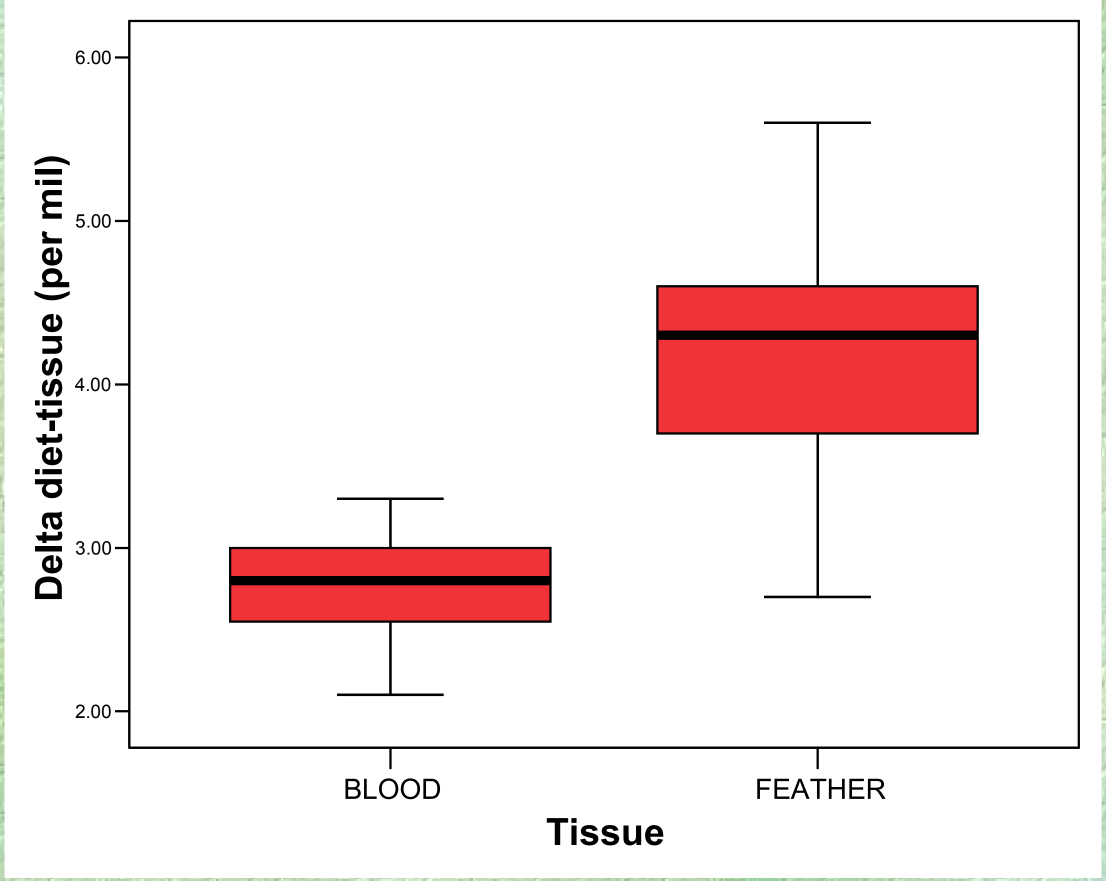


Isotopic discrimination and elemental turnover ….

Stable-N isotope discrimination (non herbivores)

King Penguin
Rockhopper Penguin
Ring-billed Gull
Great Skua
Peregrine Falcon
Garden Warbler

Humboldt's Penguin
King Penguin
Rockhopper Penguin
Common Cormorant
European Shag
Ring-billed Gull
Black-tailed Gull
Great Skua
Nankeen Night Heron
Great White Egret
Grey Heron
Scarlet Ibis
White Ibis
Flamingo
Peregrine Falcon
Garden Warbler

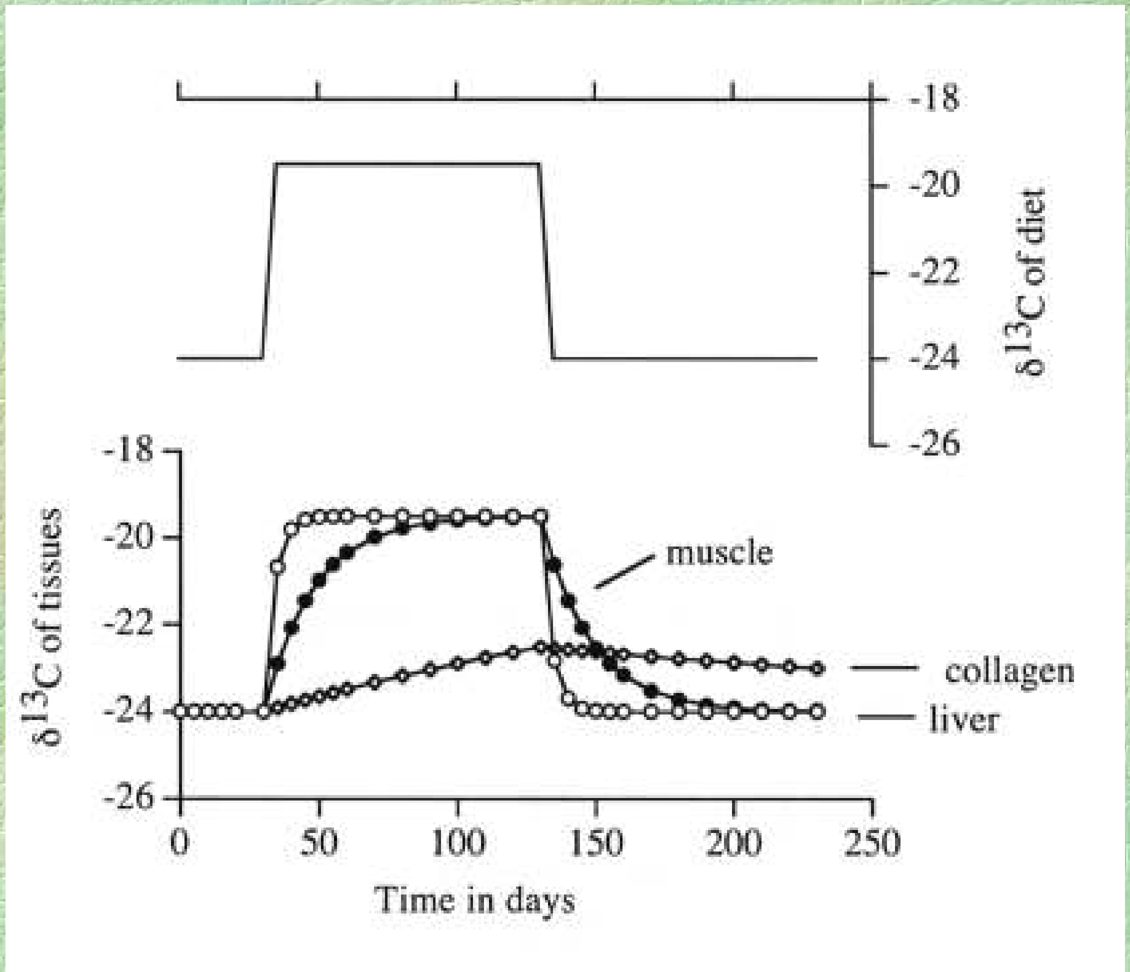


Cherel et al. 2005,Hobson and Clark 1992, Bearhop et al. 2002,
Evans-Ogden et al 2004, Hobson and Bairlein 2003, Mizutani et al. 1992.

High protein diets:

Tissue	$\Delta\delta^{13}C$	$\Delta\delta^{15}N$	$\Delta\delta D$
Whole Blood	1.5	2.9	?
Plasma	0.5	3.3	?
Muscle	1.9	3.1	?
Feather	2 to 3	3.8	-19 to -35
Claw	?	?	?

More on turnover experiments:



Hobson and Clark *Condor* 1992

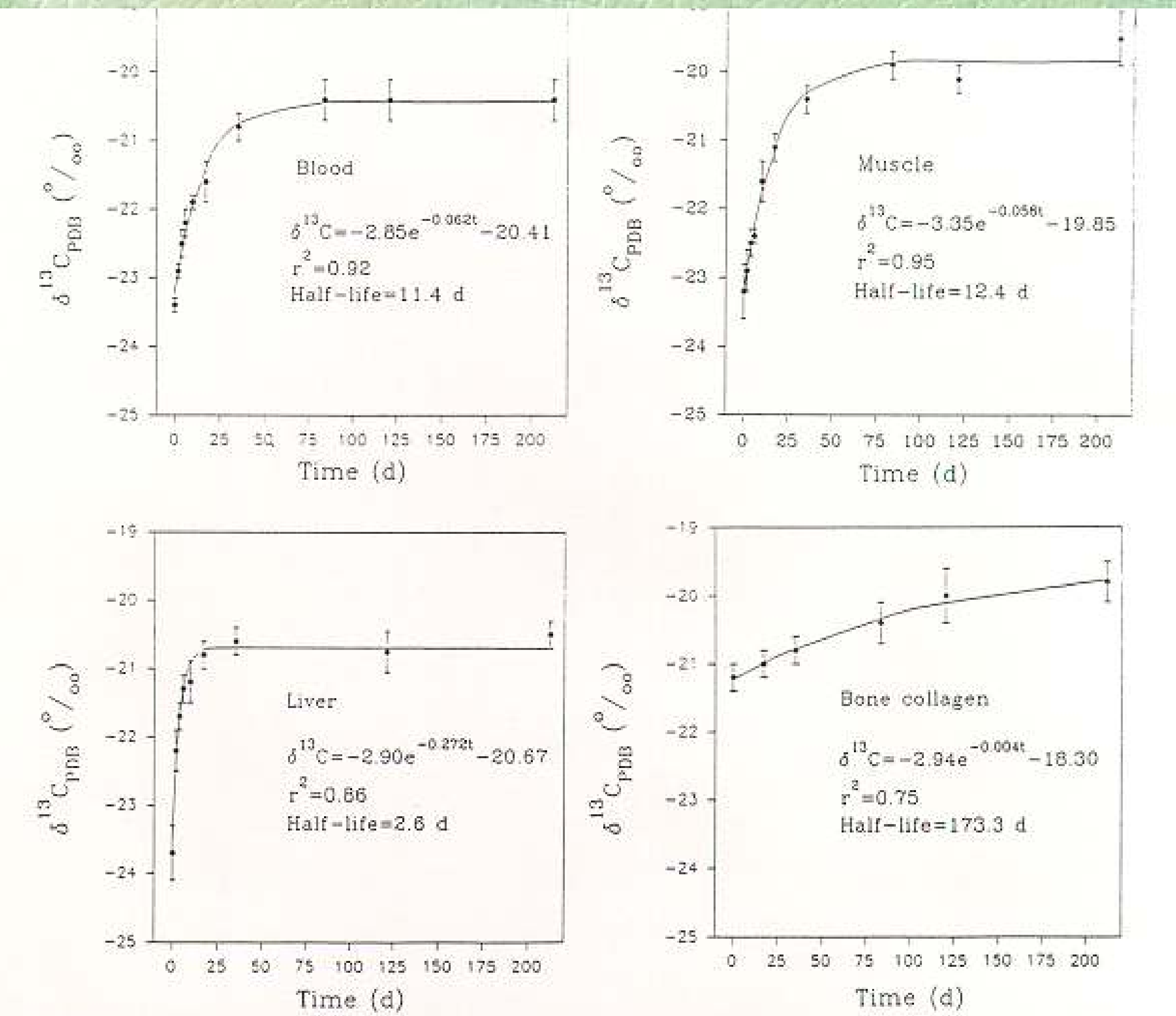
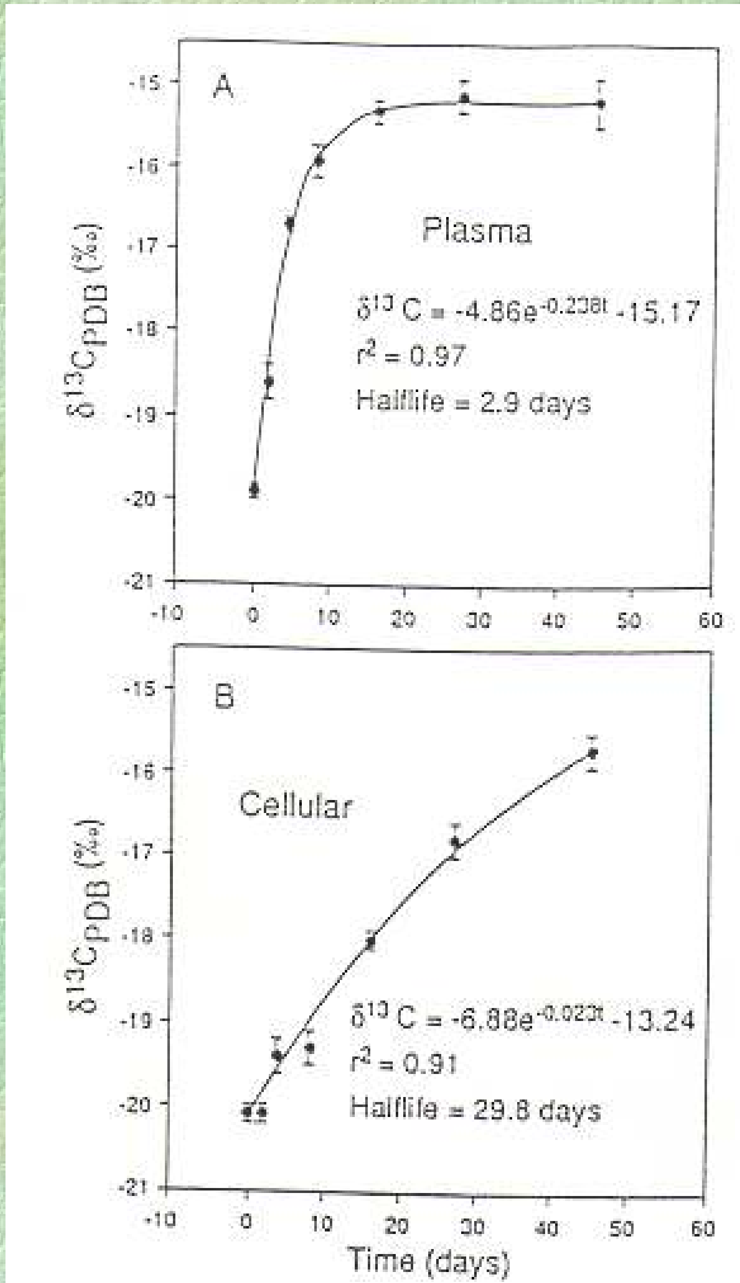


FIGURE 1. Stable-carbon isotope exponential models for quail tissues. Data are means (closed circles) ± SD (vertical lines) and sample sizes are n = 3 for each point.

Hobson and Clark *Condor* 94:181-188

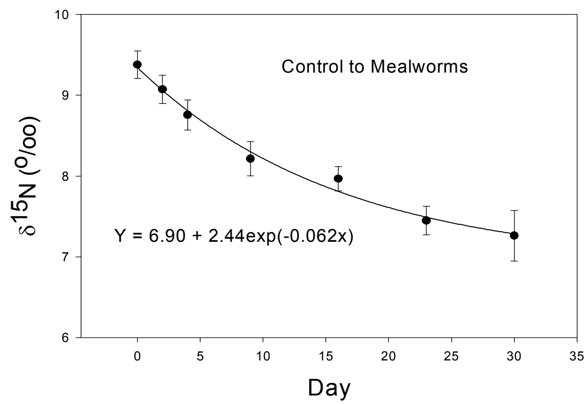


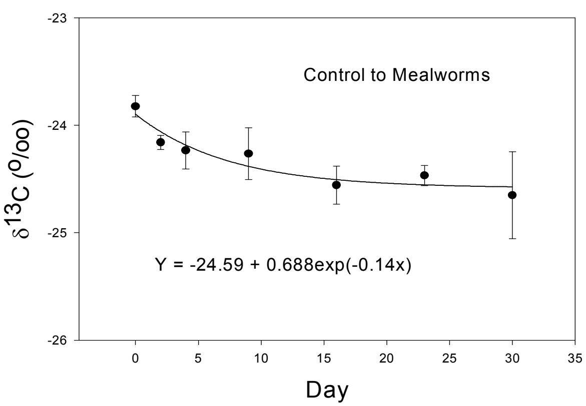
Hobson and Clark *Auk* 110:638-641

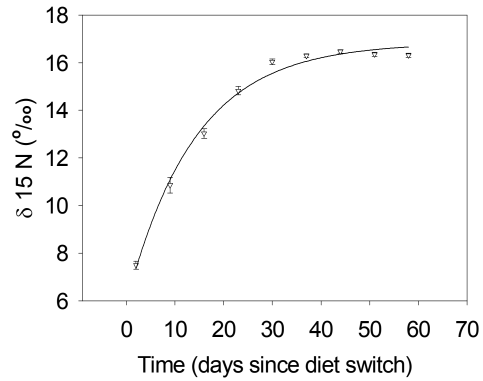
Tissue turnover ….

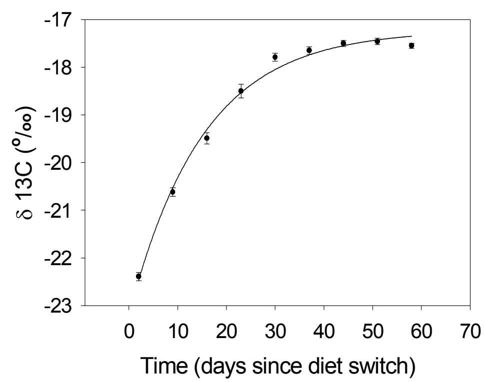
$$Y = ae^{(-bt)} + c$$

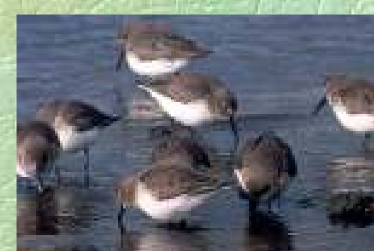
$$T[1/2] = 0.6932/b$$





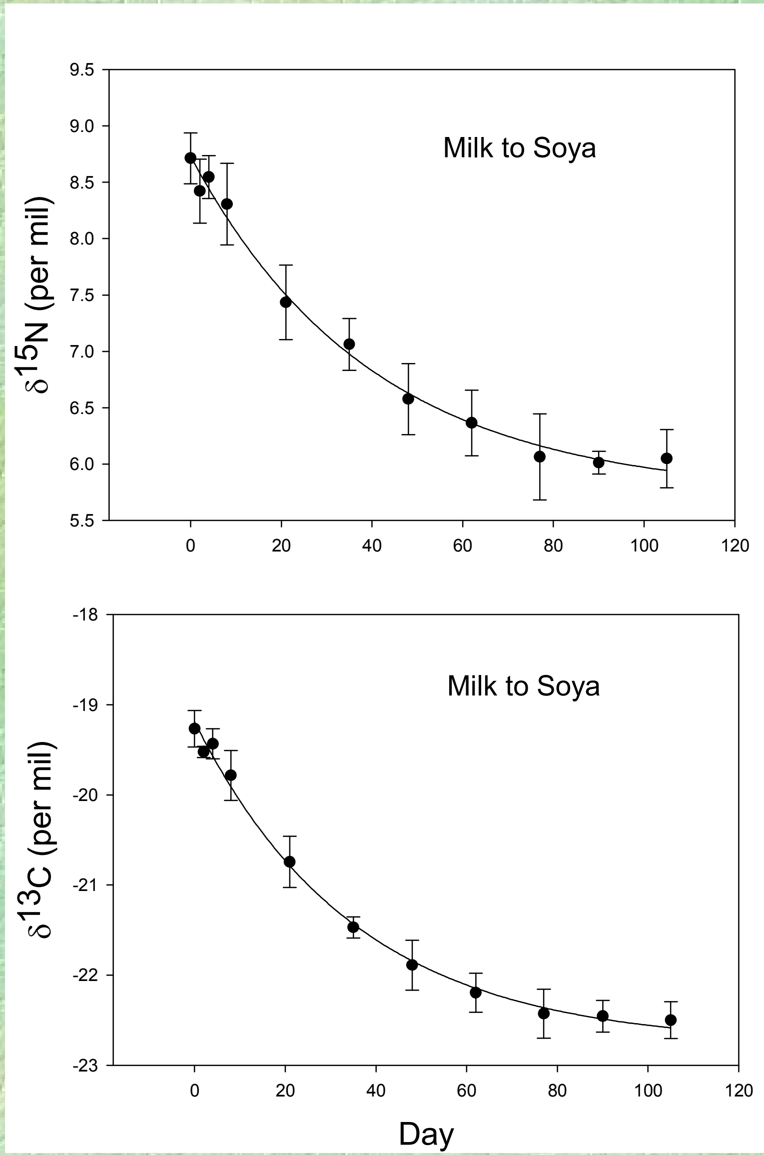






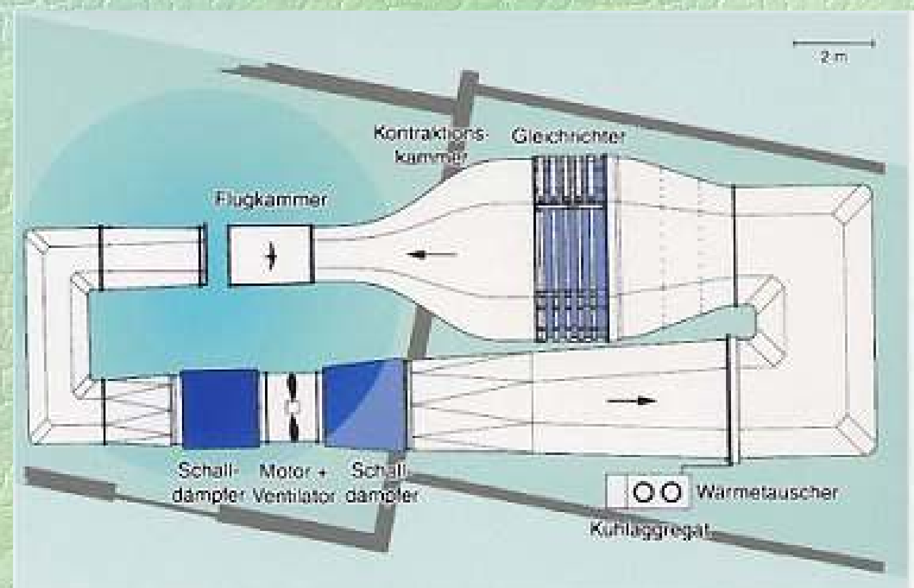
Hobson and Bairlein *CJZ81:1630-1635*

Evans-Ogden et al *Auk* . 121:170-177



Mirón et al. 2006 J. Exp. Biol

Using a wind tunnel and isotopic dietary shifts to mimic migration

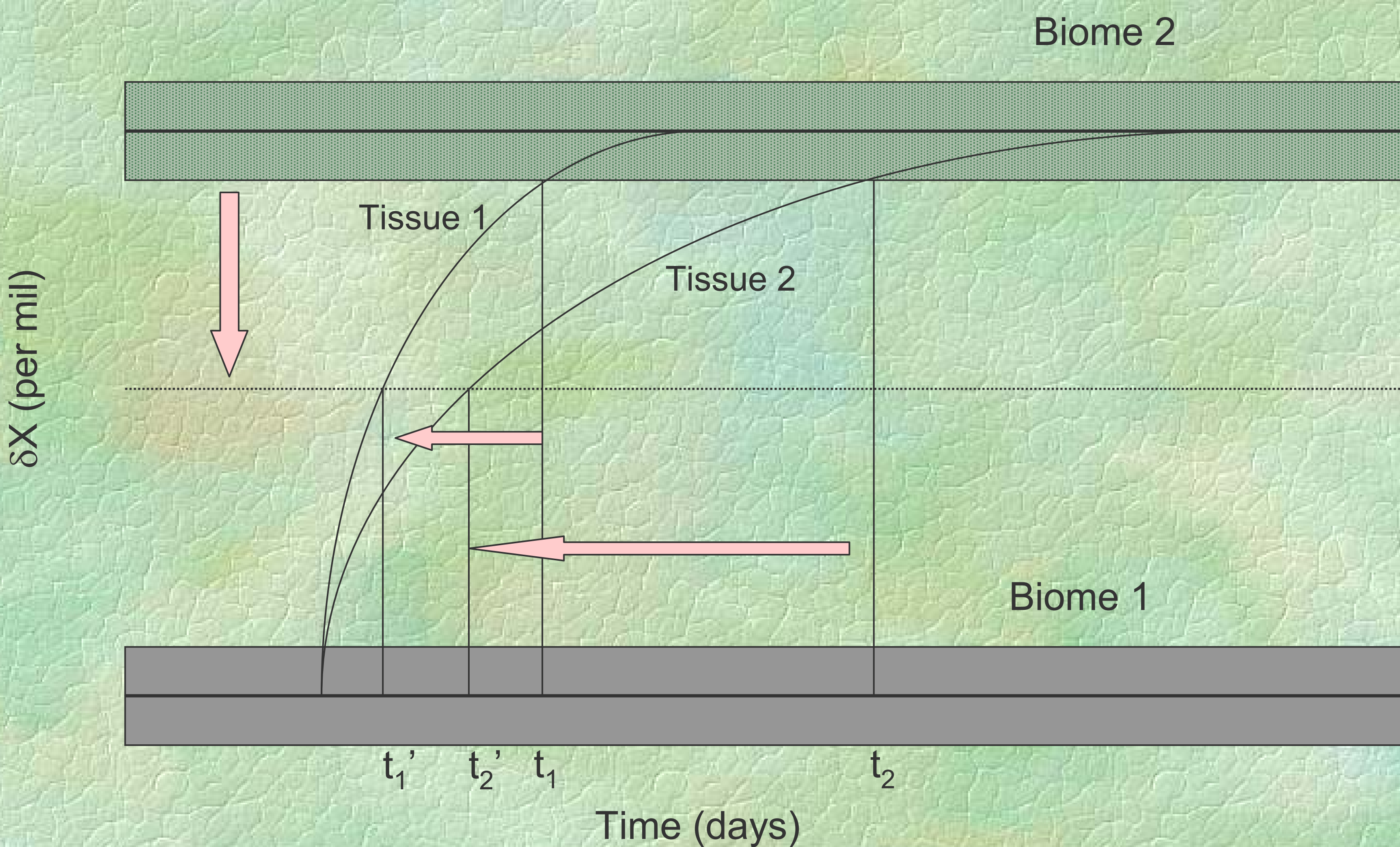


Max Planck Institute for Ornithology

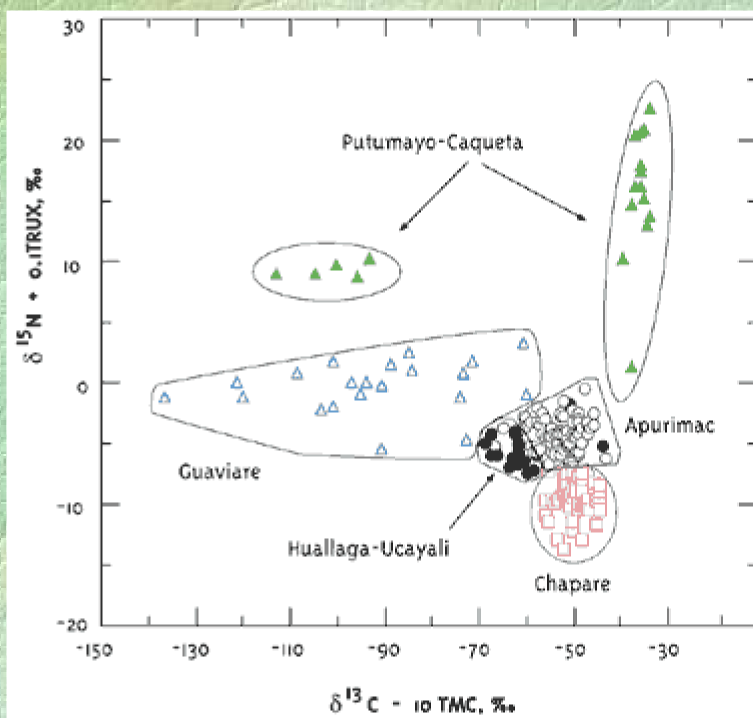
Principles of isotopic tracking

- Animals move between unambiguous isotopically distinct “landscapes” and their tissues retain this information.
- Information “time window” depends on tissue chosen.
- Physiological aspects of movement and migration are understood in terms of turnover, metabolic routing etc.

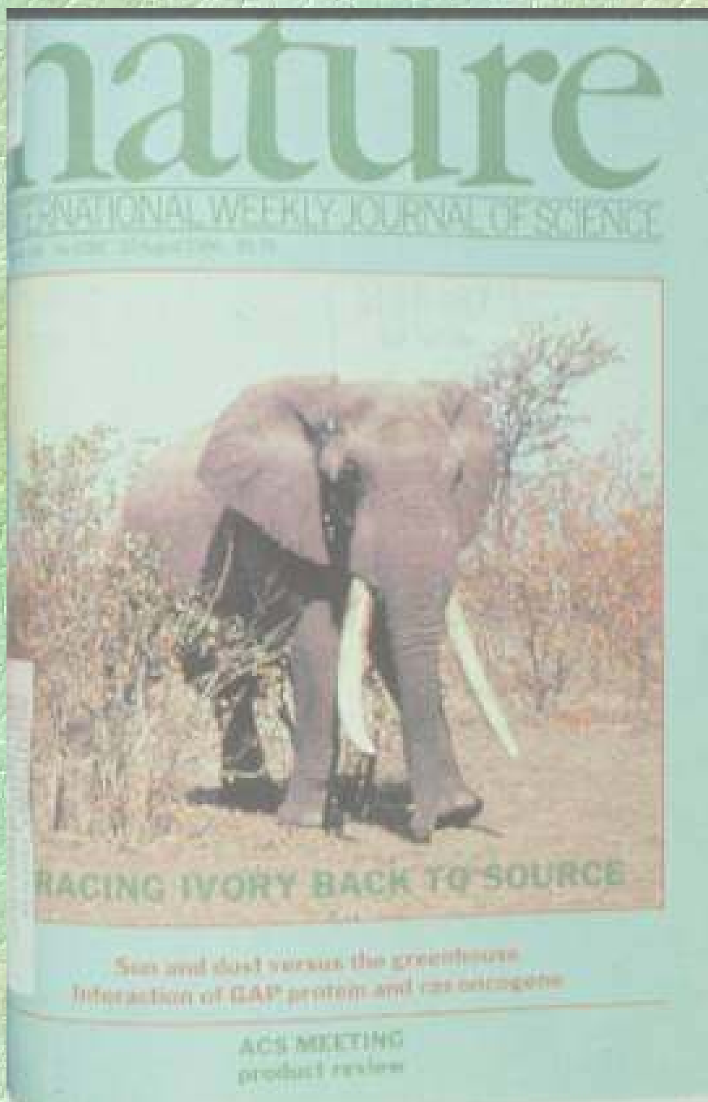
The isotopic clock and movement



Forensic applications are broad:



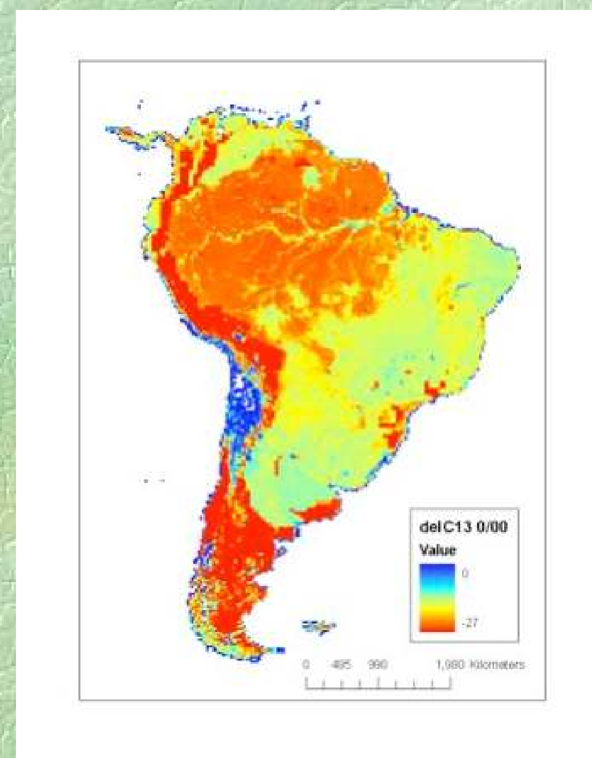
Forensic tracing of African ivory ….



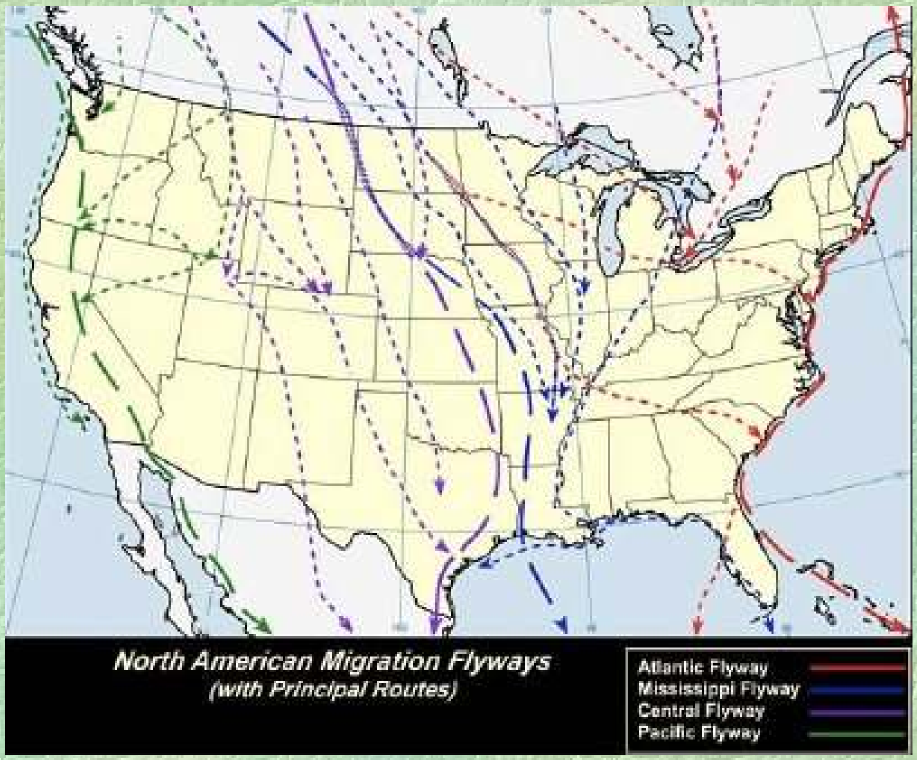
$\delta^{13}C$, $\delta^{15}N$, $\delta^{87}Sr$, $\delta^{204}Pb$

Vogel et al. (1990); van der Merwe et al (1990)

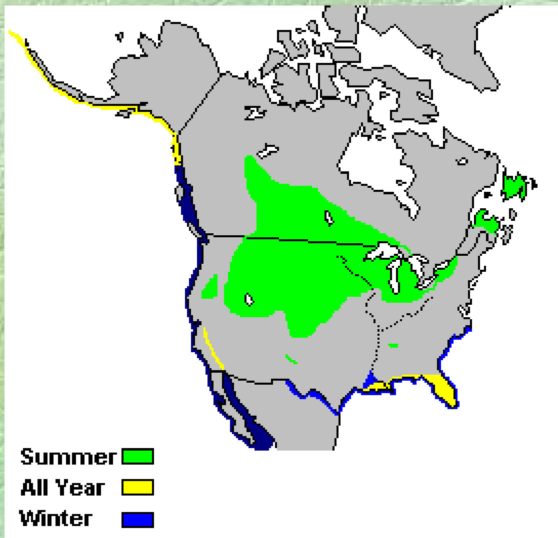
Biogeochemical processes result in isotopic patterns or "isoscapes" …



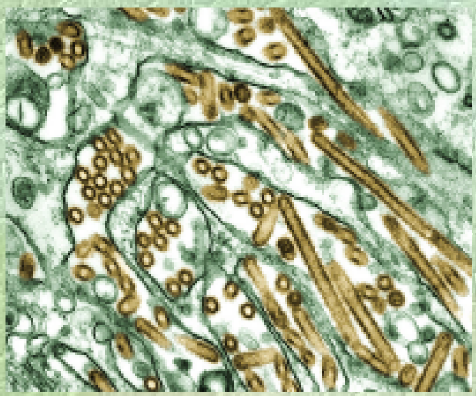
Some avian applications:
1. Game bird management

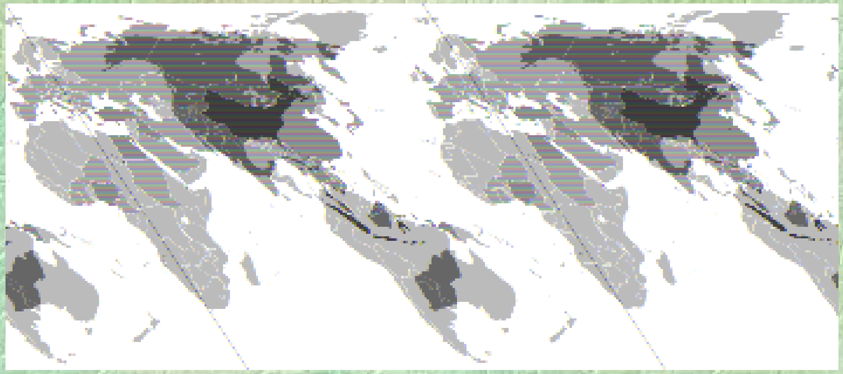


2. Movement of contaminants

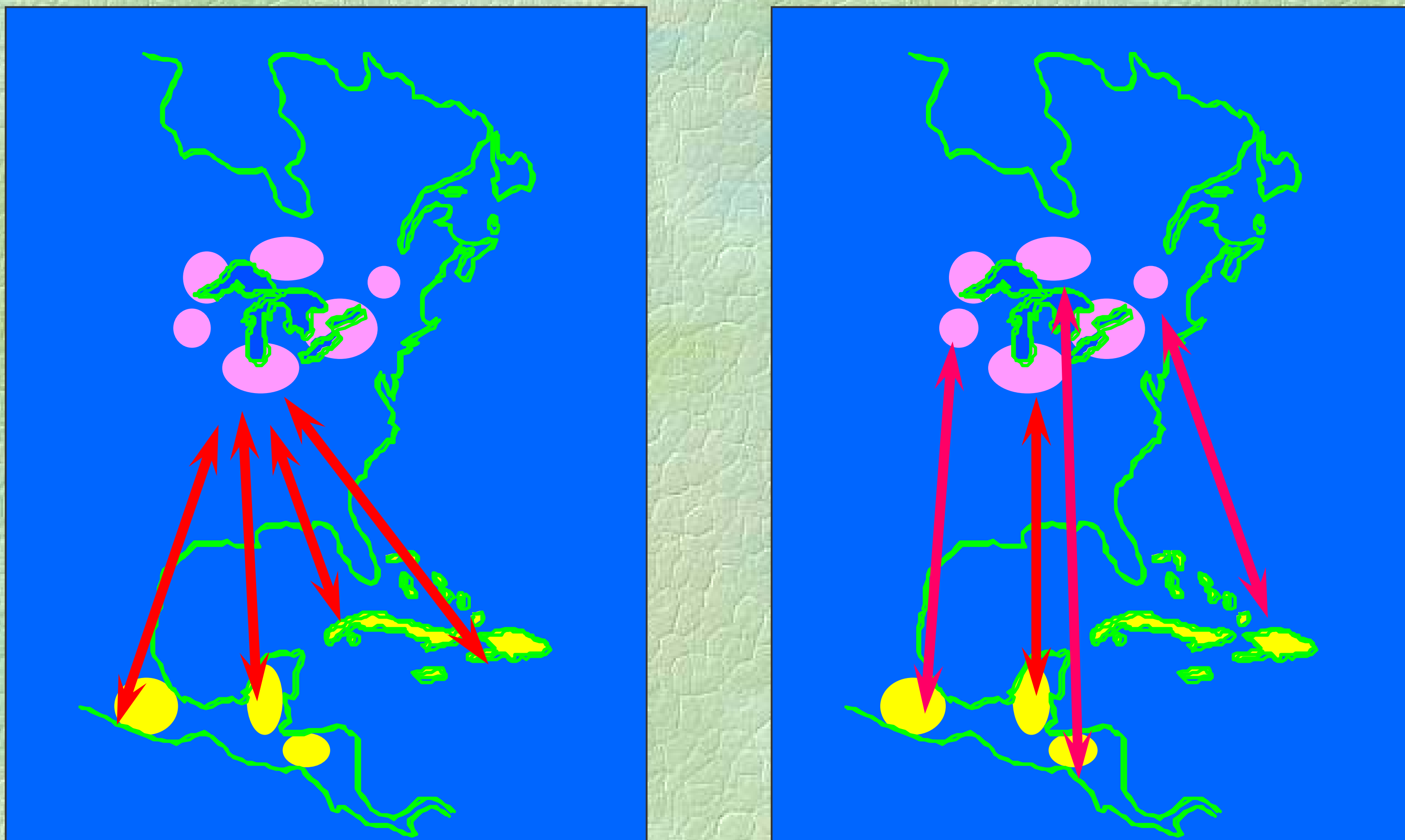


3. Disease tracking: Avian Influenza



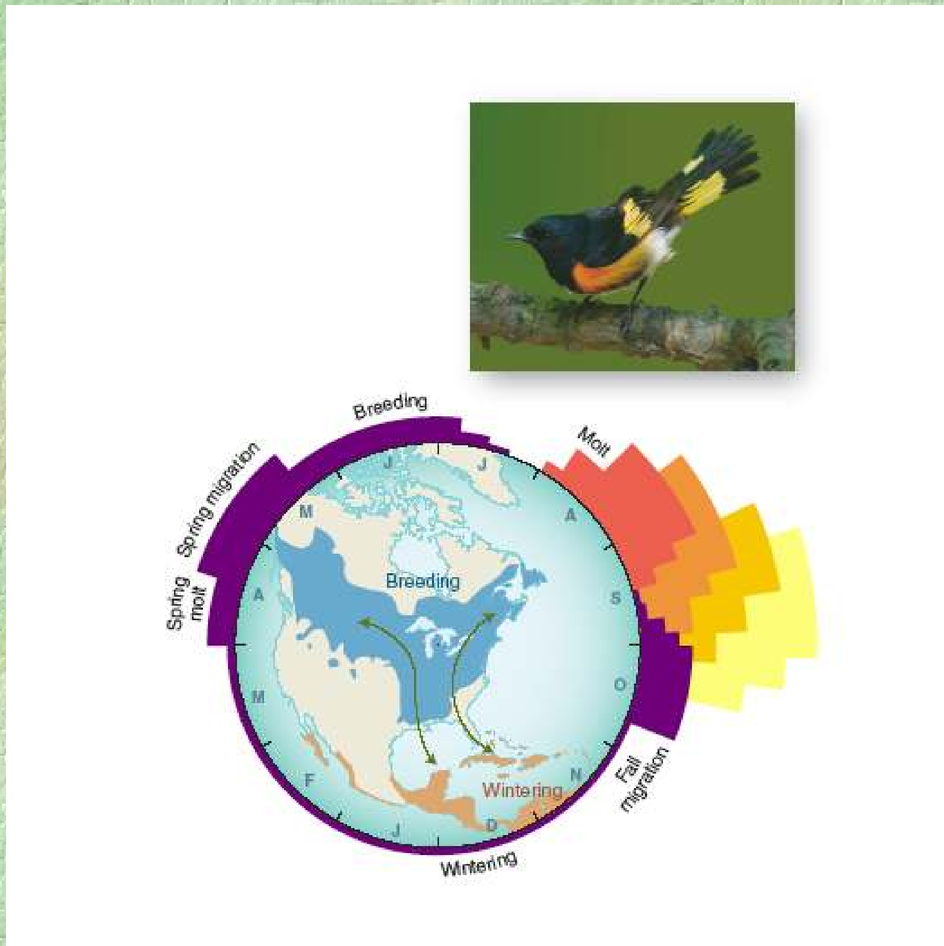


4. Connectivity and stable isotope tracking …….



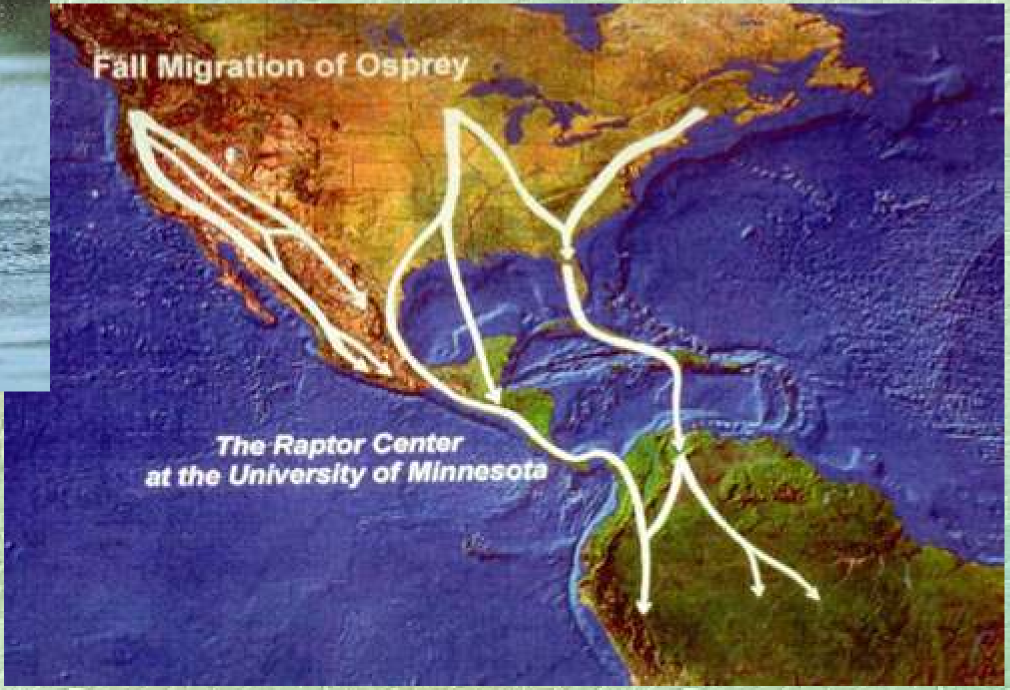
Idea from Webster et al. *TREE* 17:76-83

5. Seasonal interactions …



Lots of exogenous markers …

Satellite transmitters are the best! But only for BIG birds …



N.A. avian band recoveries (1955-2000)

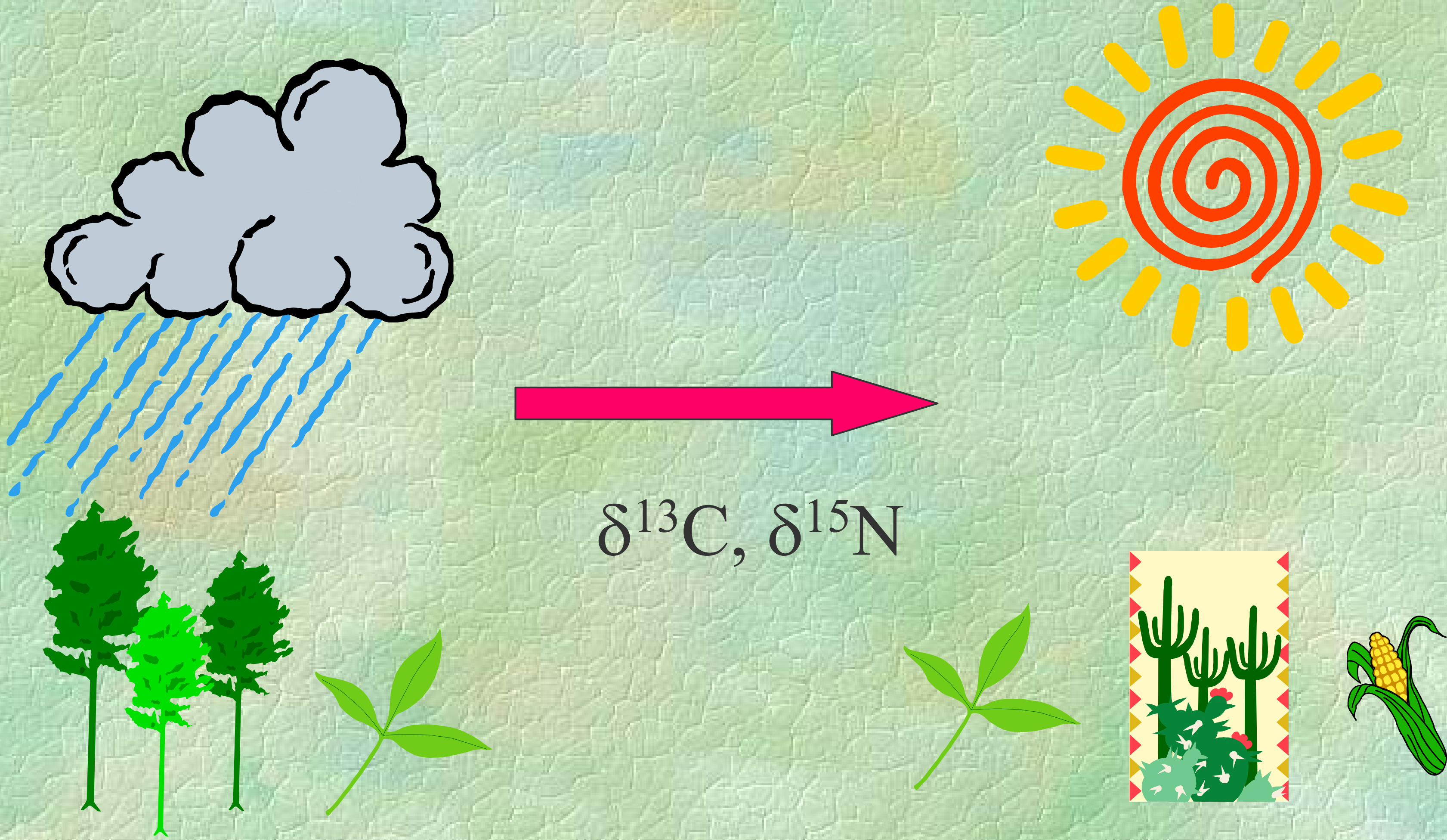
Species	Banded	recap	%
Canada Goose	2,991,538	594,114	19.9
Mallard	5,935,960	878,704	14.8
N. Pintail	1,286,499	142,449	11.1
Merlin	26,308	674	2.6
Logg.shrike	22,897	196	0.86
Sp. sandpiper	13.673	79	0.58
R-t. hummingbird	54,218	53	0.10
Am. redstart	275,222	256	0.09
Myrtle warbler	824,013	704	0.09
W. flycatcher	28,194	20	0.07
Sw. thrush	371,313	251	0.07

So, banding doesn't work, Can we use isoscapes?

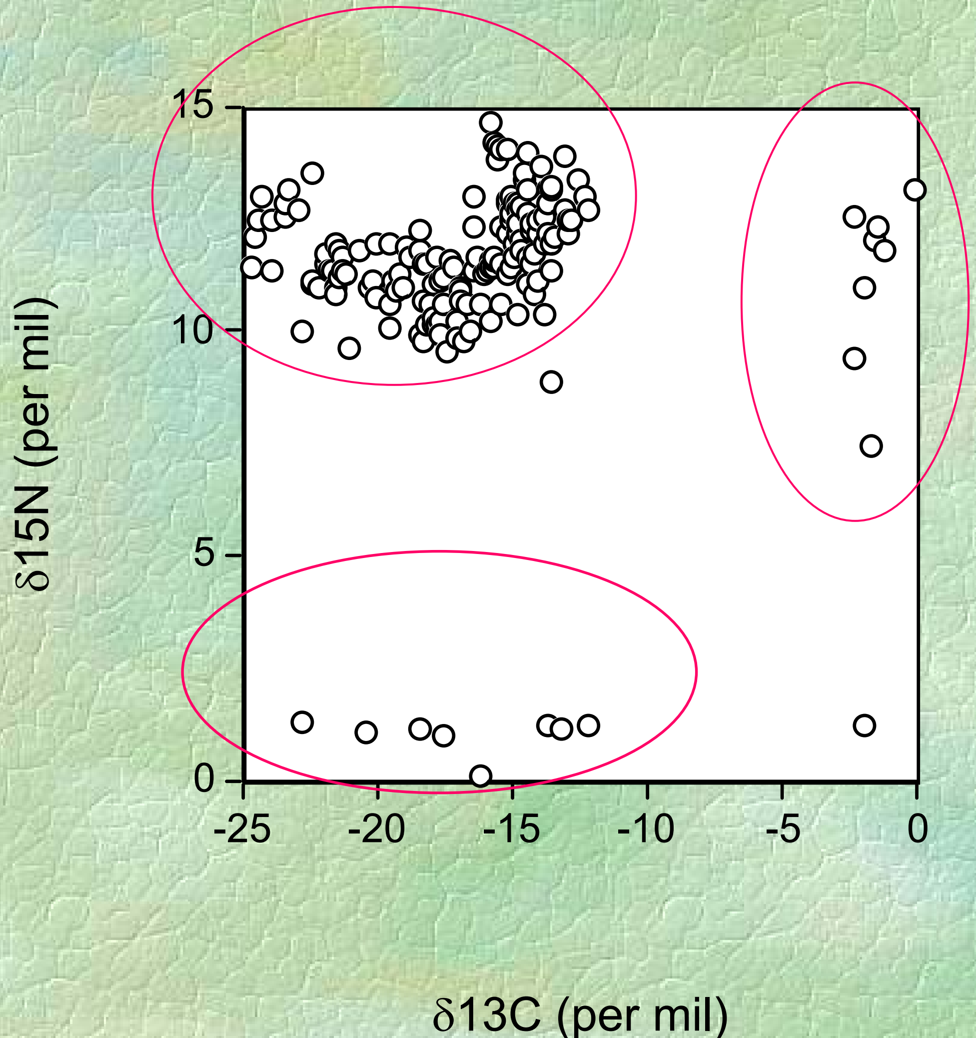
- Terrestrial-marine ($\delta^{13}C$, $\delta^{15}N$ $\delta^{34}S$)
- Inshore-offshore ($\delta^{13}C$, $\delta^{34}S$, $\delta^{15}N$)
- C-3 vs. C-4, CAM ($\delta^{13}C$)
- Xeric vs. Mesic ($\delta^{13}C$, $\delta^{15}N$)
- Latitudinal/altitudinal gradients (δD, $\delta^{13}C$)
- Surficial geology (Sr, Pb, others)

If so, “Every capture becomes a recapture”

Mesic to xeric isotopic gradients help "locate" individuals and their tissues …

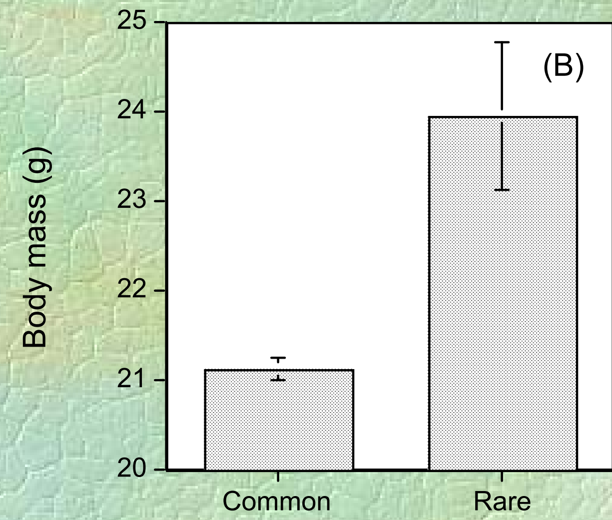


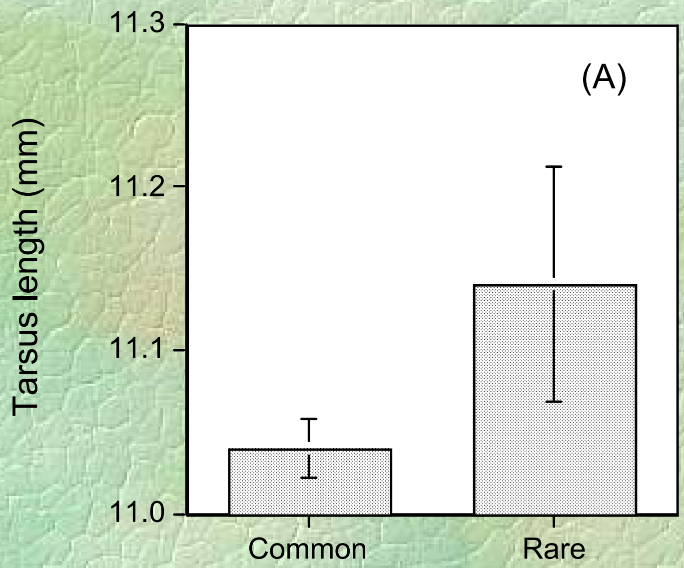
Barn swallows from Denmark are not all wintering in the same part of Africa …

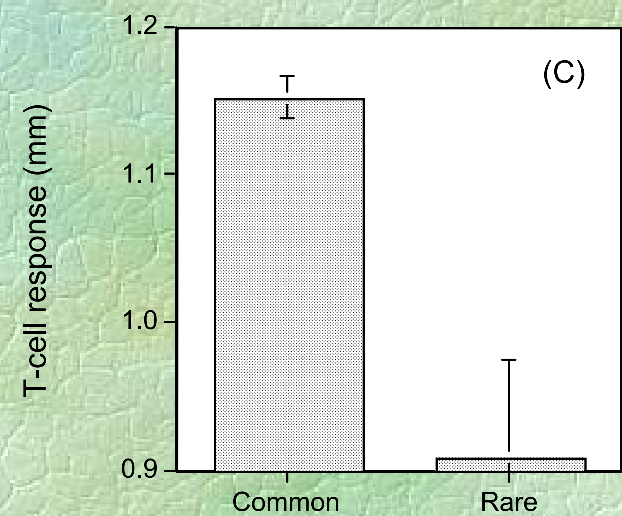


Møller and Hobson (2004)

Population heterogeneity ….







Møller and Hobson (2004)

Using three stable isotopes to distinguish migrants from residents

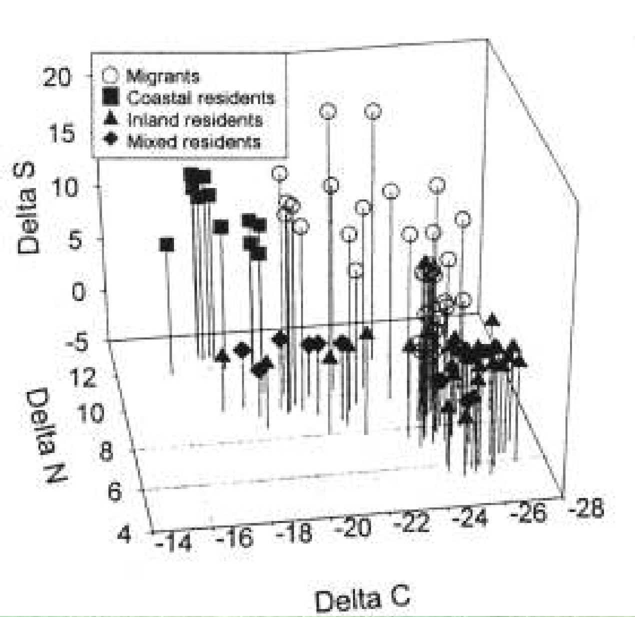


Photo:Wyman Meinzer, USFWS

DISTINGUISHING MIGRATORY AND RESIDENT CANADA GEESE USING STABLE ISOTOPE ANALYSIS

DONALD F. CACCAMISE, Department of Wildlife and Fishery Sciences, New Mexico State University, Las Cruces, NM 88003, USA
LISA M. REED, Department of Entomology, Rutgers University, New Brunswick, NJ 08903, USA
PAUL M. CASTELLI, New Jersey Division of Fish and Wildlife, Nacote Creek Research Station, Port Republic, NJ 08241, USA
SAM WAINRIGHT,[1] Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ 08903, USA
TED C. NICHOLS, New Jersey Division of Fish and Wildlife, L. G. MacNamara Wildlife Management Area, 2201 County Route 631, Woodbine, NJ 08270, USA

Abstract: Effective management of Canada geese (*Branta canadensis*) requires a reliable method to determine the population affiliation of geese in the harvest. We determined if stable isotope analysis of feather tissue could distinguish between migrant and resident populations. We obtained feather samples of migrants from Atlantic population of Canada geese in northern Quebec near Ungava Bay, Canada. We grouped resident population Canada geese as coastal residents and inland residents according to the habitats where they were captured in New Jersey. We analyzed for isotopes of carbon ($\delta^{13}C$), nitrogen ($\delta^{15}N$) , and sulfur ($\delta^{34}S$). We found significant differences among migrants, coastal residents, and inland resident for all 3 isotopes. Combinations of isotopic ratios for the 3 elements resulted in unique patterns among groups of geese. We entered the isotopic ratios into a discriminant analysis using collection site as the grouping variable (migrants, inland residents, and coastal residents). We formed 2 significant functions that discriminated among the 3 groups 92% of the time. The first function accounted for most of the variance, and was highly influenced by the isotope ratios for carbon and sulfur. The results indicate that stable isotope analysis of primary feathers can provide a reliable means to discriminate between migratory and resident populations of Canada geese. Stable isotope analysis is a promising technique for identifying the breeding areas of Canada geese, but additional studies are needed to determine inherent variability over broad geographic areas.

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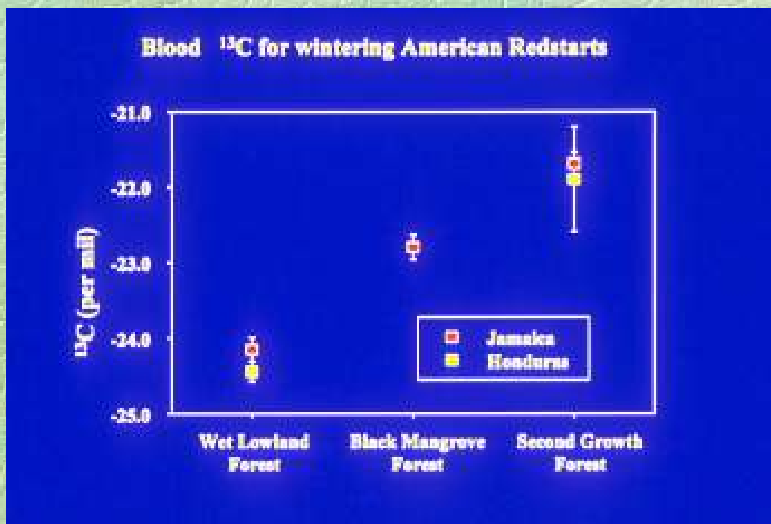
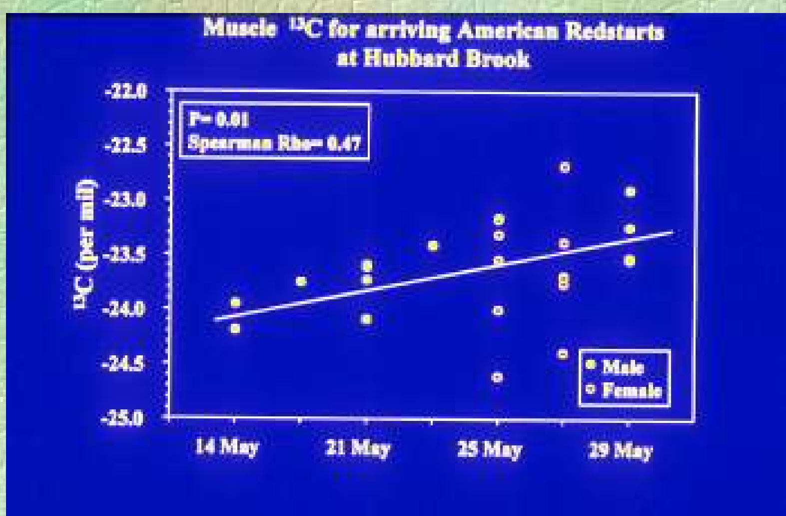
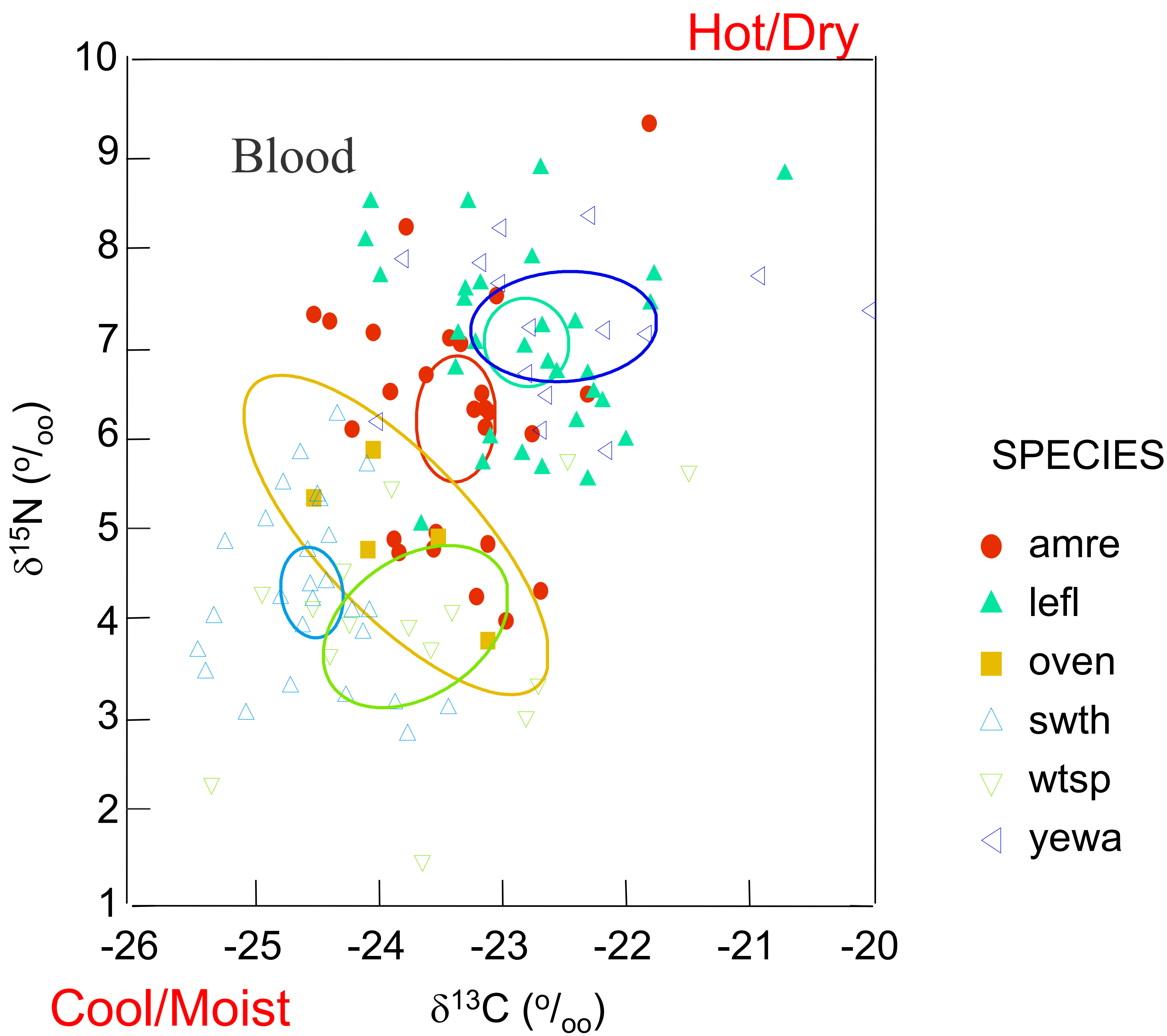
Wintering habitat determines arrival time on breeding grounds



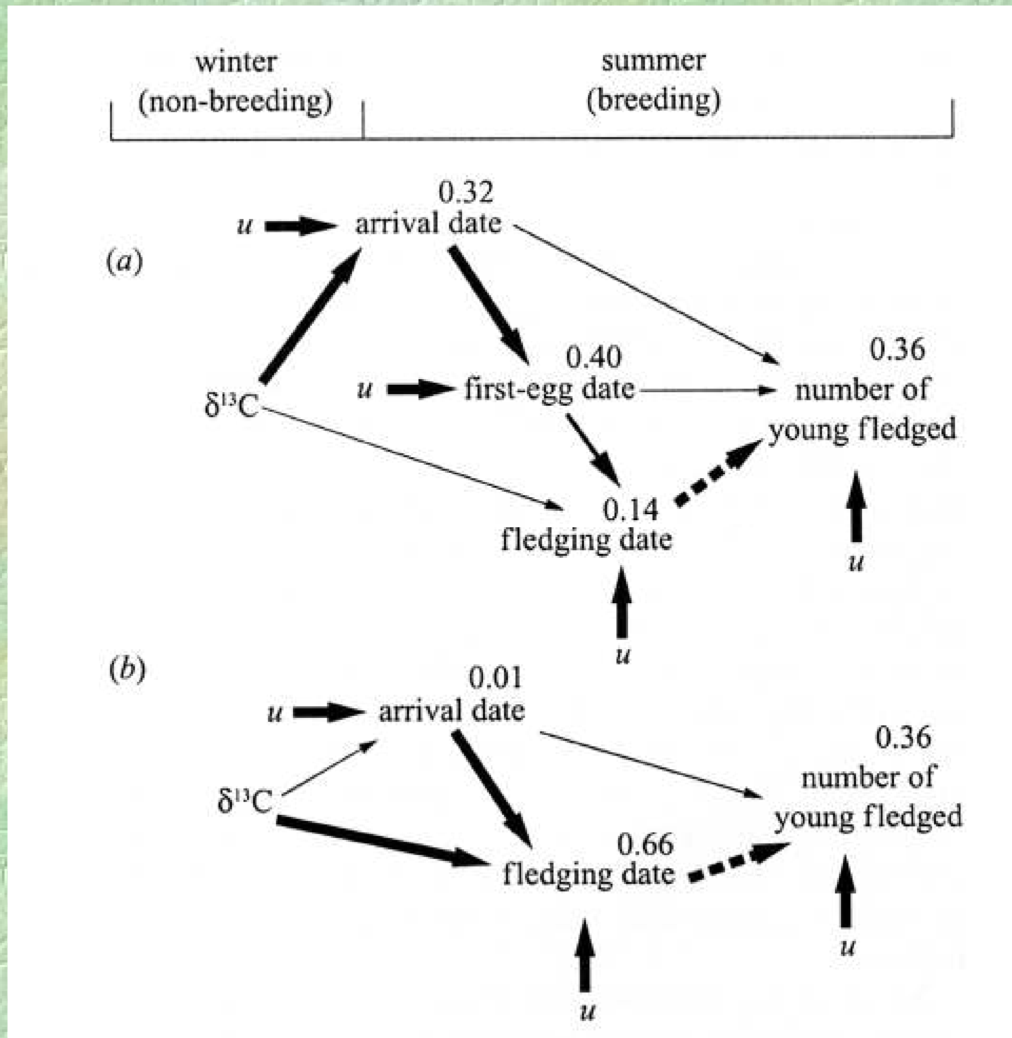


Marra et al. (Science 1998)



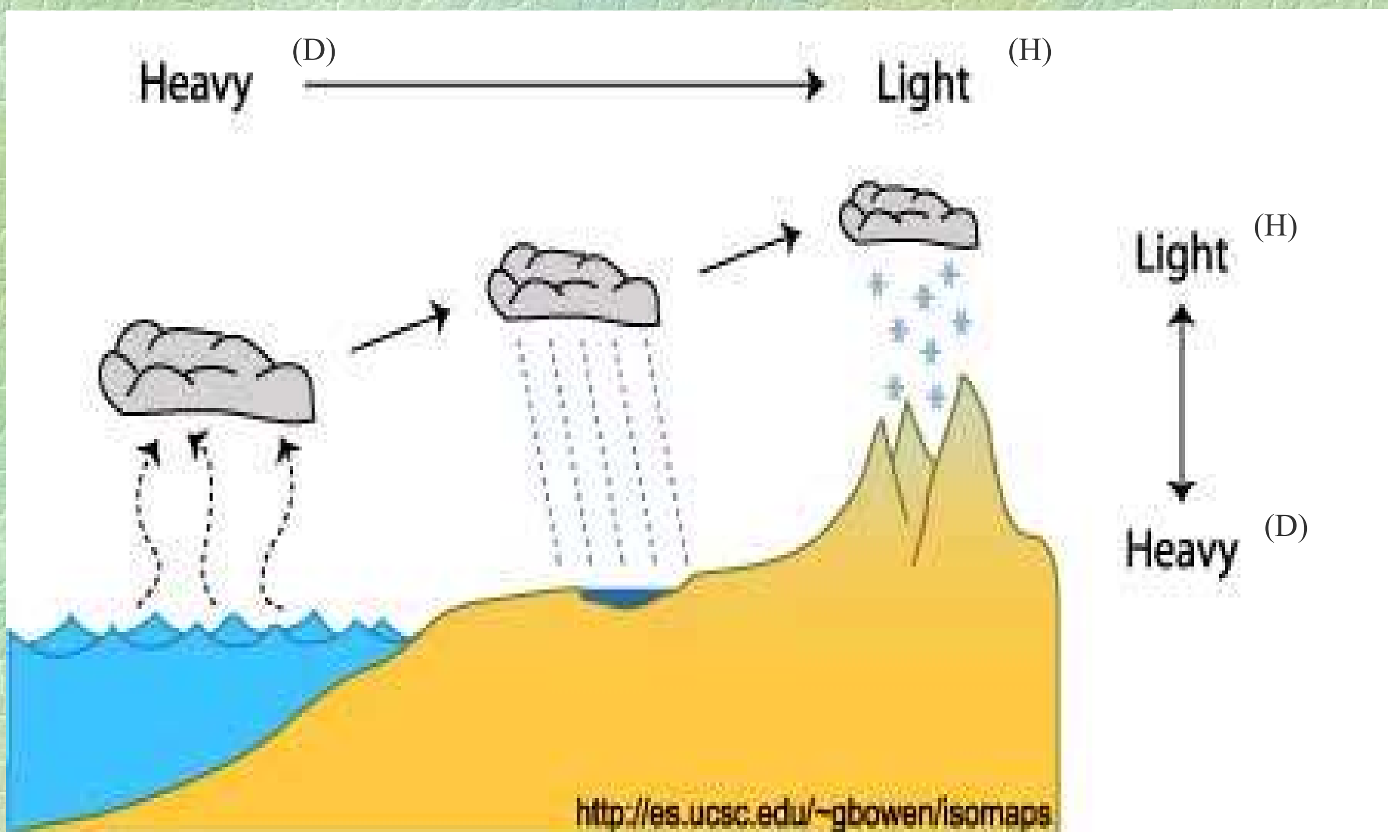
Hot/Dry
Blood
10
9
8
7
6
5
4
3
2
1
δ15N (o/oo)
-26
-25
-24
-23
-22
-21
-20
Cool/Moist
δ13C (o/oo)
SPECIES
amre
lefl
oven
swth
wtsp
yewa

Turning isotopes signatures into offspring produced!

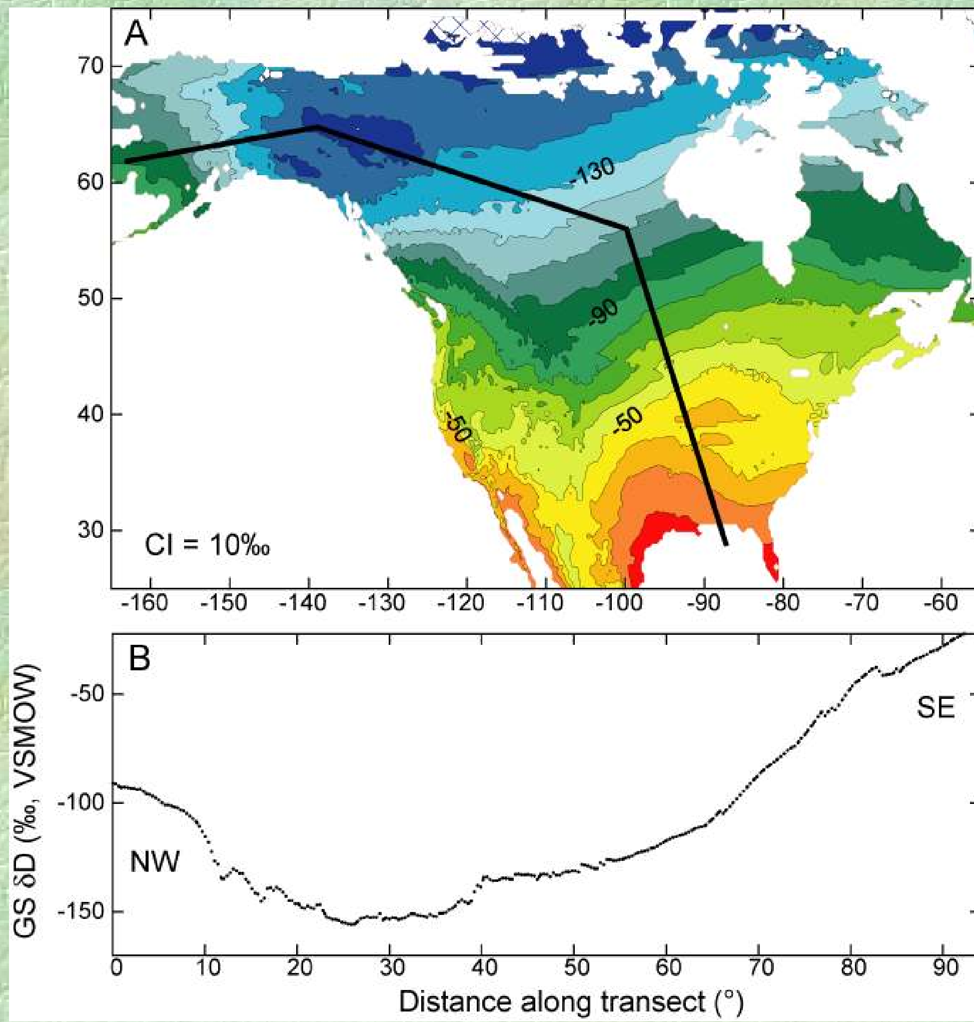


Norris et al. (2003)

The BIG breakthrough: Using deuterium …..

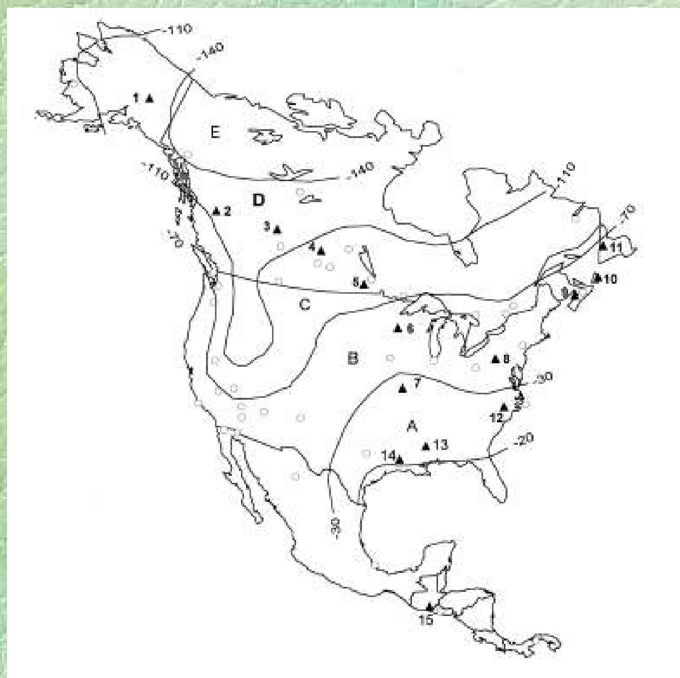


The mean annual precipitation δD pattern:

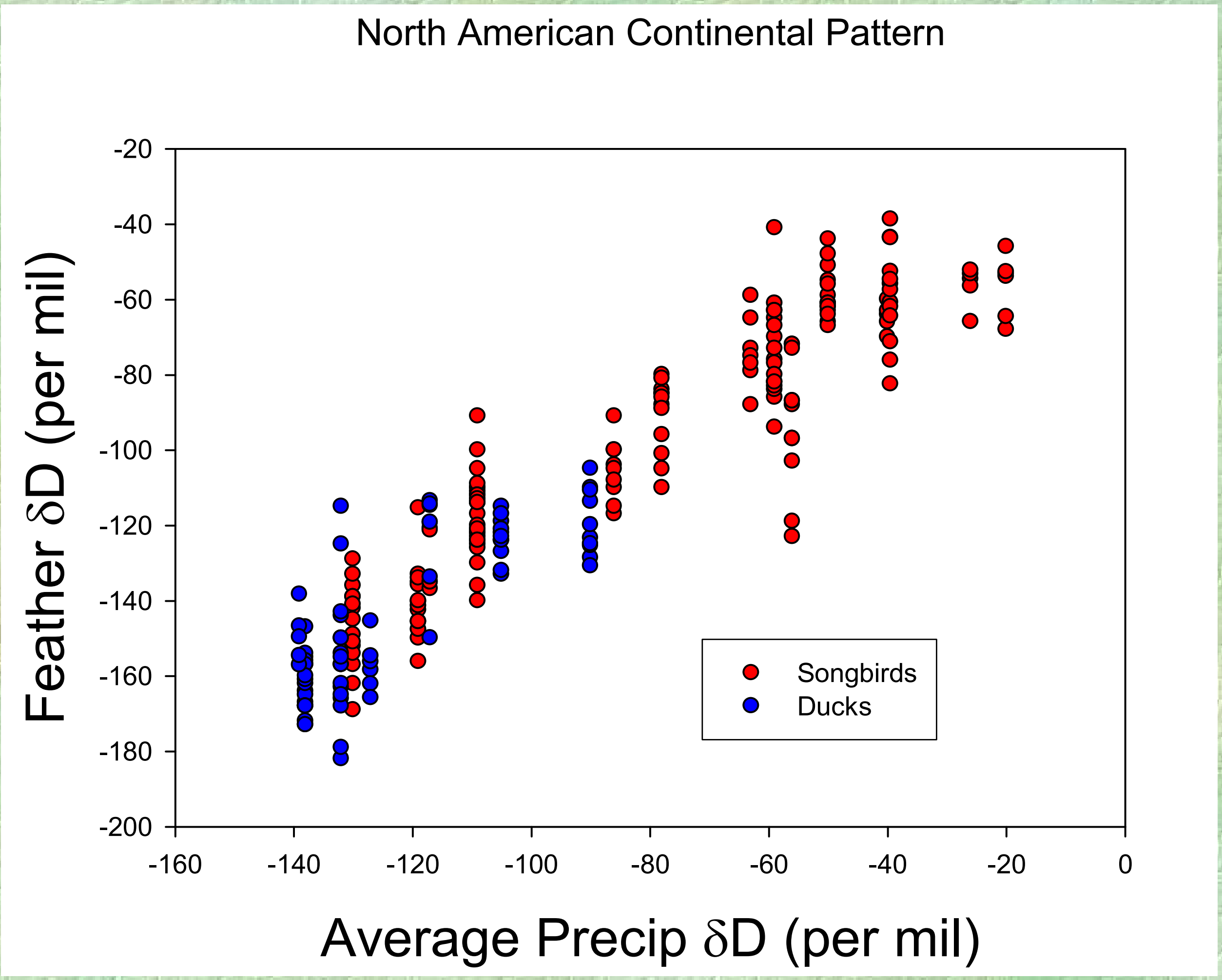


Bowen et al. 2005

How does this pattern translate into bird feathers?



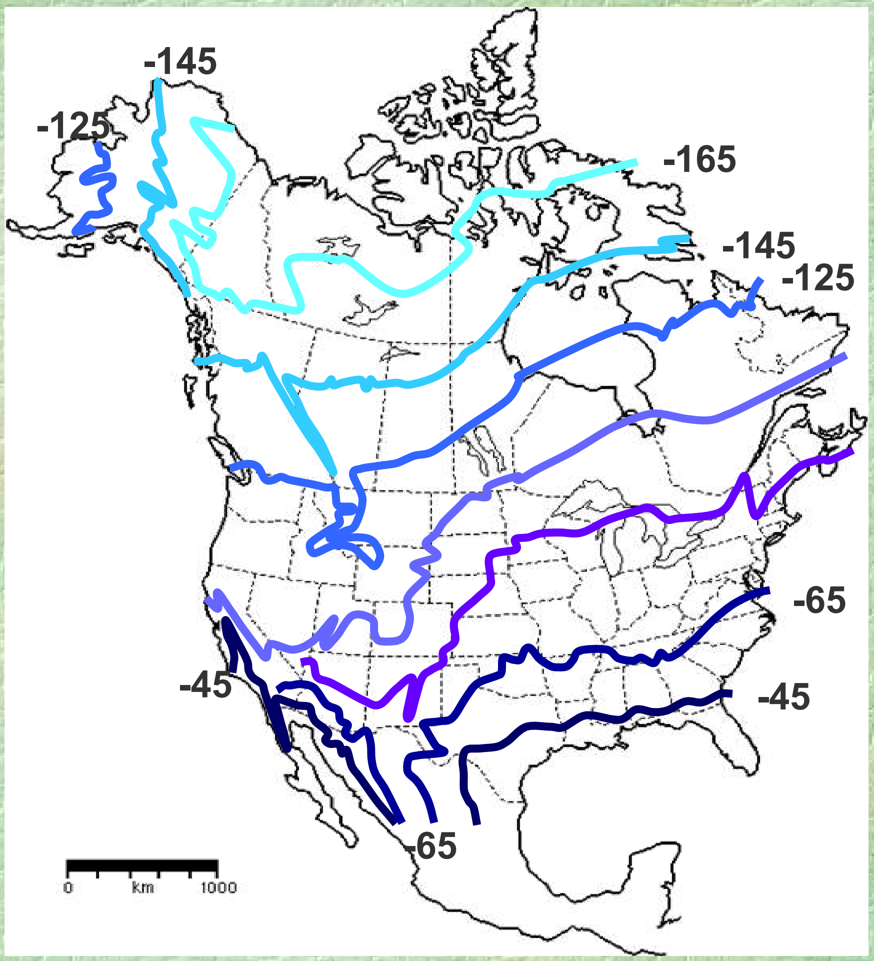
Hobson and Wassenaar *Oecologia* 109:142-148


North American Continental Pattern
Feather δD (per mil)
Average Precip δD (per mil)
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-160
-140
-120
-100
-80
-60
-40
-20
0
Songbirds
Ducks

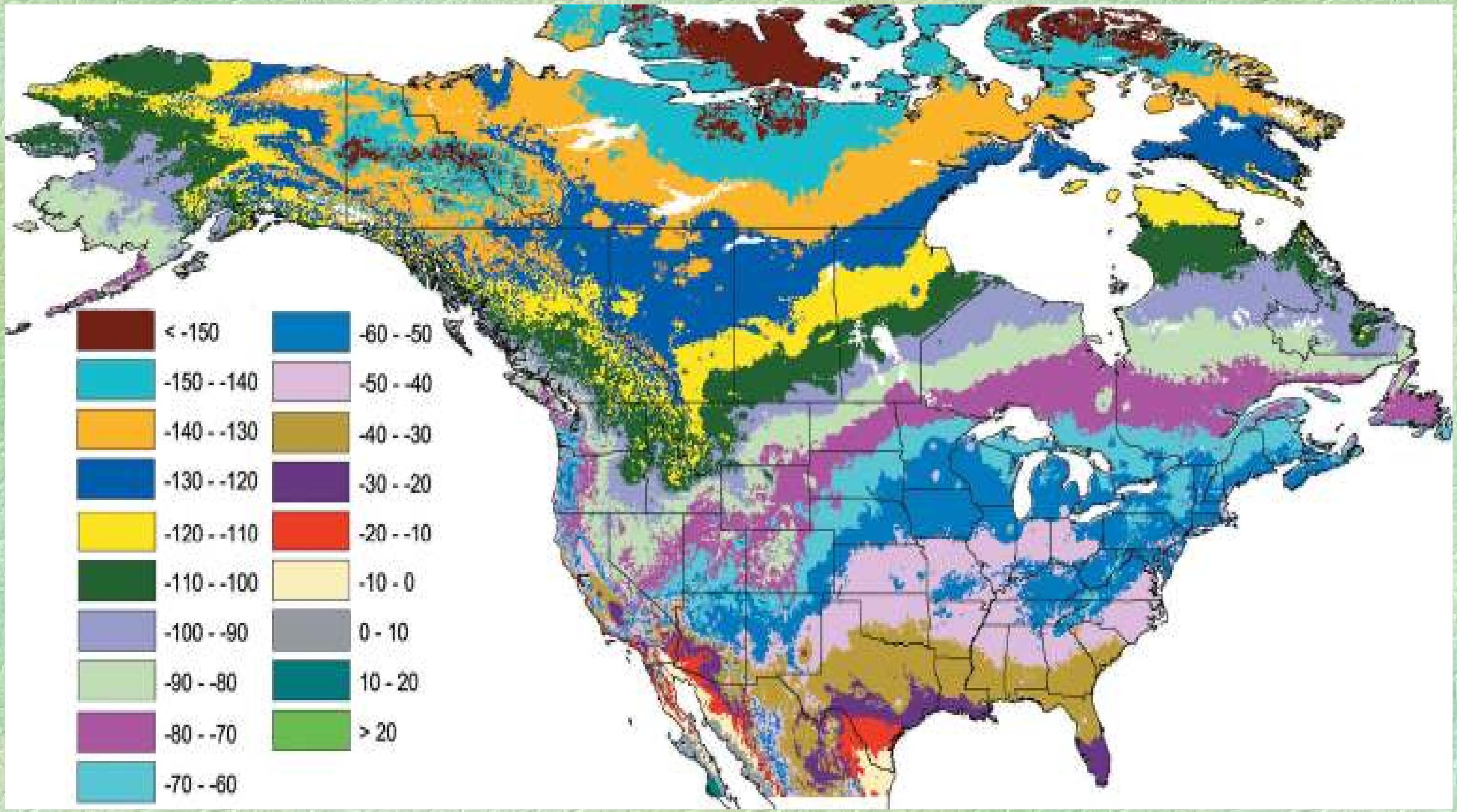
- Based on a 40+ year IAEA dataset
- Can be portrayed as the “growing-season average” pattern (e.g. Meehan et al. 2004) OR as an annual average (Bowen et al.) or monthly.
- Involves patterns corrected for elevation or not in the interpolation.
- Lacks an analysis of spatial/temporal variance.
- Some areas of the continent are poorly represented

- However, we are typically interested in the pattern of deuterium in organisms and not in precipitation per se.
- This requires knowledge of the isotopic discrimination between precipitation and the organism of interest.
- For songbirds, ducks and cranes, we use a value of -25 per mil, but other groups differ.

For most birds …



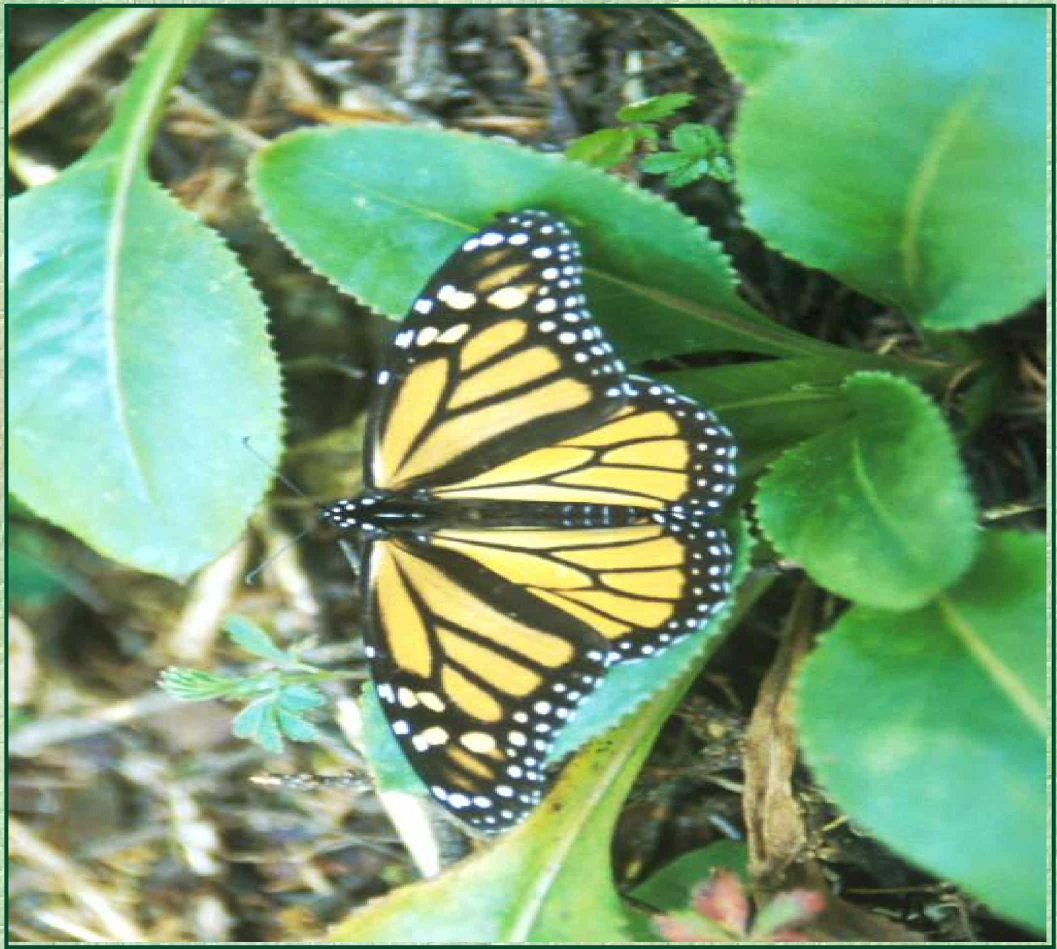
For raptors …



< -150
-150 - -140
-140 - -130
-130 - -120
-120 - -110
-110 - -100
-100 - -90
-90 - -80
-80 - -70
-70 - -60
-60 - -50
-50 - -40
-40 - -30
-30 - -20
-20 - -10
-10 - 0
0 - 10
10 - 20
> 20

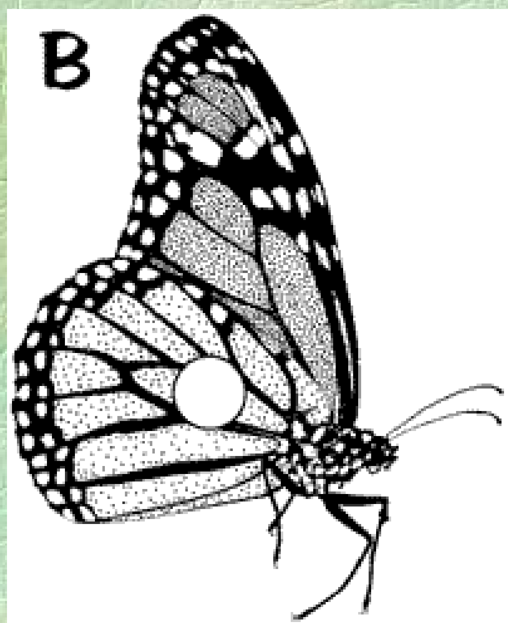
Species	Equation	r^2	Model	Source
Birds:				
6 species of North American songbird	$\delta D = -31 + 0.9\delta Dp$	0.83	H	Hobson and Wassenaar (1997)
6 species of North American songbird	$\delta D = -25 + 0.9\delta Dp$	0.88	B	Clark et al. (2006)
6 species of North American songbird	$\delta D = -19.4 + 1.07\delta Dp$	0.86	B	Bowen et al. (2005)
Black-throated Blue Warbler	$\delta D = -51 + 0.5\delta Dp$	0.86	CH	Chamberlain et al. (1997)
Red-winged blackbird	$\delta D = -27 + 1.1\delta Dp$	0.83	H	Wassenaar and Hobson (2000)
Bicknell's Thrush	$\delta D = -26 + 0.7\delta Dp$	0.48	H	Hobson et al (2001)
Wilson's Warbler	$\delta D = -51.7 + 0.4\delta Dp$	0.36	B	J. Kelly (unpublished)
Wilson's Warbler	$\delta D = +14.47 + 1.41\delta Dp$	0.91	M	Paxton et al. (2007)
Wilson's Warbler	$\delta D = -21 + 0.7\delta Dp$	0.48	M	Meehan et al. (2004)
Mountain Plover	$\delta D = +17.4 + 1.26\delta Dp$	0.36	B	Wunder (2007)
23 species of European birds	$\delta D = -7.8 + 1.27\delta Dp$	0.65	B	Hobson et al. (2004d)
23 species of European birds	$\delta D = -22.3 + 0.77\delta Dp$	0.85	B	Bowen et al. (2005)
Cooper's Hawk	$\delta D = -34 + 1.0\delta Dp$	0.83	H	Meehan et al. (2001)
Inland generalist raptors	$\delta D = -40 + 0.62\delta Dp$	0.59	H	Lott et al. (2003)
Inland bird-eating raptor	$\delta D = -44.2 + 0.54\delta Dp$	0.37	H	Lott et al. (2003)
Coastal generalist raptors	$\delta D = -38.8 + 0.55\delta Dp$	0.19	H	Lott et al. (2003)
Coastal bird-eating raptors	$\delta D = -104.7 - 0.59\delta Dp$	0.12	H	Lott et al. (2003)
Non-coastal bird-eating raptors	$\delta D = -41.1 + 0.58\delta Dp$	0.46	H	Lott et al. (2003)
9 species of raptors	$\delta D = -52.2 + 0.28\delta Dp$	0.09	H	Lott et al. (2003)
9 species of diurnal raptors	$\delta D = -37 + 0.6\delta Dp$	0.51	M	Meehan et al. (2004)
Raptors in South Carolina	$\delta D = -25 + 0.7\delta Dp$	0.18	M	Meehan et al. (2004)
Flammulated Owl	$\delta D = -8 + 0.9\delta Dp$	0.66	M	Meehan et al. (2004)
12 species of raptors	$\delta D = -5.6 + 0.91\delta Dp$	0.62	M	Lott and Smith (2006)
Scaup	$\delta D = -27.8 + 0.95Dp$	0.64	B	Clark et al. (2006)
Mallards and Northern Pintail	$\delta D = -57 + 0.835Dp$	0.56	M	Hebert and Wassenaar (2005)
Other animals:				
Deer collagen	$\delta D = 4 + 1.02\delta Dp$	0.94	C	Cormie et al. (1994)
Hoary bat	$\delta D = -25 + 0.8\delta Dp$	0.60	M	Cryan et al. (2004)
Monarch butterfly	$\delta D = -79 + 0.62\delta Dp$	0.69	H	Hobson et al. (1999)
Beetle (chitin)	$\delta D = 33.2 + 1.60\delta Dp$	0.74	B	Gröcke et al. (2006)

Using δD to track Monarch migration ….



Two populations, one long distance journey ….

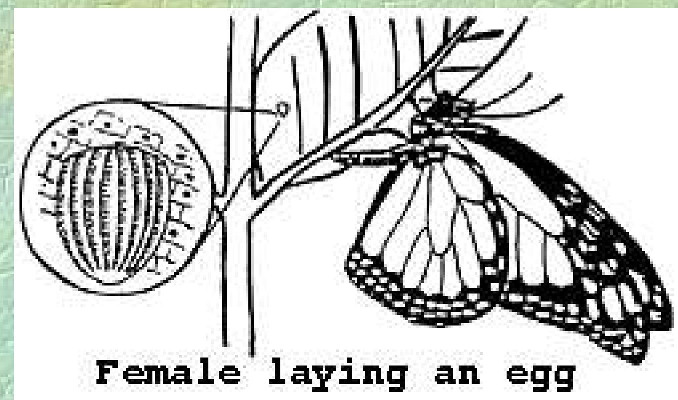
Previously, tagging was used:

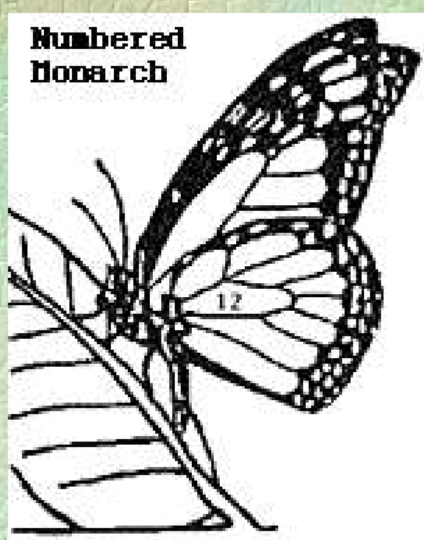


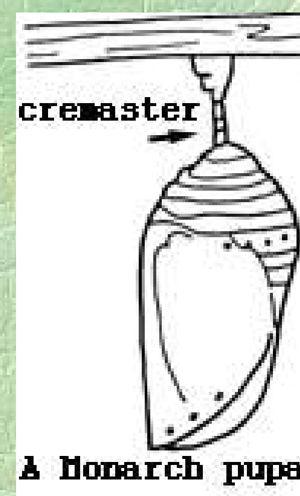
Needle in a haystack?

How to create an isotopic base map?

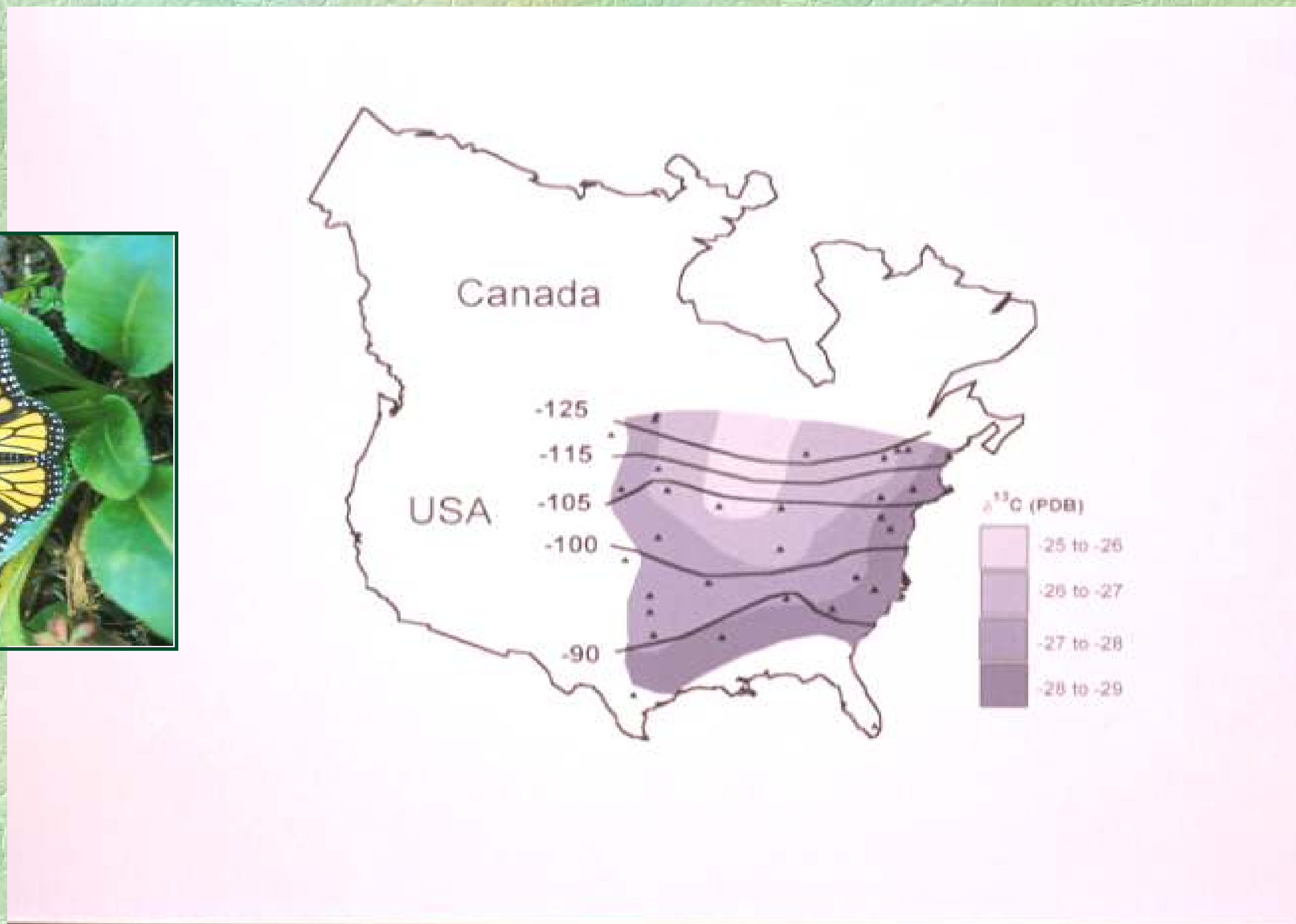
Monarchs can be “grown” anywhere!



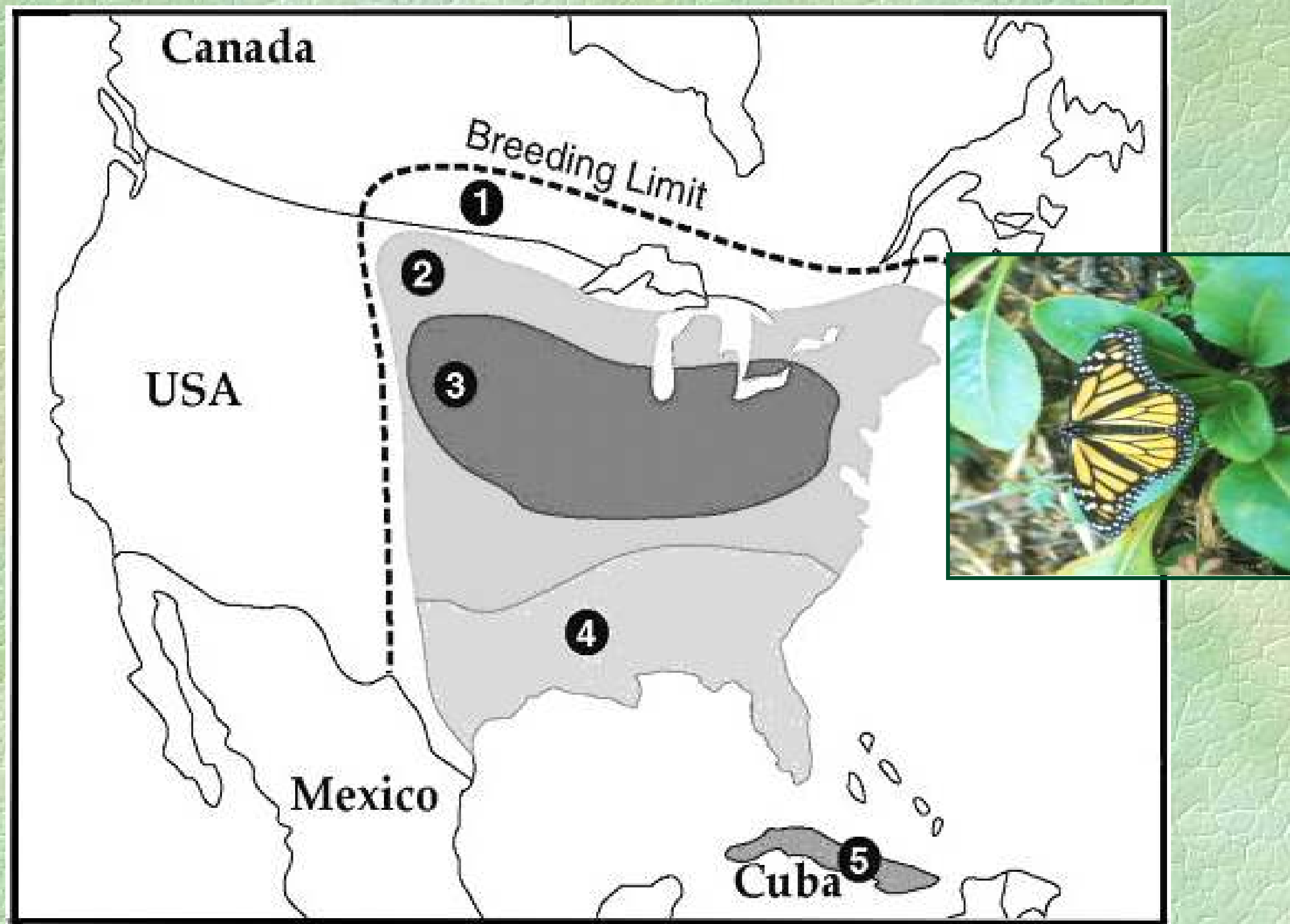




The basemap for the year of interest:

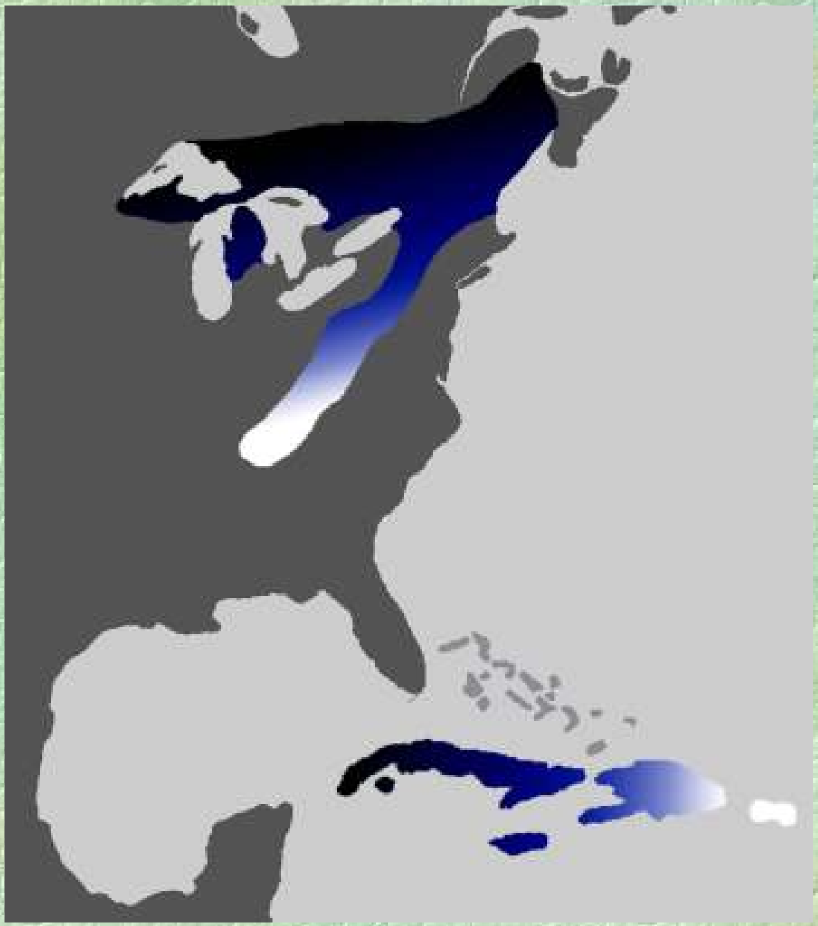


Origins: 50% of the population is produced in the US cornblelt:



Docykx et al. Ecol. Applic., in press

Other isotopic delineations of population structure …

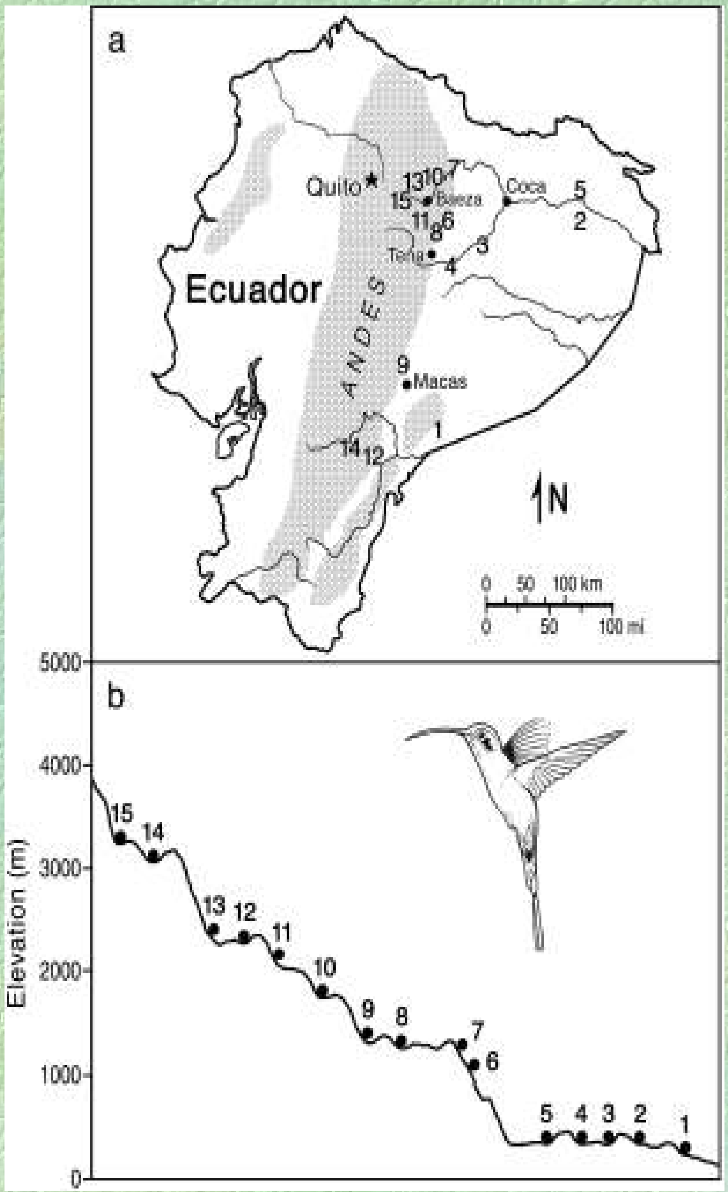


Rubenstein et al. (Science 2002)

“Leapfrog” migration revealed ..

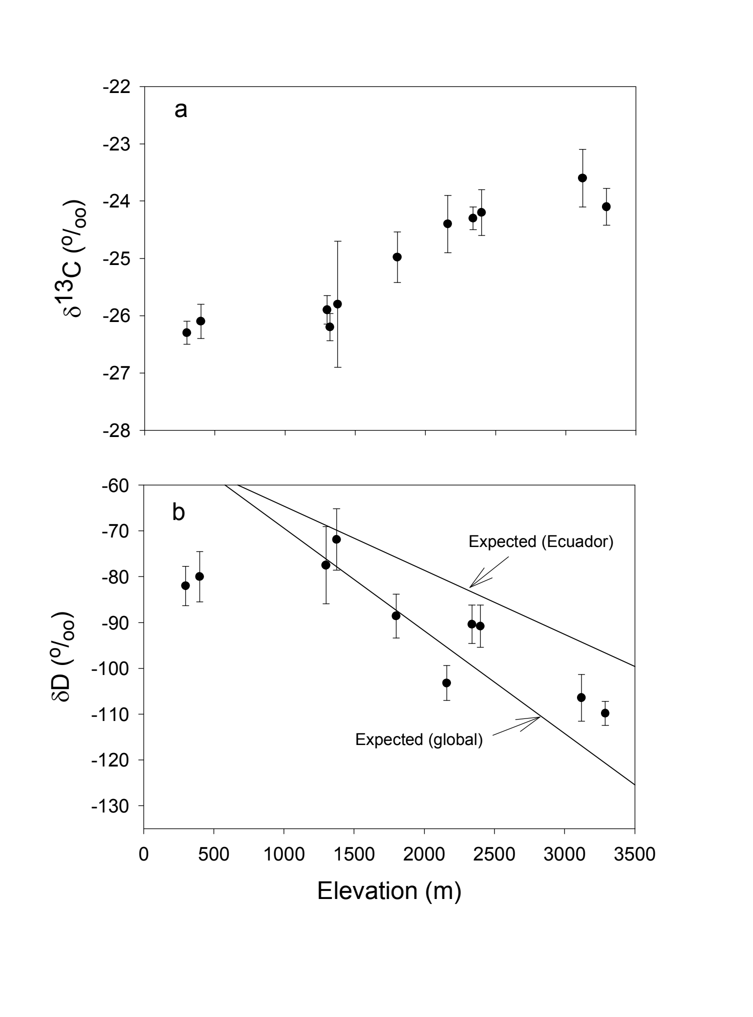
Kelly et al. (Oecologia 2002)

Altitudinal gradients are recorded in hummingbird feathers:



Hobson et al. *Oecologia* 136:302-308

The feather isotopes follow large scale trajectories in precip δD



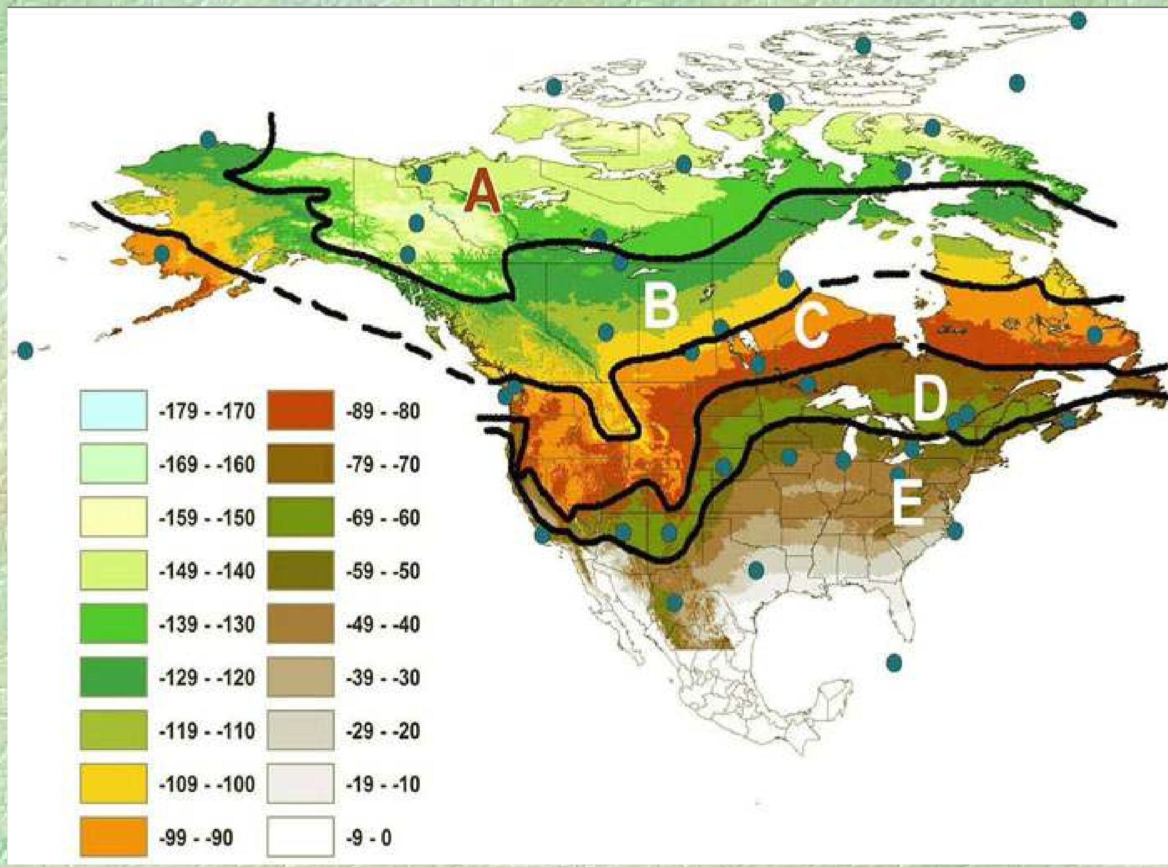
Ecuador:

$\delta D_f = -25.6 + E(-0.014) -25$ °/oo

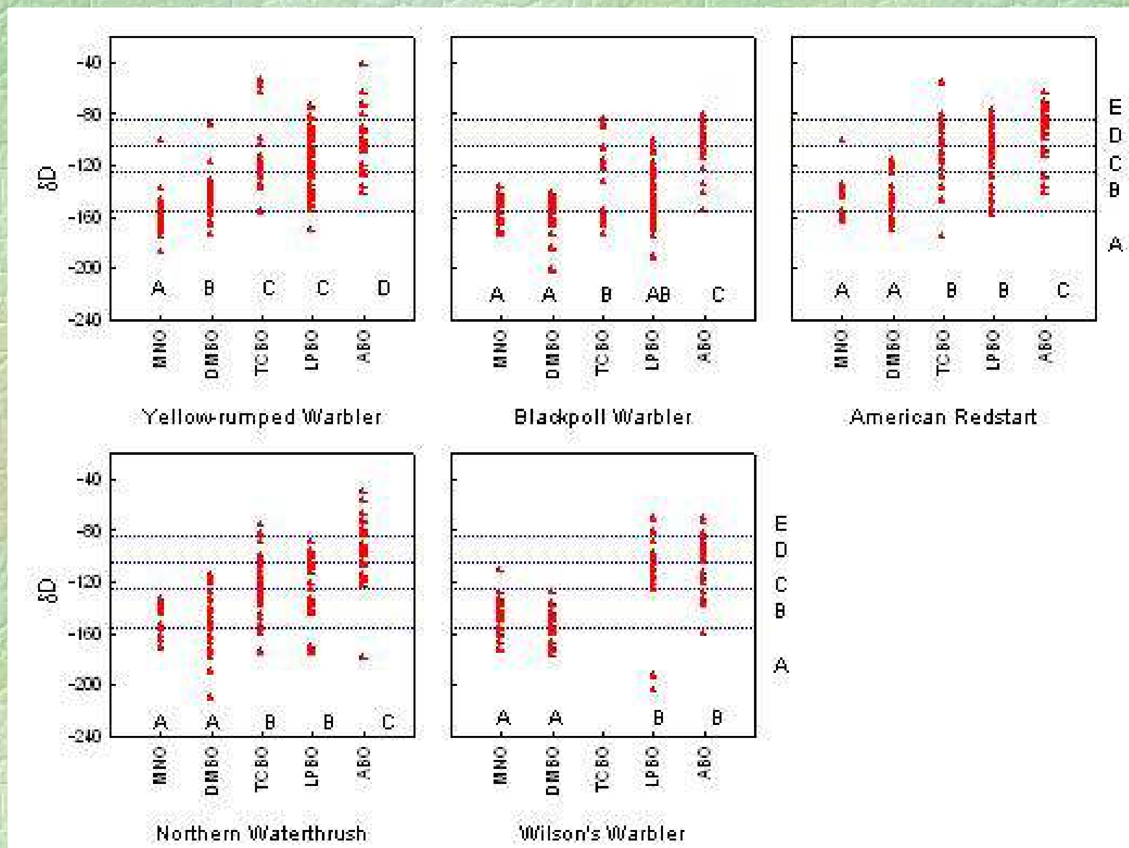
Global:

$\delta D_f = -22 + E(0.0224) -25$ °/oo

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22

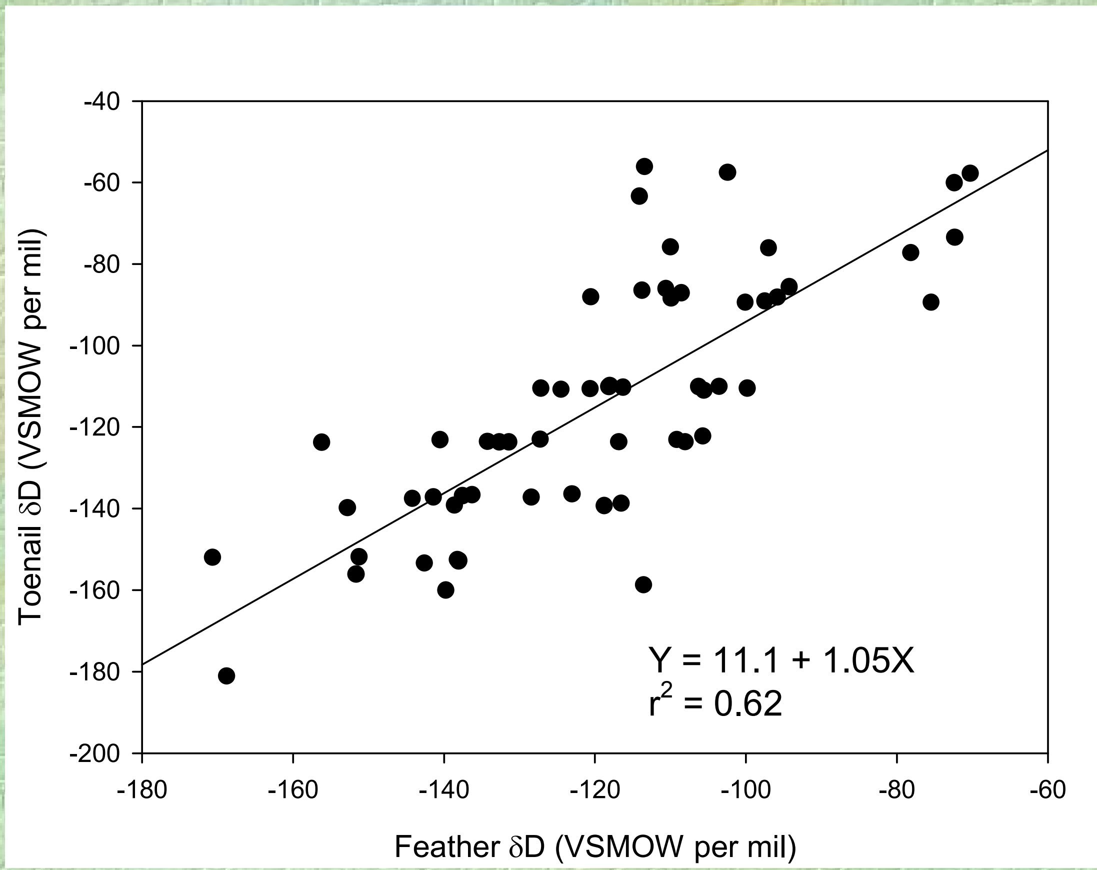


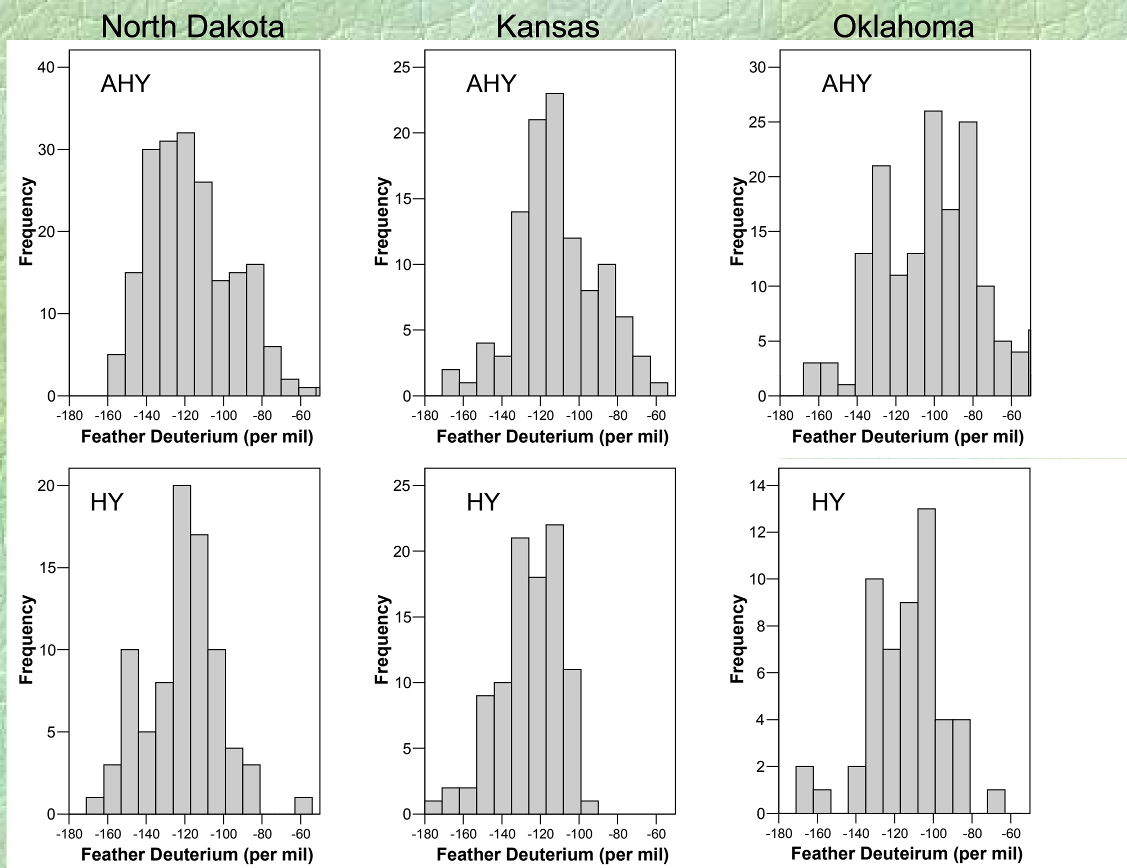
A
B
C
D
E
-179 - -170
-169 - -160
-159 - -150
-149 - -140
-139 - -130
-129 - -120
-119 - -110
-109 - -100
-99 - -90
-89 - -80
-79 - -70
-69 - -60
-59 - -50
-49 - -40
-39 - -30
-29 - -20
-19 - -10
-9 - 0


δD
-40
-80
-120
-160
-200
-240
A B C C D
MNO DMBO TCBO LPBO ABO
Yellow-rumped Warbler
A A B AB C
MNO DMBO TCBO LPBO ABO
Blackpoll Warbler
A A B B C
MNO DMBO TCBO LPBO ABO
American Redstart
E
D
C
B
A
δD
-40
-80
-120
-160
-200
-240
A A B B C
MNO DMBO TCBO LPBO ABO
Northern Waterthrush
A A B B
MNO DMBO TCBO LPBO ABO
Wilson's Warbler
E
D
C
B
A

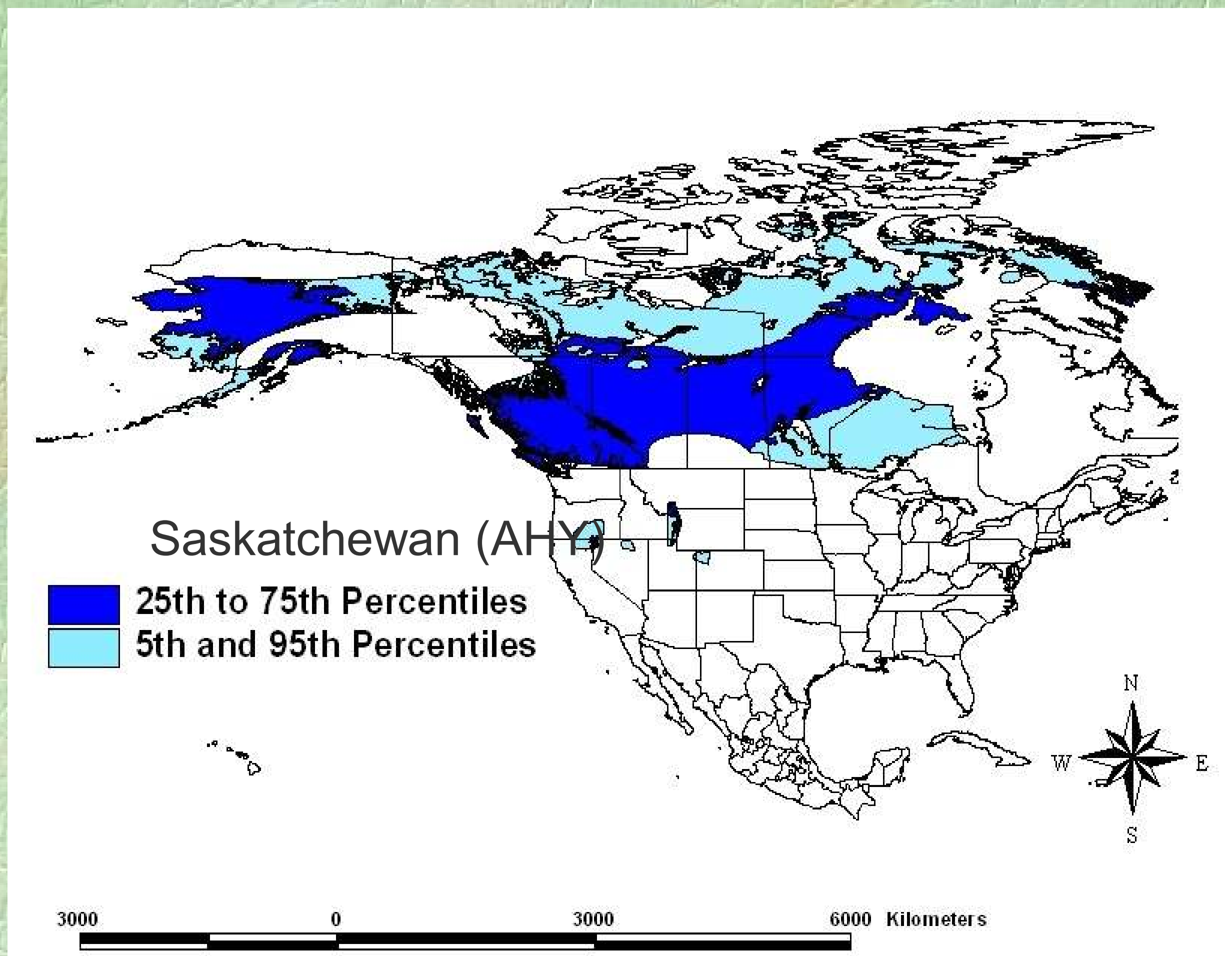
Origins of hunter-killed Sandhill Cranes?

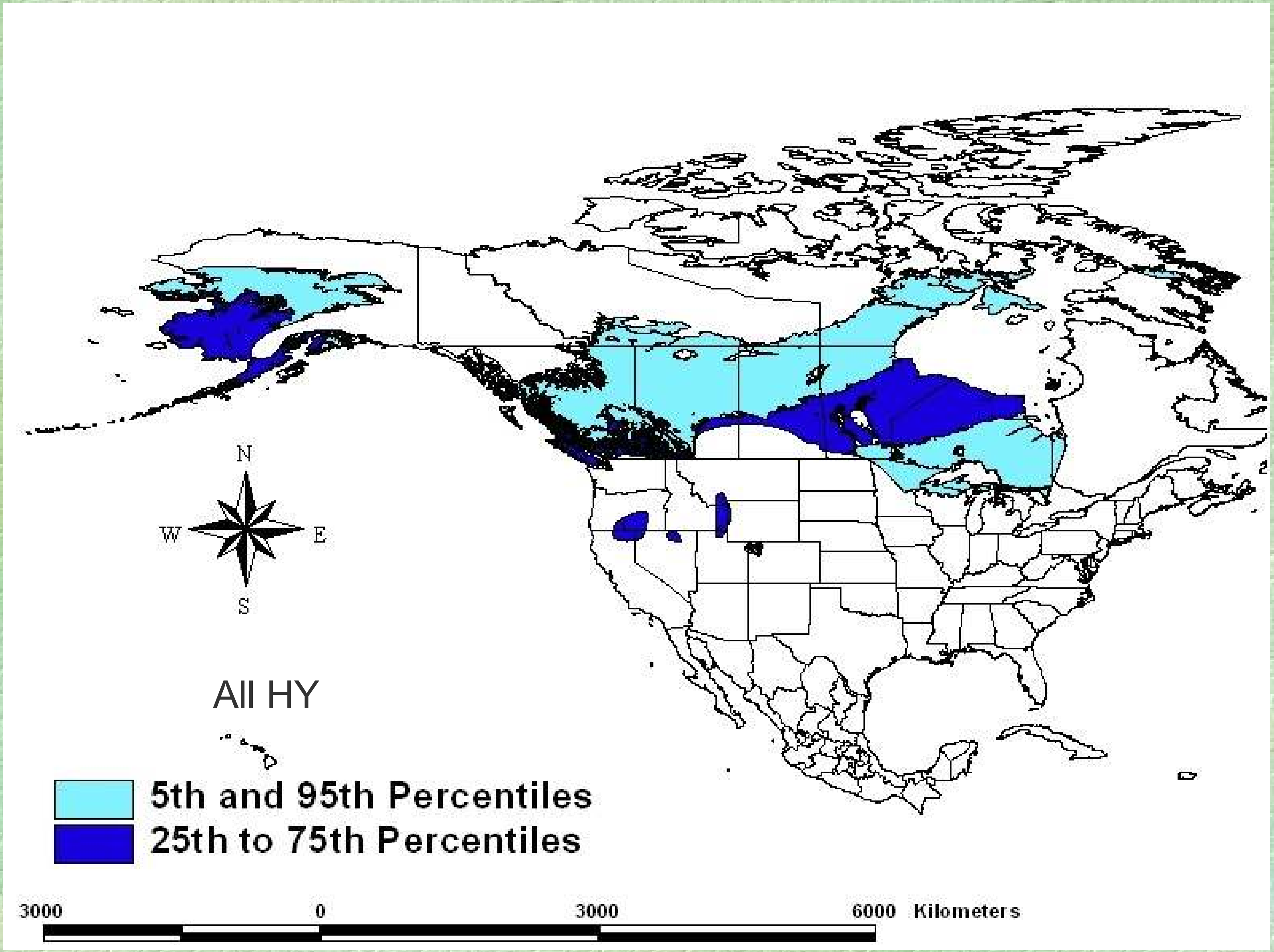
Toenails or feathers?

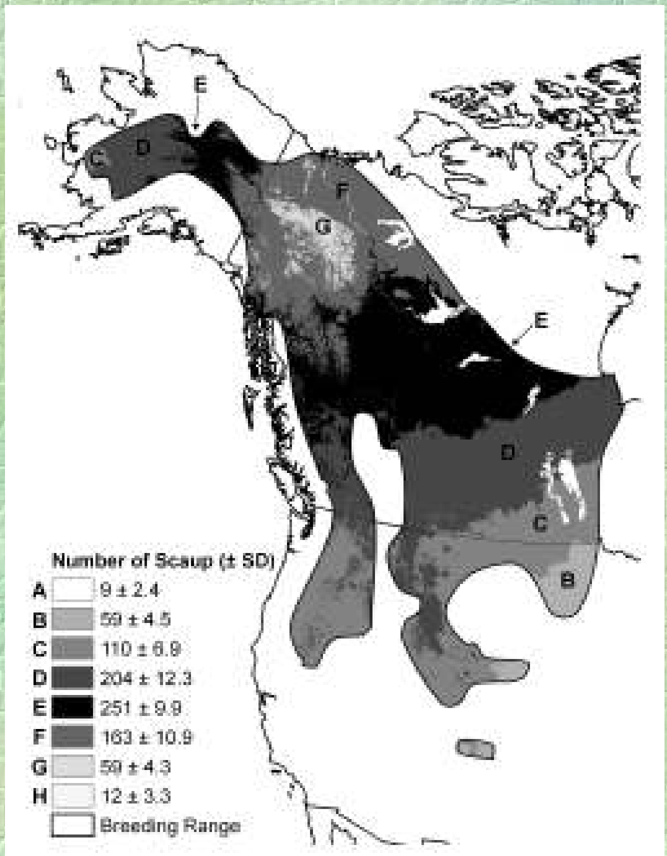


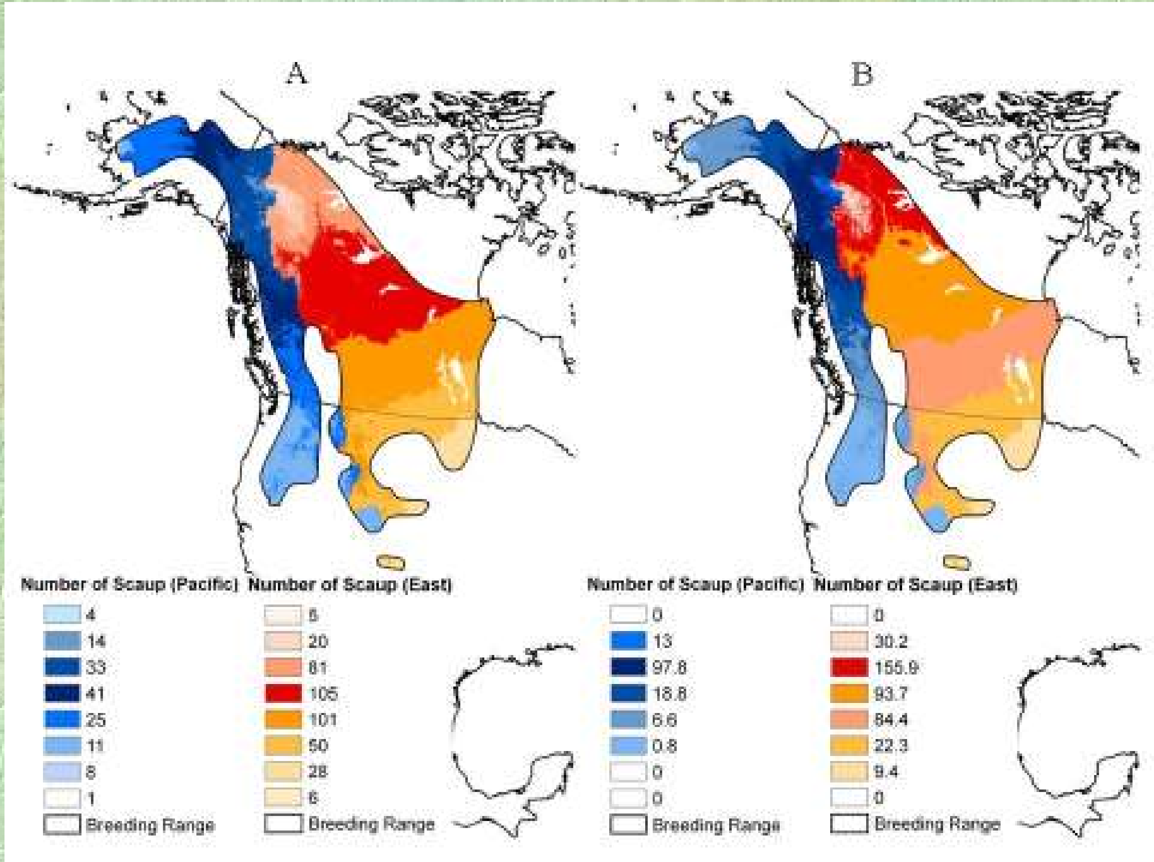

North Dakota
Kansas
Oklahoma
AHY
AHY
AHY
HY
HY
HY
Frequency
Feather Deuterium (per mil)
Feather Deuteirum (per mil)
-180 -160 -140 -120 -100 -80 -60

Combining isotope results with the isotope basemap GIS layer ….



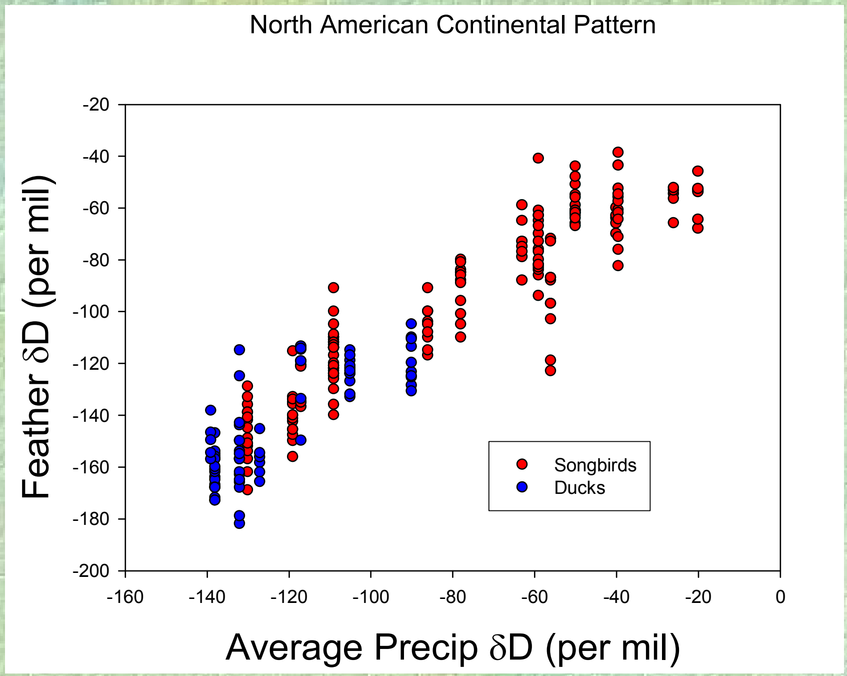

N
W
E
S
All HY
5th and 95th Percentiles
25th to 75th Percentiles
3000
0
3000
6000 Kilometers


E
C
D
F
G
E
D
C
B
Number of Scaup (± SD)
A 9 ± 2.4
B 59 ± 4.5
C 110 ± 6.9
D 204 ± 12.3
E 251 ± 9.9
F 163 ± 10.9
G 59 ± 4.3
H 12 ± 3.3
Breeding Range

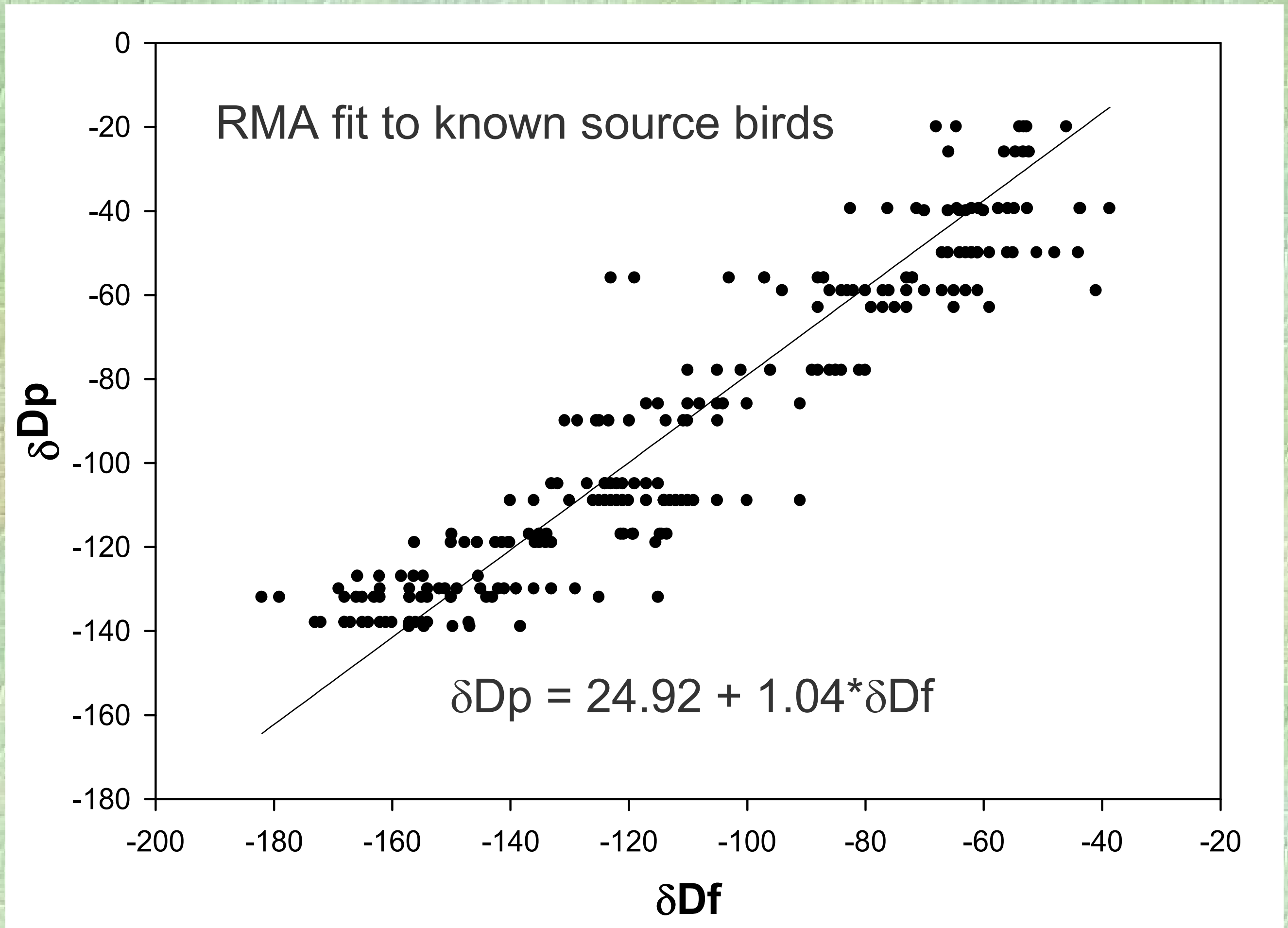

A
B
Number of Scaup (Pacific)
4
14
33
41
25
11
8
1
Breeding Range
Number of Scaup (East)
5
20
81
105
101
50
28
6
Breeding Range
Number of Scaup (Pacific)
0
13
97.8
18.8
6.6
0.8
0
0
Breeding Range
Number of Scaup (East)
0
30.2
155.9
93.7
84.4
22.3
9.4
0
Breeding Range

Moving beyond the “map lookup” approach …..

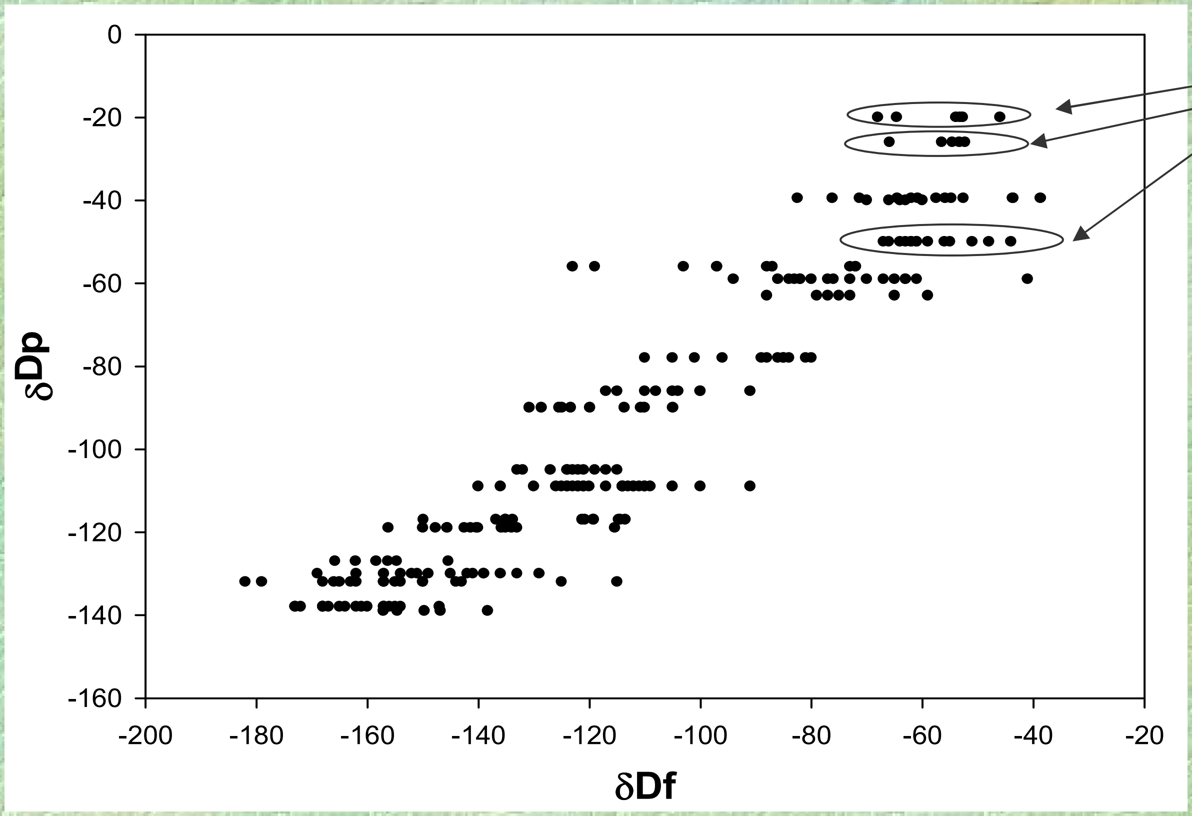
- Propagate error associated with analytical measurement and geospatial models of δDp.



Converting to δDp units



Within Site "Errors"

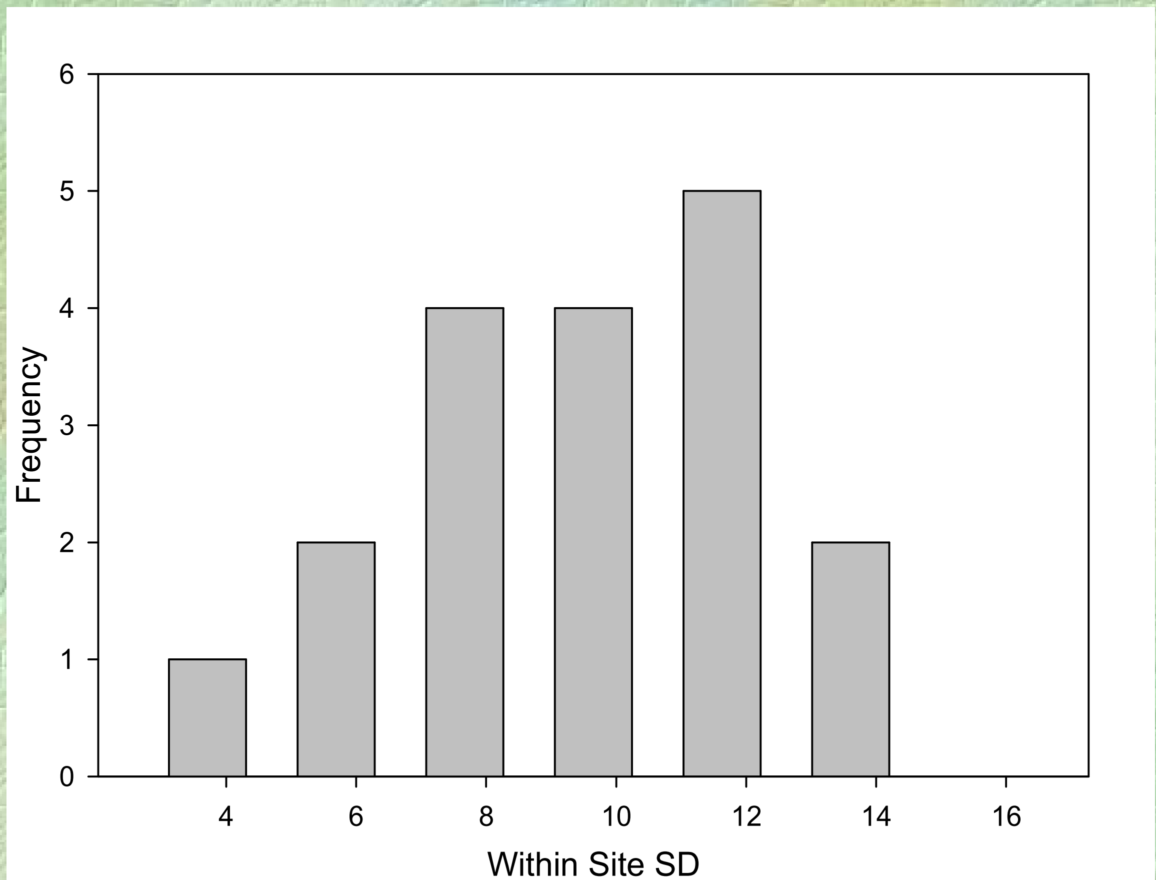


Calculate SD for each Site

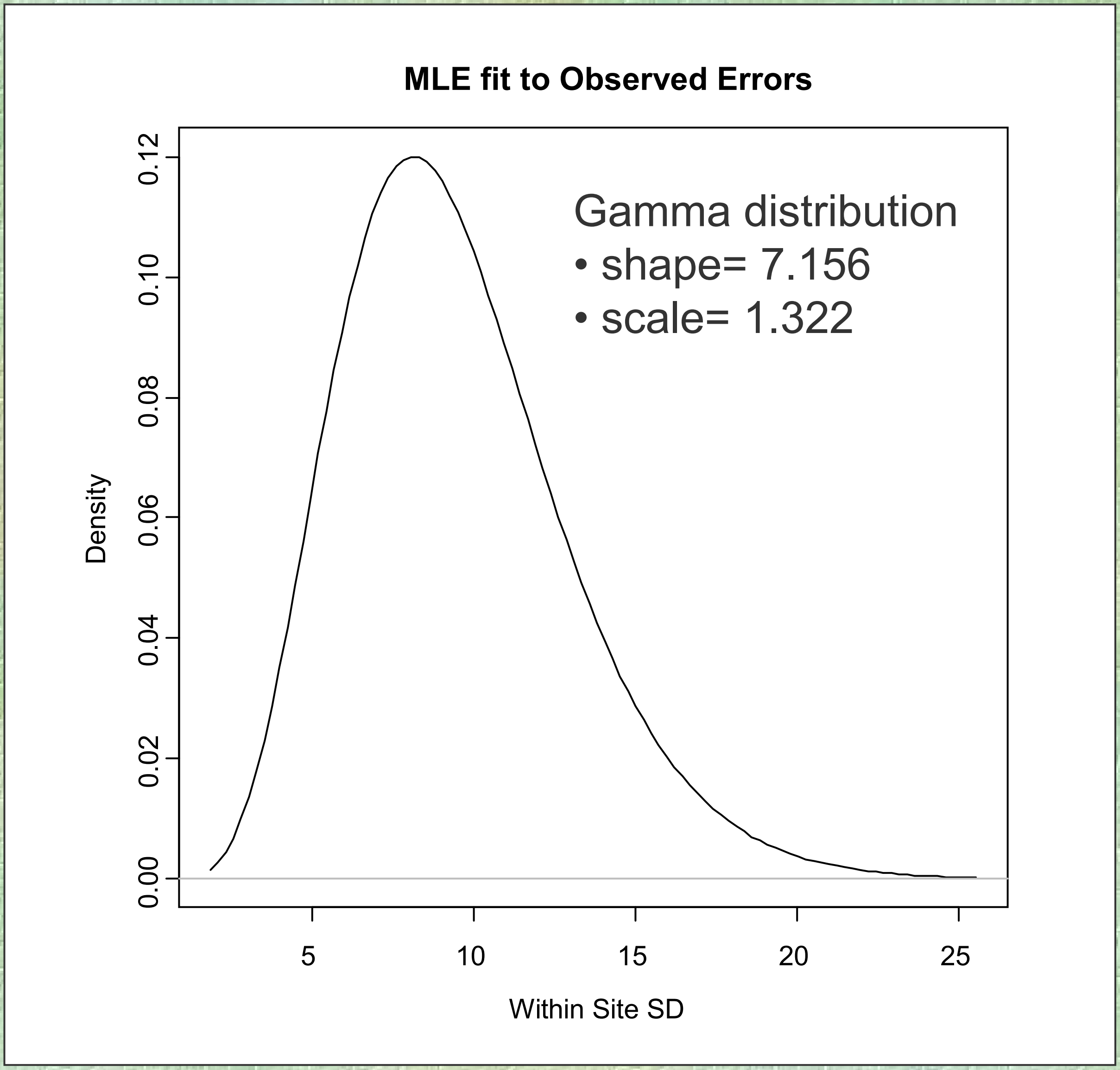
Incorporates:

- analytical error
- individual heterogeneity

Observed Distribution of errors



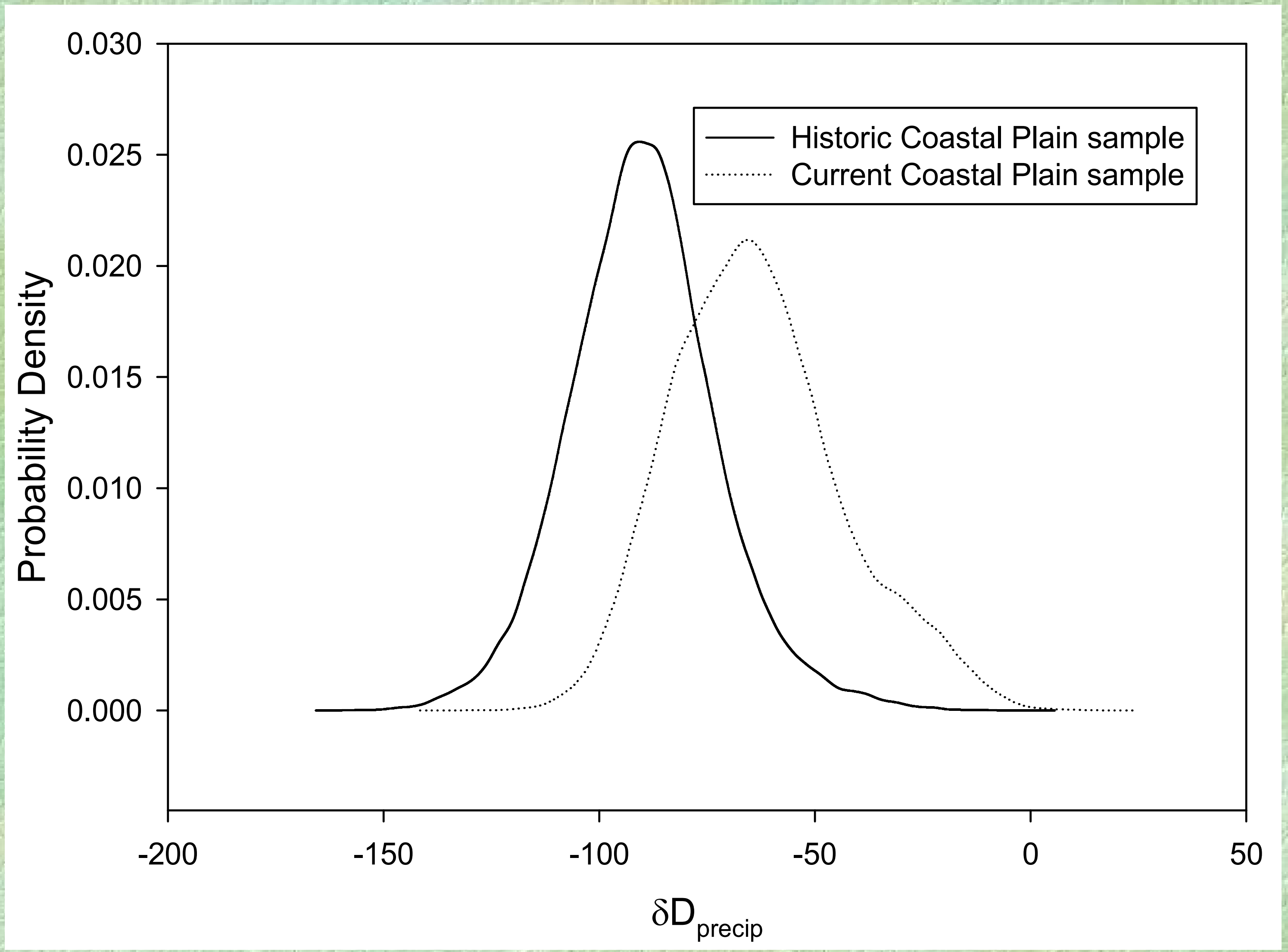
Fit distribution to errors



Propagate errors (simulation)

- 1000 simulations per measured δD_f (in δD_p units)
- Where:
  - Mean = measured δD_p equivalent value of feather
  - SD drawn at random from estimated error distribution

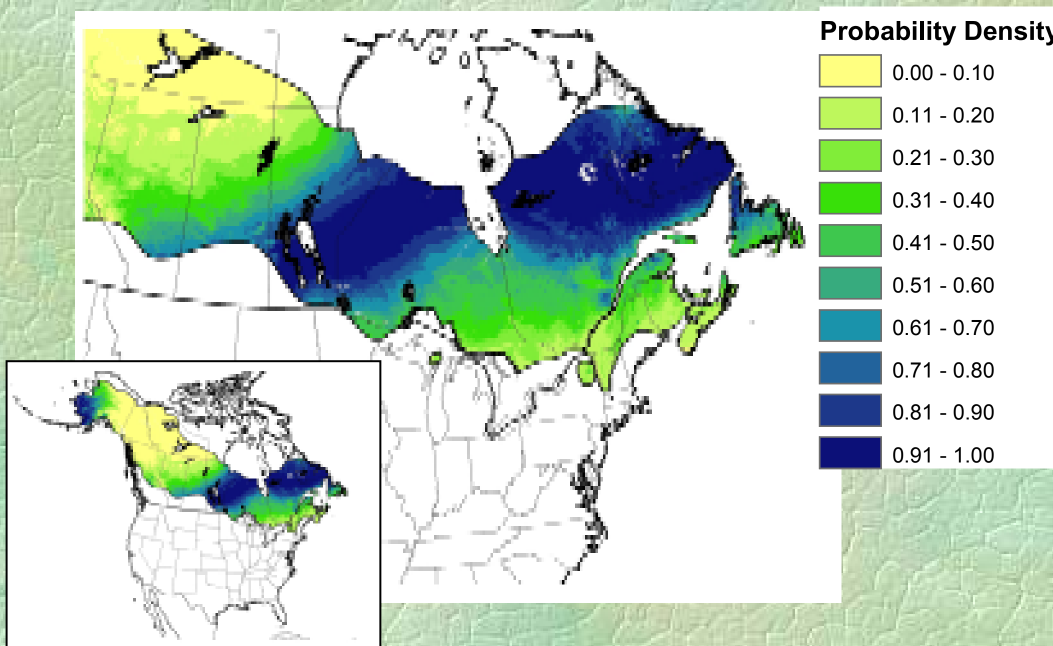
e.g. origins if Rusty Blackbirds



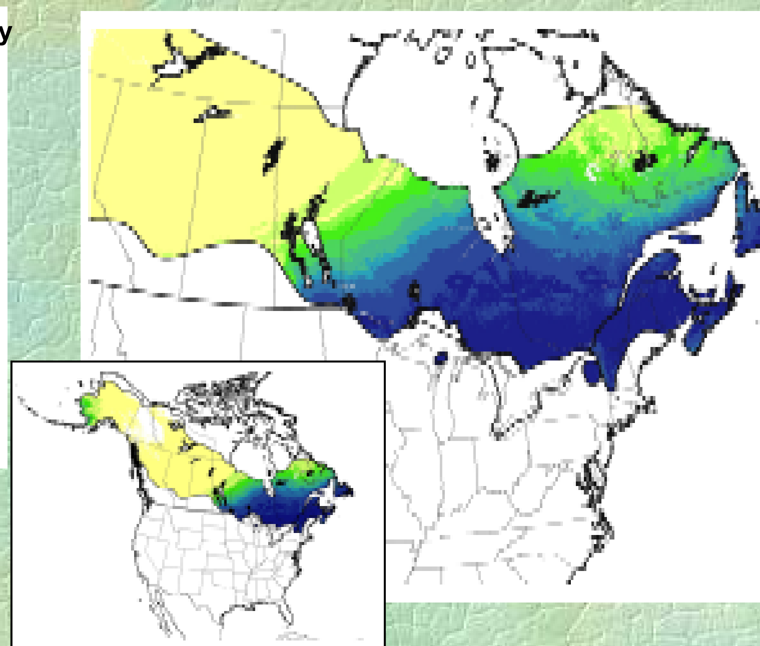
e.g. Probability Density

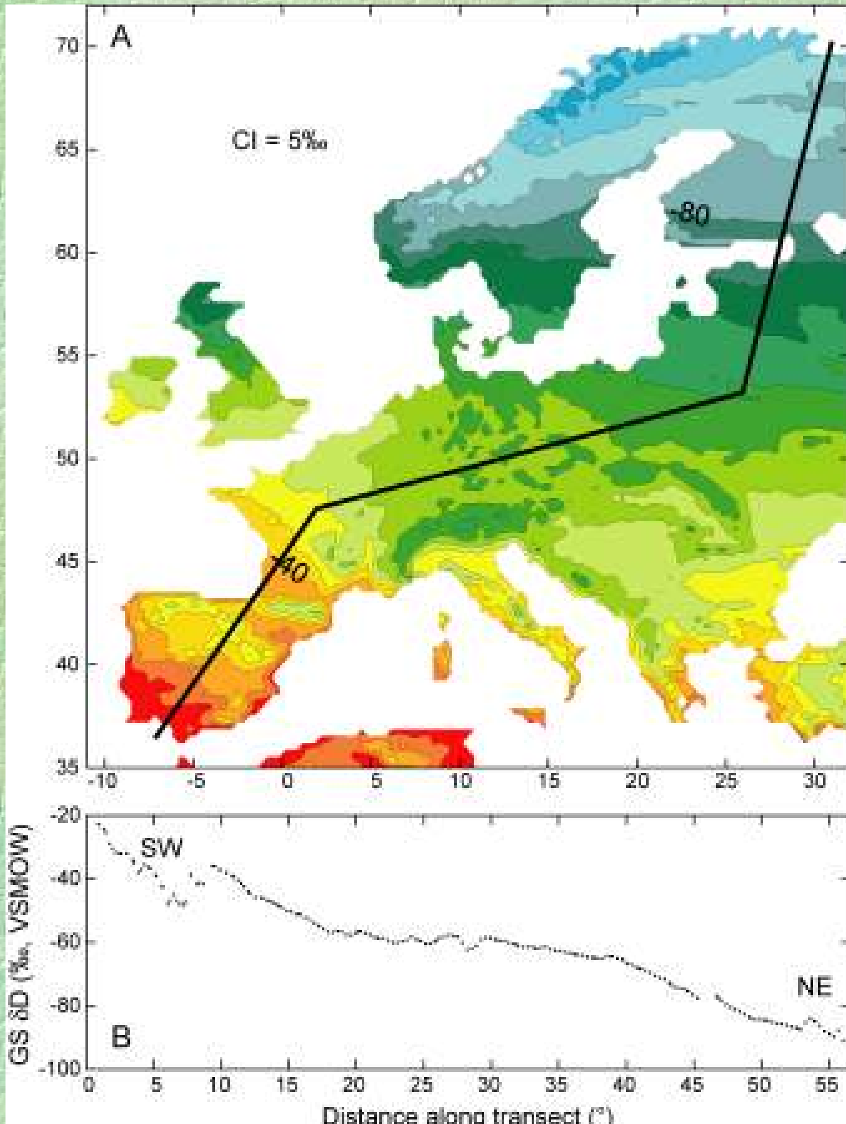
- normalize values to maximum

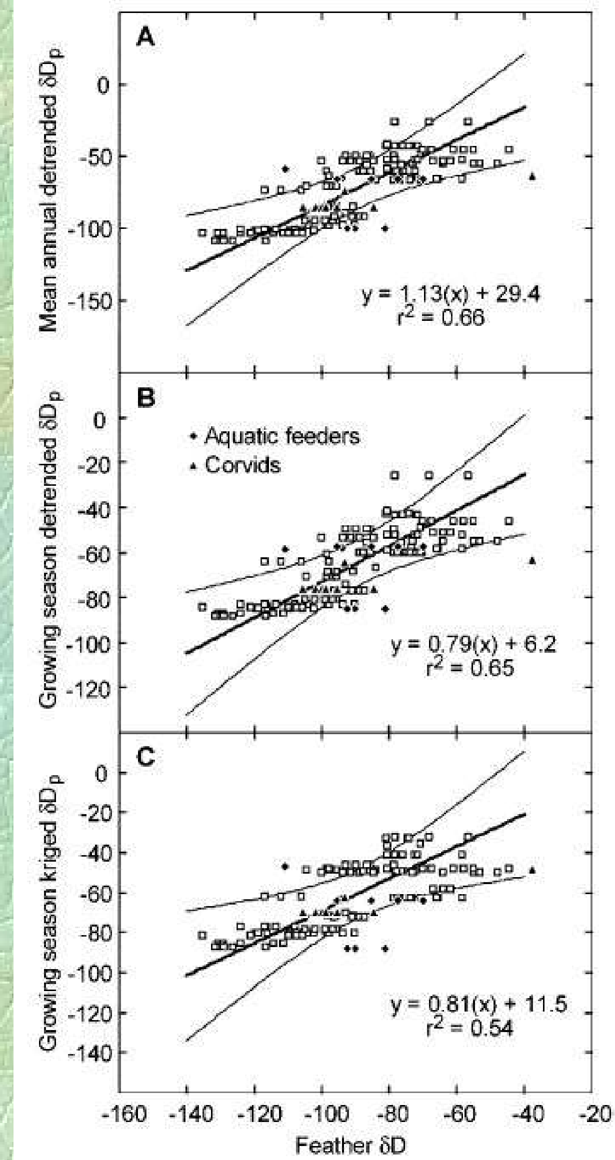
Historic



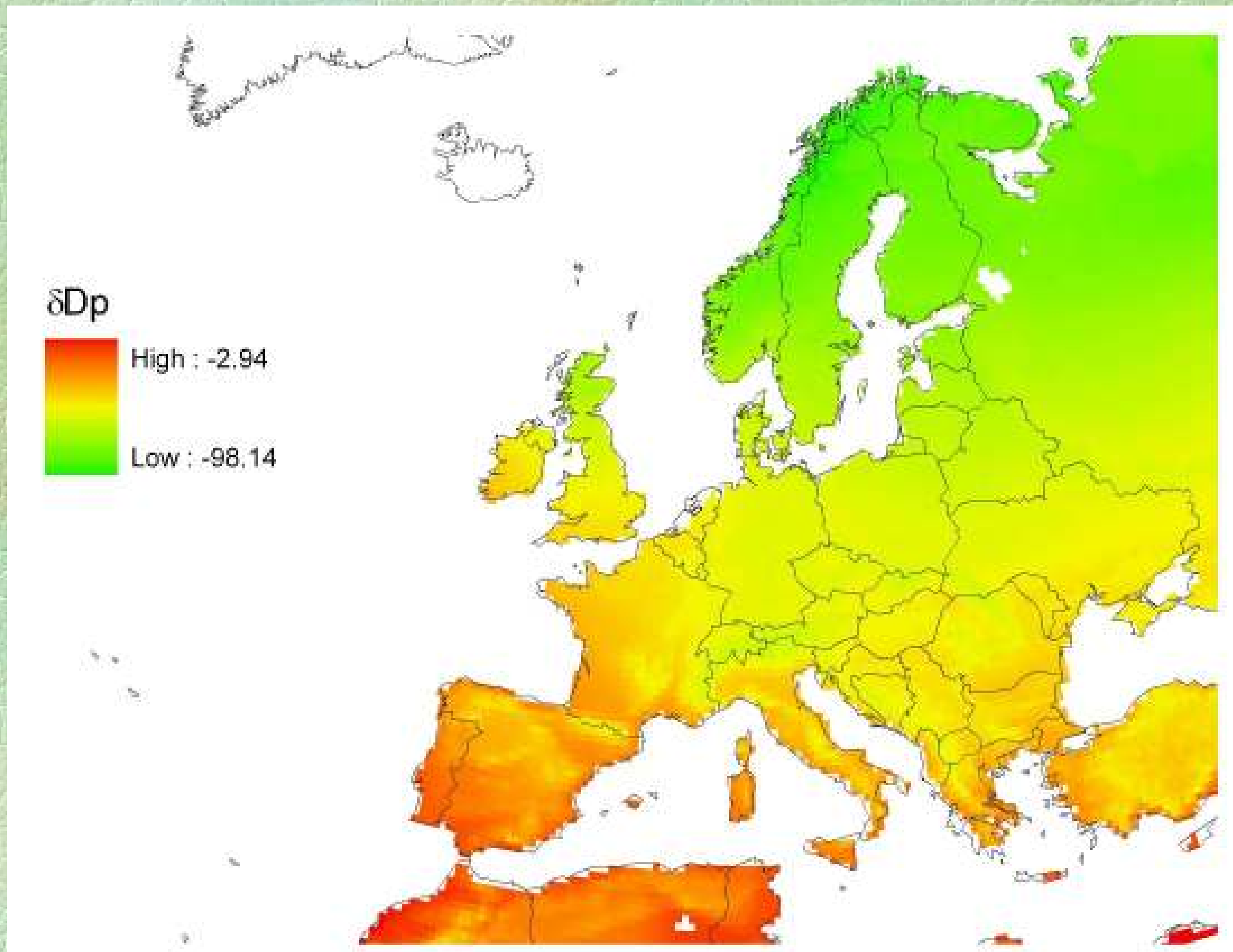
Current




A
CI = 5‰
-80
-40
SW
NE
B
GS δD (‰, VSMOW)
Distance along transect (°)

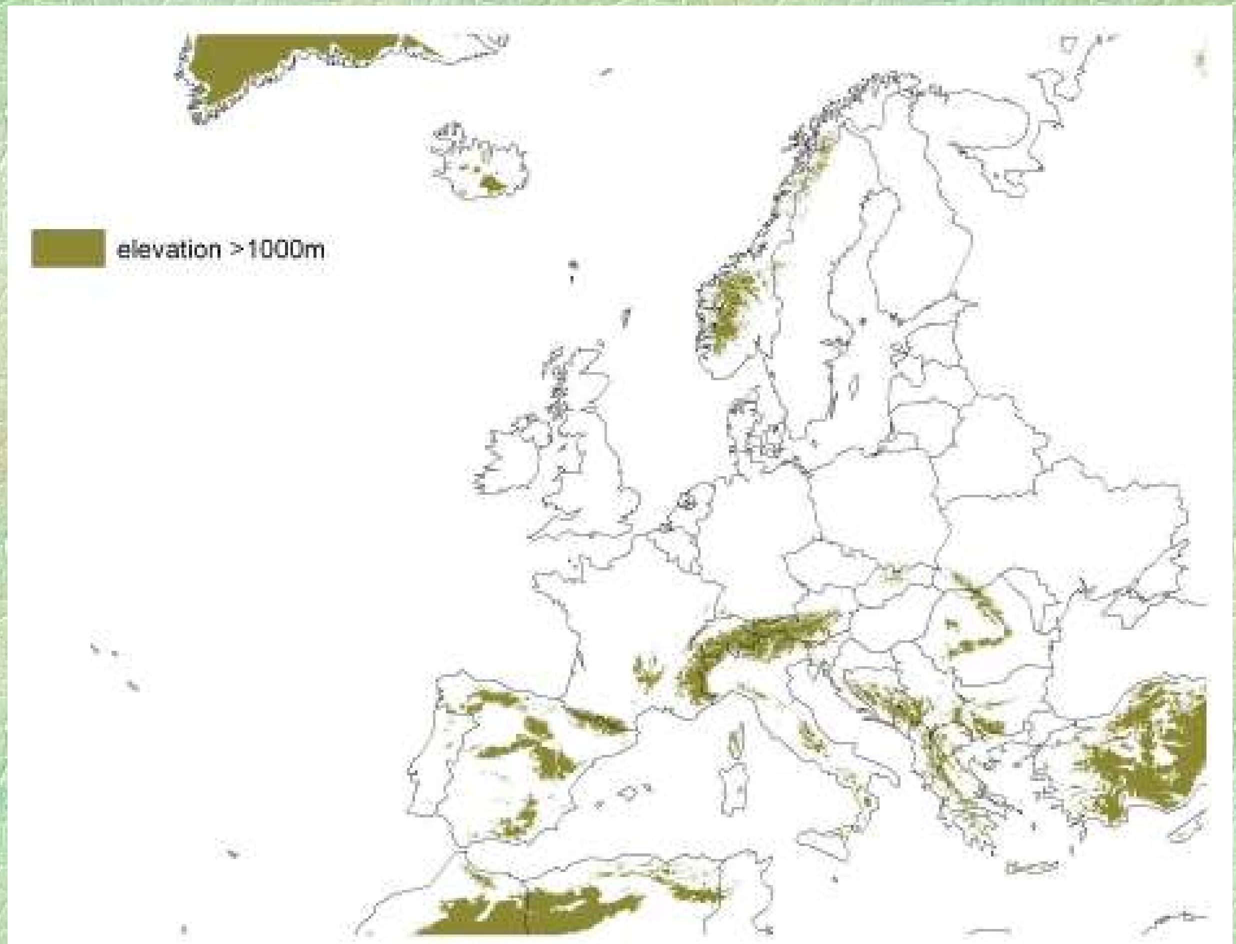

A
Mean annual detrended δDp
y = 1.13(x) + 29.4
r2 = 0.66
B
Growing season detrended δDp
Aquatic feeders
Corvids
y = 0.79(x) + 6.2
r2 = 0.65
C
Growing season kriged δDp
y = 0.81(x) + 11.5
r2 = 0.54
Feather δD

Constraining Origins

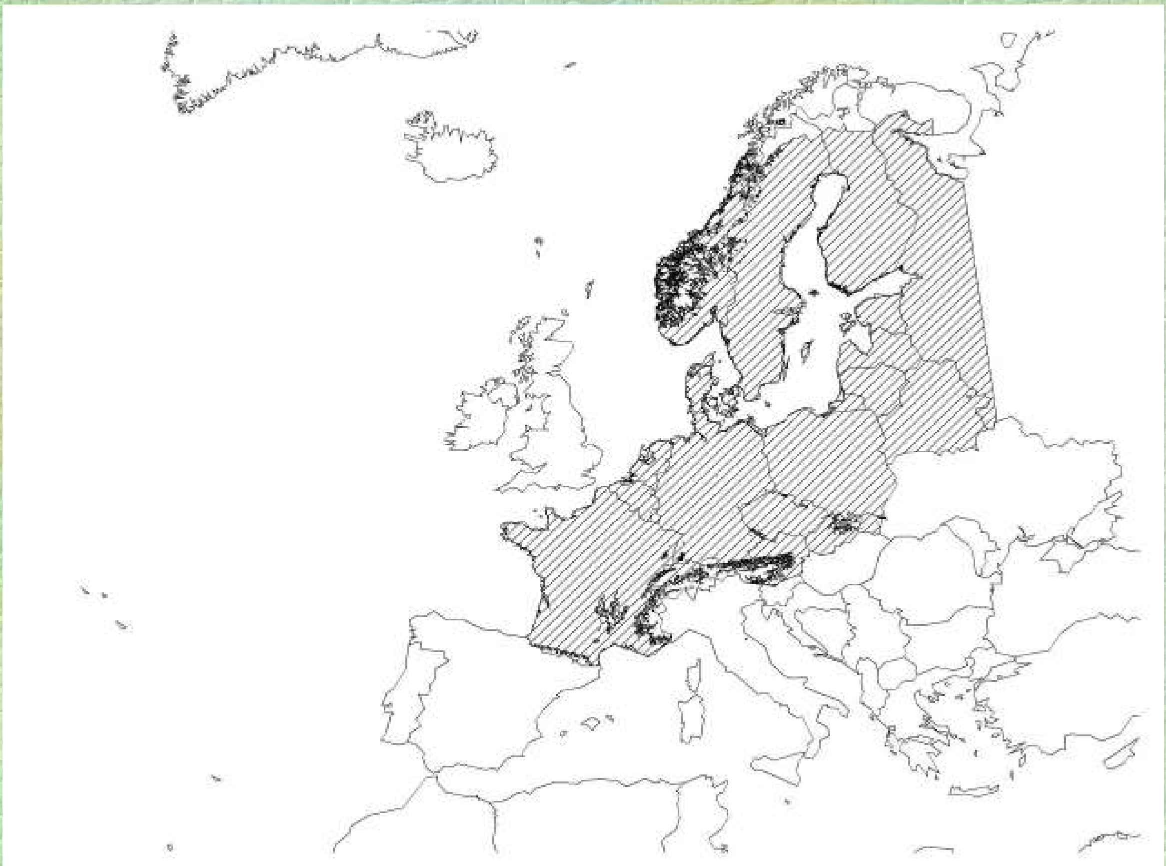


Constraining to Potential Range

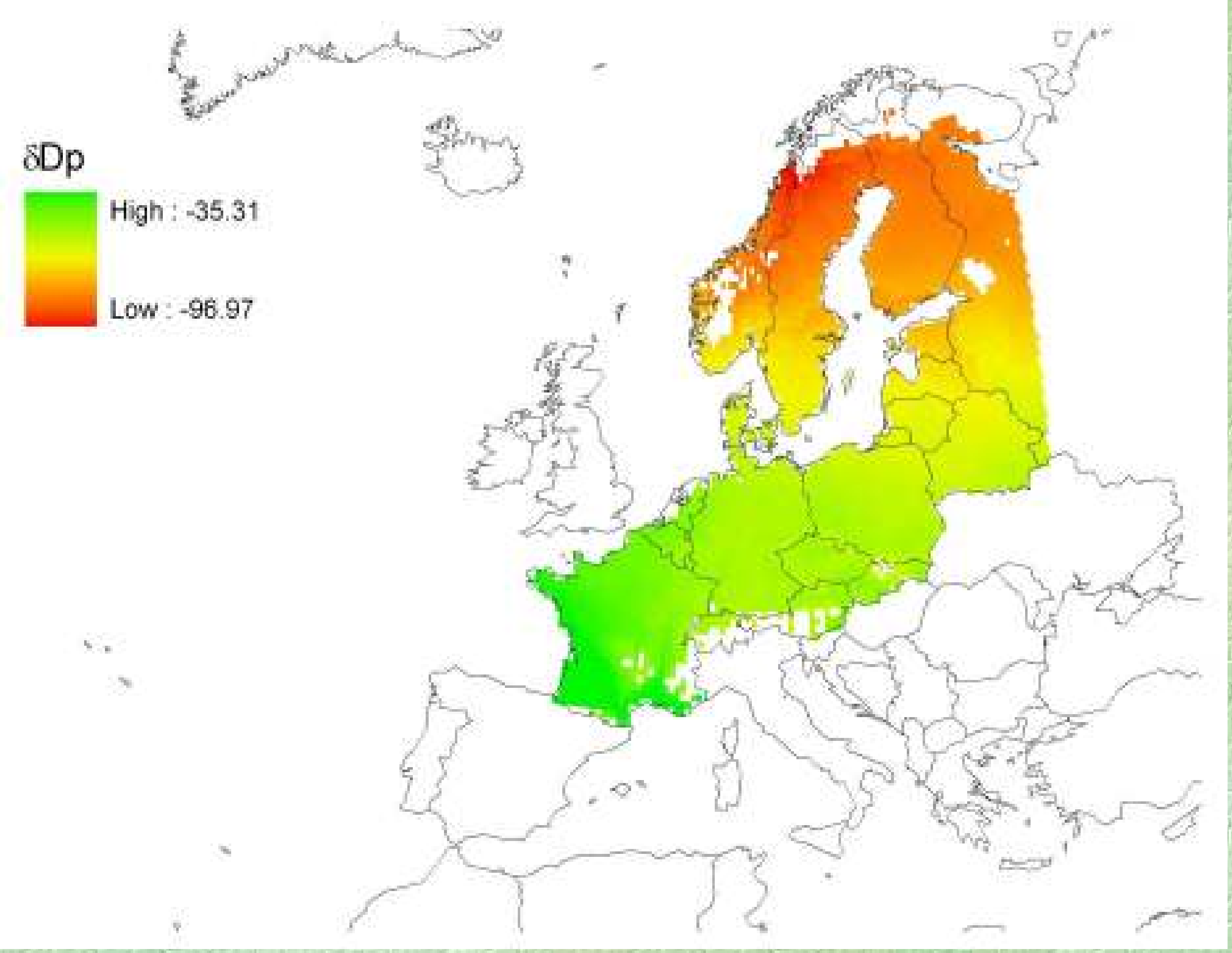
Constraint- Elevation



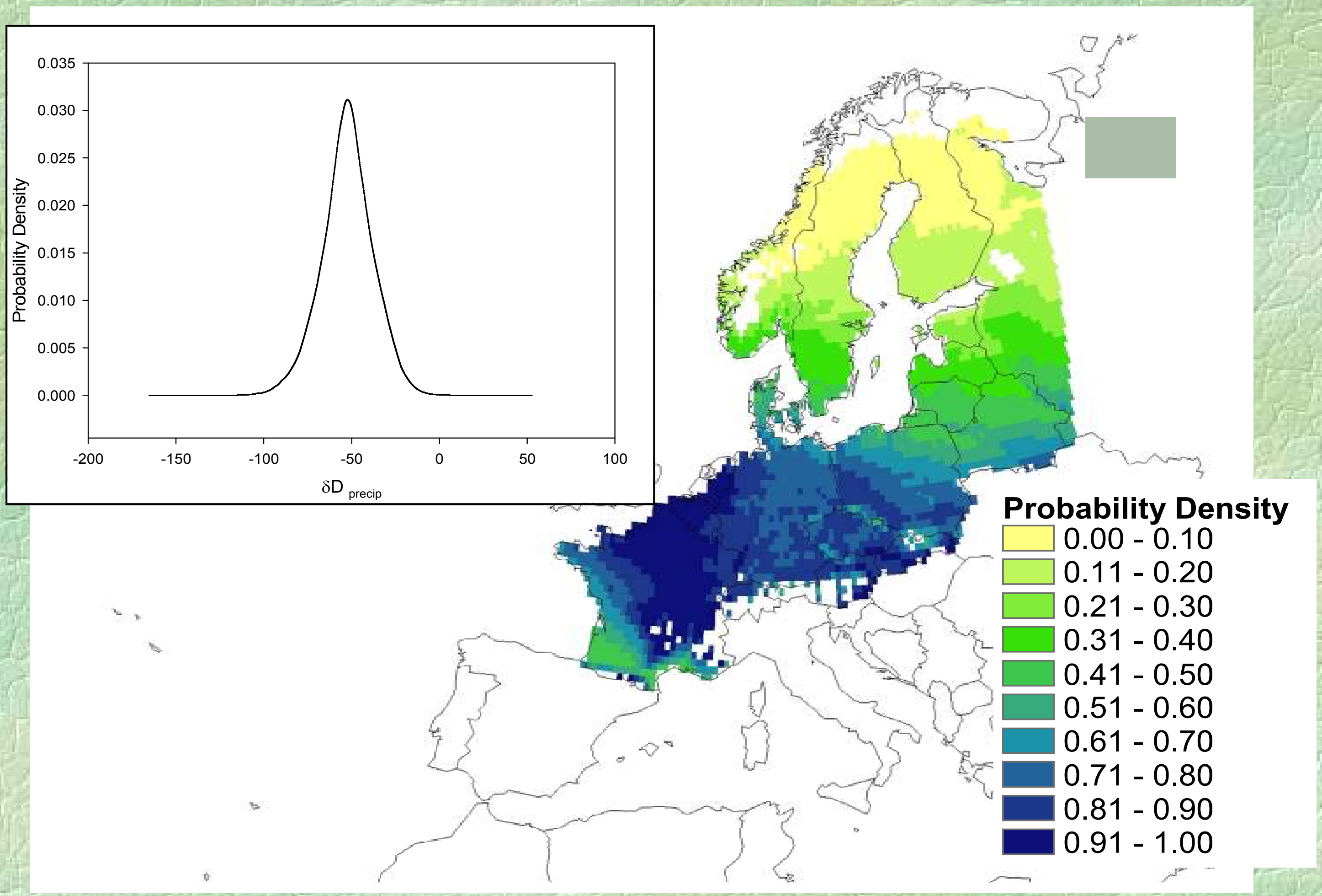
Reduced solution space- remove high elevation



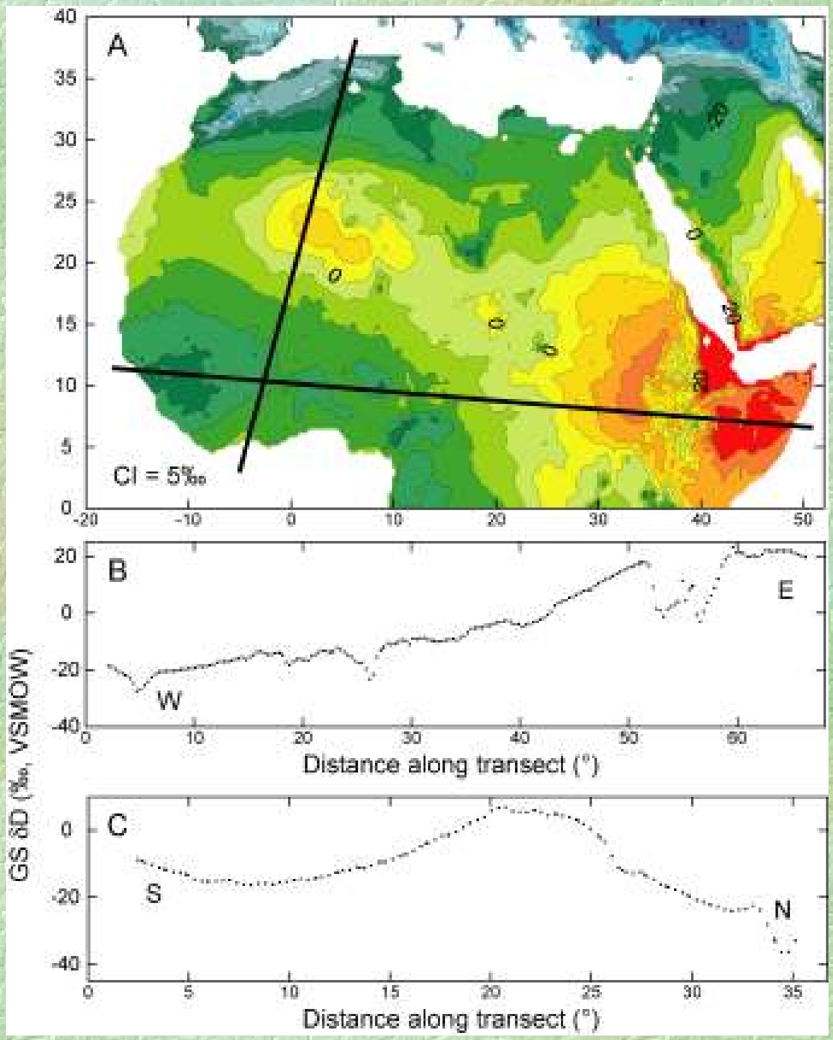
GSD- for reduced range



Assignment of Origins

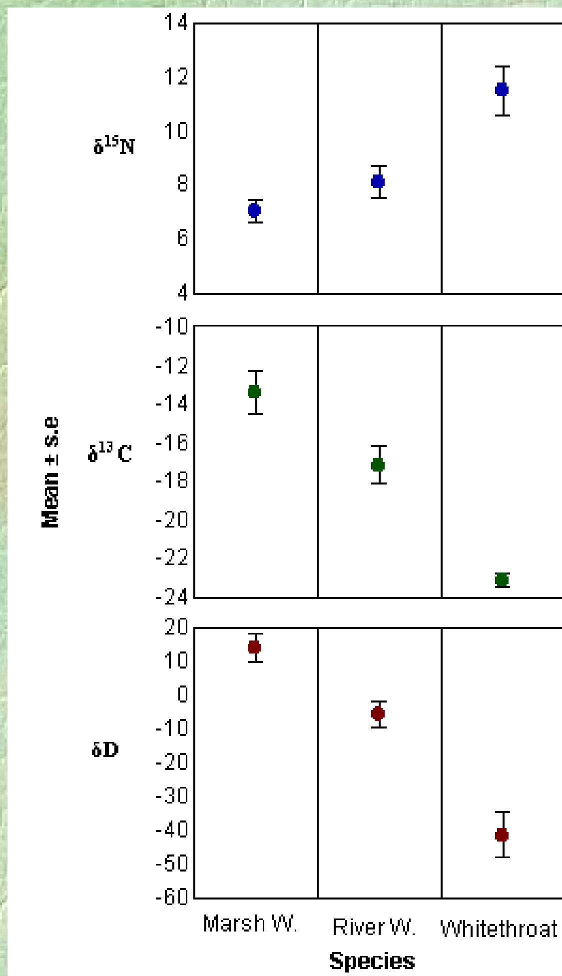


For North Africa …



Bowen et al., 2005

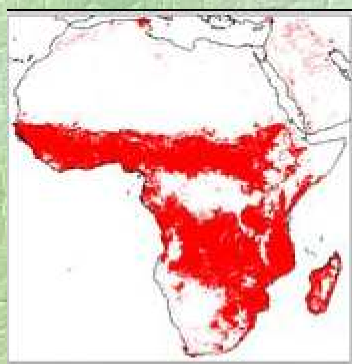
And as an investigative tool ….



Yohanes et al. J.Avian Biology 2005

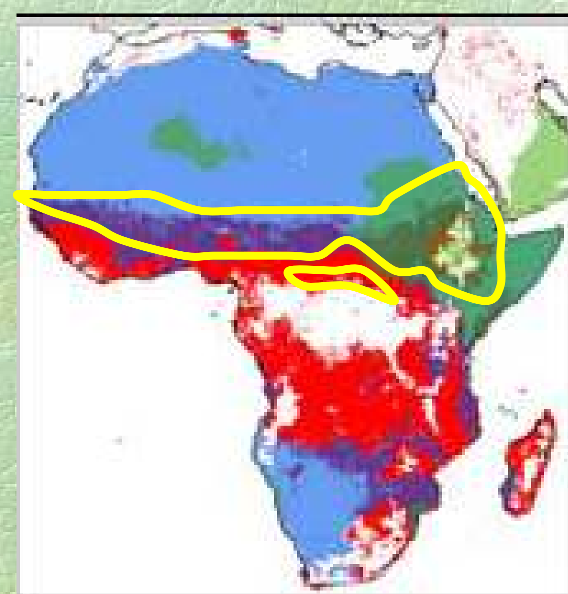
3-dimensional isoscape for trans-Saharan migrants ….

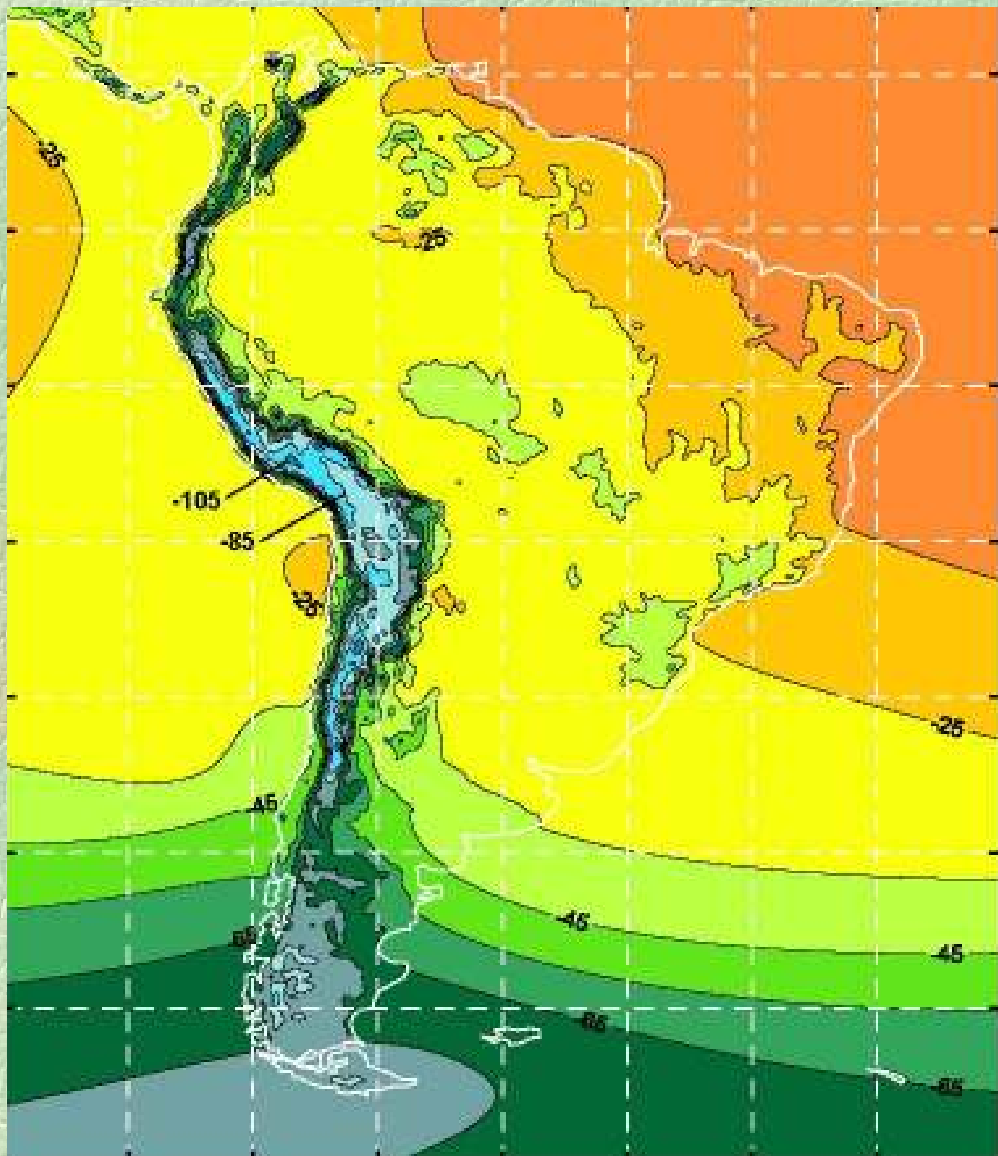
$\delta^{13}C$



$\delta^{15}N$

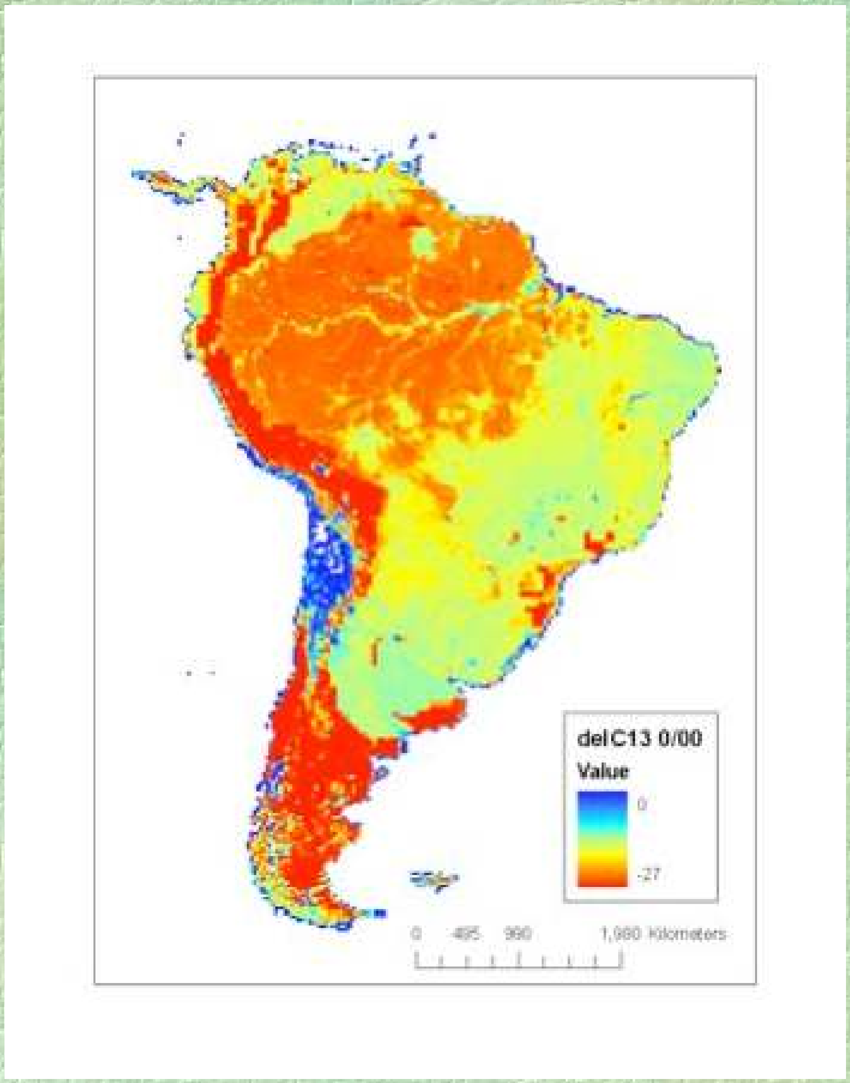
δD





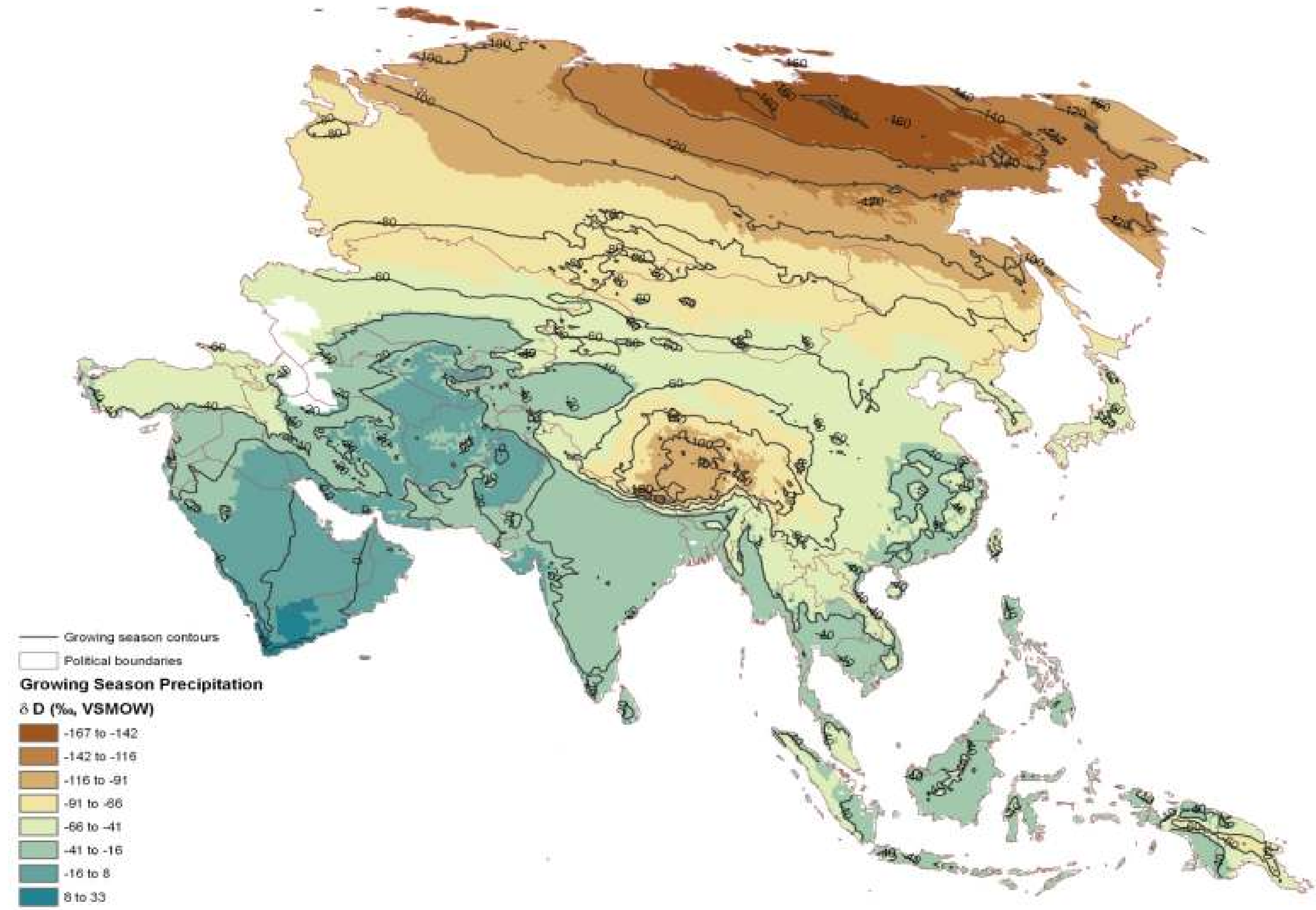
Bowen, unpub.

Continental ^{13}C map??

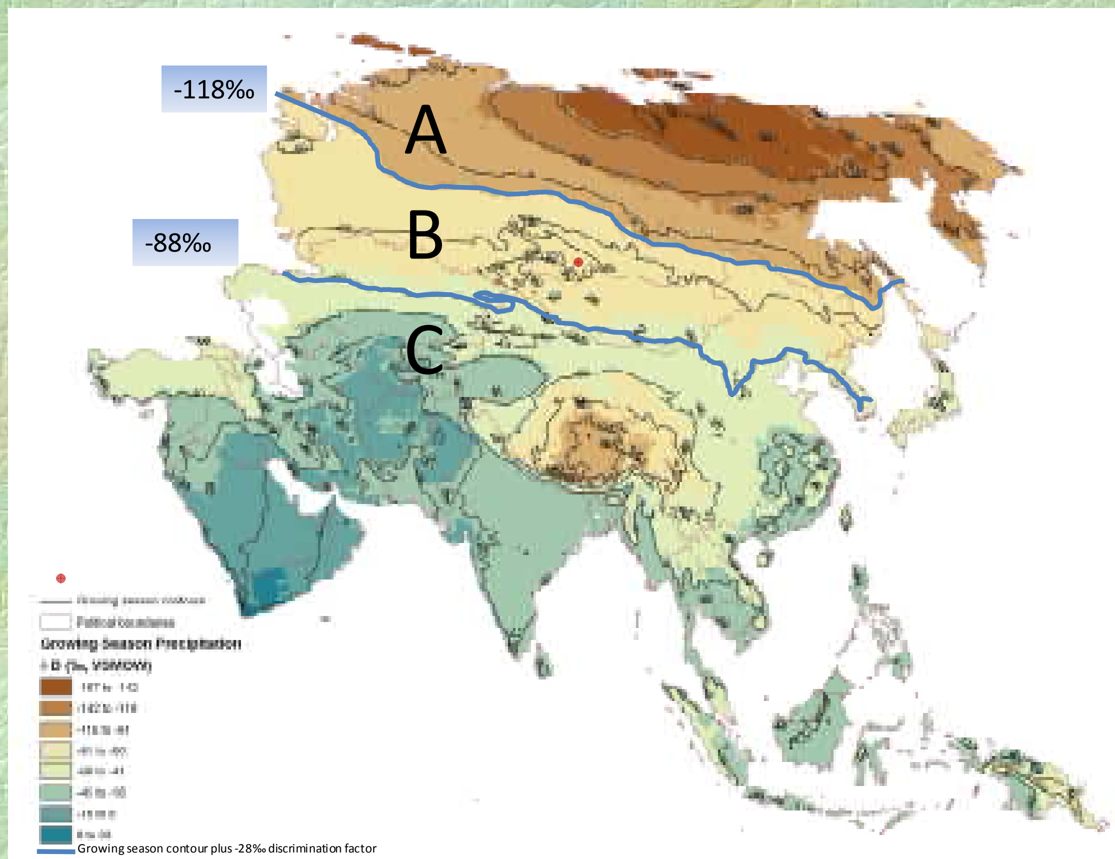


From Chris Still
UC Santa Barbara

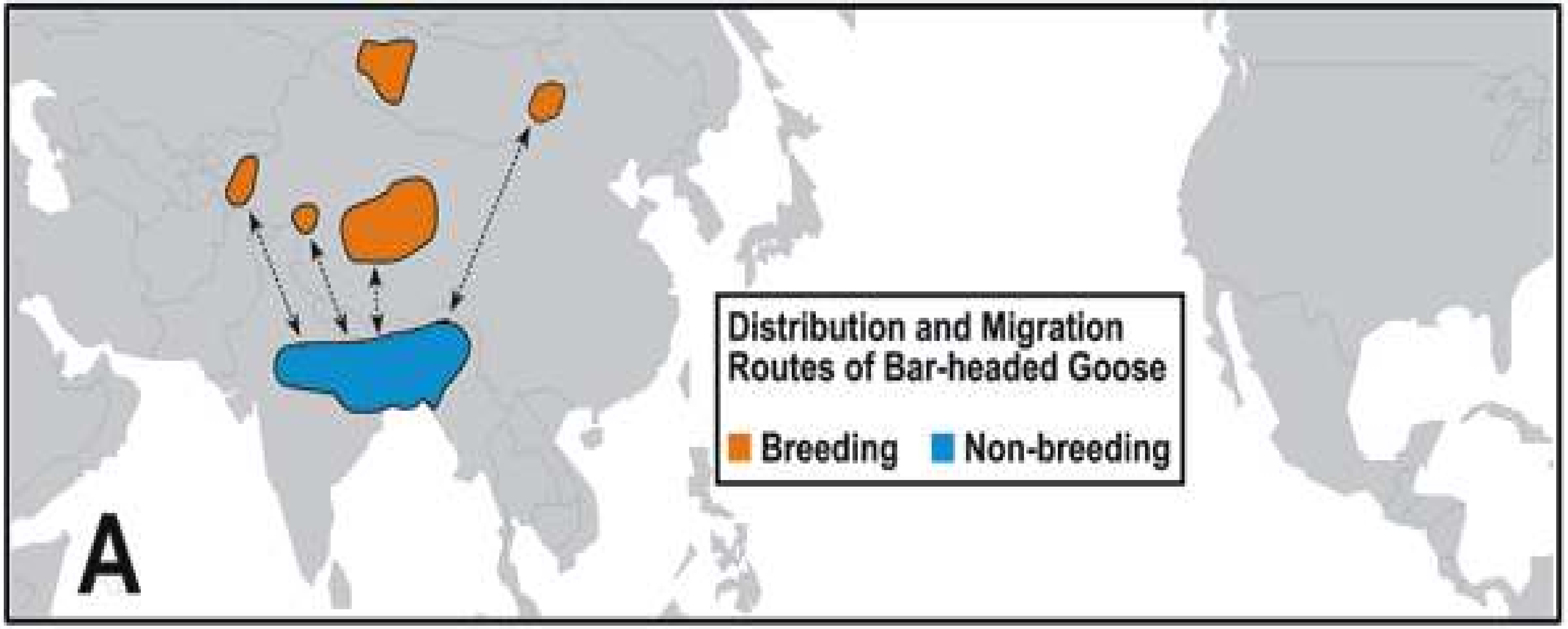
What about Asia?

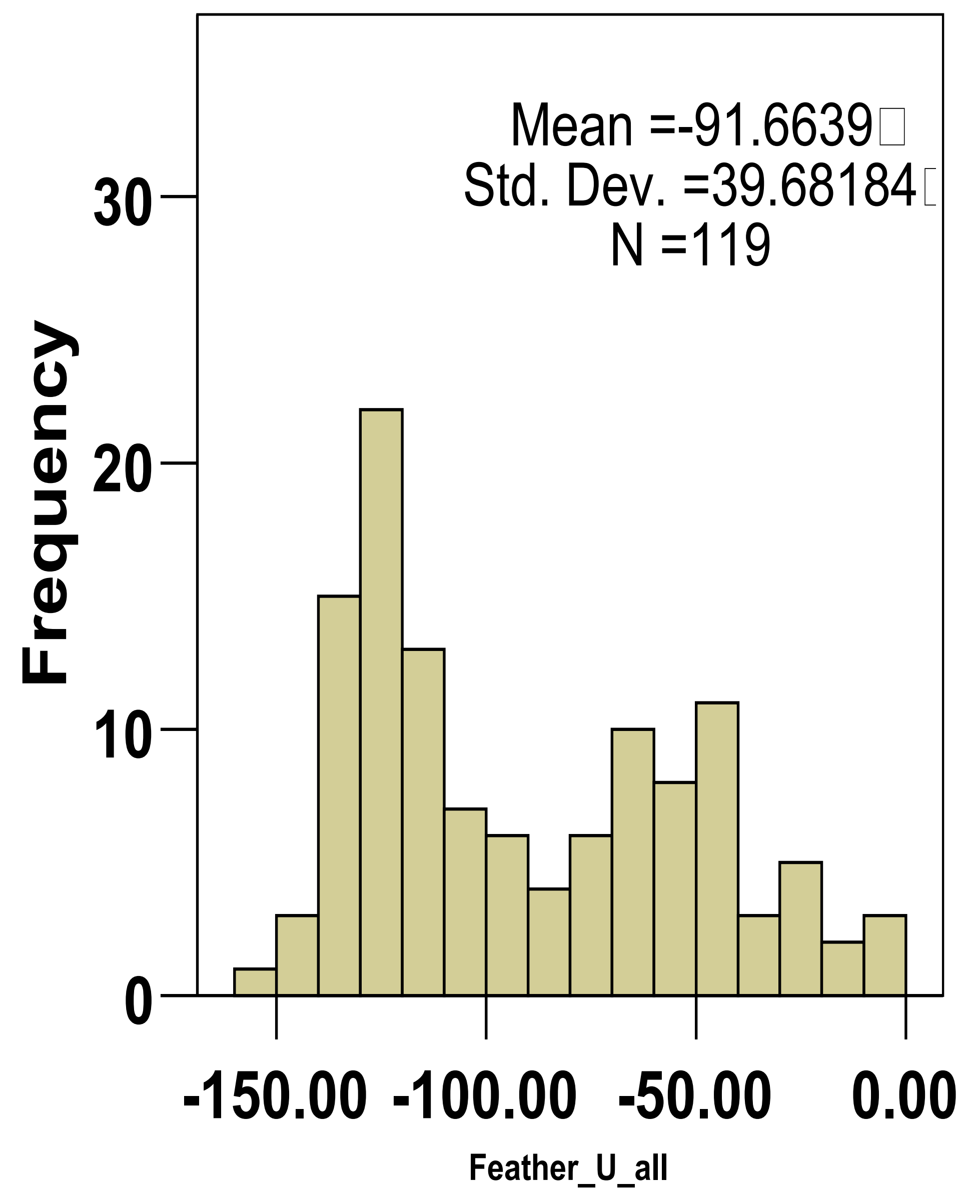

Growing season contours
Political boundaries
Growing Season Precipitation
δ D (‰, VSMOW)
-167 to -142
-142 to -116
-116 to -91
-91 to -66
-66 to -41
-41 to -16
-16 to 8
8 to 33

3 useable zones?



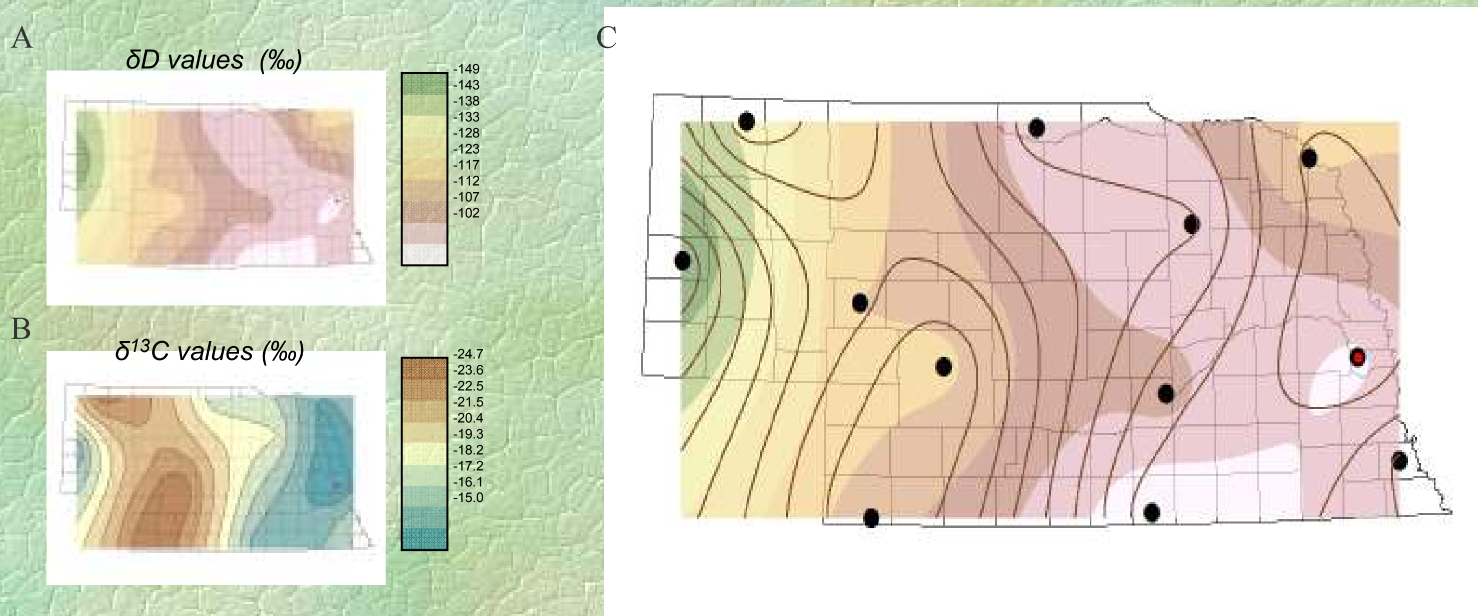
Of use for N-S movements




Mean =-91.6639
Std. Dev. =39.68184
N =119
Frequency
30
20
10
0
-150.00
-100.00
-50.00
0.00
Feather_U_all

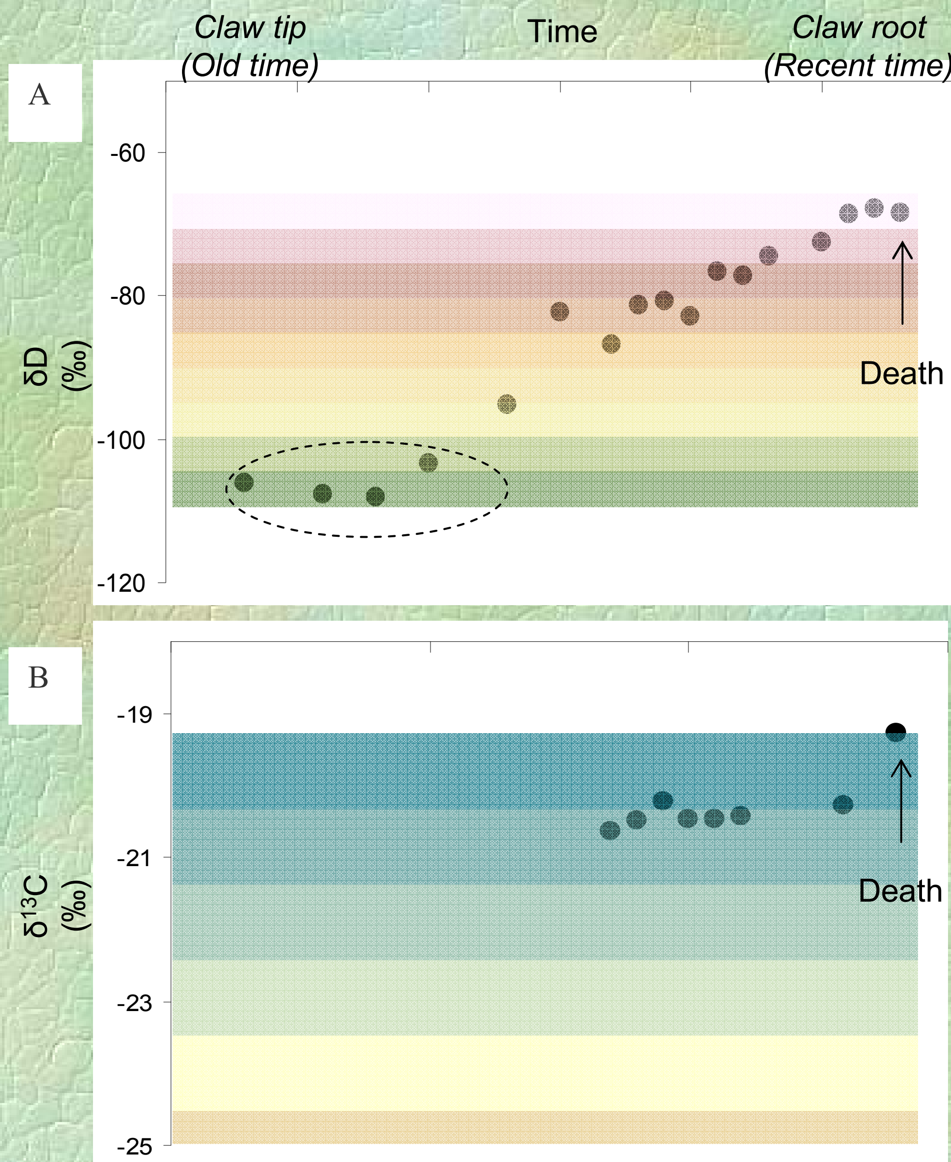
Scaling down: Can we use more local isoscapes?

Local-scale isoscapes: Nebraska
Here is a “deer isoscape”

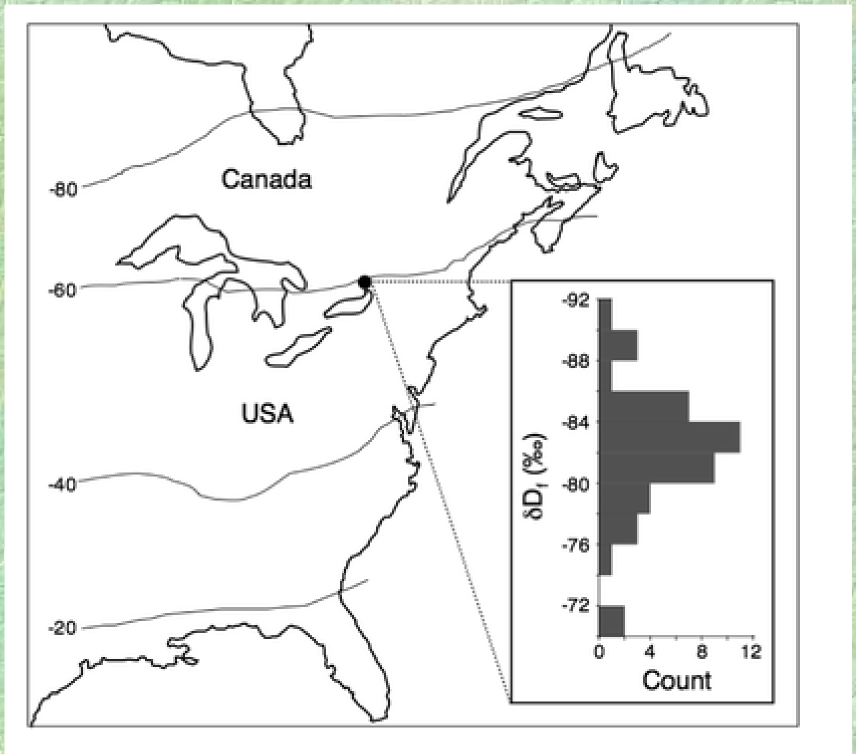


With Larkin Powell

Travels of an unfortunate cougar

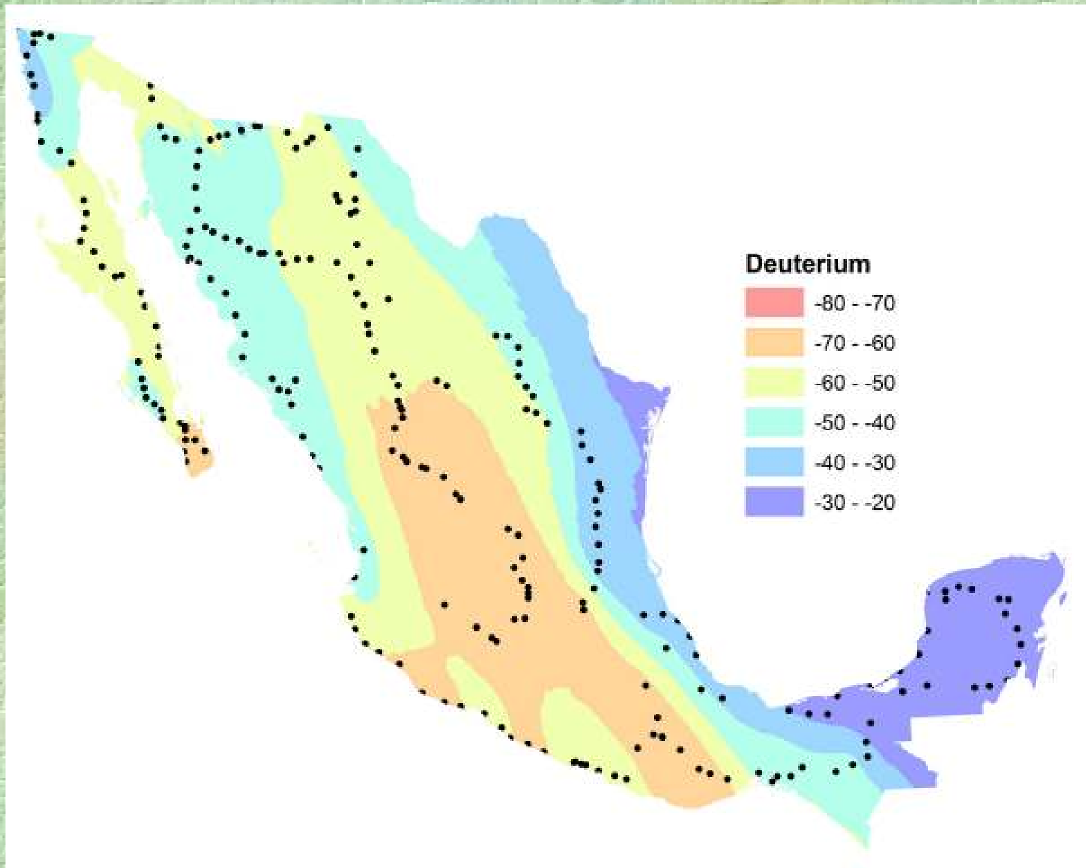


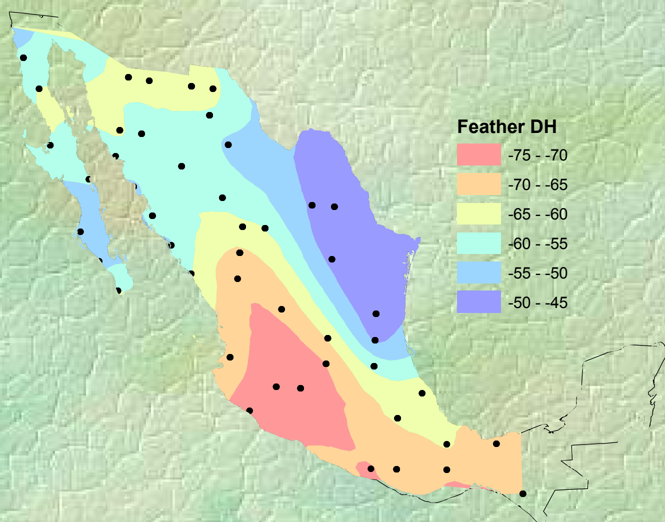
Variance in assignment:

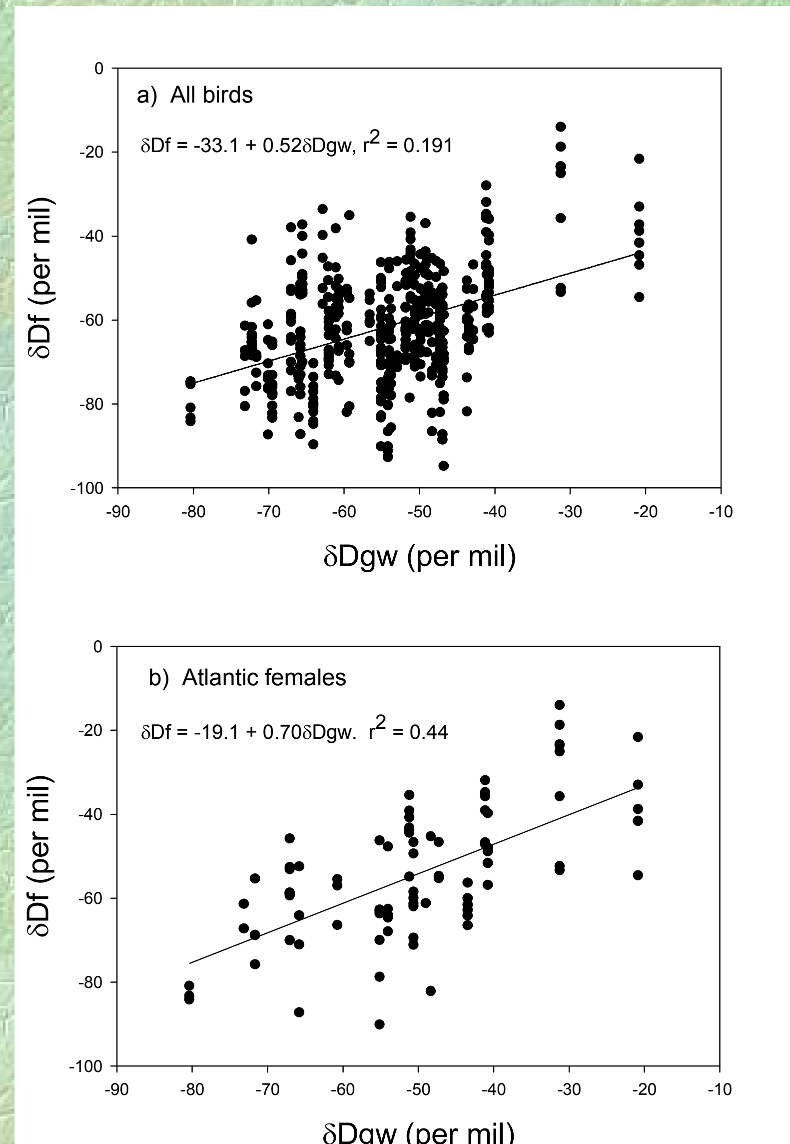


Langin et al. 2007 Oecologia

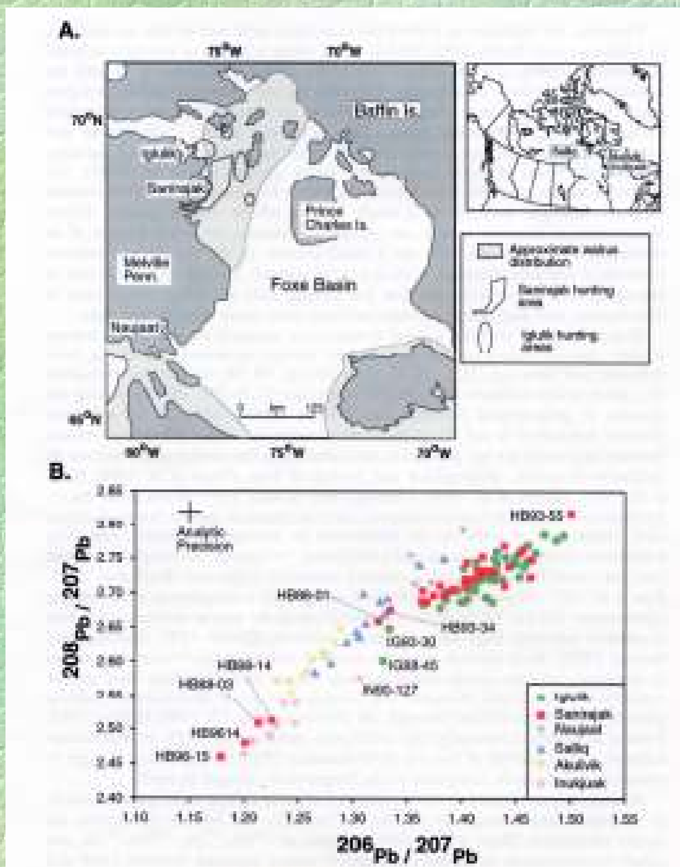
Can we use groundwater as a proxy?

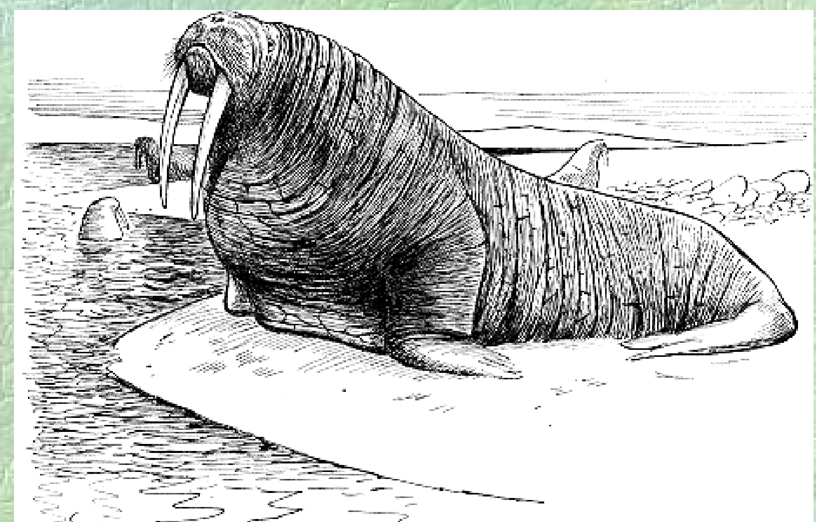



Feather DH
-75 - -70
-70 - -65
-65 - -60
-60 - -55
-55 - -50
-50 - -45


a) All birds
δDf = -33.1 + 0.52δDgw, r2 = 0.191
δDf (per mil)
δDgw (per mil)
b) Atlantic females
δDf = -19.1 + 0.70δDgw. r2 = 0.44
δDf (per mil)
δDgw (per mil)

Promise with Pb isotopes:





Stewart et al. *MMS* 19:806-818

More promise with trace elements?:

DFA: 95% success

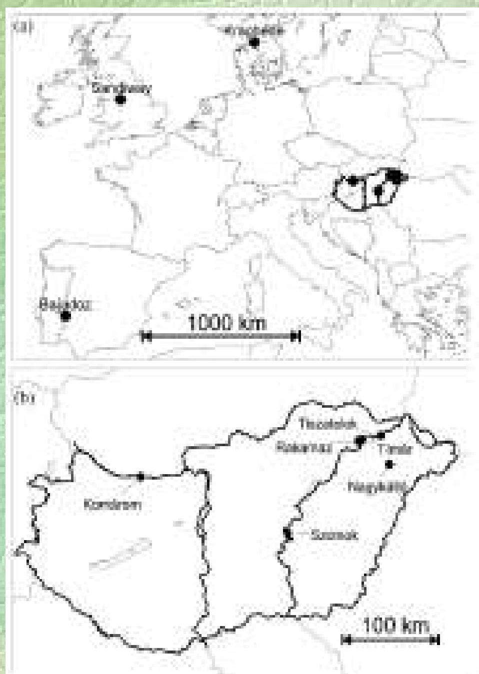
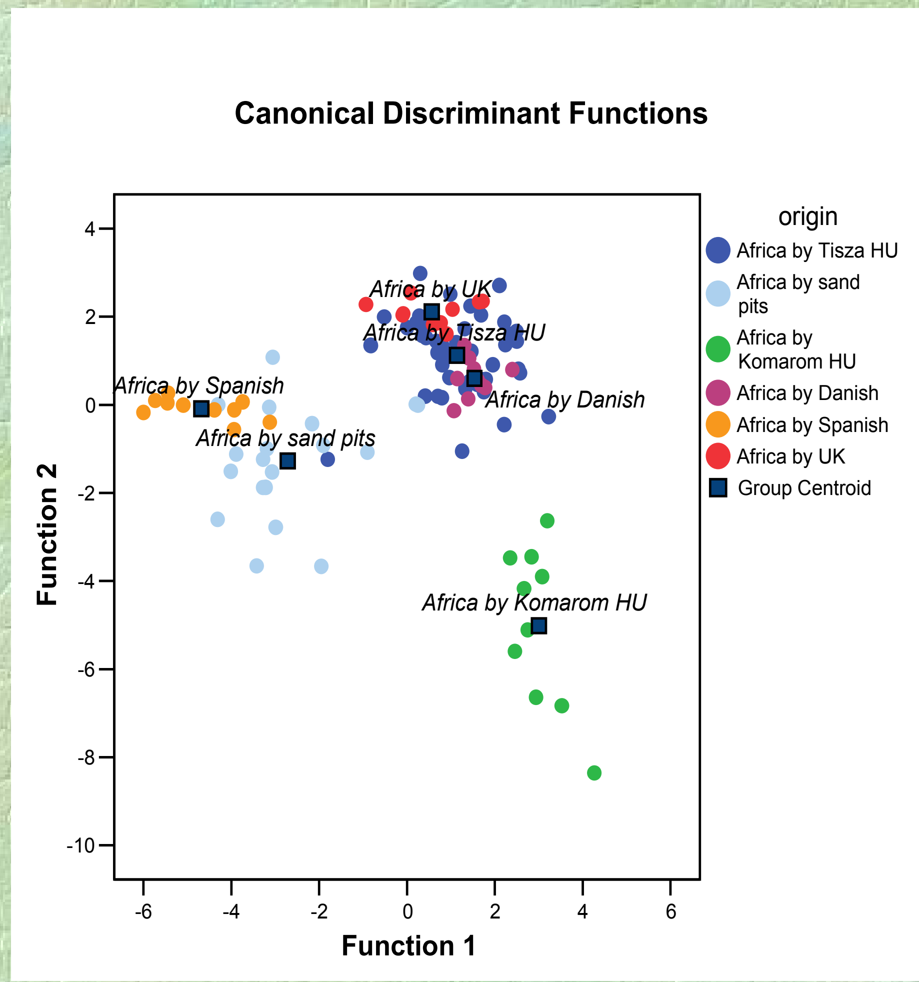
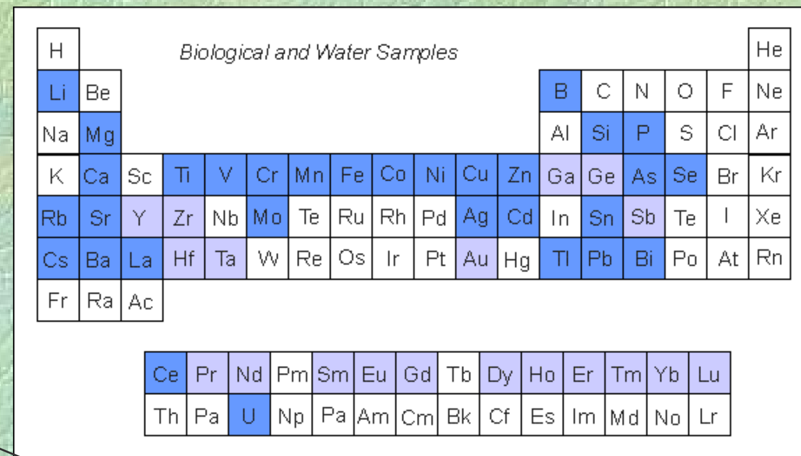


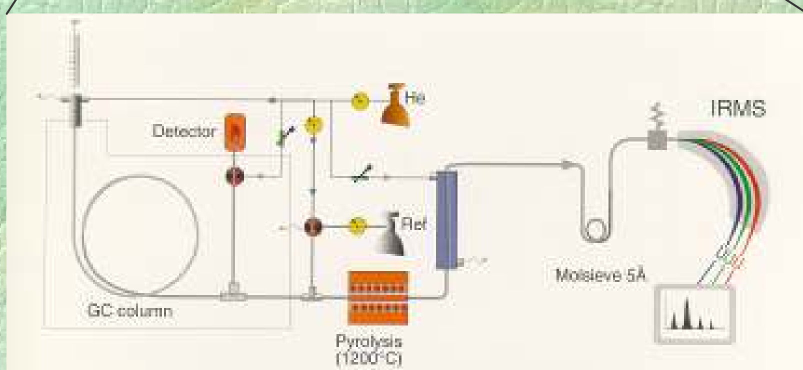
Fig. 1. Sampling sites in (a) Europe and (b) Hungary.



Tibor Szep, pers. comm.

Trace element/heavy isotope





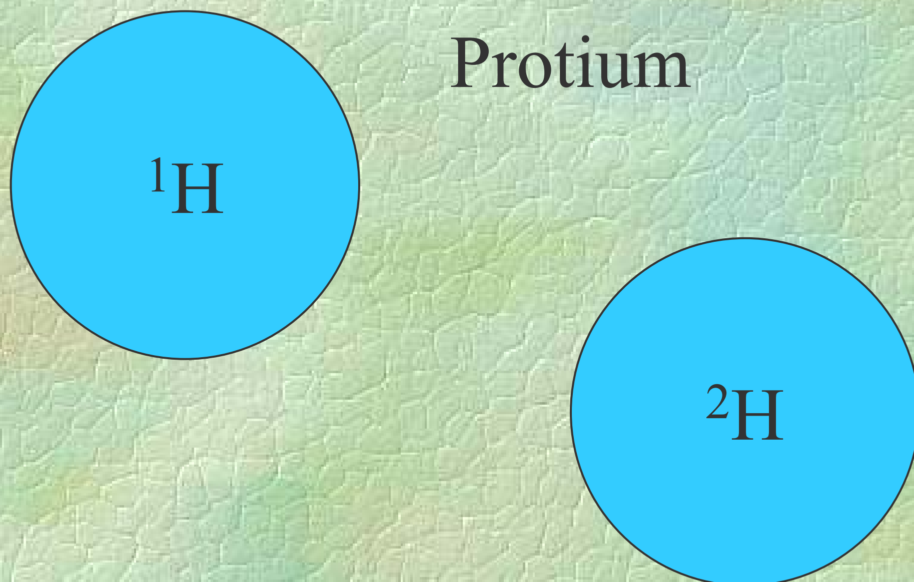
Compound specific Mass spectrometry

Future?

- Improved Isoscapes
  - Spatial and temporal variance?
  - Remote sensing
  - Plant physiology models
- Improved statistical approaches
  - Inferring origin with uncertainty
  - Use of prior probabilities

Hydrogen

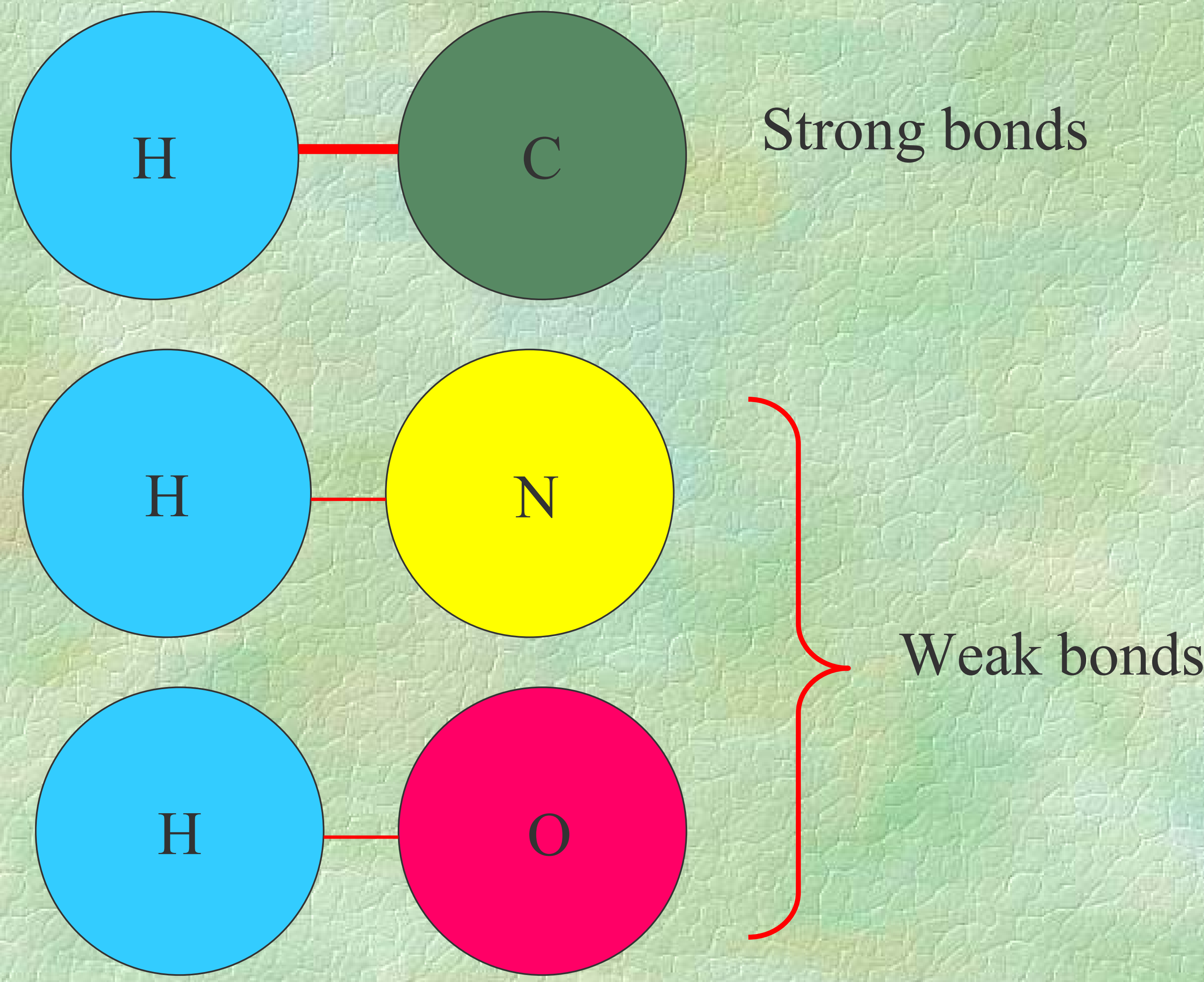
Protium



Deuterium

Involves a doubling of mass, so isotopic effects are large

Hydrogen exchange:

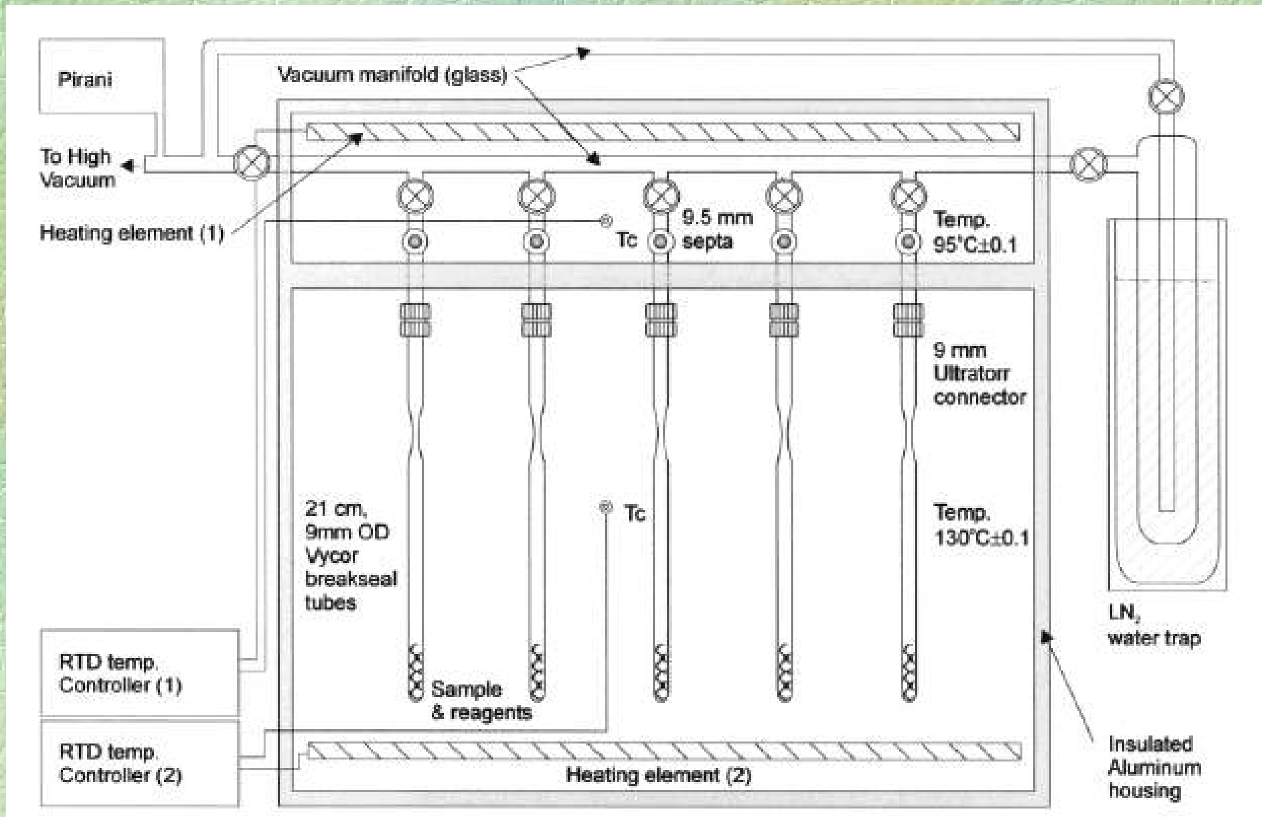


Things to know about H:

- $^{2}H/^{1}H$ represents high potential for isotopic discrimination.
- O-H and N-H bonds are weak: exchange.
- Drinking water and diet are sources of H.
- Recent analytical advances (CFIRMS) have lead to small sample requirements:
  - Sample inhomogeneities are now important.
  - Laboratory standards are esp. important.

Accounting for exchange:

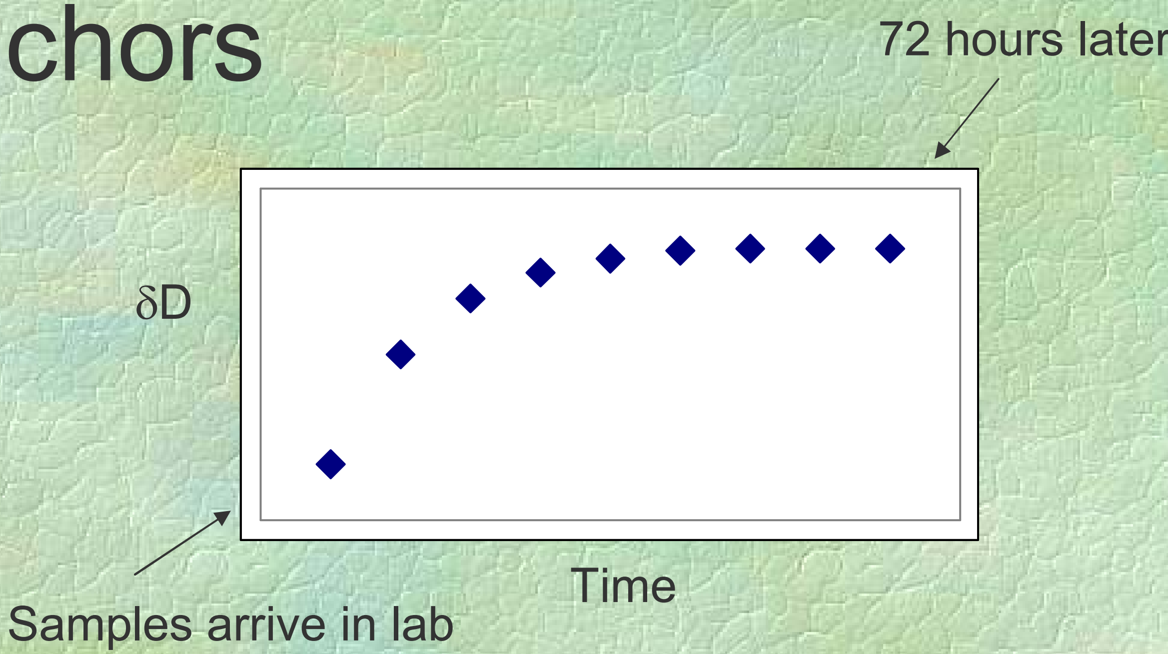
1) Steam Equilibration:

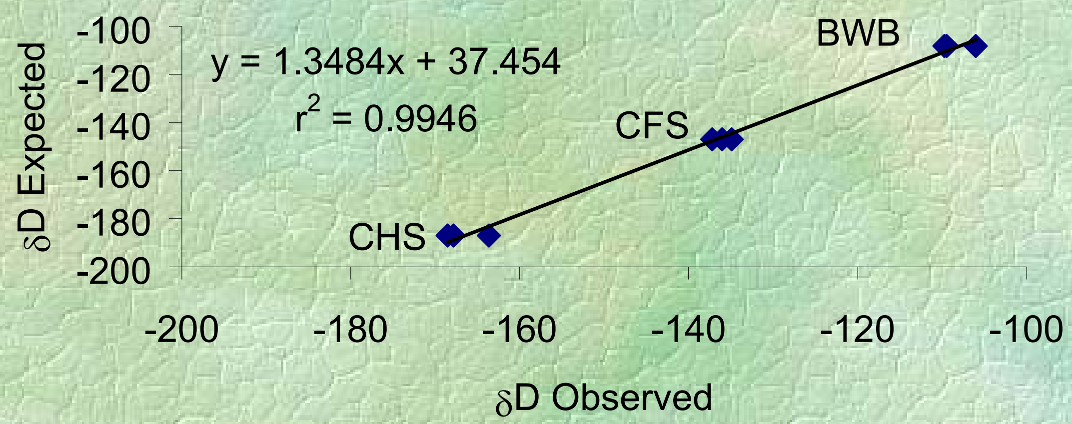


Solution - Anchors

Comparative (room temp) equilibration with standards of known δD

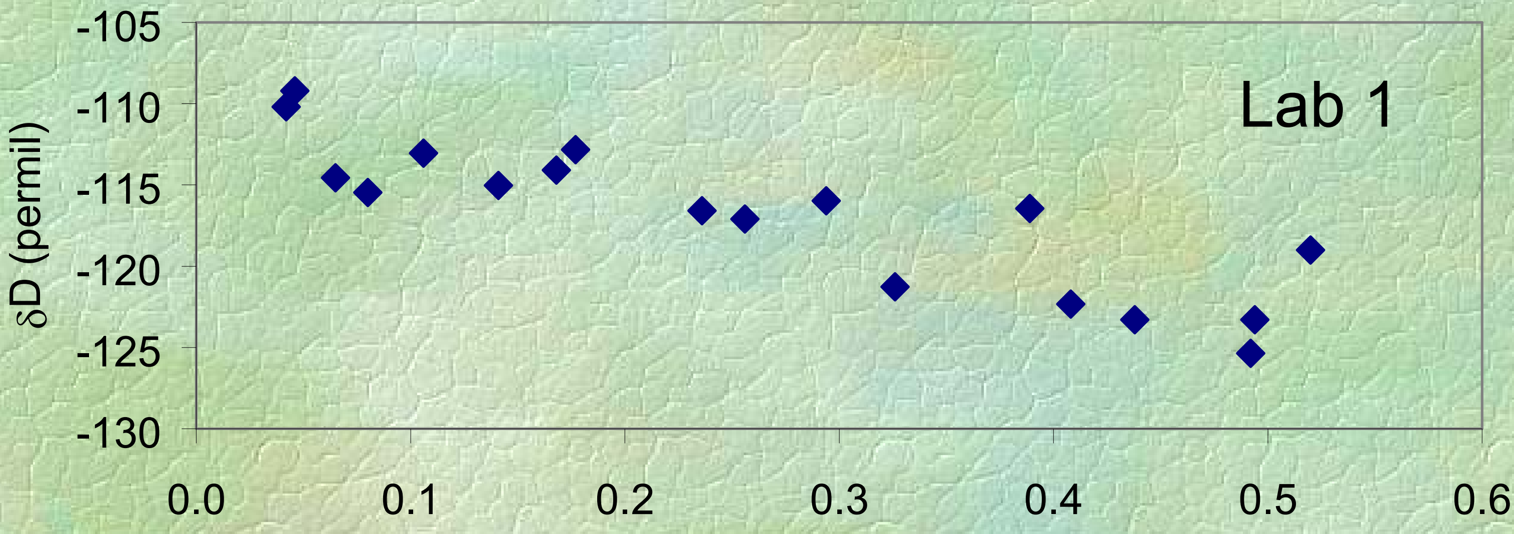
Cow Hoof Standard (CHS; δD = -187‰)
Chicken Feather Standard (CFS; δD = -147‰)
Bowhead Whale Baleen (BWB; δD = -108‰)





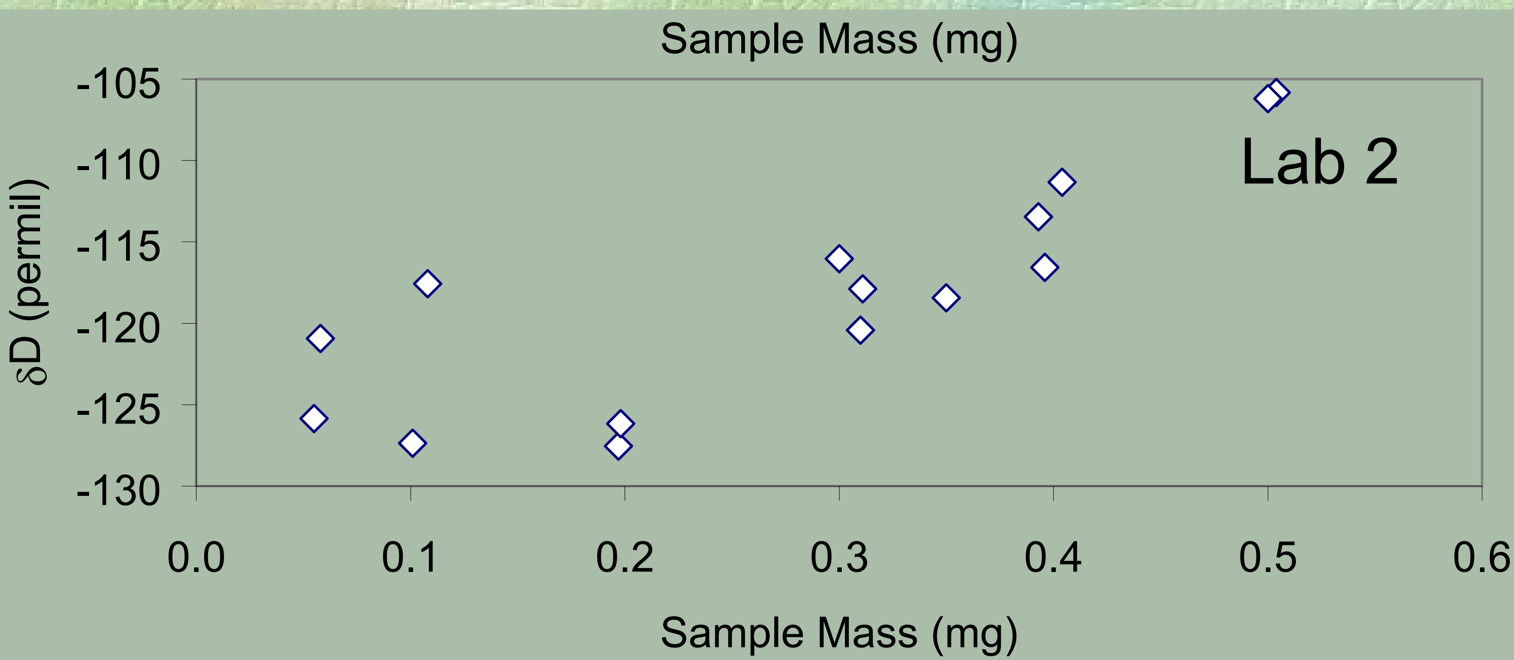
Wassenaar and Hobson 2000 Environ Sci Technol, 2003 Isotopes Environ. Health Stud.

Other considerations (linearity)



Uncorrected
1 SD = 4.6‰

Corrected
1 SD = 2.8‰



Uncorrected
1 SD = 7.0‰

Corrected
1 SD = 3.2‰

Part 1 - Keratins

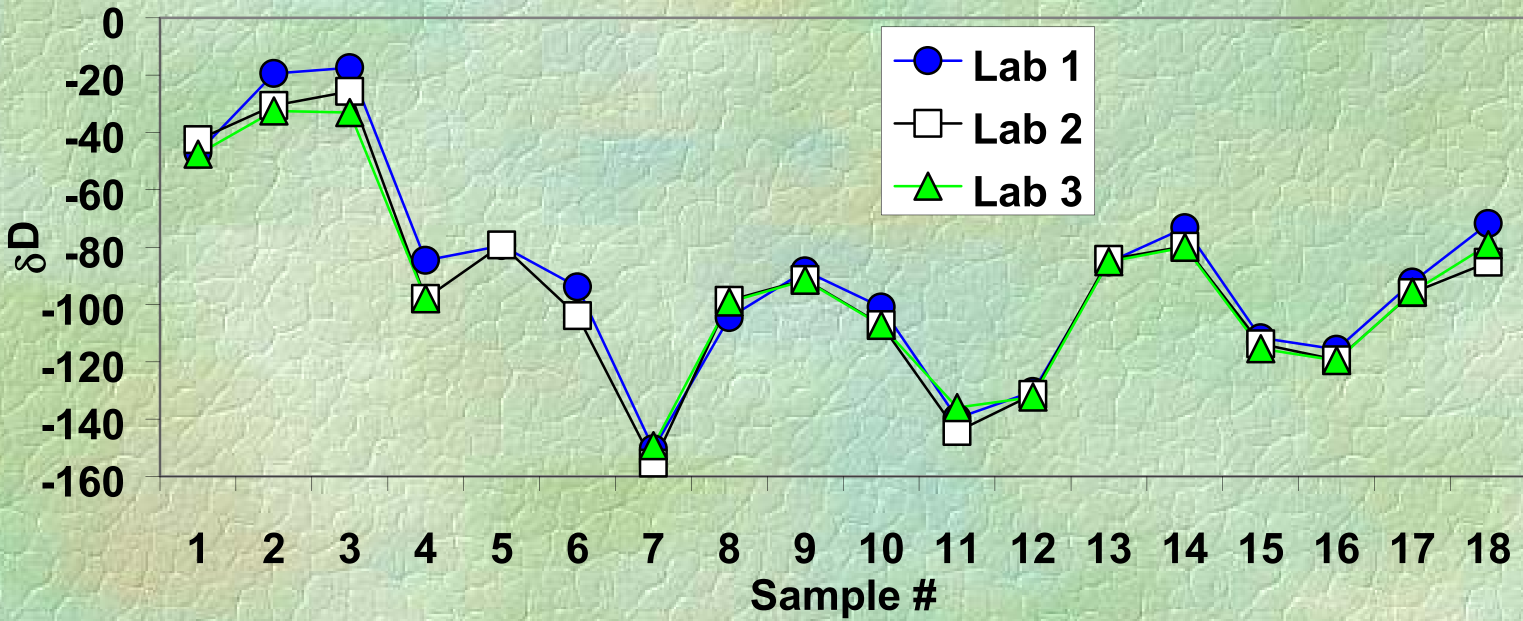
Inter-laboratory comparison

-18 songbird feathers collected in New Brunswick

-analyzed in three different labs

-corrected with keratin standards (CFS, CHS, BWB)

Part 1 - Keratins



Average range = 7‰

Similar to within-feather heterogeneity analyzed in a single lab (Wassenaar and Hobson 2006 Rapid Comm. Mass Spec)

Recommendations

Routine Organic Hydrogen Analysis

Keratins

-calibrate with available anchors (CFS, CHS, BWB)
-benchtop equilibration (allow 72 hours)
-no heating required
-constrain sample masses used or include standards of varying masses