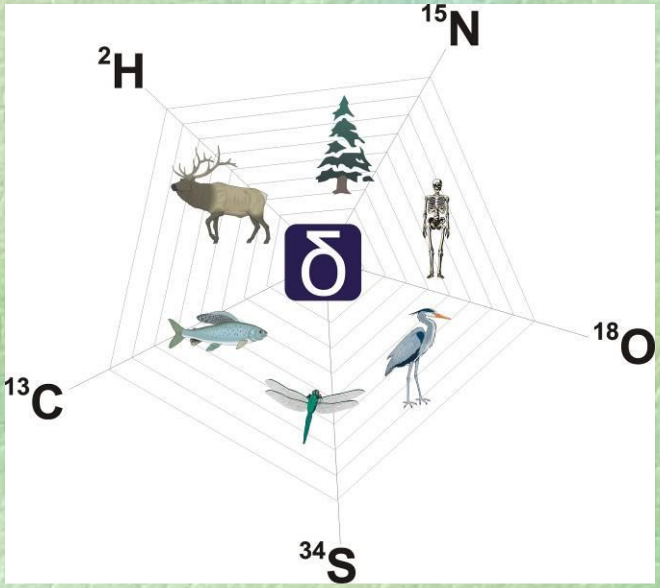
Isotopes and Animal Movement

Utah 23 June 2015

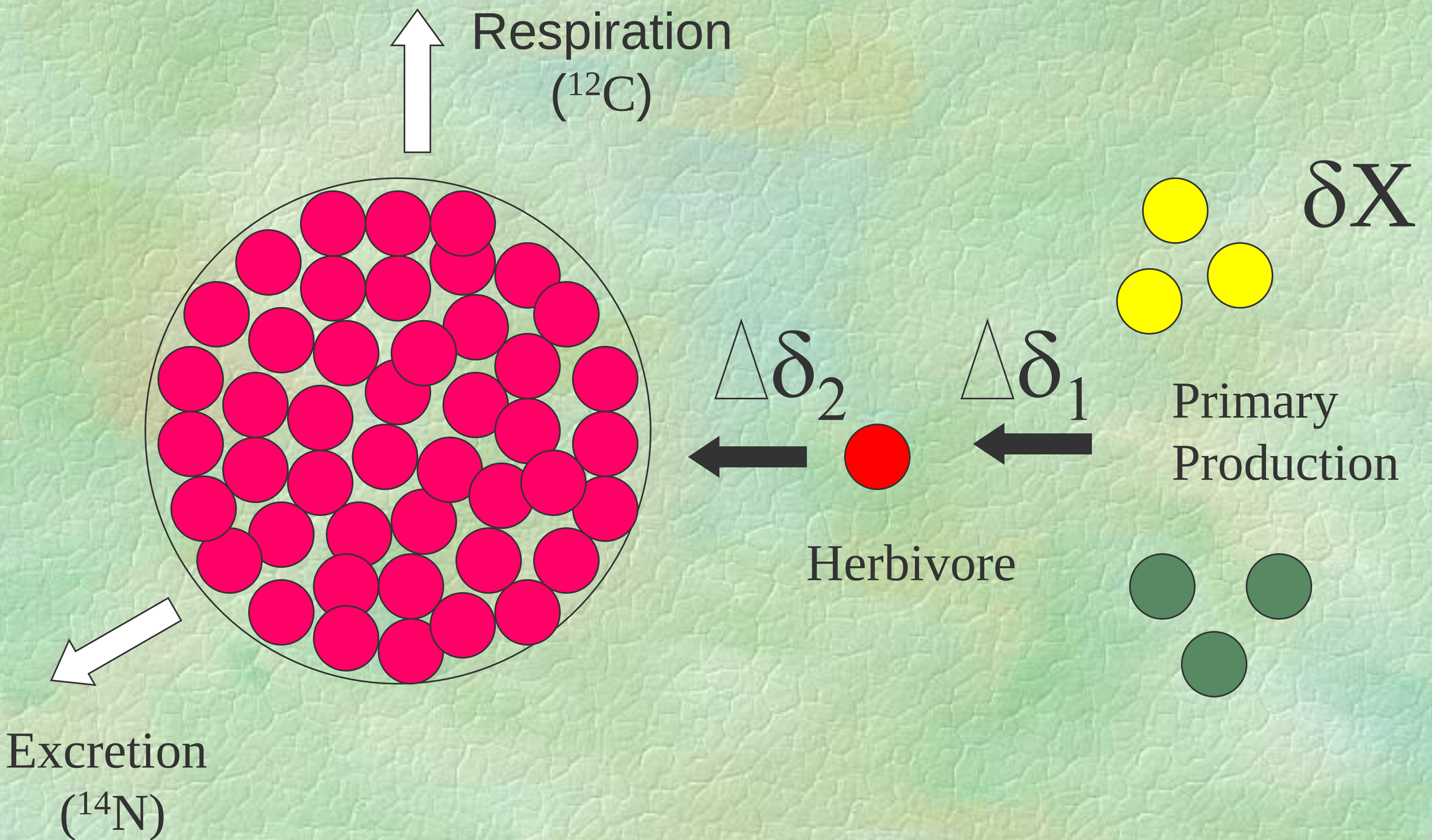
Keith A. Hobson

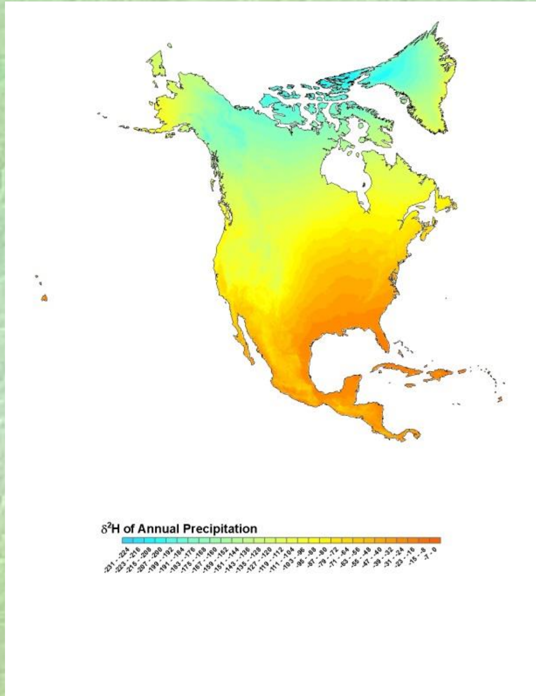


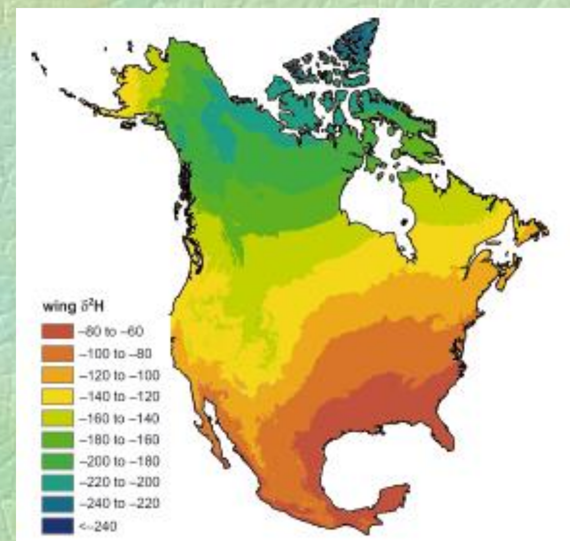
Outline

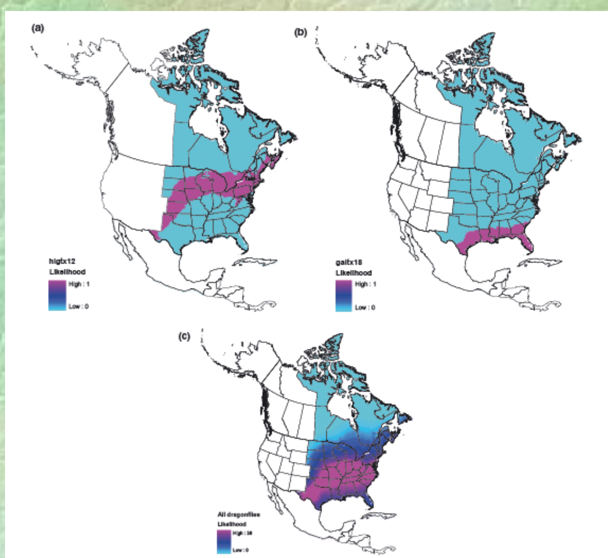
- Linking animals to isoscapes: animals add variance!
  - Transfer functions and turnover …
  - Physiology/nutrition/ecology …
  - Reflections on δ^2H measurements …
- Applications:
- Where to from here?

The basic principles of trophic level and source determinations




δ²H of Annual Precipitation

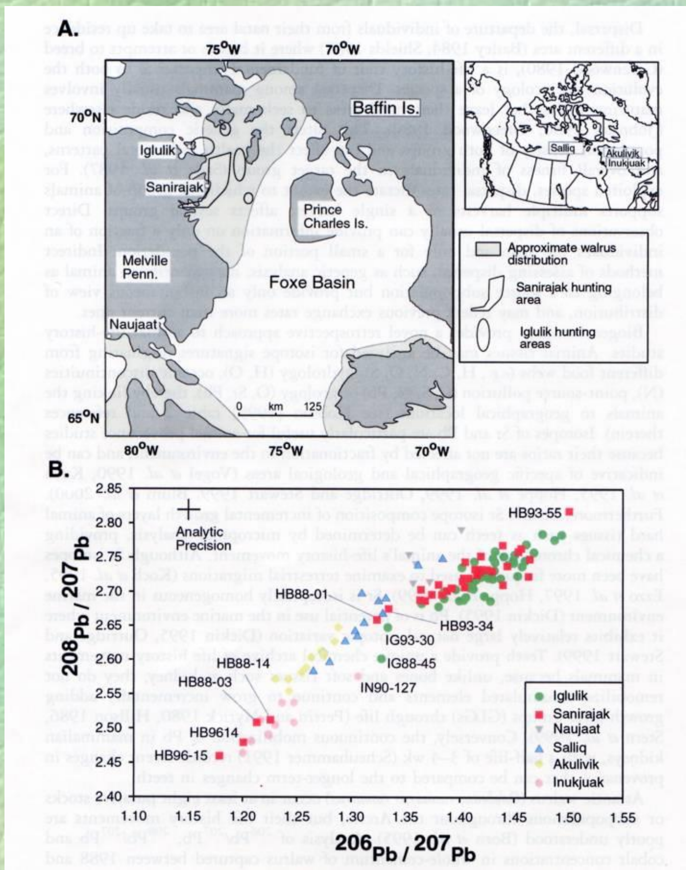

wing δ²H
–80 to –60
–100 to –80
–120 to –100
–140 to –120
–160 to –140
–180 to –160
–200 to –180
–220 to –200
–240 to –220
<–240

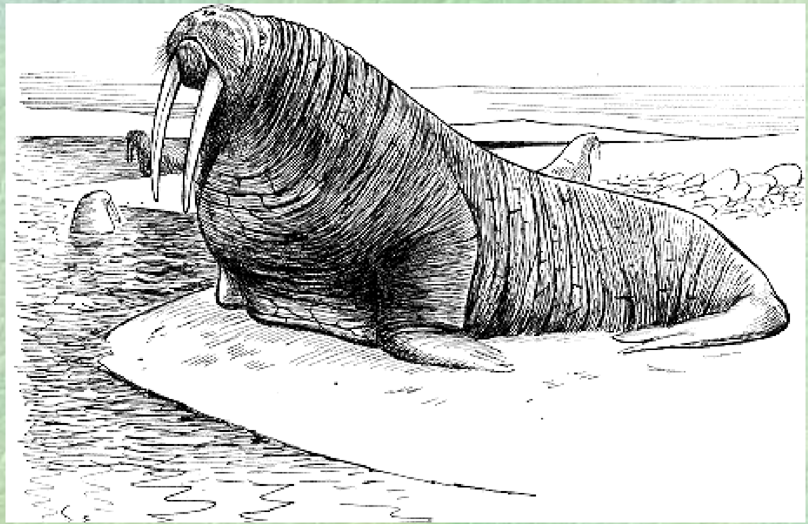

(a)
(b)
higtx12
Likelihood
High : 1
Low : 0
gaitx18
Likelihood
High : 1
Low : 0
(c)
All dragonflies
Likelihood
Low : 0

Need for a transfer function will depend on isotope …

- No need if there is no discrimination
  - e.g. heavy elements
- Important if there is discrimination
  - e.g. lighter elements
    - Metabolism and other rate-limiting steps
    - Ecology/physiology

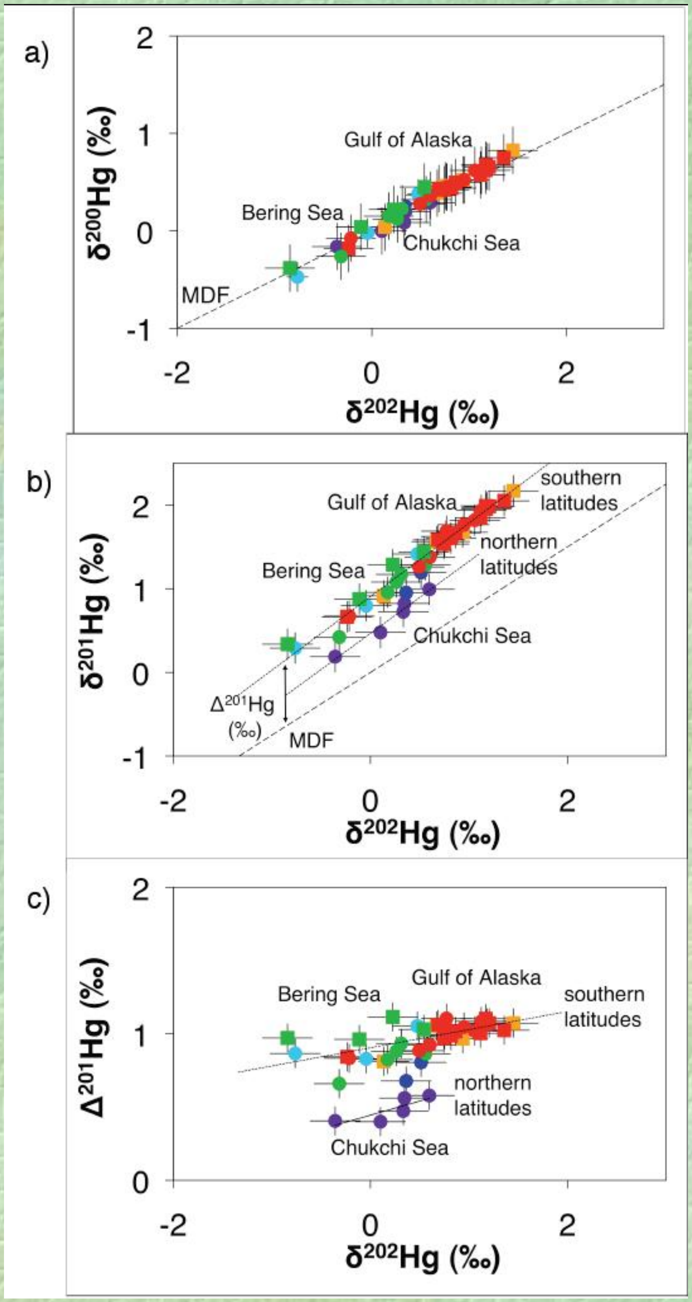
Pb isotopes linked to surficial geology …





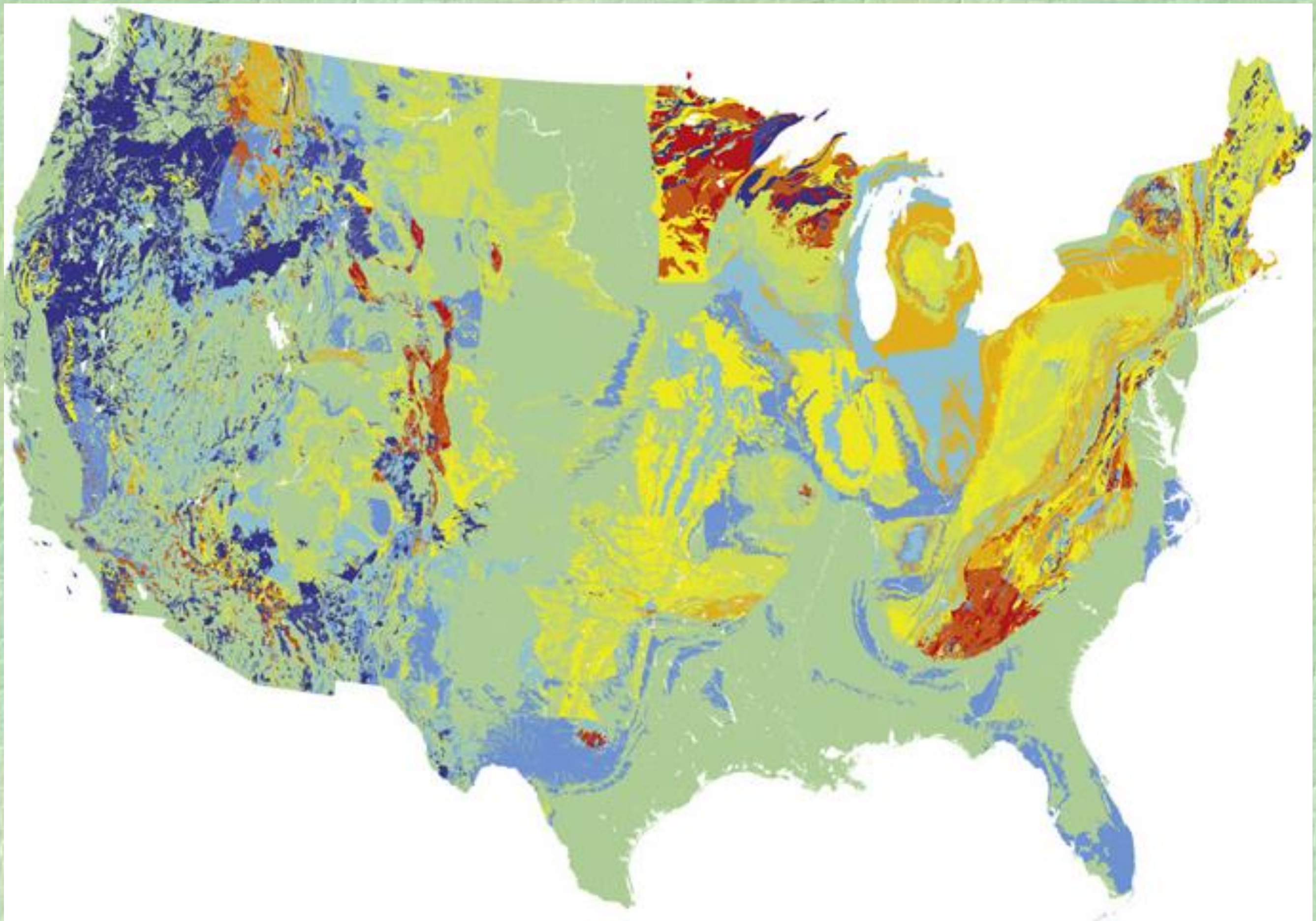
Stewart et al. *MMS* 19:806-818

Hg isotopes

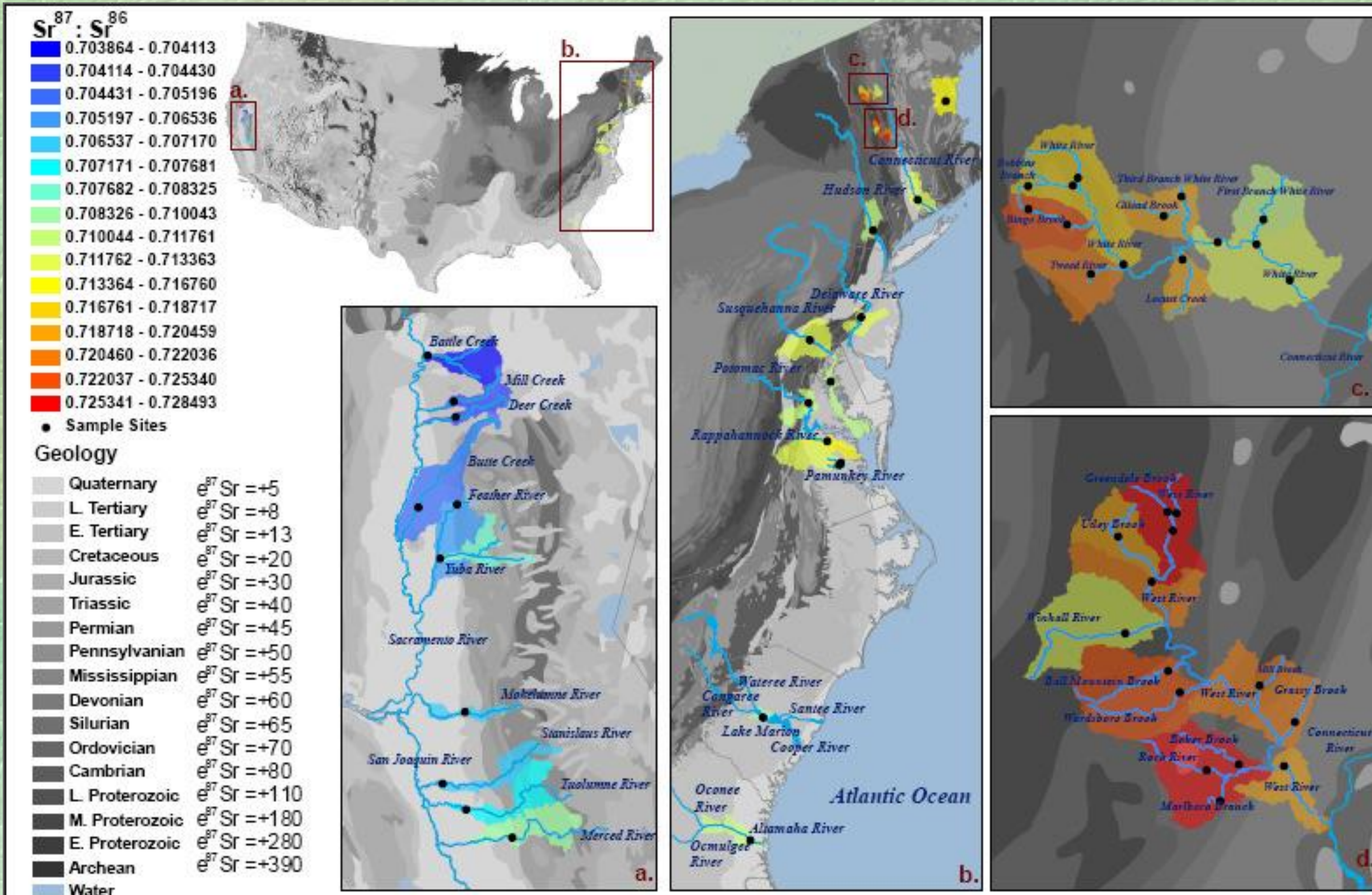


Point et al. 2011 Nature Geoscience

Strontium (bedrock model)



C.P. Bataille, G.J. Bowen / Chemical Geology 304-305 (2012) 39–52

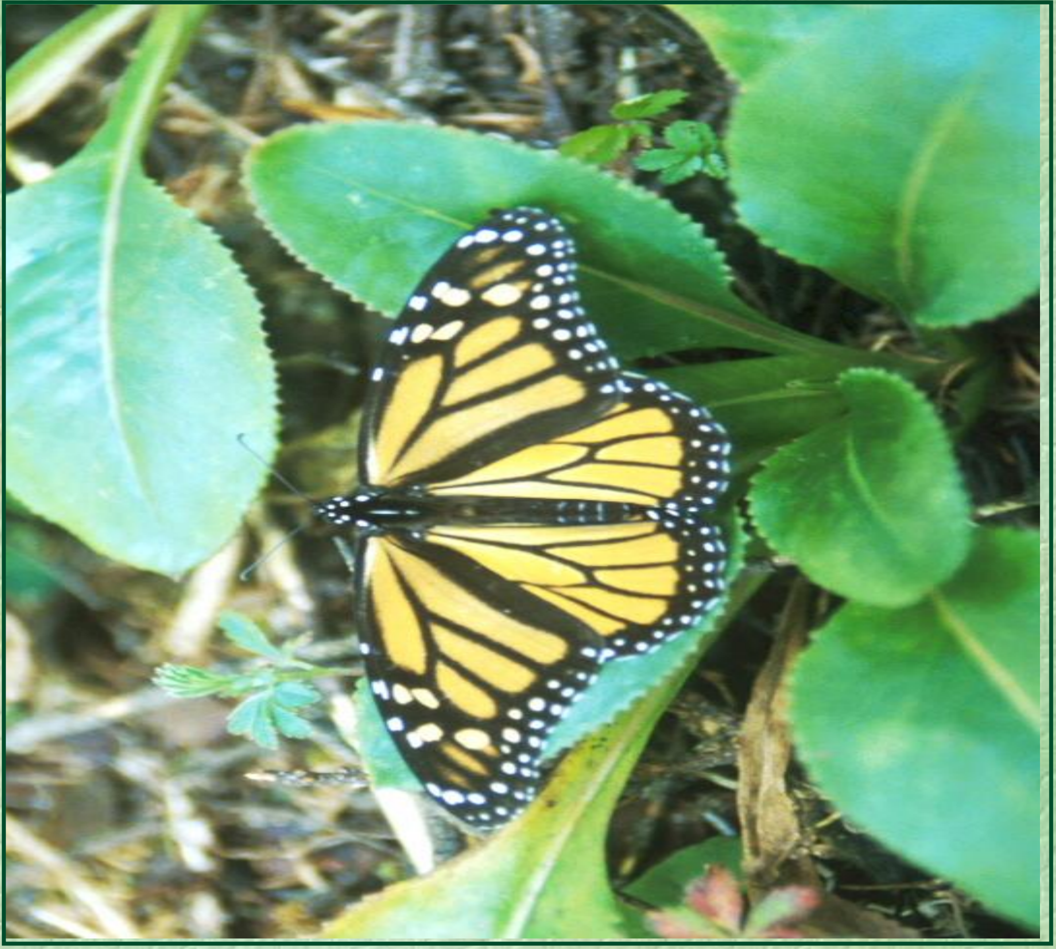


Work of Barnet-Johnson in Hobson, Barnet-Johnson and Cerling (isoscapes book, 2010)

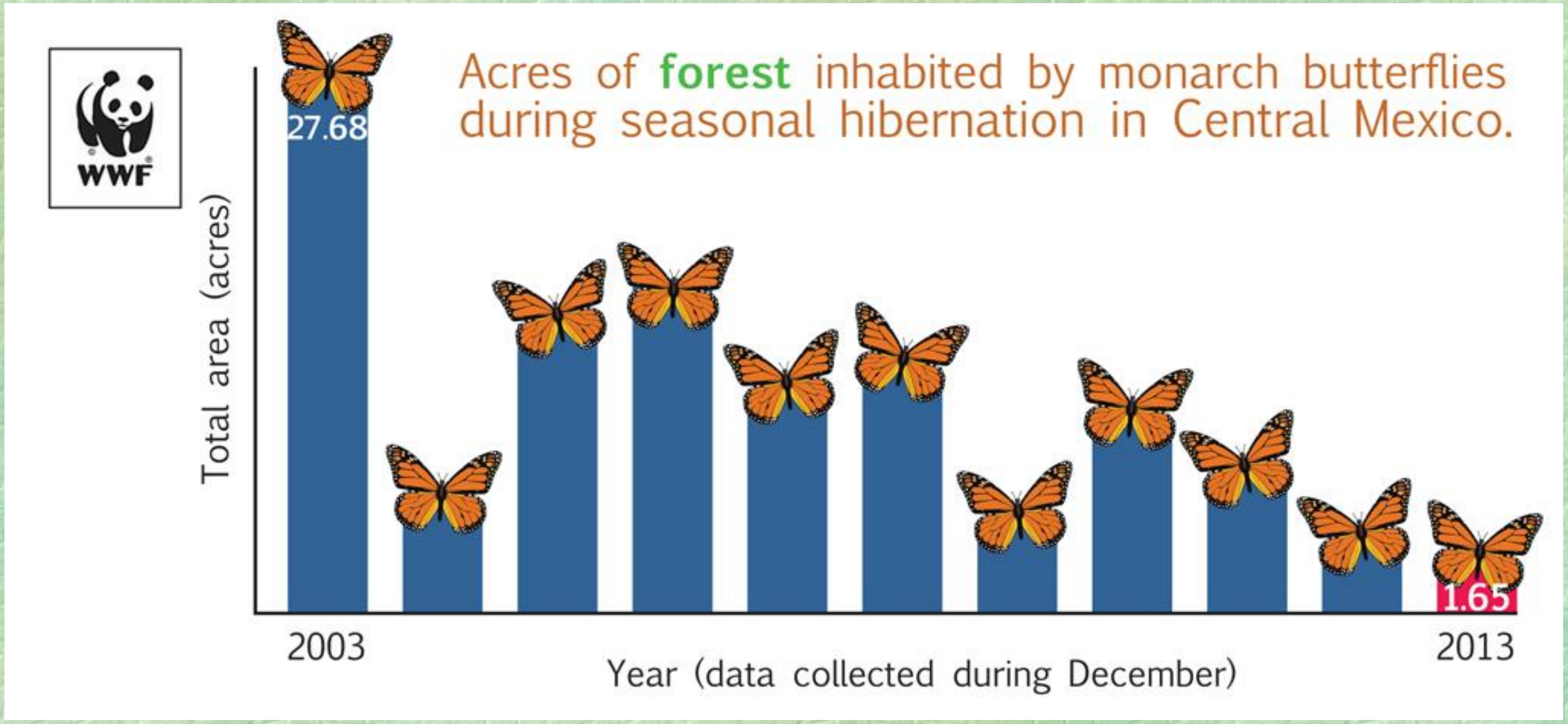
For the light isotopes …

- 1. Create a simple basemap through broad spatial sampling of animal tissue.
- 2. Infer a calibration *relationship* through limited spatial sampling across an isotopic gradient.
- 3. Experimentally derive the calibration relationship through controlled (captive) studies.

An early application using δ^2H to track Monarch migration ….



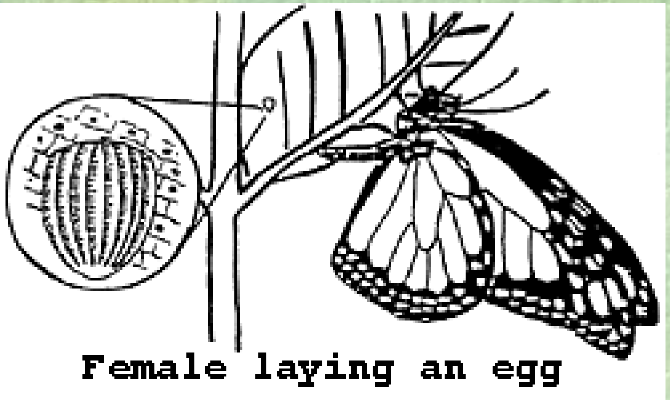
- Are monarchs declining due to factors on breeding grounds? Wintering grounds? Both?

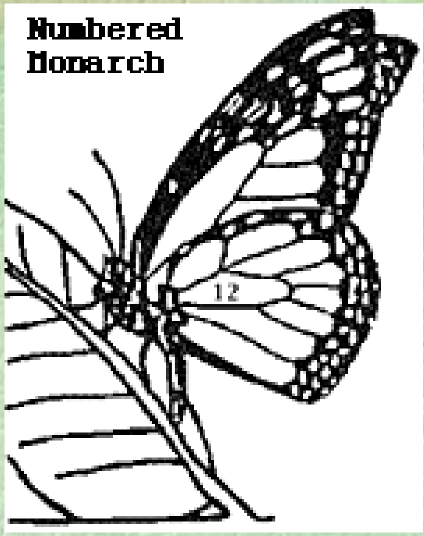


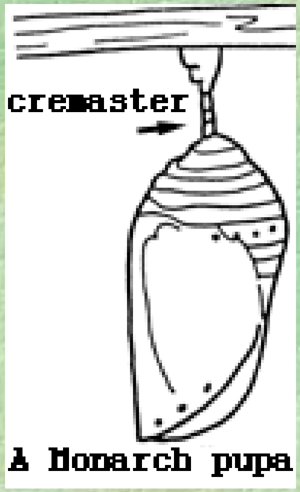
Two populations, one long distance journey ….

Previously, tagging was used:

Monarchs can be “grown” anywhere!



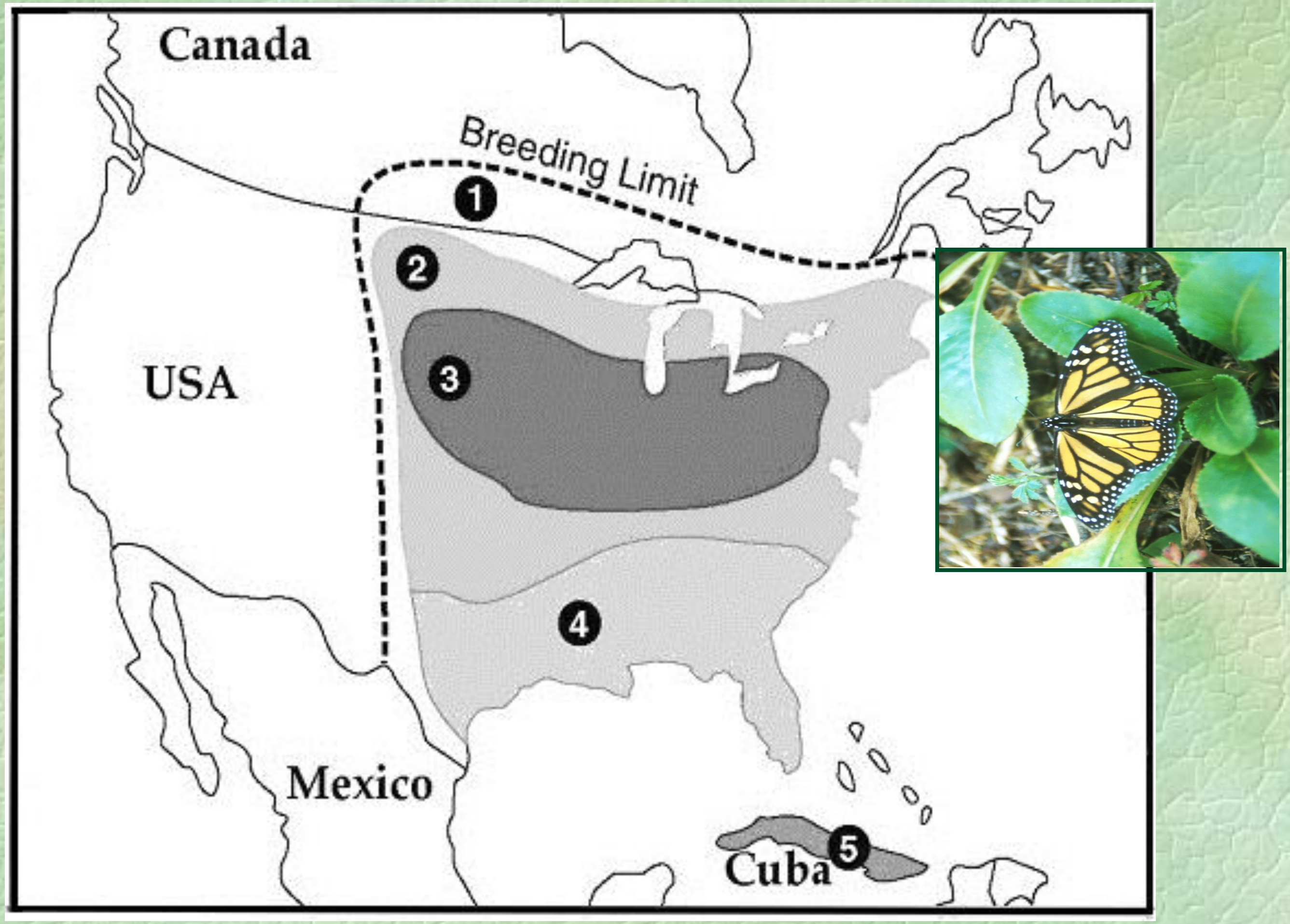




80 elementary schools recruited throughout the range …..

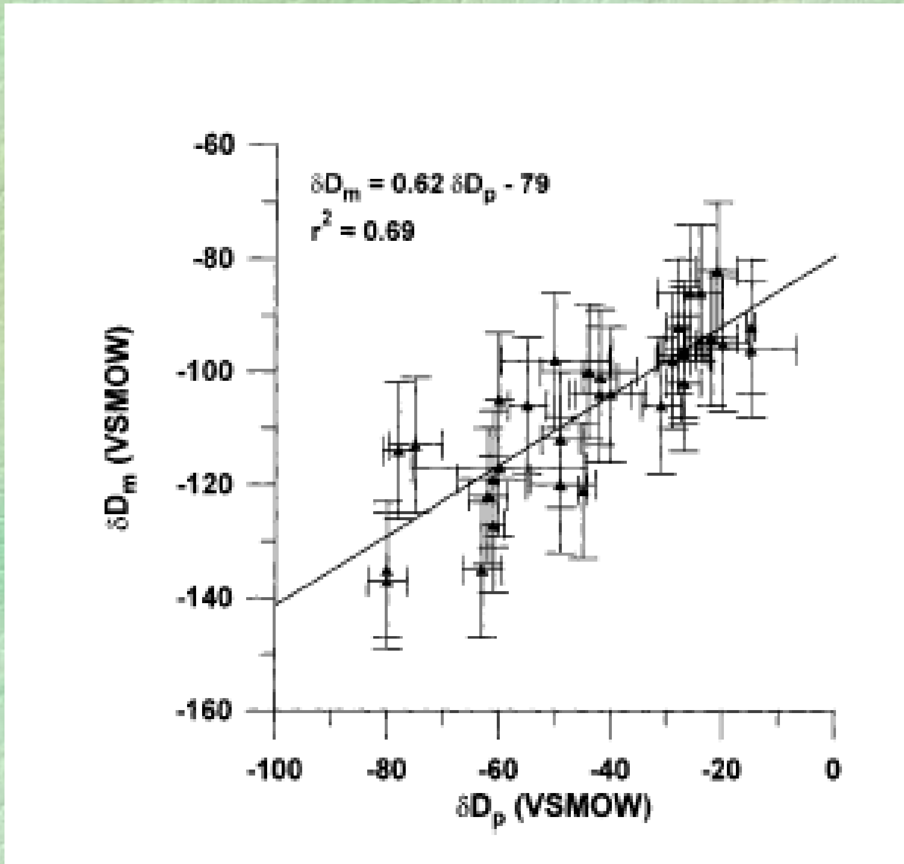
The basemap for the year of interest:

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



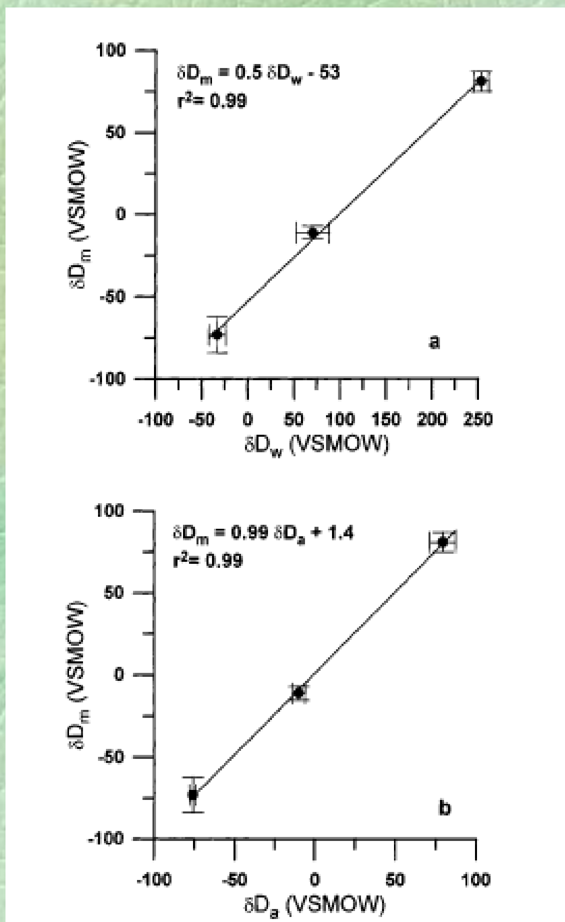
Docykx et al. Ecol. Applic., in press

Transfer function ….



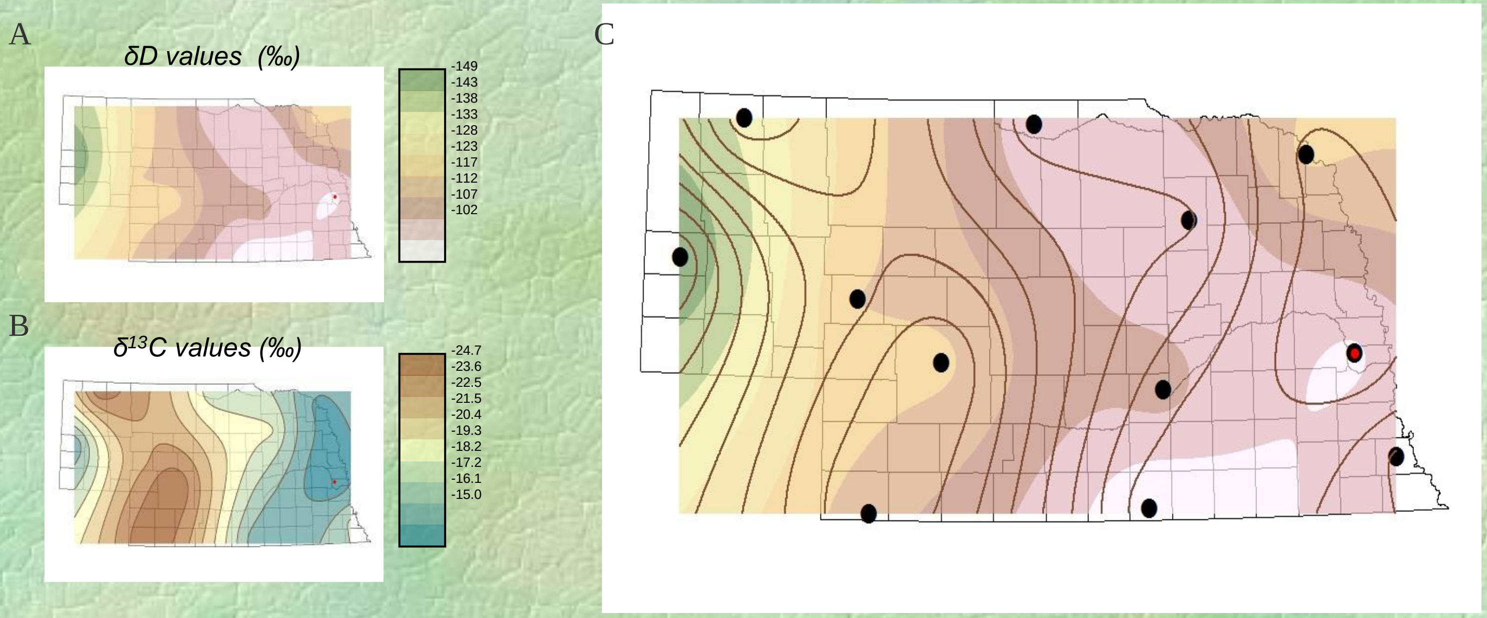
Hobson et al. 1999 Oecologia 120:397-404

Transfer function derived experimentally ….

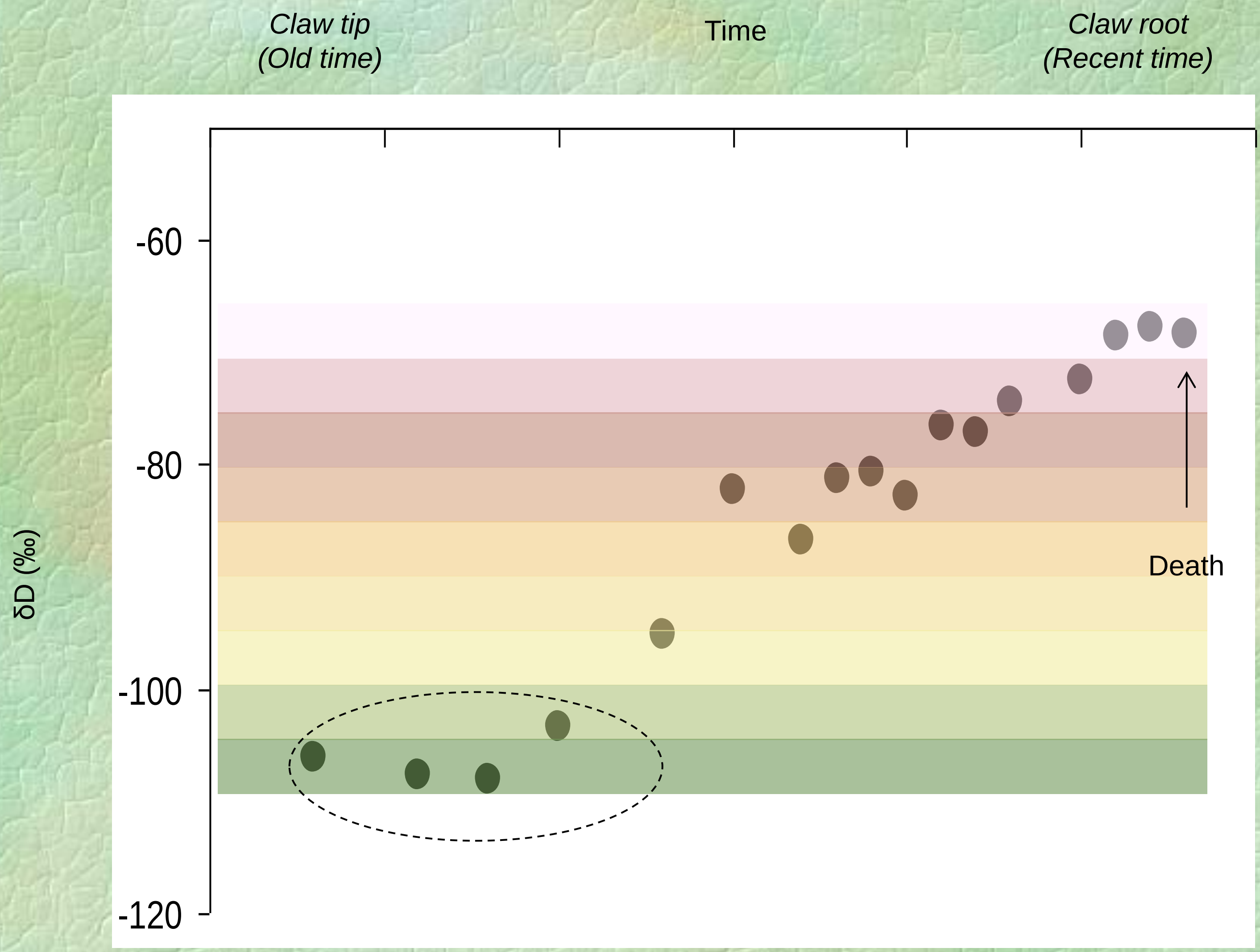


Hobson et al. 1999 Oecologia 120:397-404

Nebraska “deer isoscape”

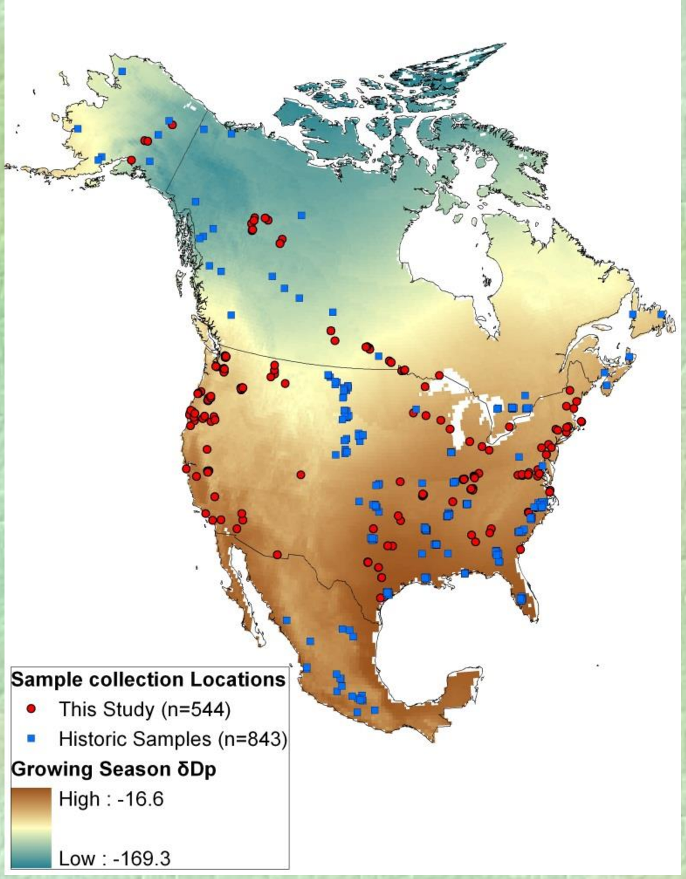


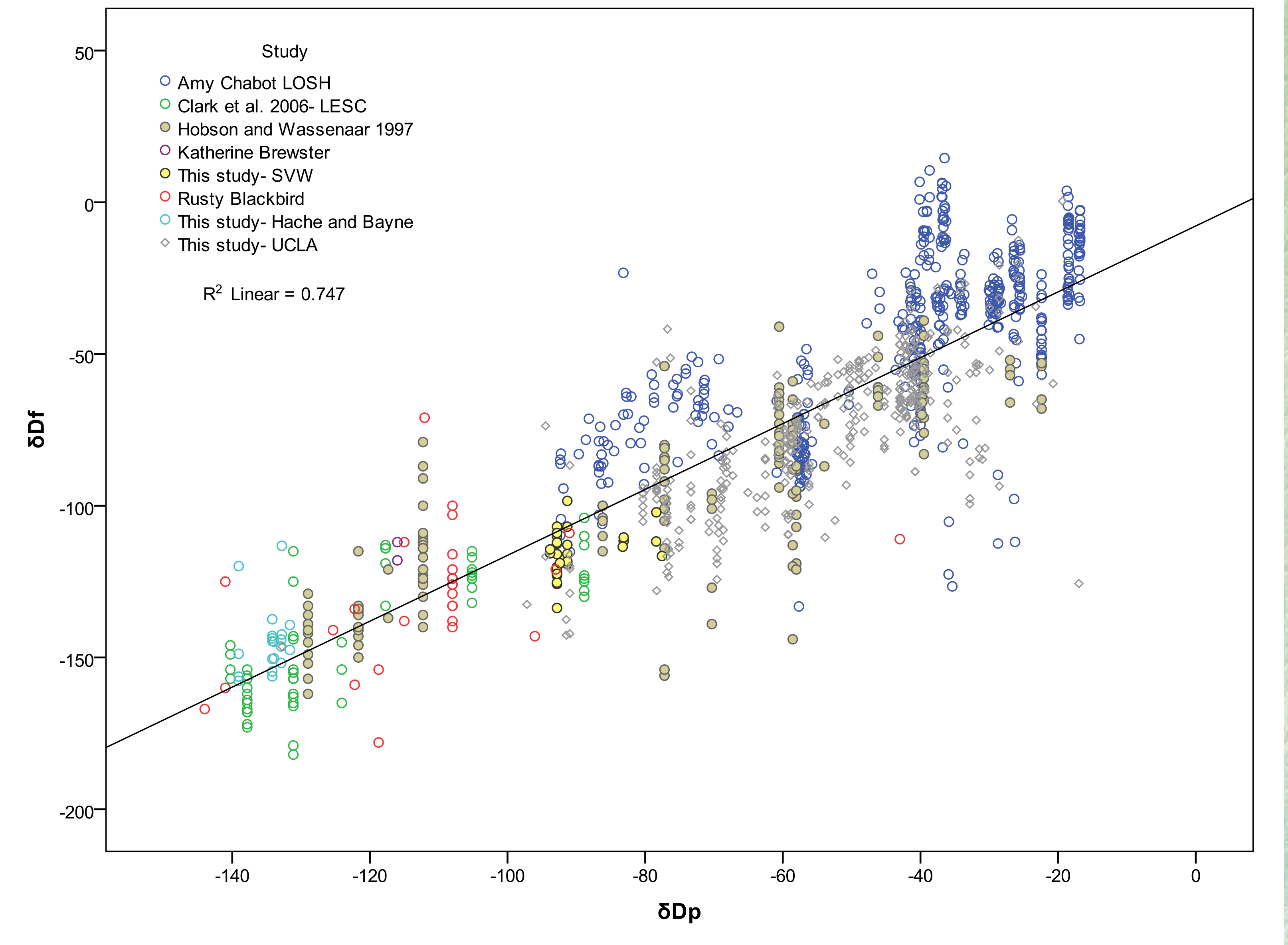
Henaux et al. MEE 2011



Claw tip
(Old time)
Time
Claw root
(Recent time)
-60
-80
-100
-120
δD (‰)
Death

Transfer function through limted sampling (gradients)





Hobson et al. 2012 PLoS ONE

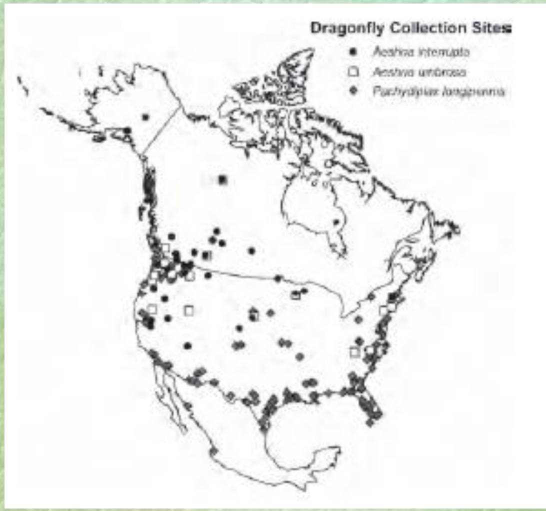
Single Top Model:

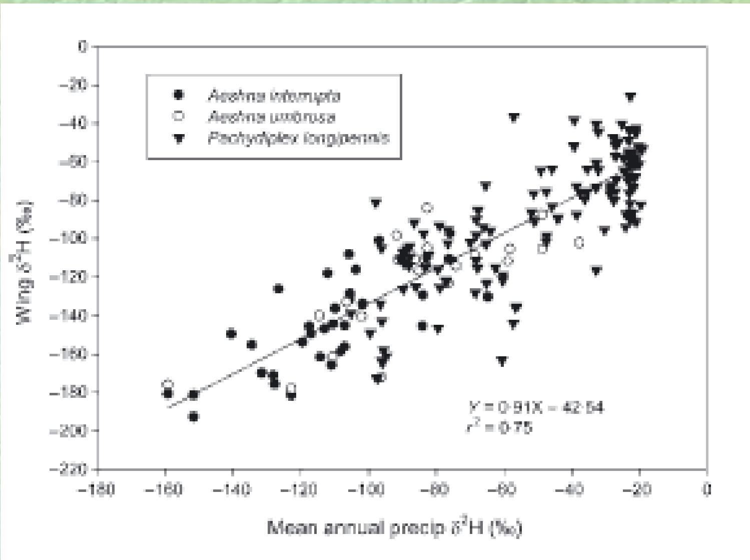
- δ^2H_f = Int. + δ^2H_p + Migratory Guild + Foraging Substrate + Guild*Substrate
- Explains ~83% of the variance in δ^2H_f

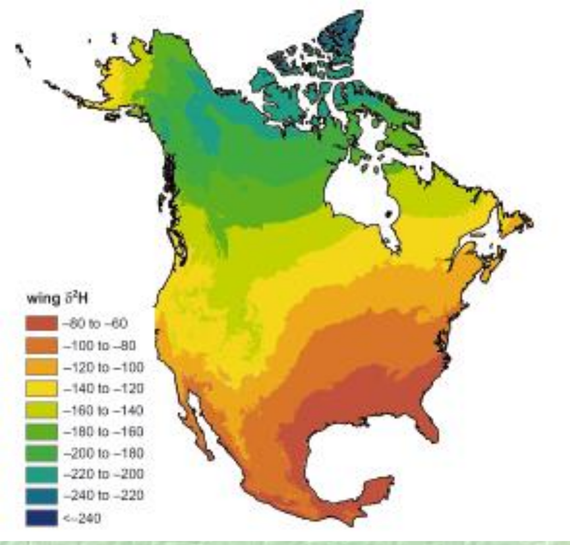
Mechanisms?

- Foraging substrate:
  - Microhabitat/dietary variation in δ^2H?
- Migratory guild:
  - Molt phenology, feather growth rate?

Dragonfly wing isoscape

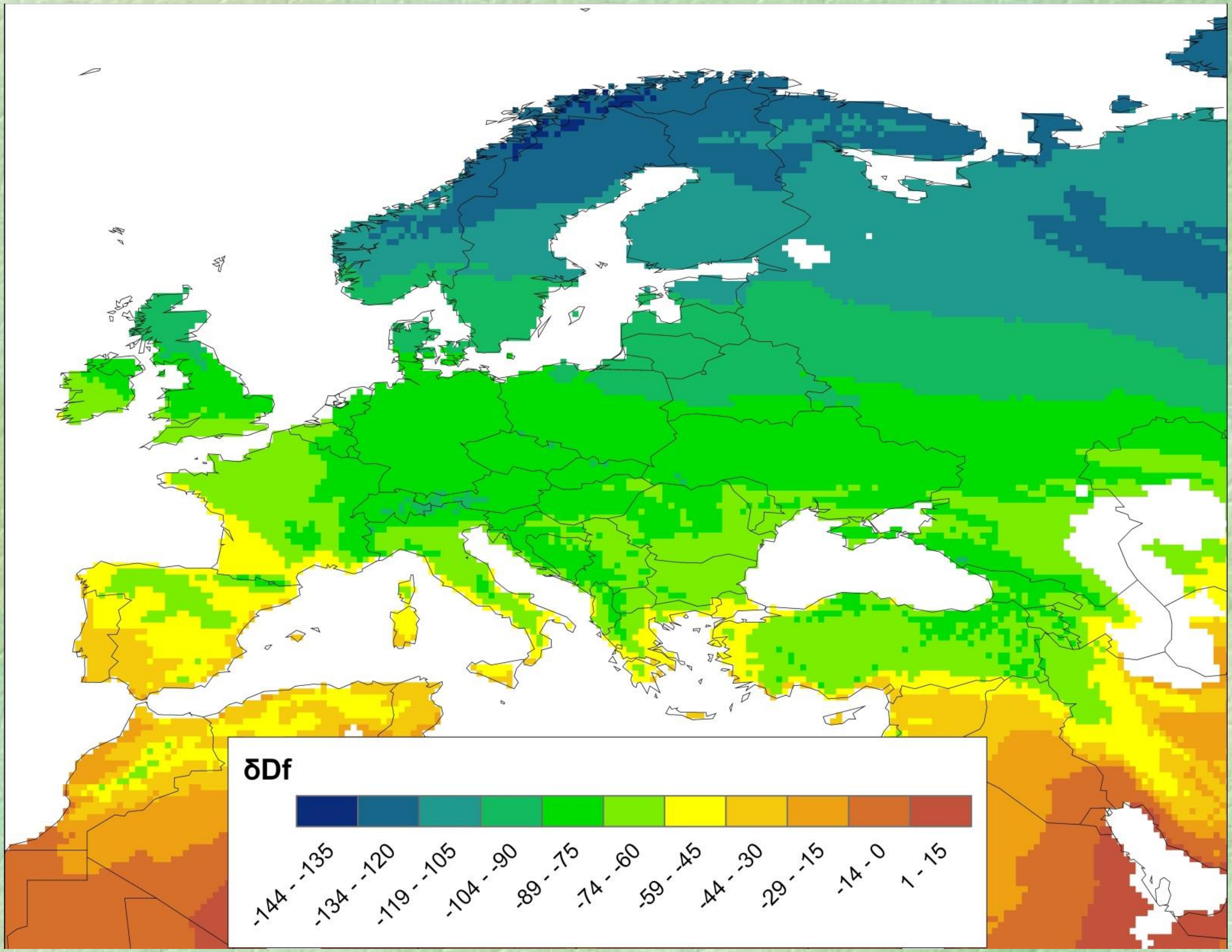




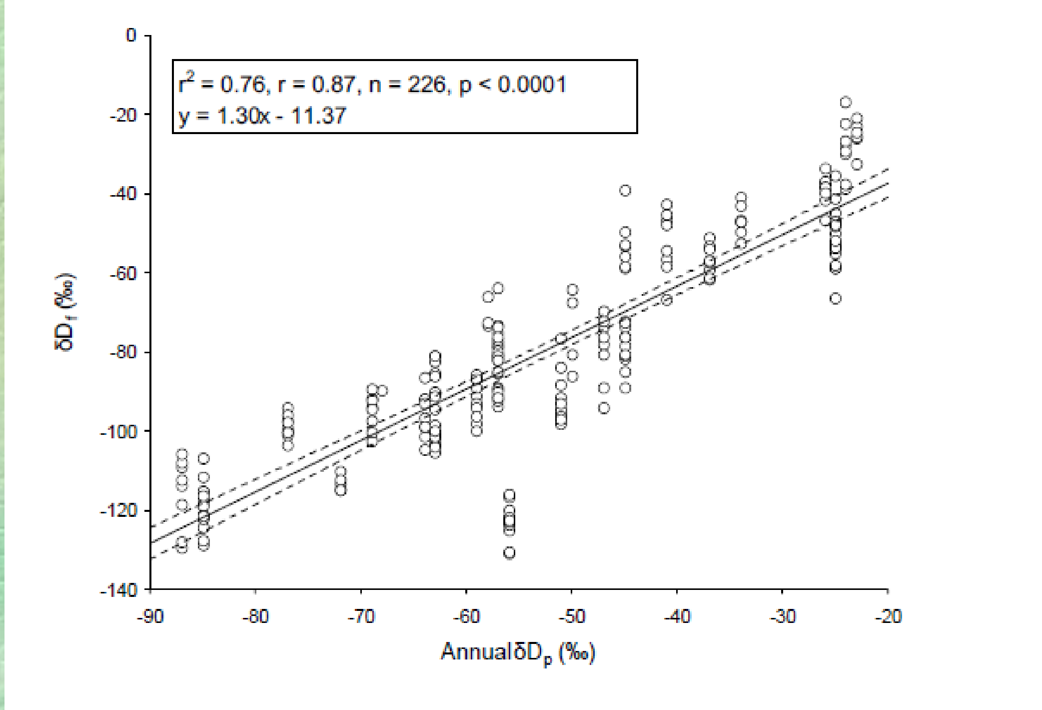


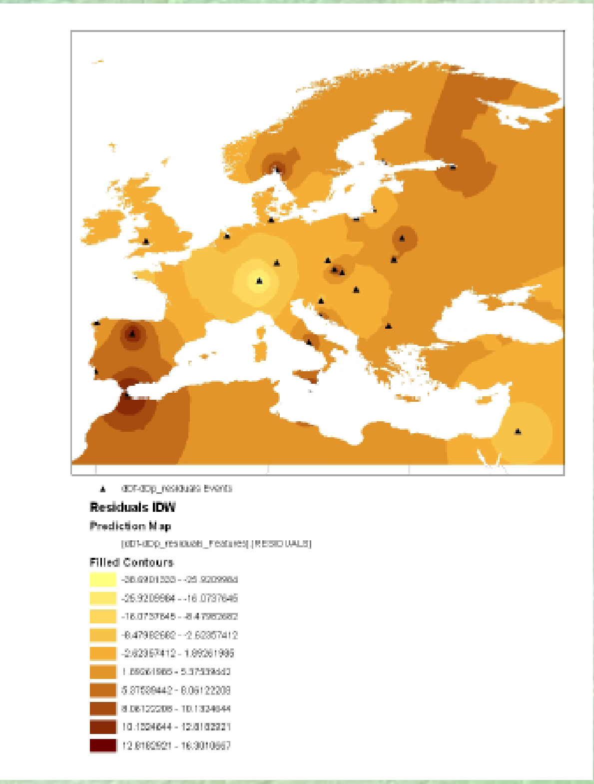
Hobson et al. 2012 MEE 3:766-772

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)

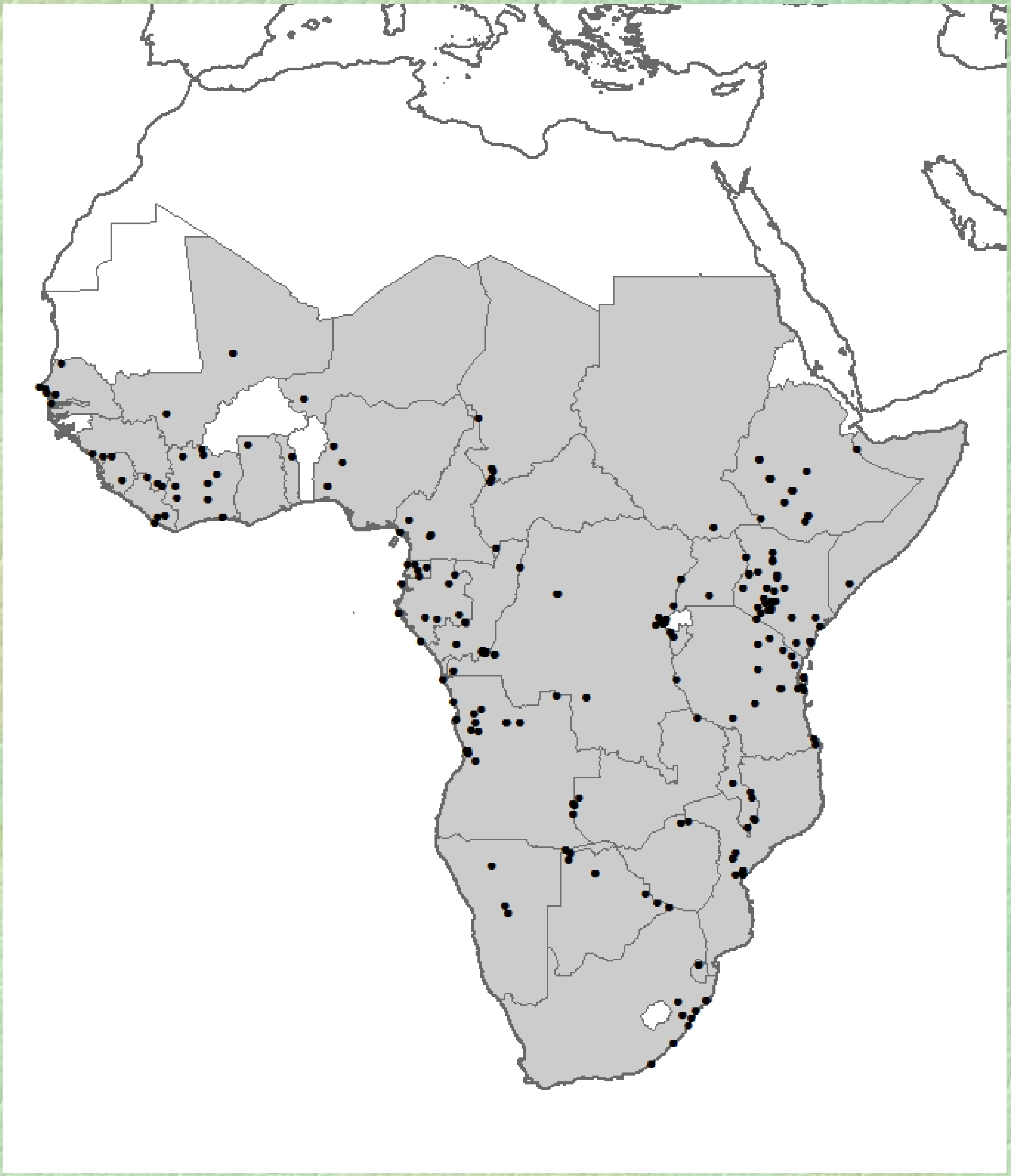


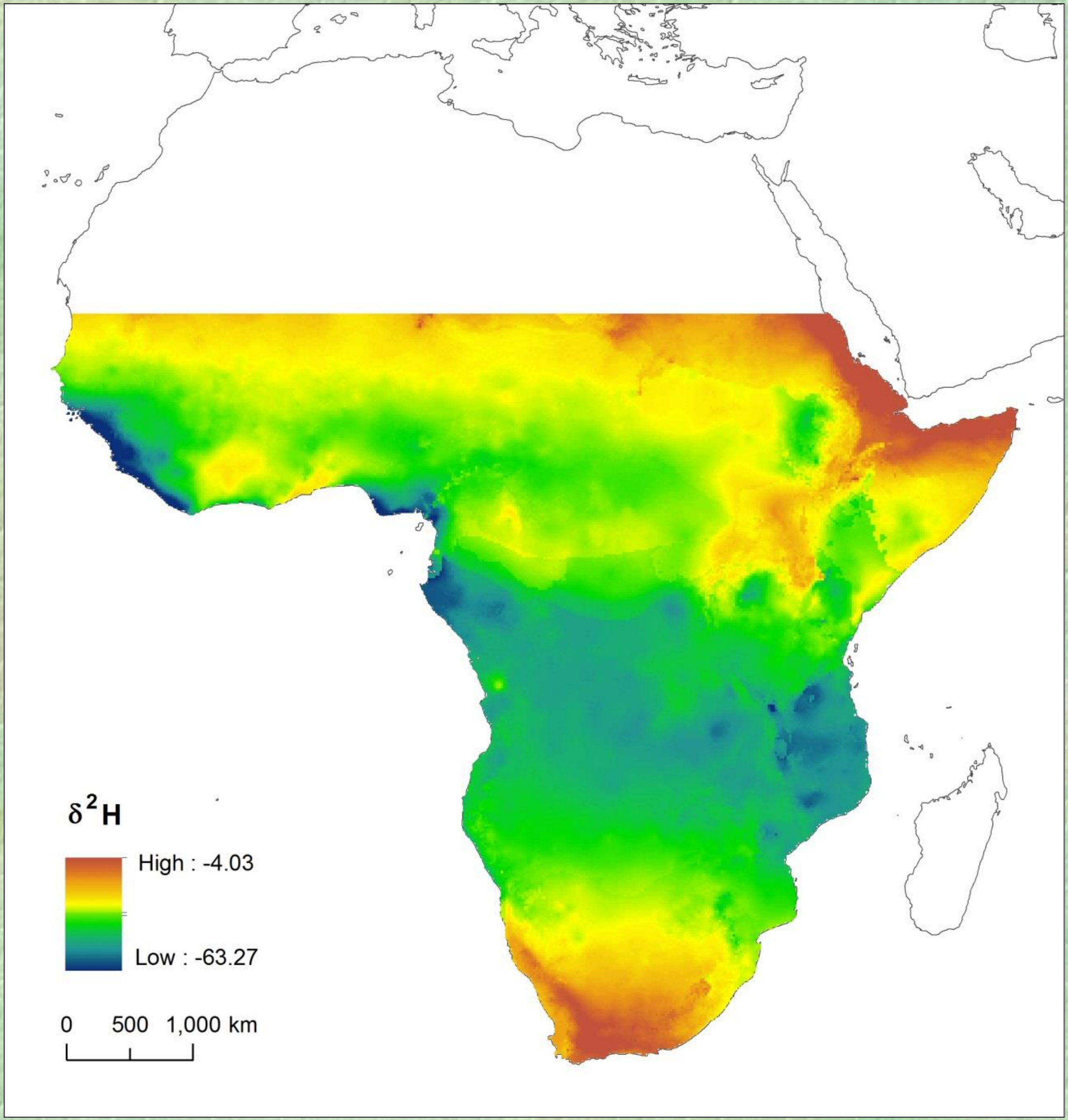
δDf
-144 - -135
-134 - -120
-119 - -105
-104 - -90
-89 - -75
-74 - -60
-59 - -45
-44 - -30
-29 - -15
-14 - 0
1 - 15

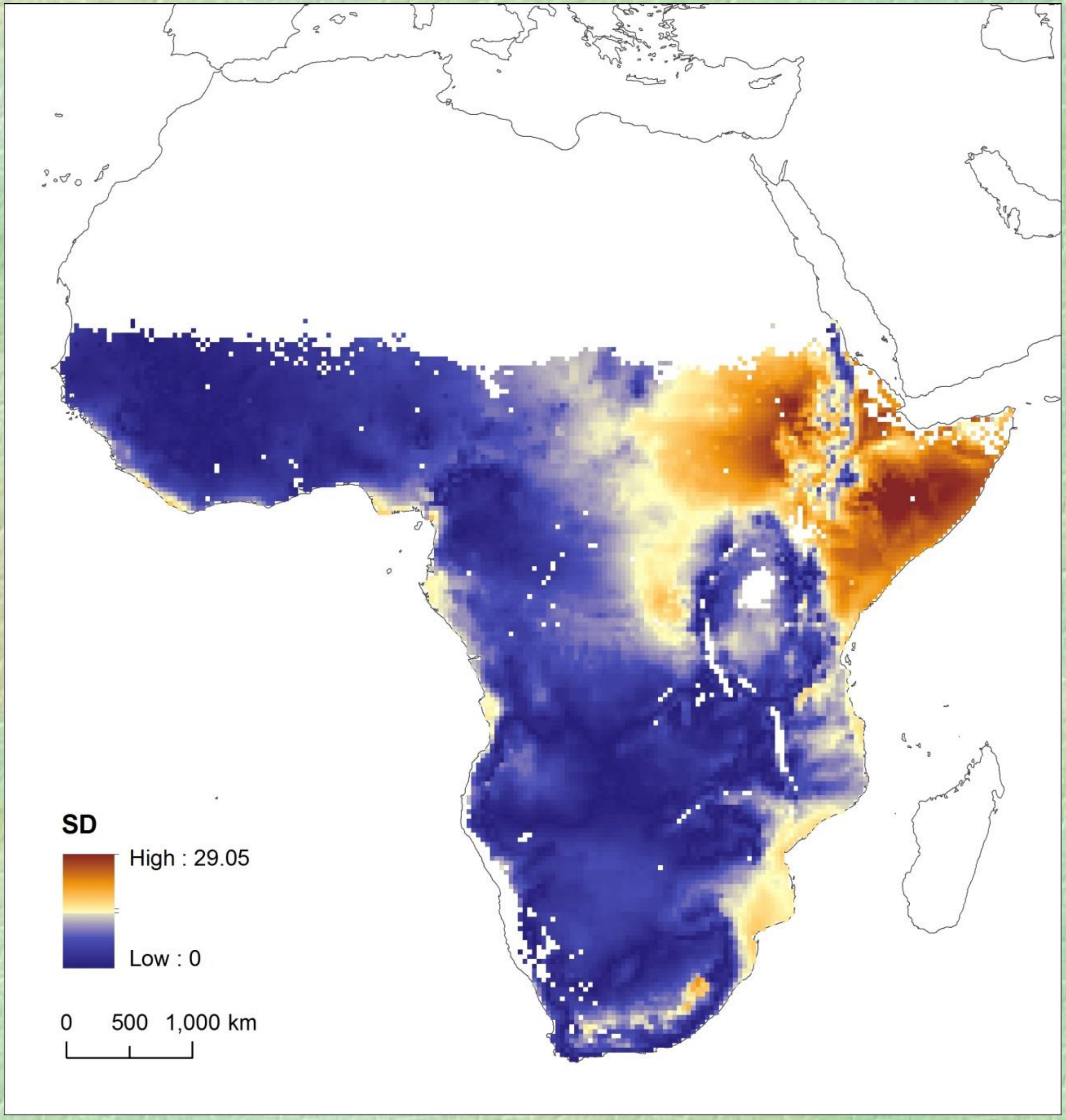




Prochazka et al. (in press)




δ²H
High : -4.03
Low : -63.27
0 500 1,000 km


SD
High : 29.05
Low : 0
0 500 1,000 km

Several controlled studies for $\delta^{15}N$, $\delta^{13}C$ but few for $\delta^{2}H$, $\delta^{18}O$ ….

- $\delta^{15}N$, $\delta^{13}C$ …



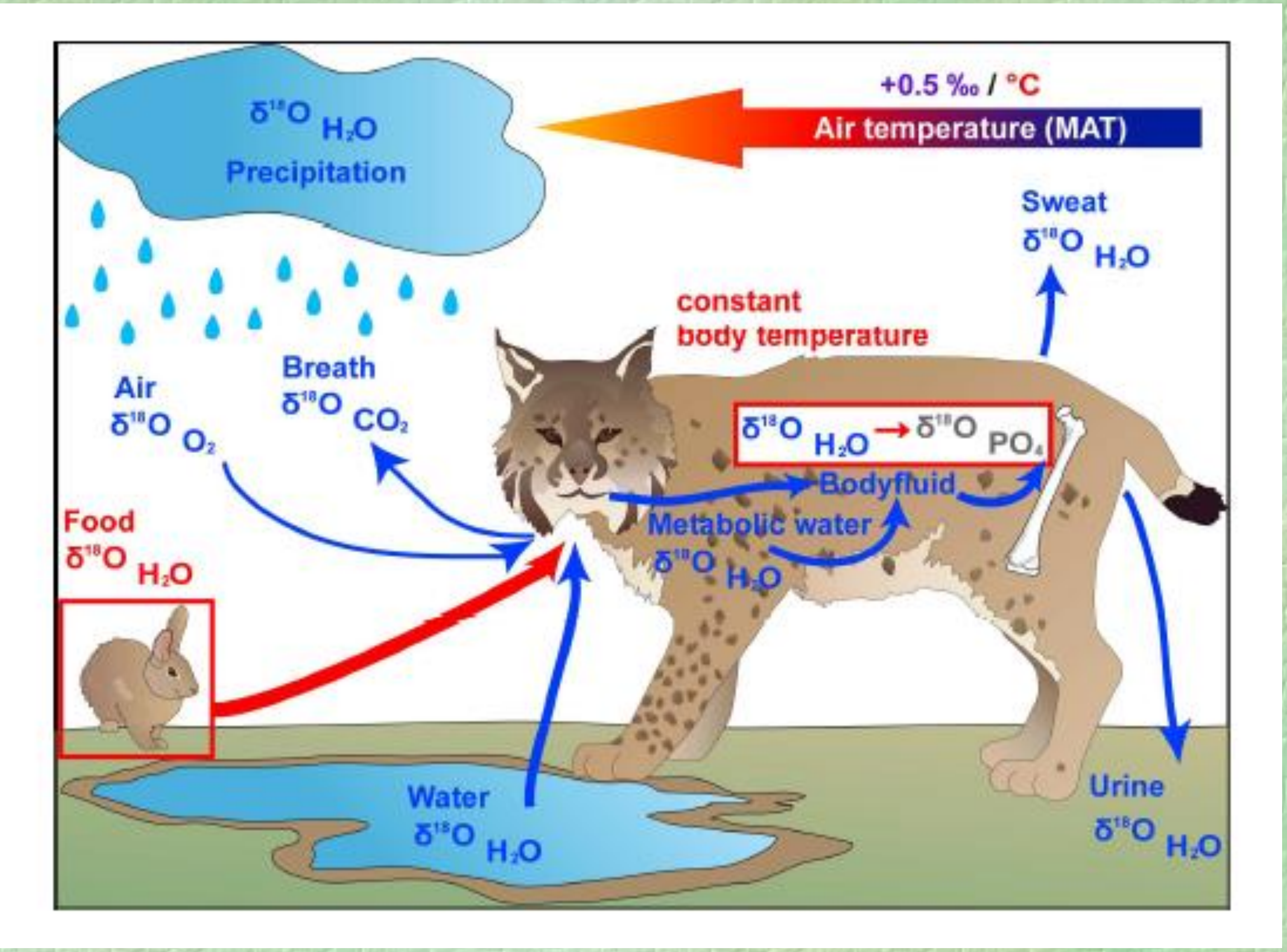




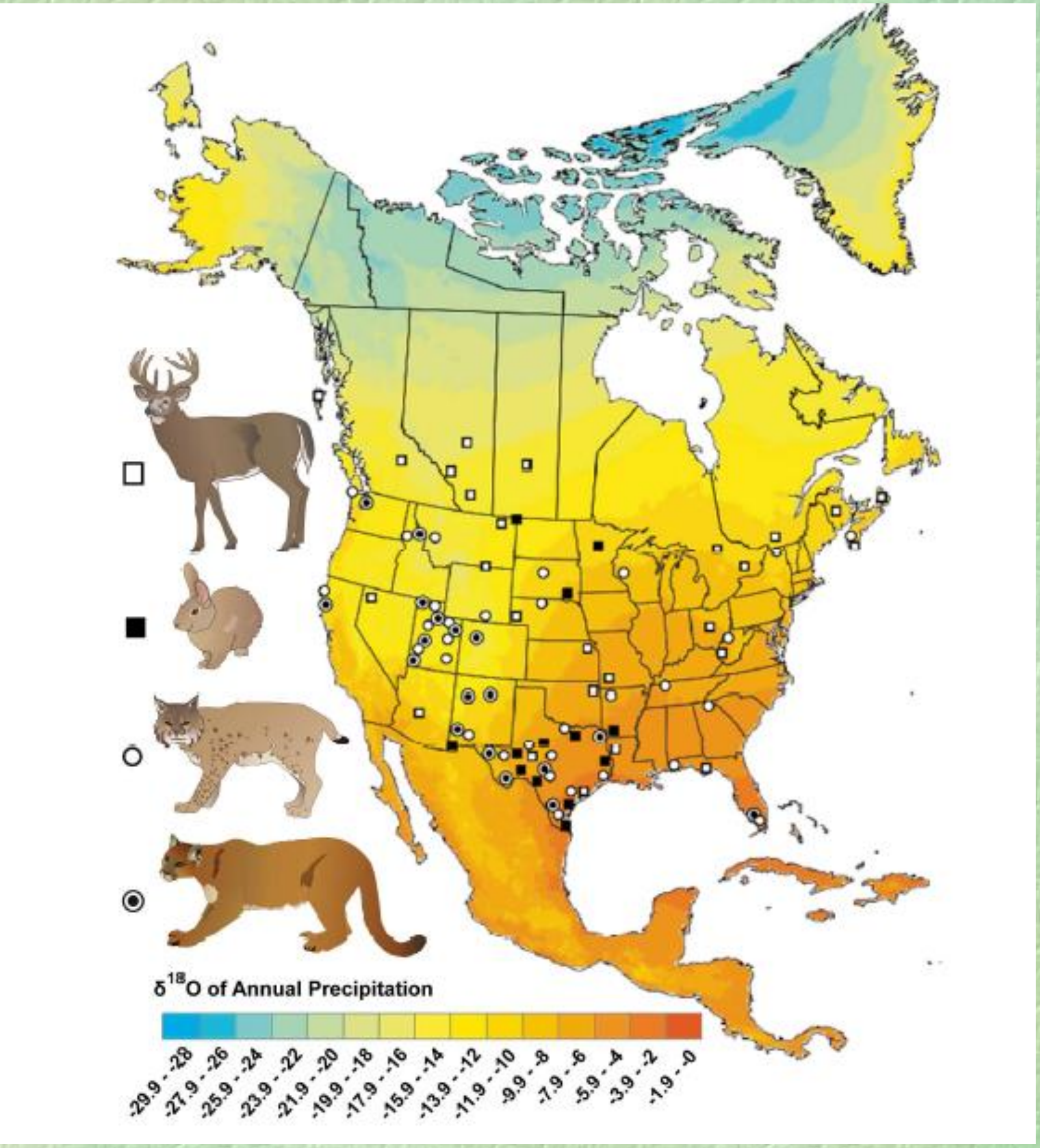

- $\delta^{2}H$, $\delta^{18}O$ …



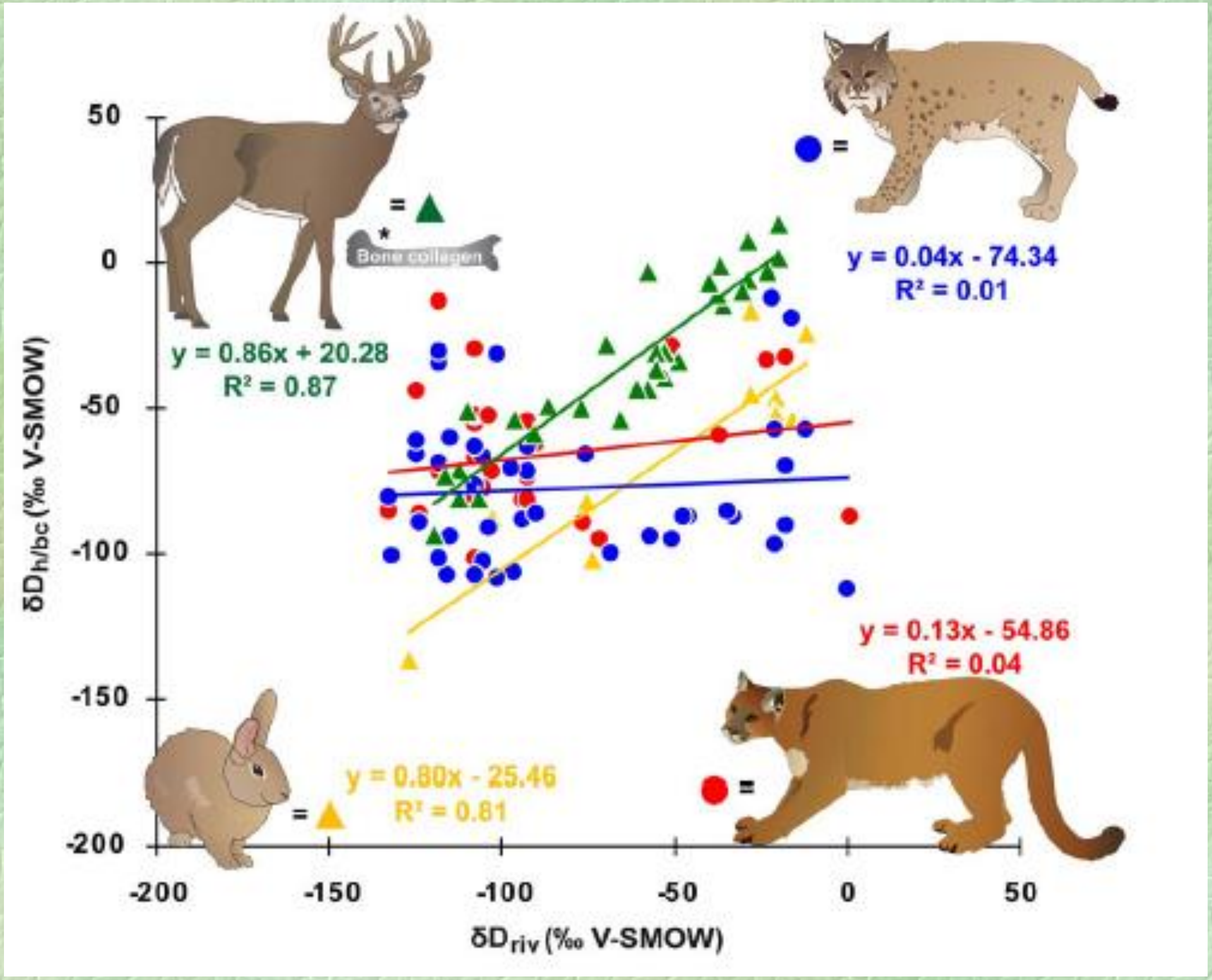

Multiple sources of O and H



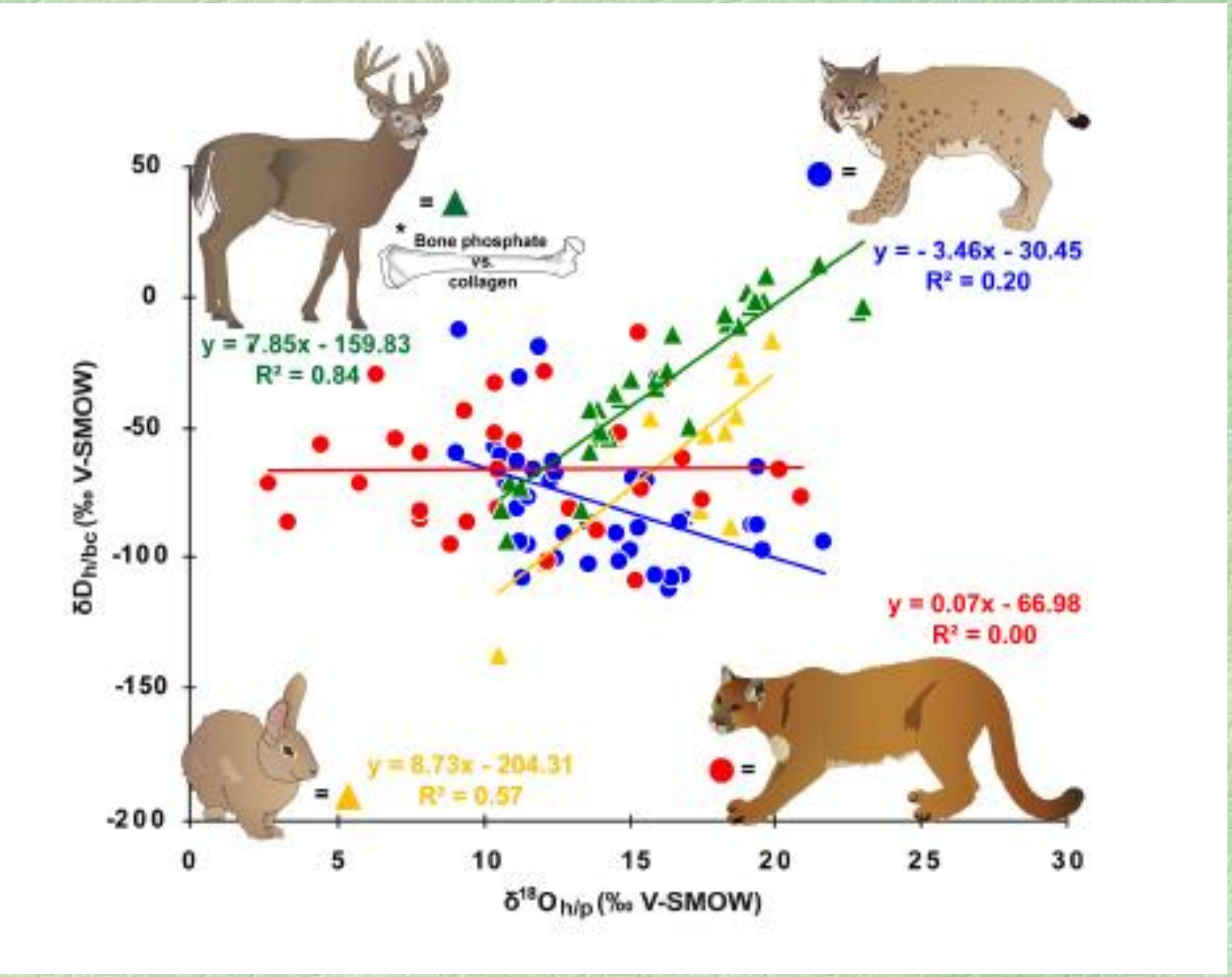
Pietsch et al. 2011 PLoS ONE



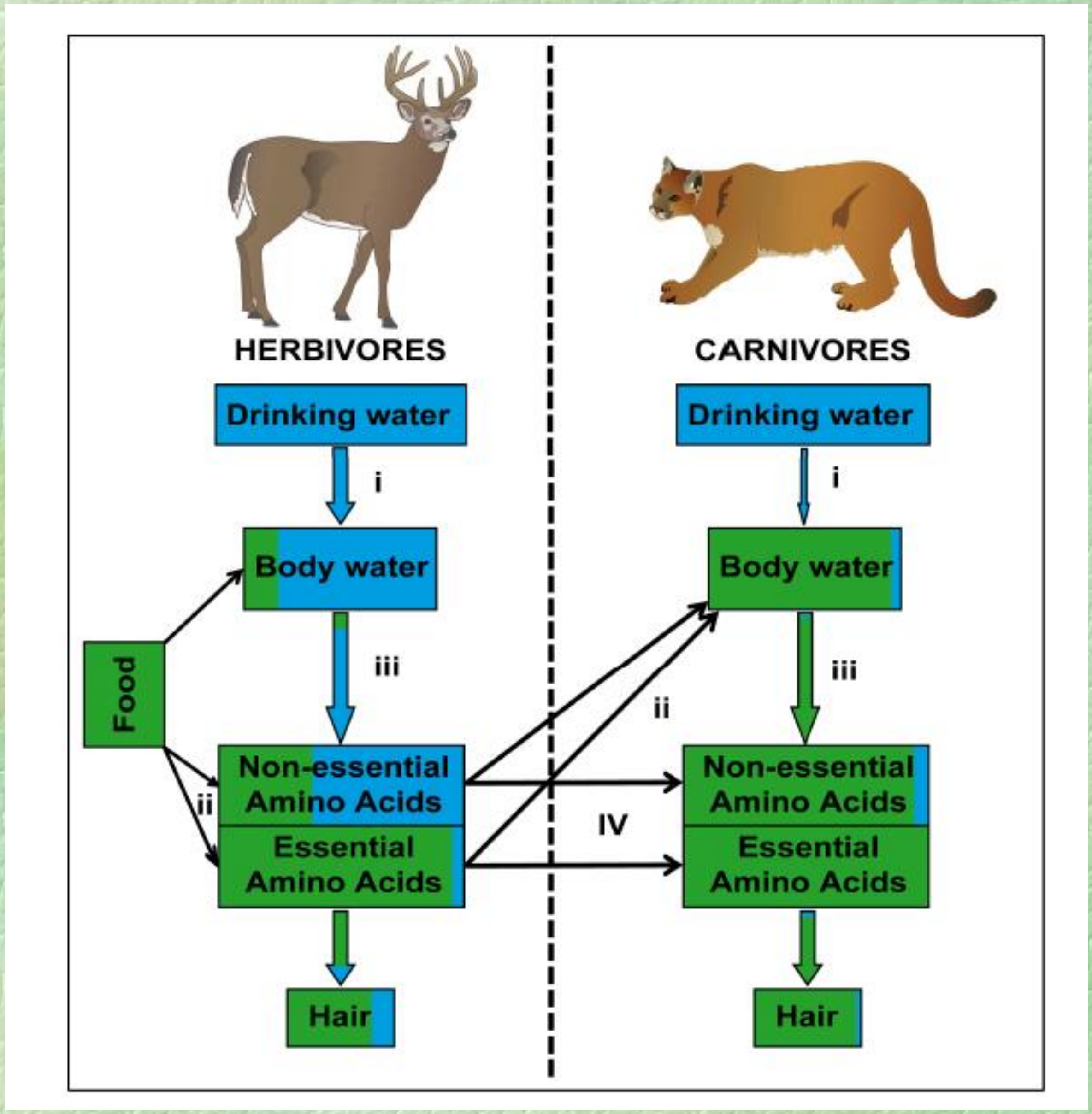
Pietsch et al. 2011 PLoS ONE



Pietsch et al. 2011 PLoS ONE



Pietsch et al. 2011 PLoS ONE



Pietsch et al. 2011 PLoS ONE

Stable-hydrogen isotope heterogeneity in keratinous materials: mass spectrometry and migratory wildlife tissue subsampling strategies

Leonard I. Wassenaar* and Keith A. Hobson

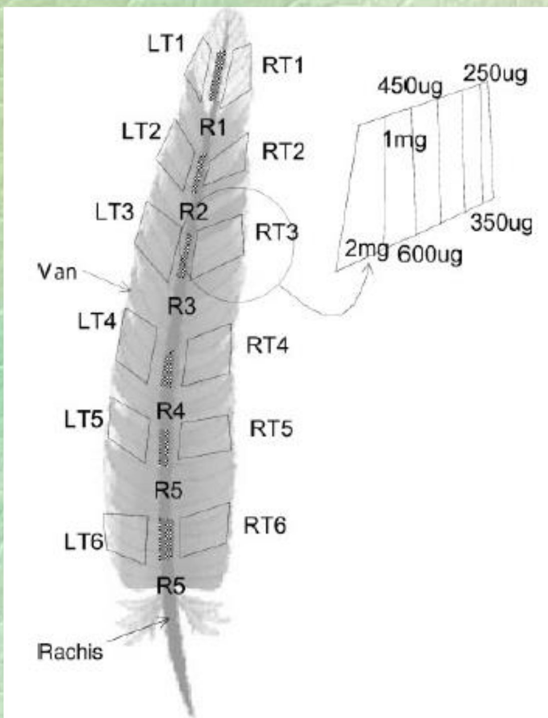
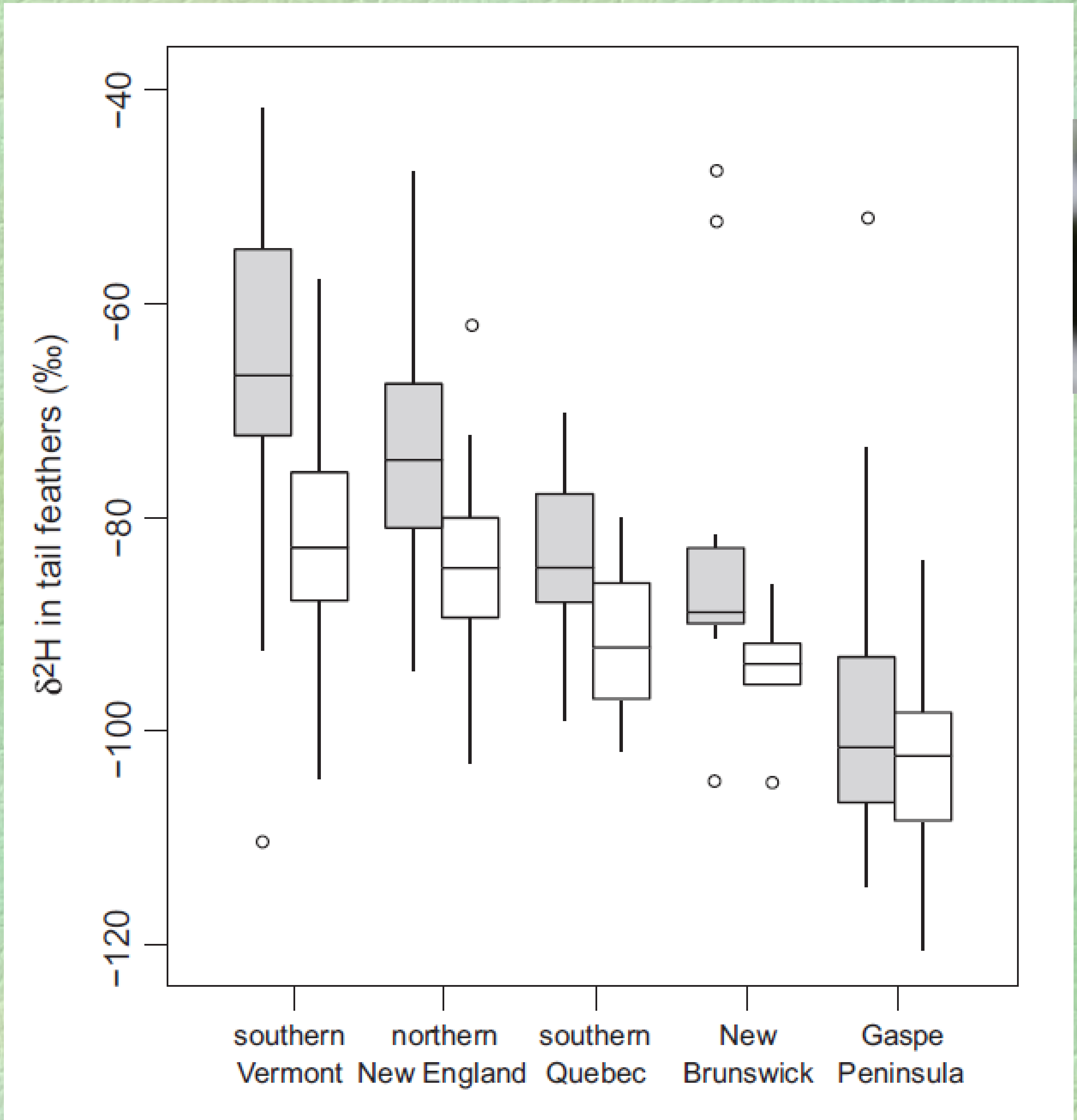


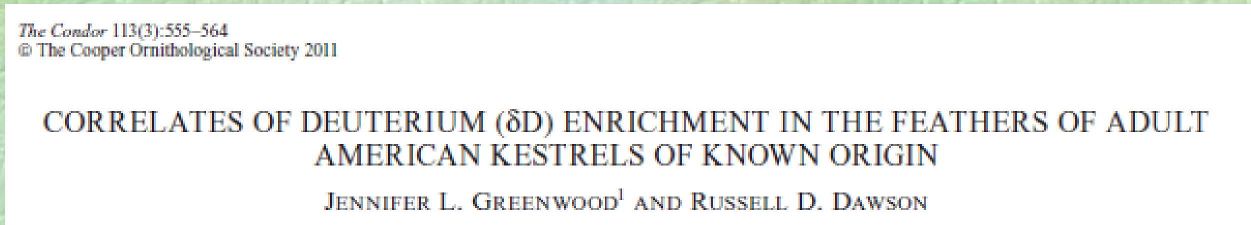
Table 1. δD (VSMOW) results for sub-samples of feather vane and rachis from captive raised and wild birds

Species	Individual # (mg)	Feather δD mean (SD), ‰	n	Feather range, ‰	Feather CV	Rachis mean (SD), ‰	n	Rachis range, ‰	Rachis CV	Δ Feather-rachis, ‰
Captive Raised										
Poultry	1 (0.25)	−145 (2.5)	12	−148 to −139	1.7					
	1 (0.35)	−147 (2.4)	12	−151 to −143	1.6	−146 (5.3)	5	−152 to −138	3.6	1.0
	1 (0.45)	−150 (2.5)	12	−154 to −146	1.7					
	2 (0.35)	−146 (4.5)	10	−137 to −150	3.1	−147 (5.5)	5	−155 to −141	3.7	1.0
	2 (1.0)	−144 (2.5)	10	−150 to −140	1.7					
	2 (2.0)[a]	−155 (10.9)	10	−170 to −133	7.0					
	3 (0.25)	−169 (1.6)	11	−171 to −166	1.0					
	3 (0.35)	−171 (1.6)	12	−174 to −169	1.0	−177 (2.8)	5	−180 to −173	1.6	6.0
	3 (0.45)	−175 (1.3)	11	−178 to −173	0.7					
	3 (0.60)	−175 (1.0)	12	−177 to −174	0.5					
Wild Birds										
Swainson's thrush	1	−64 (2)	3	−66 to −63	3.1	−74 (8)	3	−80 to −71	10.8	10.0
	2	−81 (3)	3	−84 to −78	3.7	−90 (10)	3	−97 to −78	11.1	9.0
	3	−67 (1)	3	−68 to −66	1.5	−75 (5)	3	−80 to −71	6.7	8.0
	4	−88 (4)	3	−91 to −83	4.8	−96 (2)	3	−99 to −94	2.1	8.0
	5	−81 (9)	3	−90 to −73	1.1	−85 (5)	3	−90 to −80	5.9	4.0
	6	−66 (2)	3	−69 to −64	3.0	−75 (6)	3	−81 to −69	8.0	9.0
	7	−72 (2)	3	−74 to −71	2.8	−76 (5)	3	−82 to −72	6.6	4.0
	8	−90 (1)	3	−92 to −89	1.1	−96 (5)	3	−100 to −90	5.2	6.0
	9	−85 (2)	3	−86 to −82	2.4	−88 (6)	3	−94 to −83	6.8	3.0
Lesser scaup	1	−122 (2)	6	−124 to −118	1.6	−128	2	−128 to −128	—	6.0
Roseatte spoonbill	1	−23 (6)	6	−32 to −13	26.1	−28 (7)	3	−35 to −21	25	5.0
Andean condor	1	−106 (4.6)	20	−112 to −98	4.3	−110 (6)	5	−119 to −108	5.5	4.0
Bald eagle	1	−103 (13)	19	−120 to −79	12.6	−106 (11)	5	−120 to −93	10.4	3.0

[a] 2 mg sample and reference keratins dynamically diluted by 50% with He.



Studds et al. (2012) Diversity and Distributions 1-12.


The Condor 113(3):555–564

CORRELATES OF DEUTERIUM (δD) ENRICHMENT IN THE FEATHERS OF ADULT AMERICAN KESTRELS OF KNOWN ORIGIN

JENNIFER L. GREENWOOD[1] AND RUSSELL D. DAWSON

Juveniles show strong δ^2H_f vs. δ^2H_p BUT not adults …

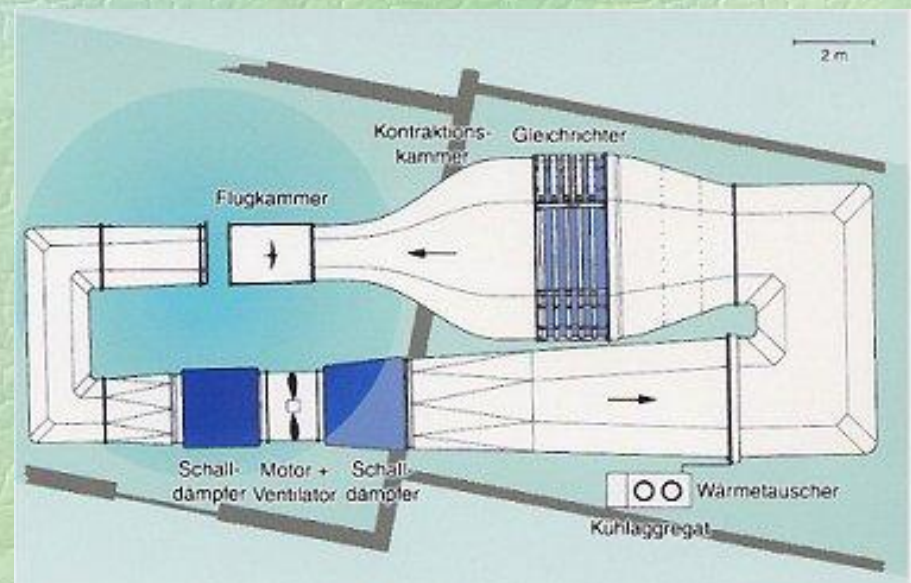
See also

Also seen in some owls

^1H_2O loss through gular fluttering

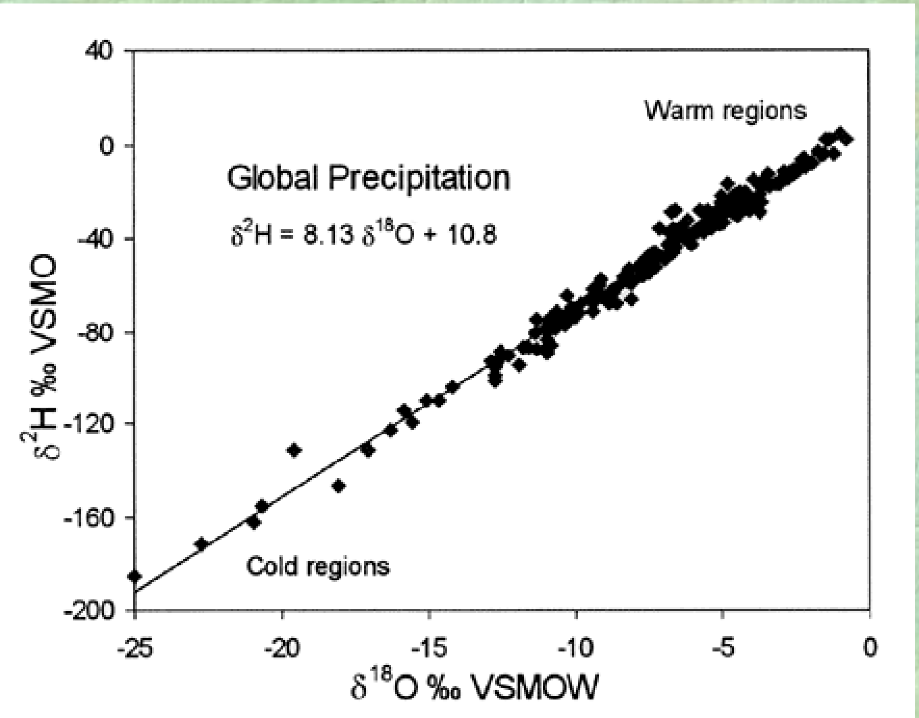
Caeca involved in H_2O regulation

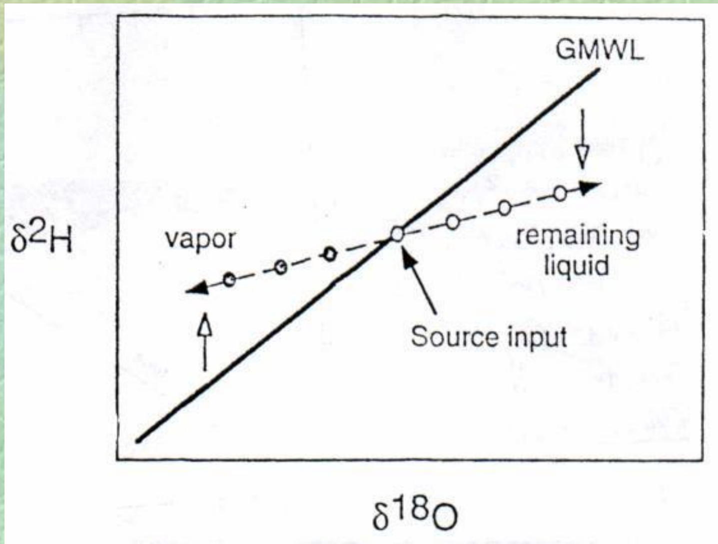
Using a wind tunnel and isotopic dietary shifts to mimic migration



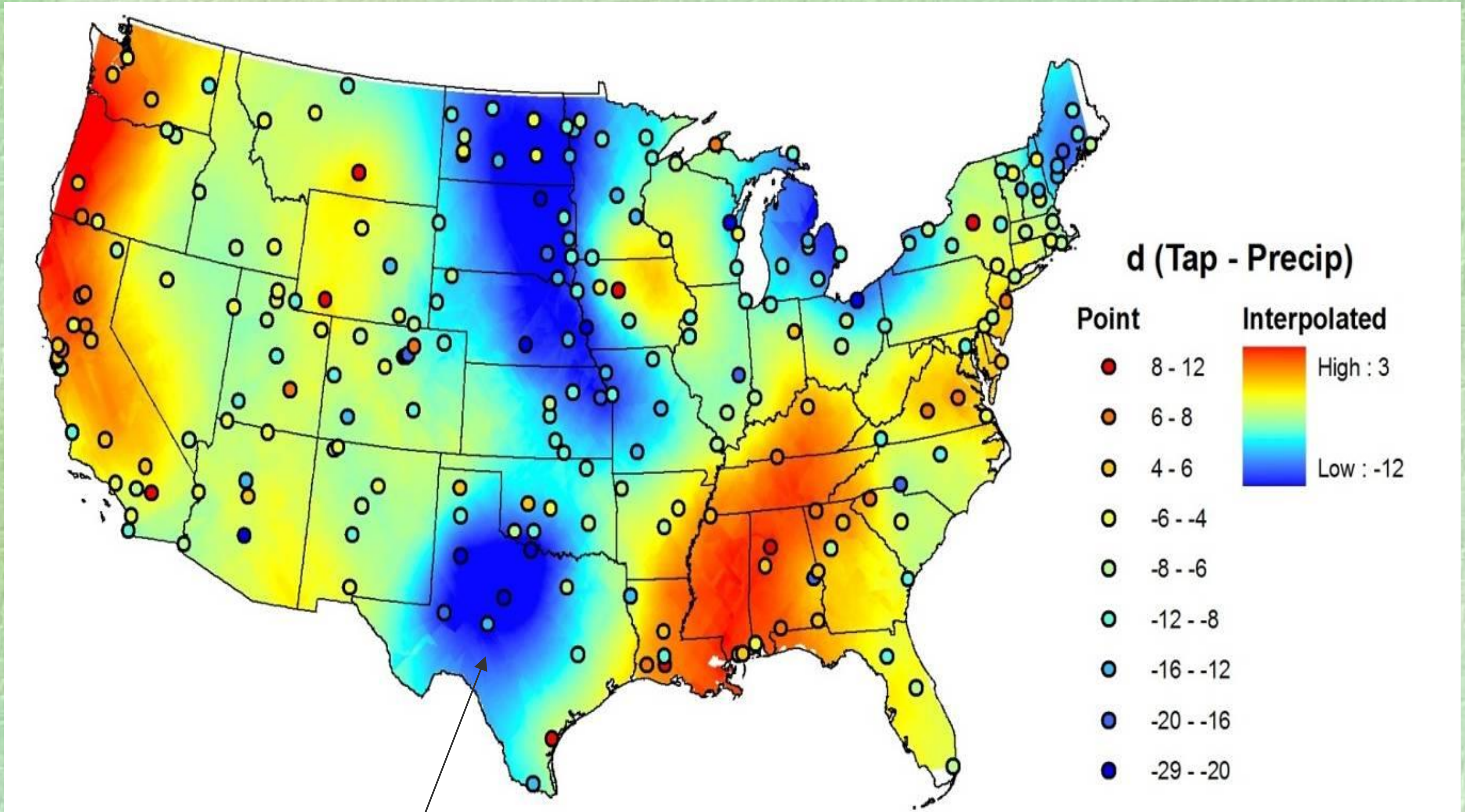
Max Planck Institute for Ornithology

Oxygen?



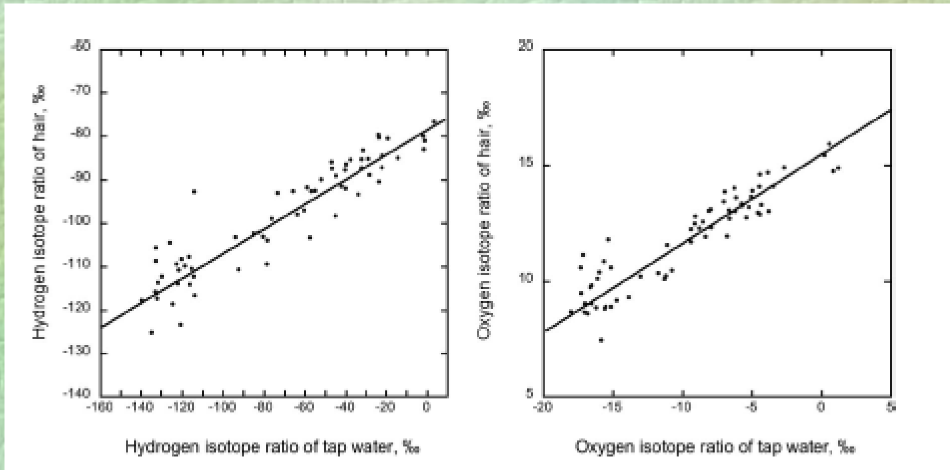


The "see-saw" affect of evporative (kinetic) isotope fractionation (after Gat 1996)



20-35%
evaporative loss

Human Hair

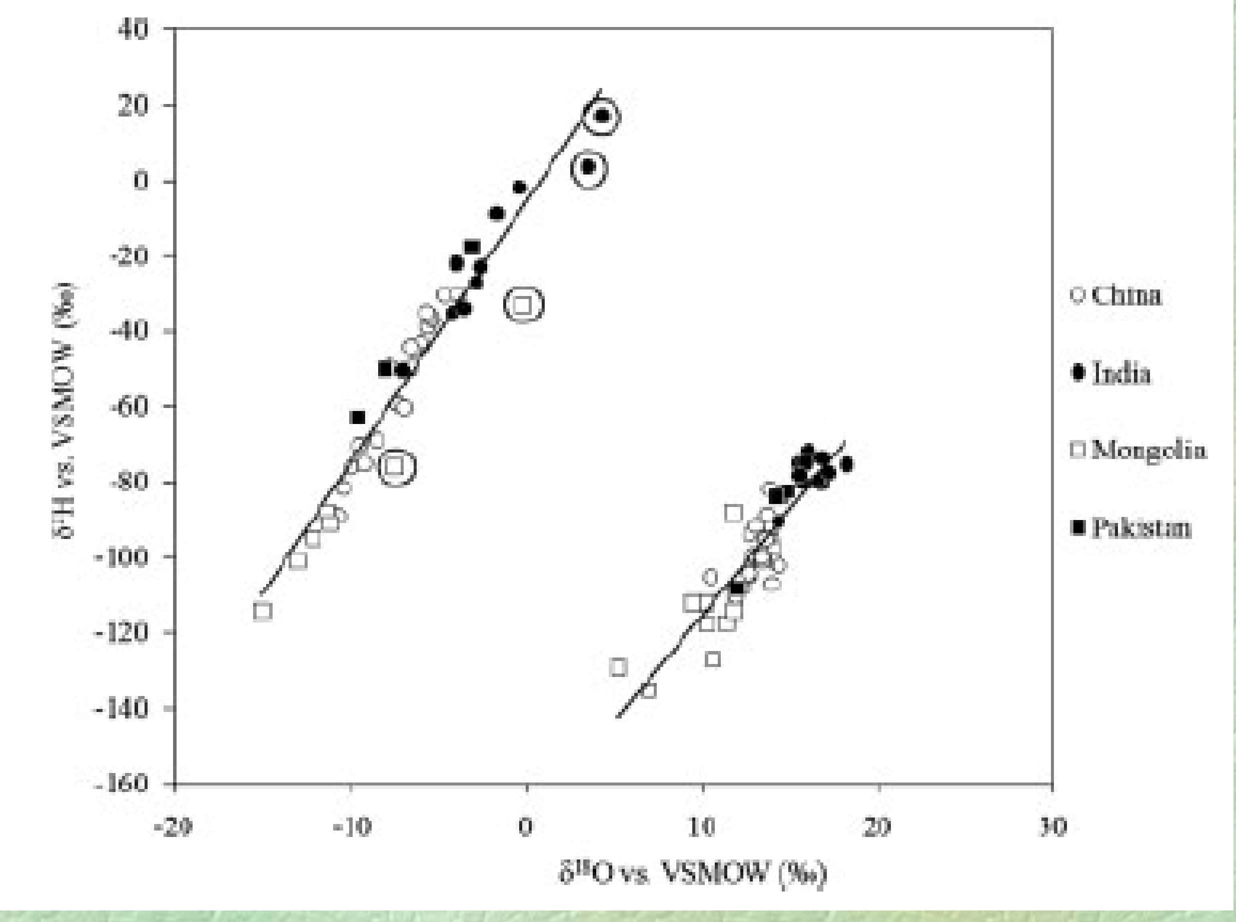


Ehleringer et al. (PNAS 2008)

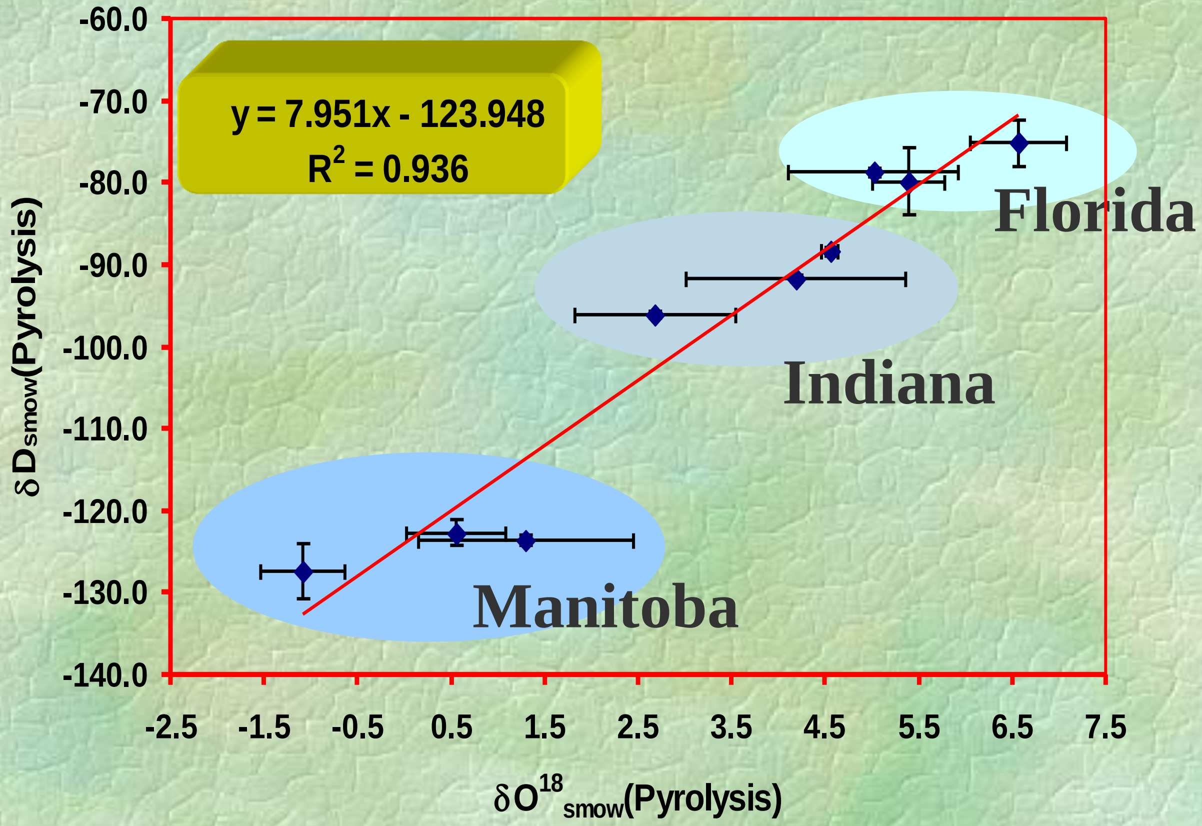
Stable Isotope Analysis of Modern Human Hair Collected From Asia (China, India, Mongolia, and Pakistan)

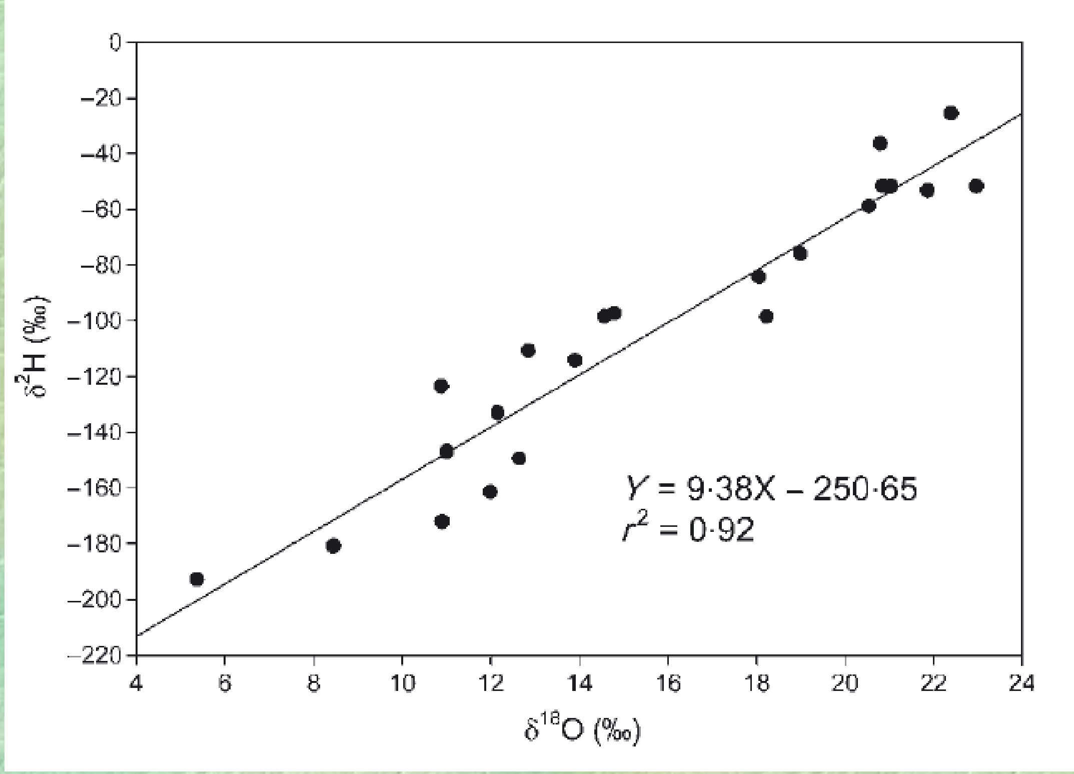
A.H. Thompson,[1,2*] L.A. Chesson,[1,2] D.W. Podlesak,[1,2] G.J. Bowen,[3] T.E. Cerling,[1,2,4] and J.R. Ehleringer[1,2]

AMERICAN JOURNAL OF PHYSICAL ANTHROPOLOGY 000:000–000 (2010)

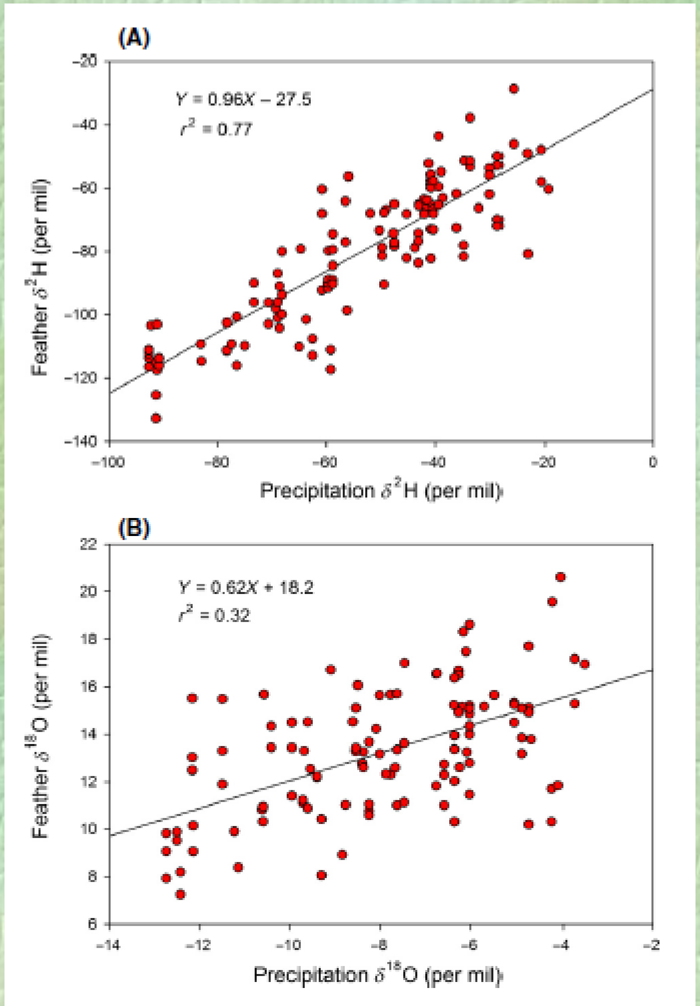


Meteoric relationship preserved in Monarch Butterflies

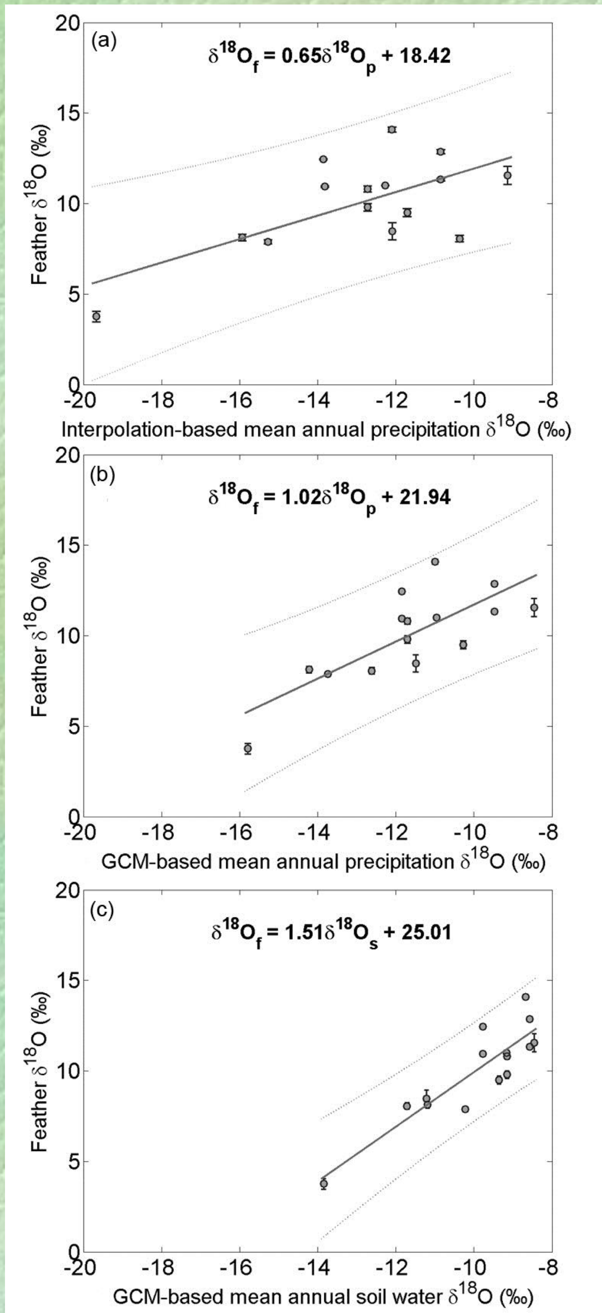


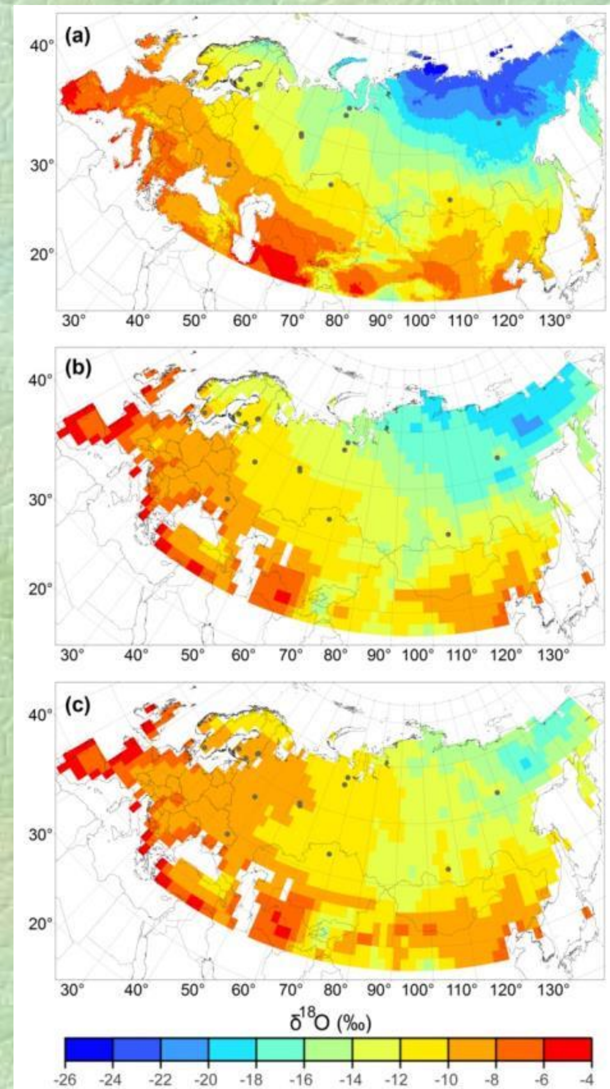


0
−20
−40
−60
−80
−100
−120
−140
−160
−180
−200
−220
4
6
8
10
12
14
16
18
20
22
24
δ2H (‰)
δ18O (‰)
Y = 9·38X − 250·65
r2 = 0·92



Hydrogen isotopes work better than Oxygen isotopes ……


(a)
δ18Of = 0.65δ18Op + 18.42
Feather δ18O (‰)
Interpolation-based mean annual precipitation δ18O (‰)
(b)
δ18Of = 1.02δ18Op + 21.94
Feather δ18O (‰)
GCM-based mean annual precipitation δ18O (‰)
(c)
δ18Of = 1.51δ18Os + 25.01
Feather δ18O (‰)
GCM-based mean annual soil water δ18O (‰)

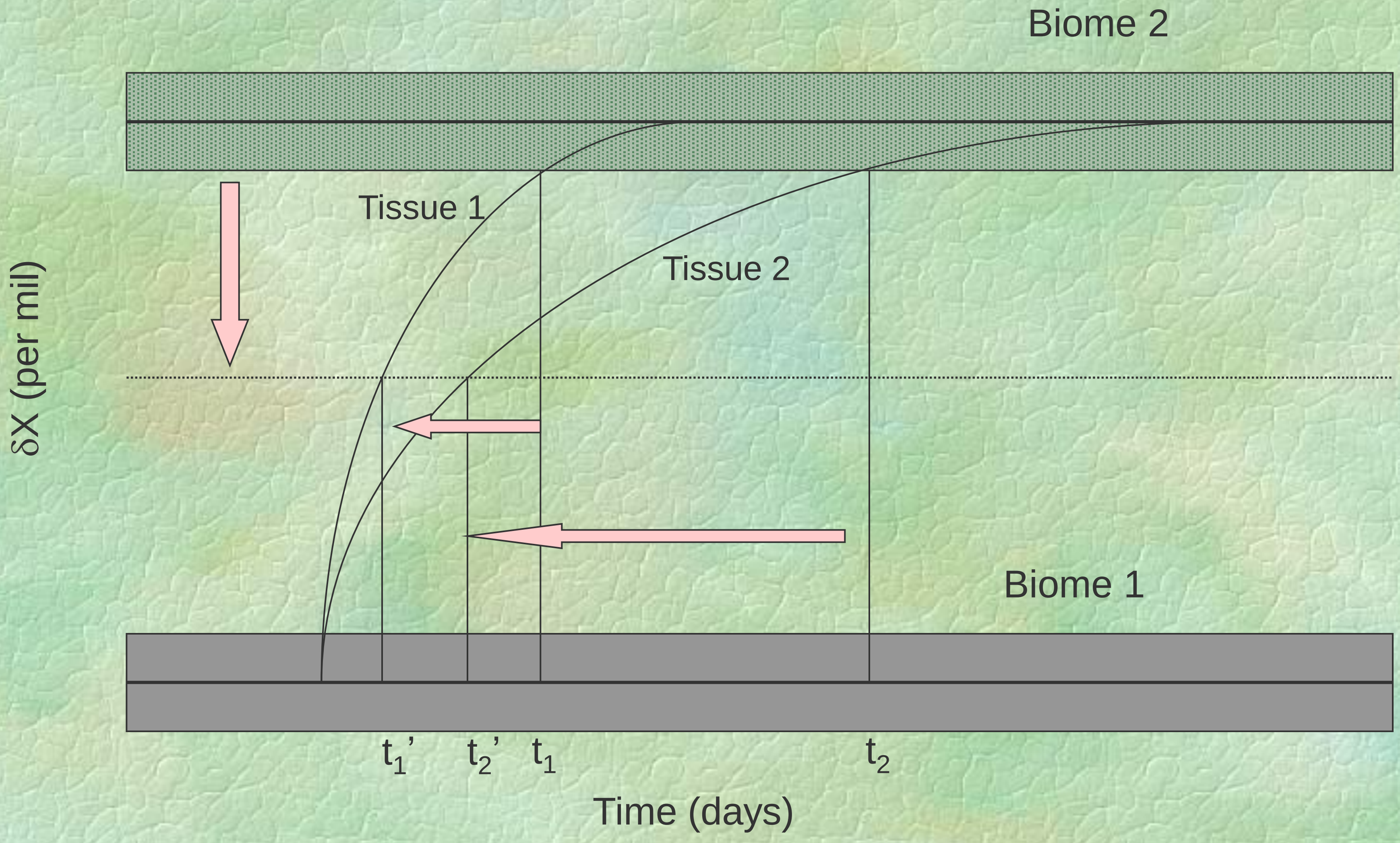

(a)
(b)
(c)
δ18O (‰)
-26 -24 -22 -20 -18 -16 -14 -12 -10 -8 -6 -4


ARKive
www.arkive.org
© Jose B. Ruiz / naturepl.com

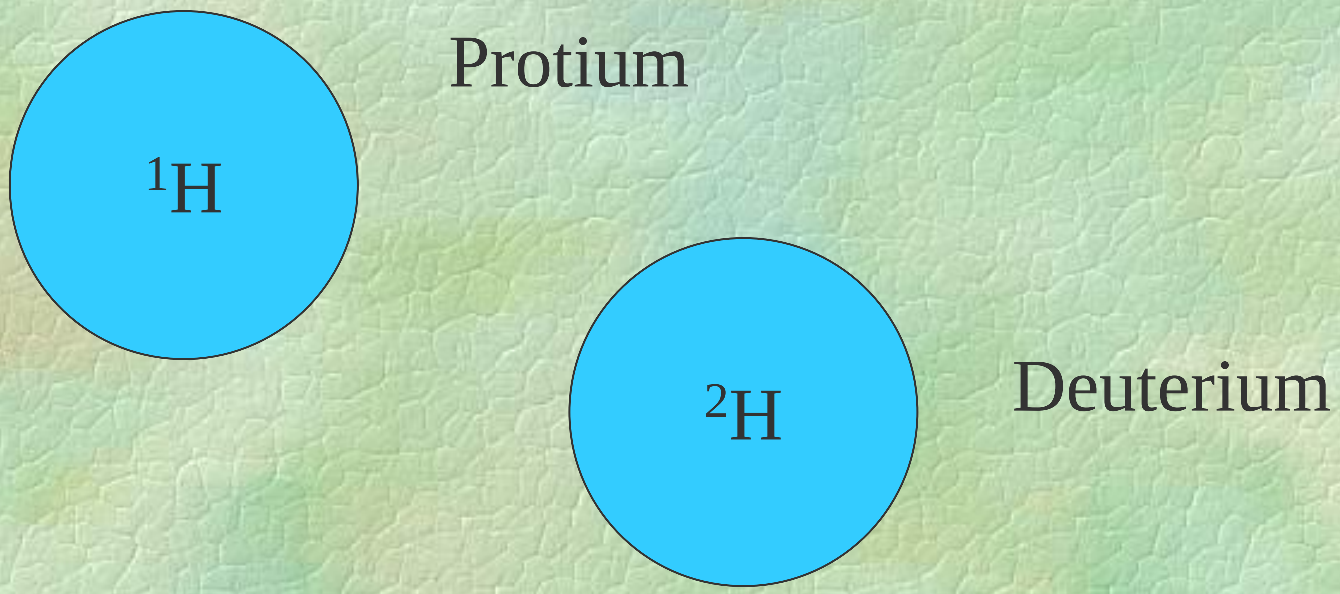
Tissue turnover

- Over what period do tissue isotope values represent dietary integration?
  - Single compartment “exponential” models
  - Multiple compartment “reaction progress” models

The isotopic clock and movement

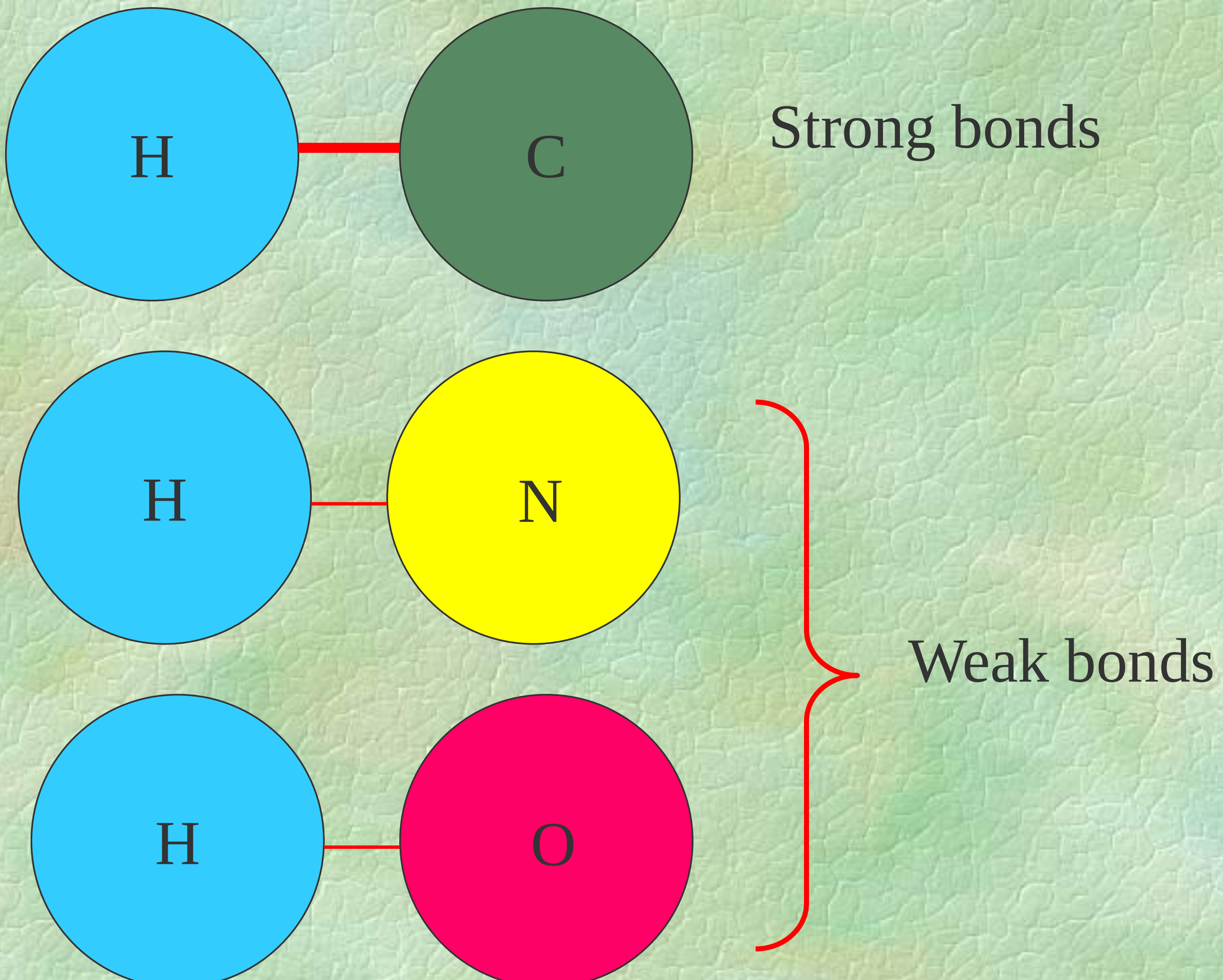


Hydrogen



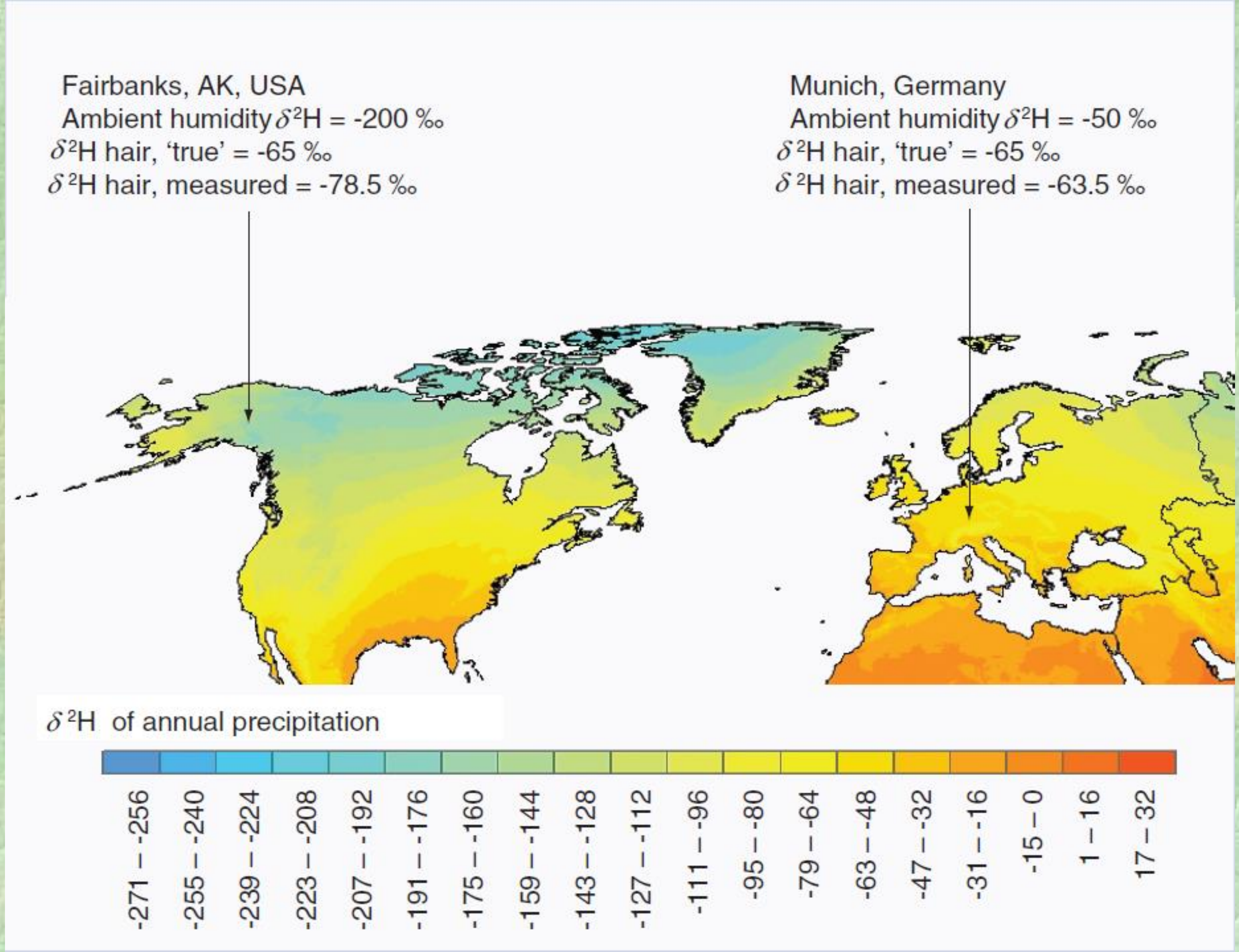
Involves a doubling of mass, so isotopic effects are large

Hydrogen exchange:

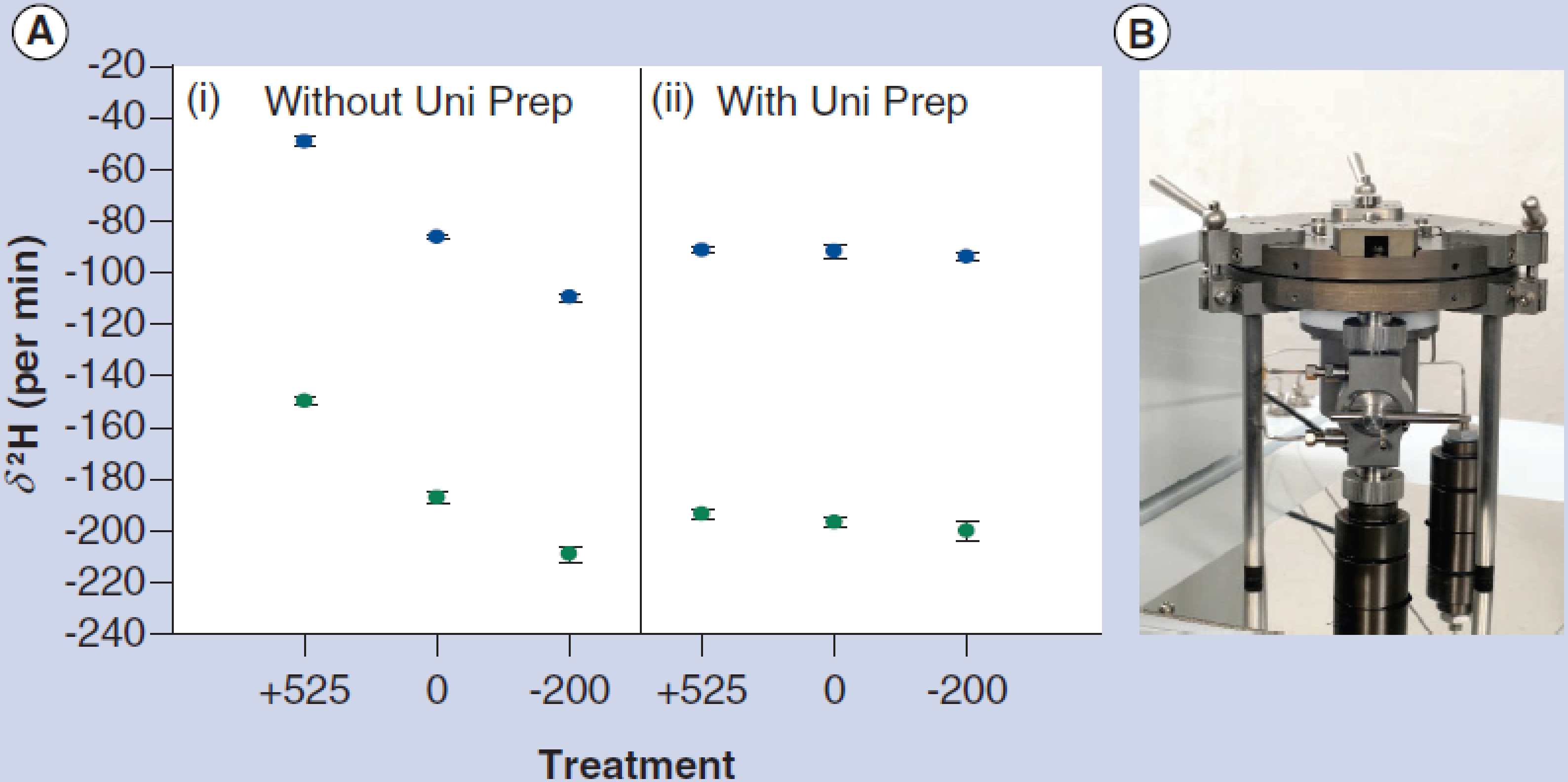


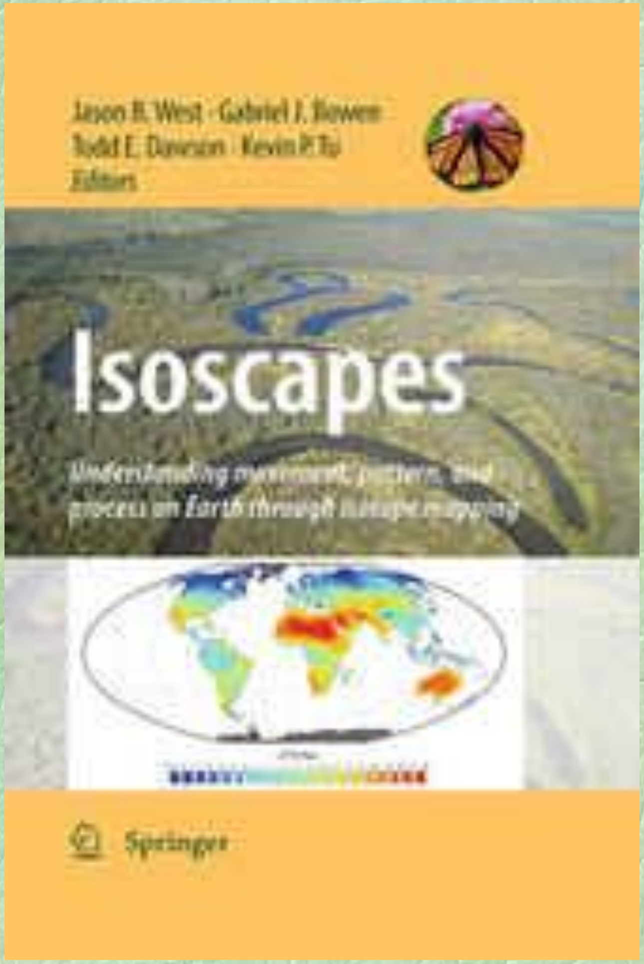
Things to know about H:

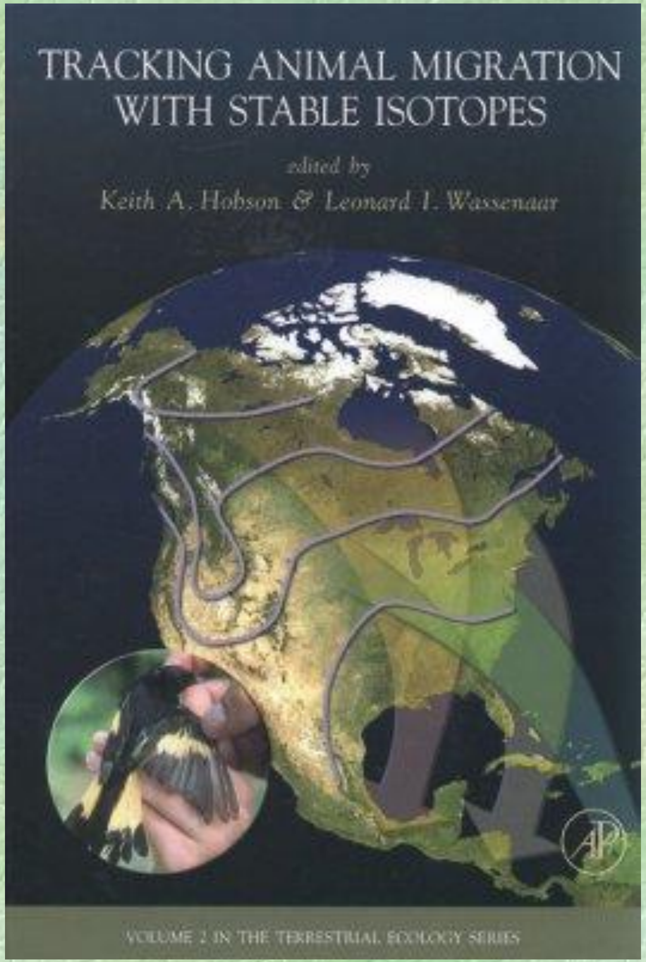
- $^{2}H/^{1}H$ represents high potential for isotopic discrimination.
- O-H and N-H bonds are weak: exchange.
- Drinking water and diet are sources of H.
- Recent analytical advances (CFIRMS) have lead to small sample requirements:
    - Sample inhomogeneities are now important.
    - Laboratory standards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



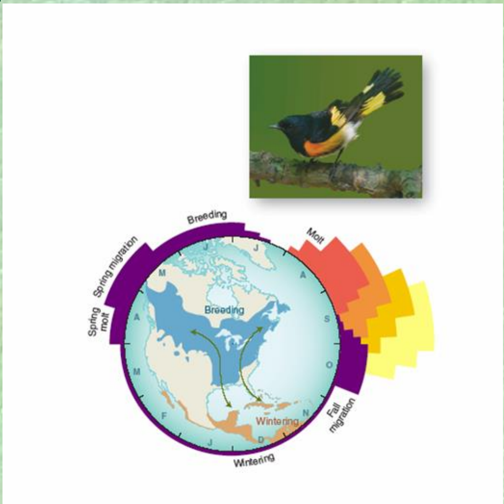
Fairbanks, AK, USA
Ambient humidity δ²H = -200 ‰
δ²H hair, 'true' = -65 ‰
δ²H hair, measured = -78.5 ‰
Munich, Germany
Ambient humidity δ²H = -50 ‰
δ²H hair, 'true' = -65 ‰
δ²H hair, measured = -63.5 ‰
δ²H of annual precipitation
-271 – -256
-255 – -240
-239 – -224
-223 – -208
-207 – -192
-191 – -176
-175 – -160
-159 – -144
-143 – -128
-127 – -112
-111 – -96
-95 – -80
-79 – -64
-63 – -48
-47 – -32
-31 – -16
-15 – 0
1 – 16
17 – 32


A
B
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
δ²H (per min)
(i) Without Uni Prep
(ii) With Uni Prep
+525
0
-200
+525
0
-200
Treatment

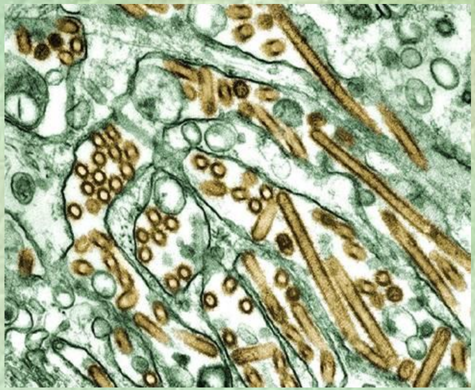

Jason B. West · Gabriel J. Bowen
Todd E. Dawson · Kevin P. Tu
Editors
Isoscapes
Springer


TRACKING ANIMAL MIGRATION
WITH STABLE ISOTOPES
edited by
Keith A. Hobson & Leonard I. Wassenaar
VOLUME 2 IN THE TERRESTRIAL ECOLOGY SERIES

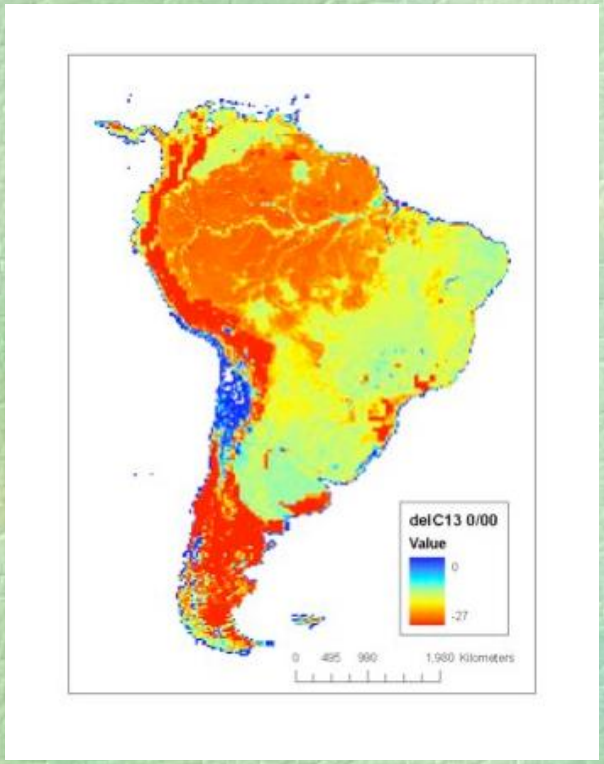
Primary Goals of Migration Research



- Evolution and Ecology.
- Conservation and Management.
- Movement of Contaminants and Disease.



Biogeochemical processes result in isotopic patterns or “isoscapes” …



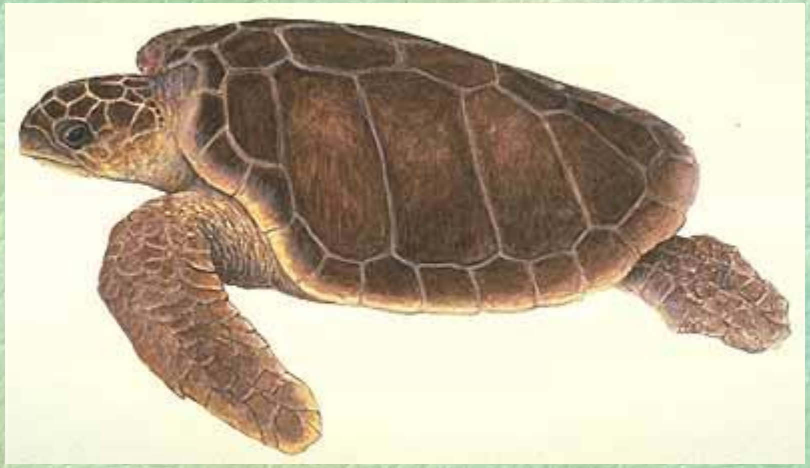
Isoscapes?

- 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 ($\delta^{13}C$, δD)
- Xeric vs. Mesic ($\delta^{13}C$, $\delta^{15}N$)
- Latitudinal/altitudinal gradients (δD, $\delta^{13}C$)
- Surficial geology (Sr, Pb, others)

First isotope applications

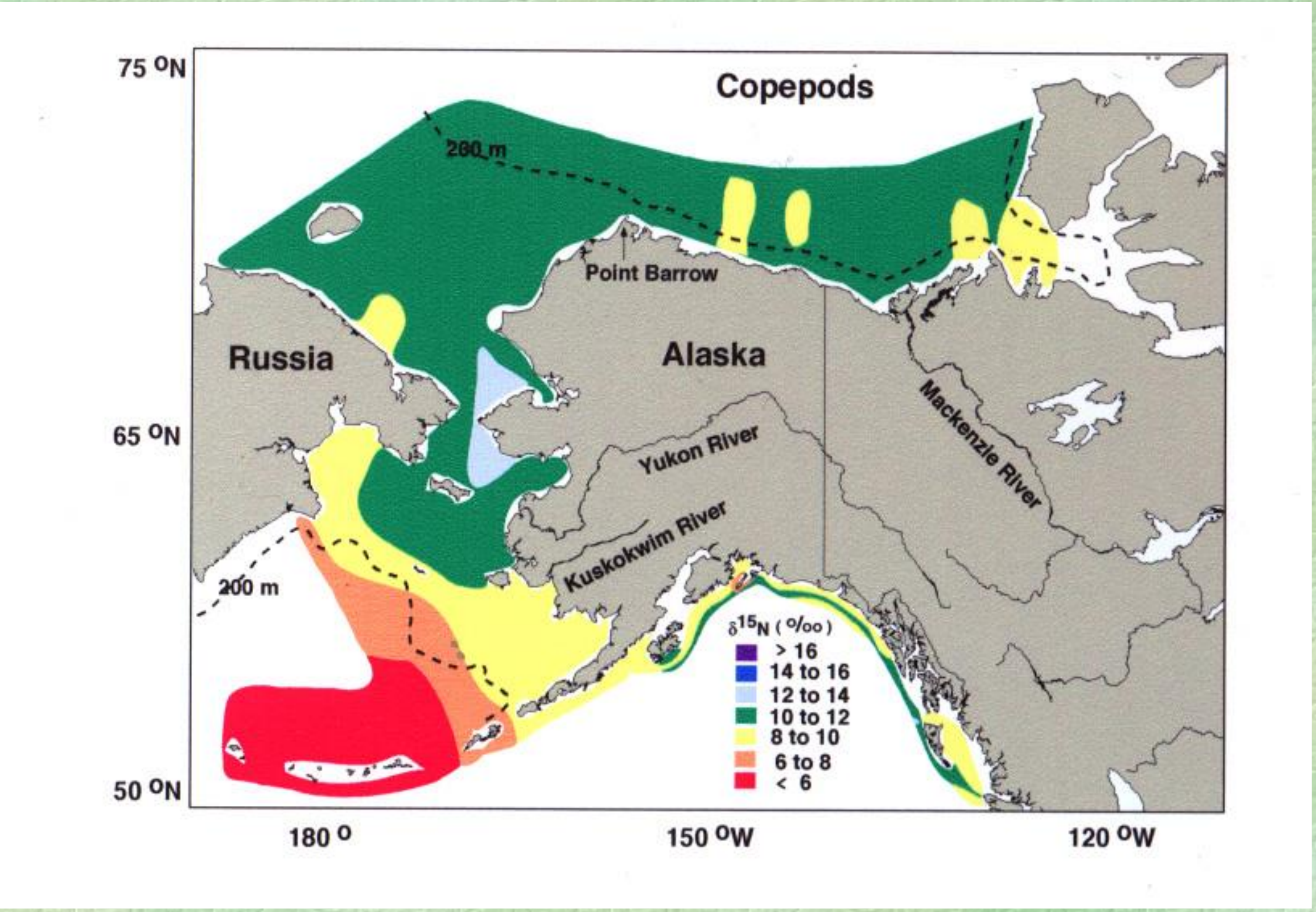
Killingley (1980) – $\delta^{18}O$ barnacles

"you are what you swim through"



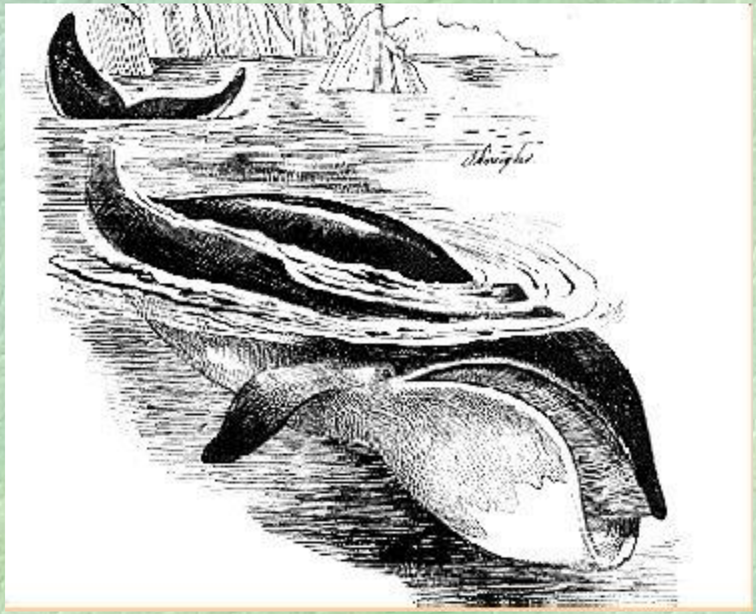
Killingley and Lutcavage (1983)

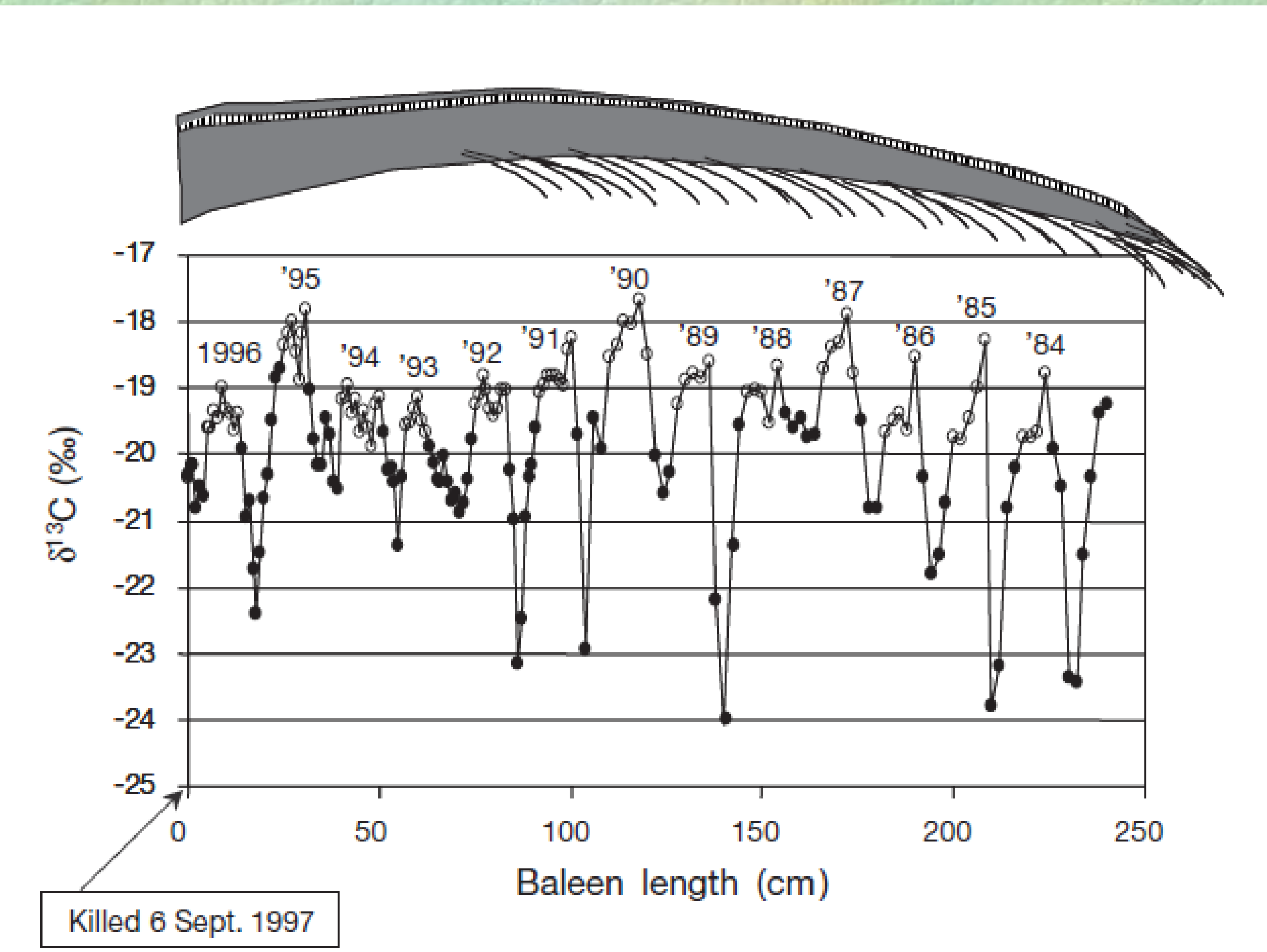
$\delta^{13}C$ and $\delta^{18}O$



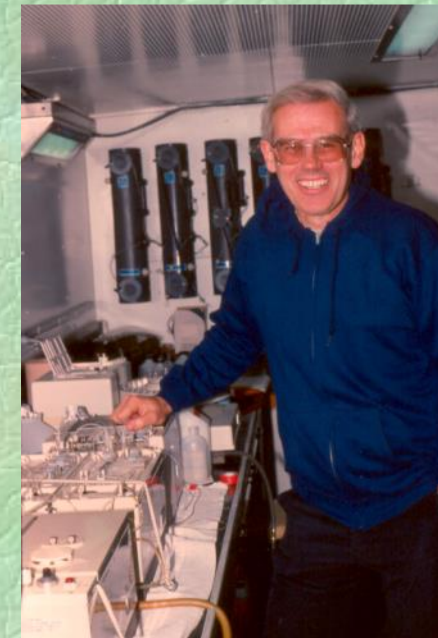
From Schell et al.2002

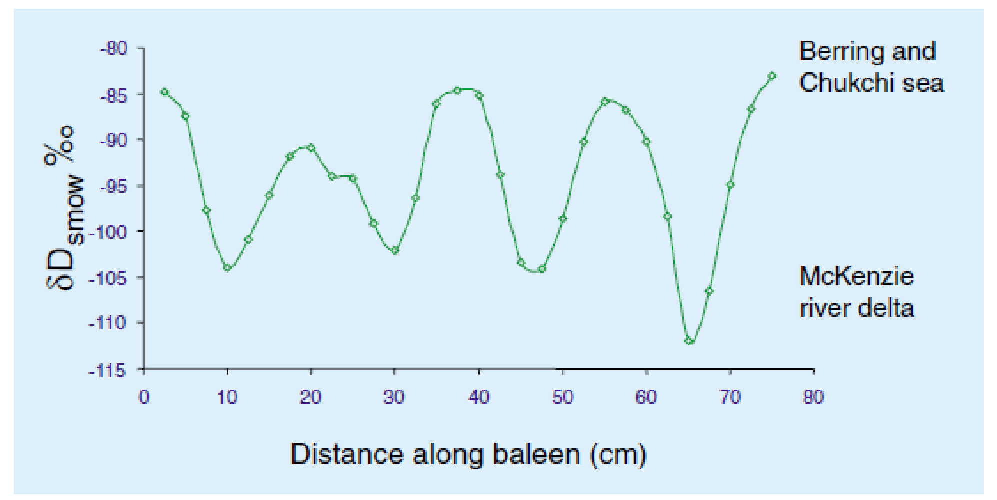
Bowhead whales



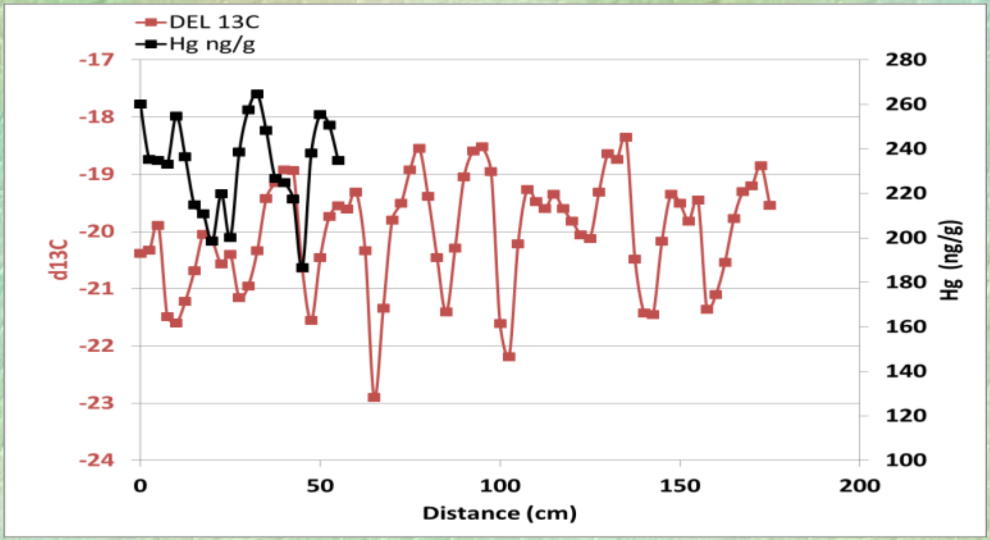


δ13C (‰)
Baleen length (cm)
1996
'95
'94
'93
'92
'91
'90
'89
'88
'87
'86
'85
'84
-17
-18
-19
-20
-21
-22
-23
-24
-25
0
50
100
150
200
250
Killed 6 Sept. 1997

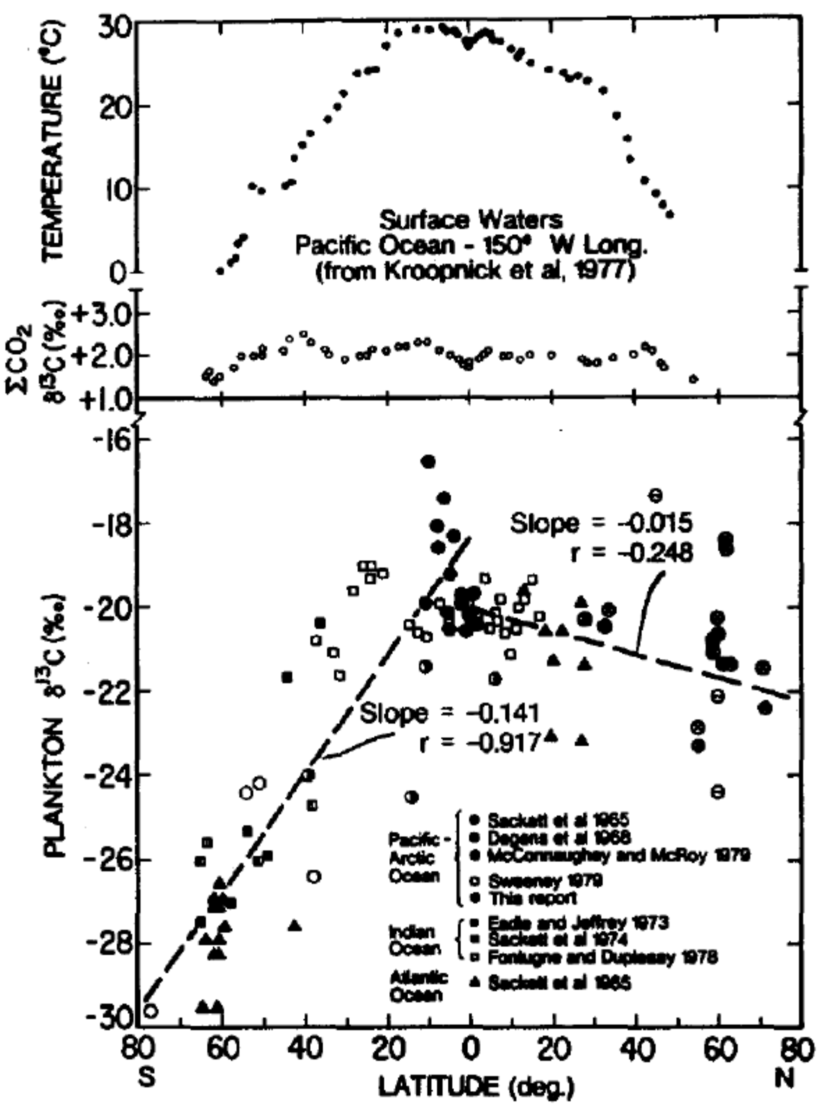




δDsmow ‰
Berring and Chukchi sea
McKenzie river delta
Distance along baleen (cm)

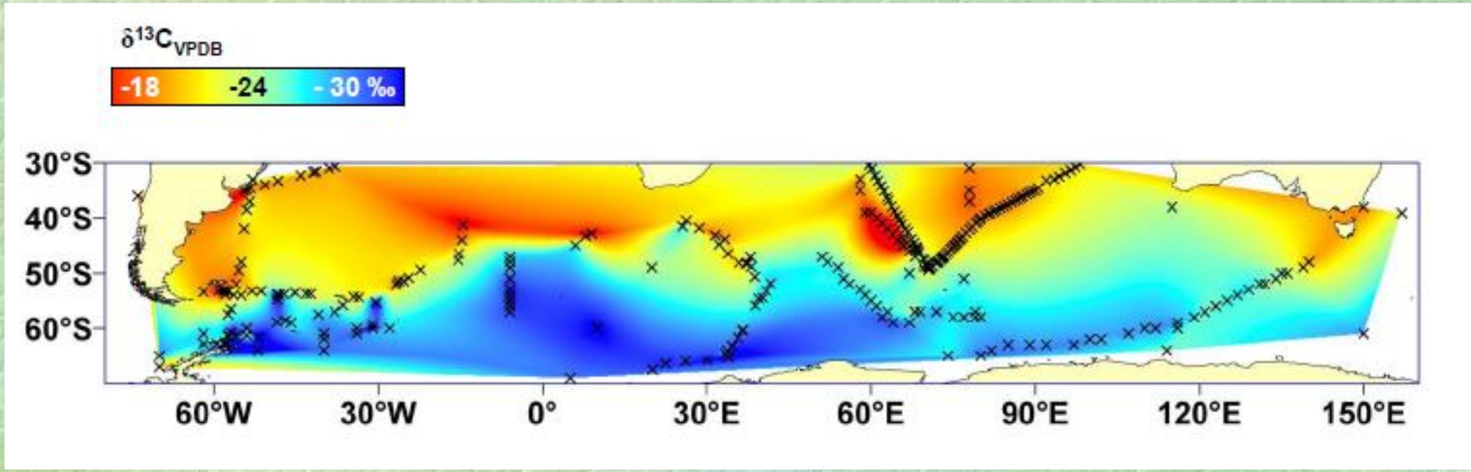


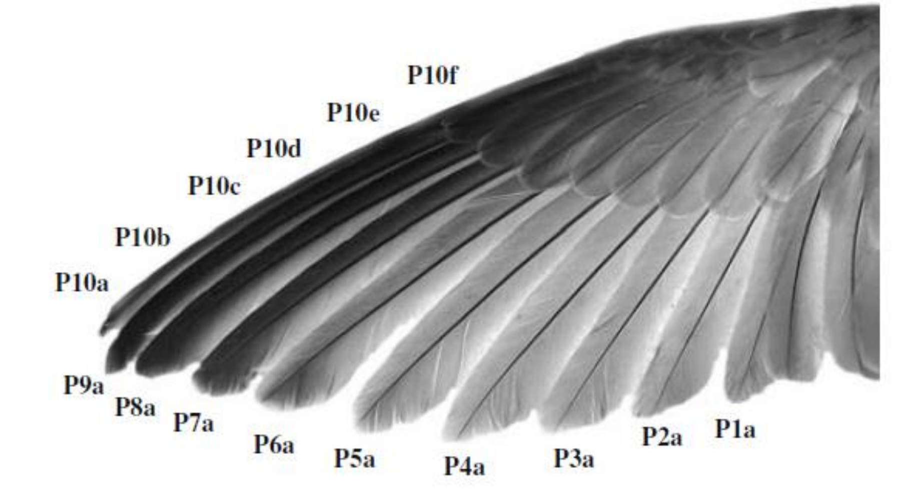
DEL 13C
Hg ng/g
d13C
Hg (ng/g)
Distance (cm)

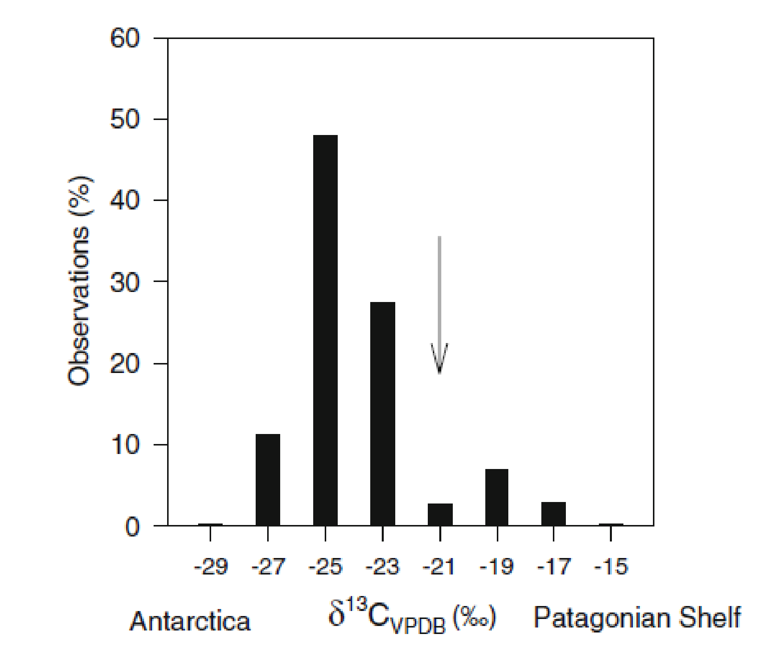


Temperature and CO_2 controls planktonic $\delta^{13}C$ across latitudes

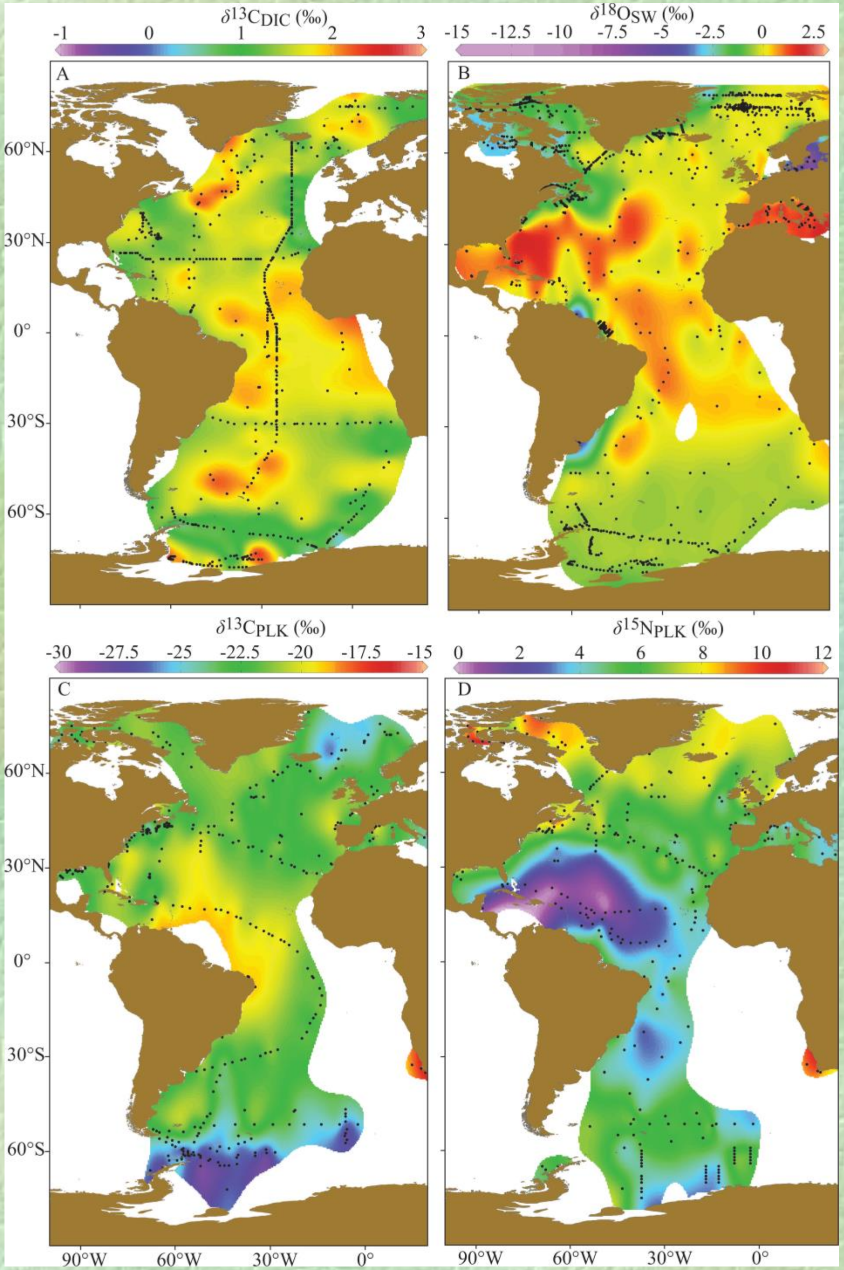
Rau et al. 1982







Quillfeldt et al. (2010) BES.



Latest marine isoscapes ….

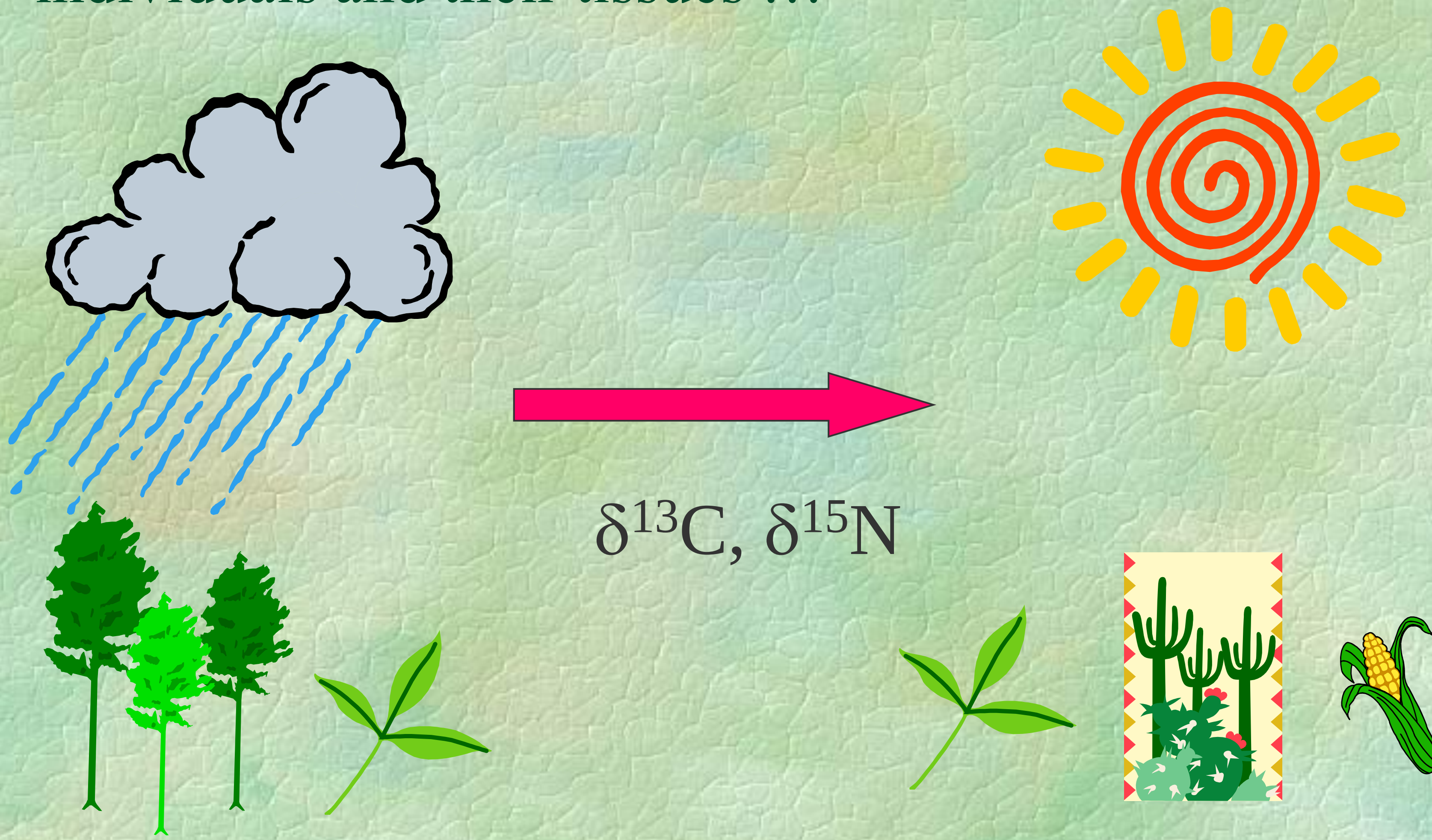
McMahon et al (2013)
Limnol. Oceanogr. 58:697-714


K779

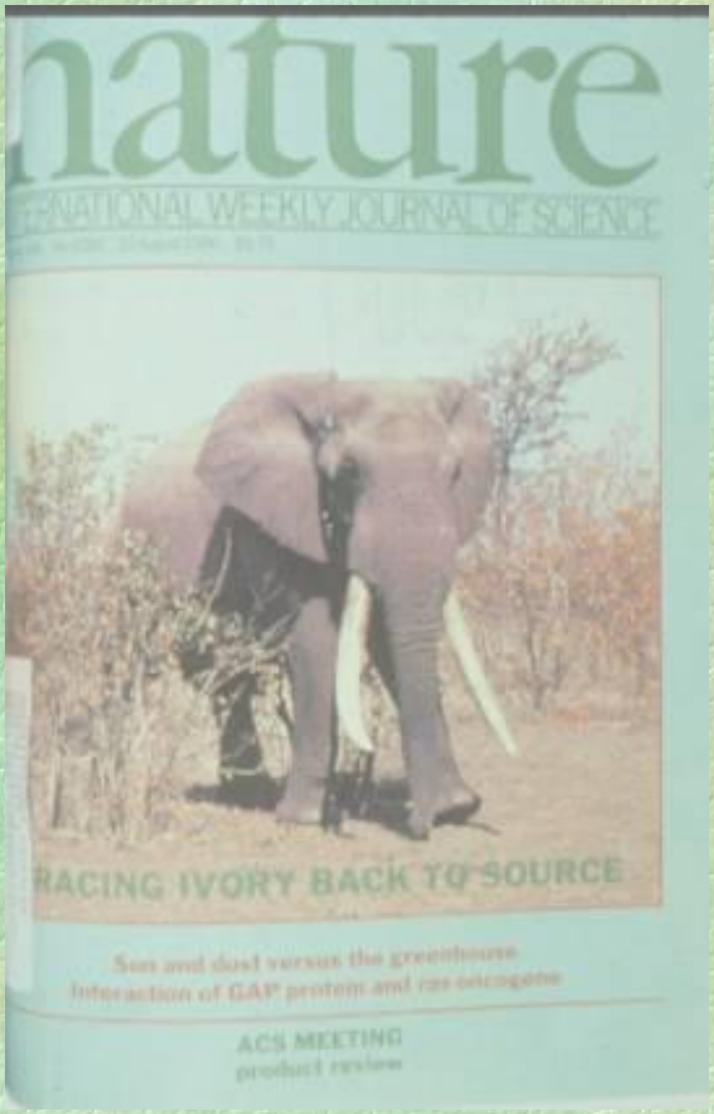
Problems with extrinsic markers

- Organism often needs to be recovered
- Expensive
- Body size requirements
- Biased to original marked population

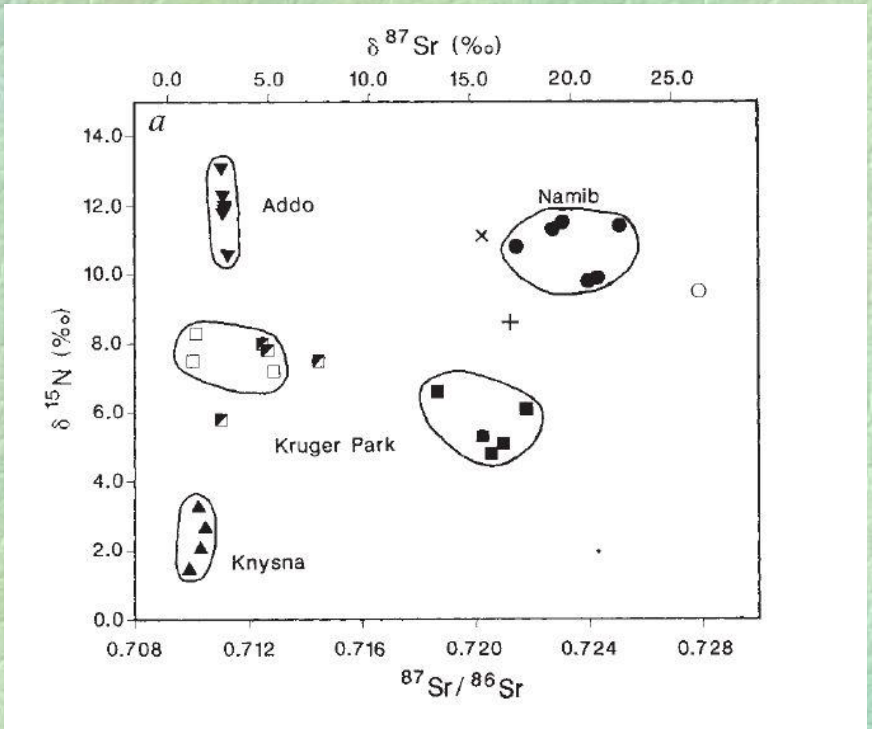
Mesic to xeric isotopic gradients help "locate" individuals and their tissues …



Forensic tracing of African ivory ….

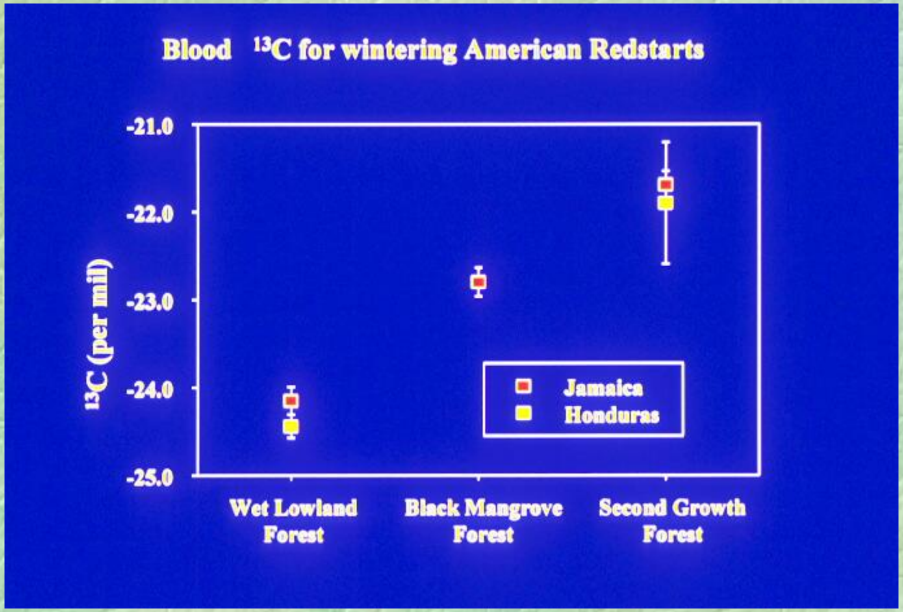


$\delta^{13}C$, $\delta^{15}N$, $\delta^{87}Sr$, $\delta^{204}Pb$

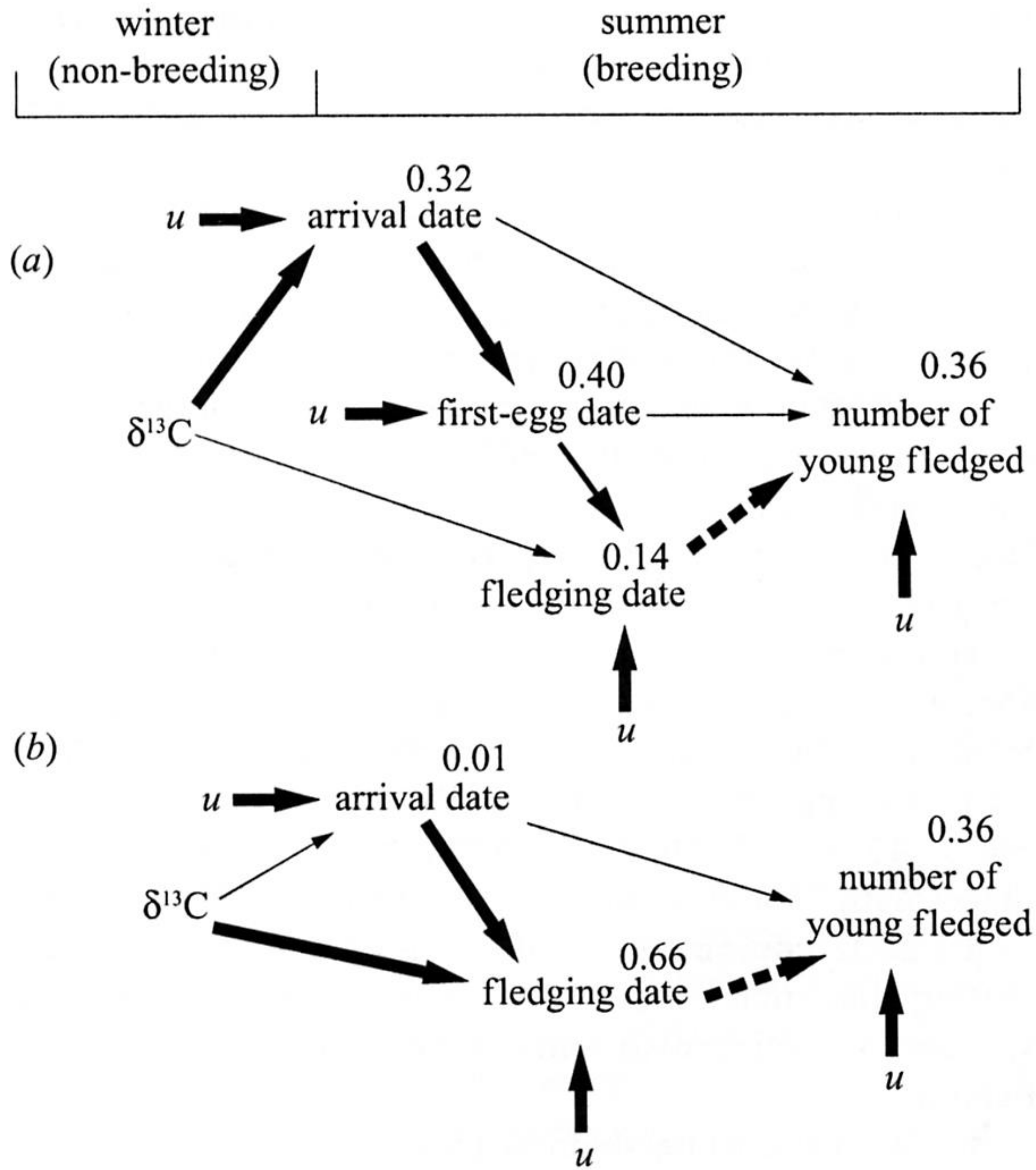


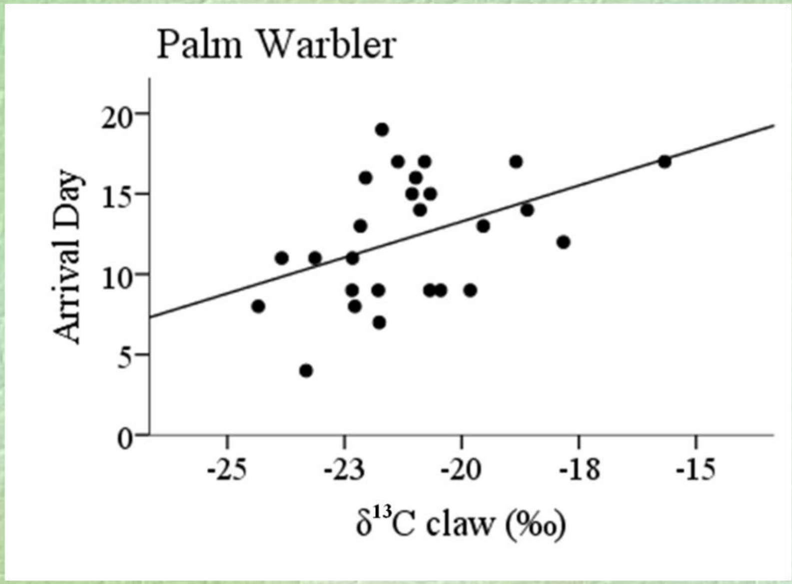
Vogel et al. (1990); van der Merwe et al (1990)

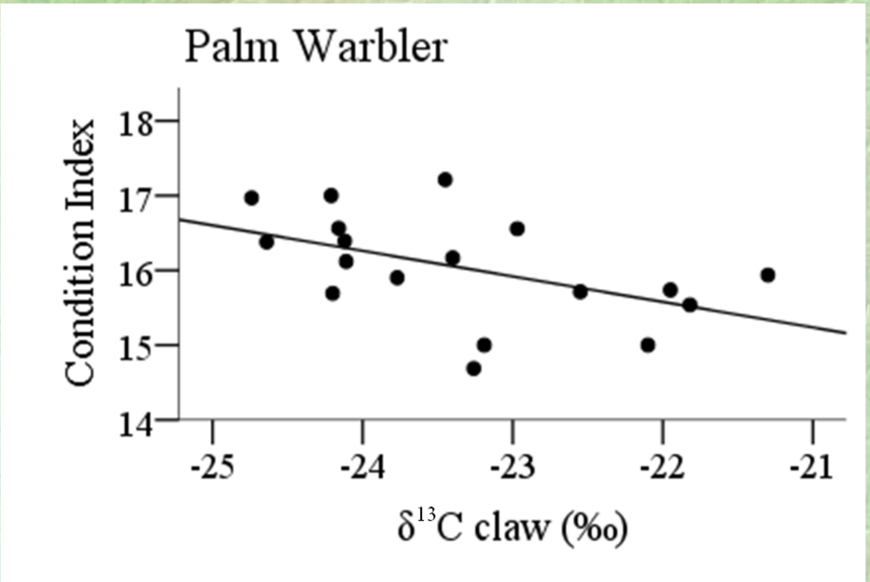
Wintering habitat determines arrival time on breeding grounds



Marra et al. (Science 1998)

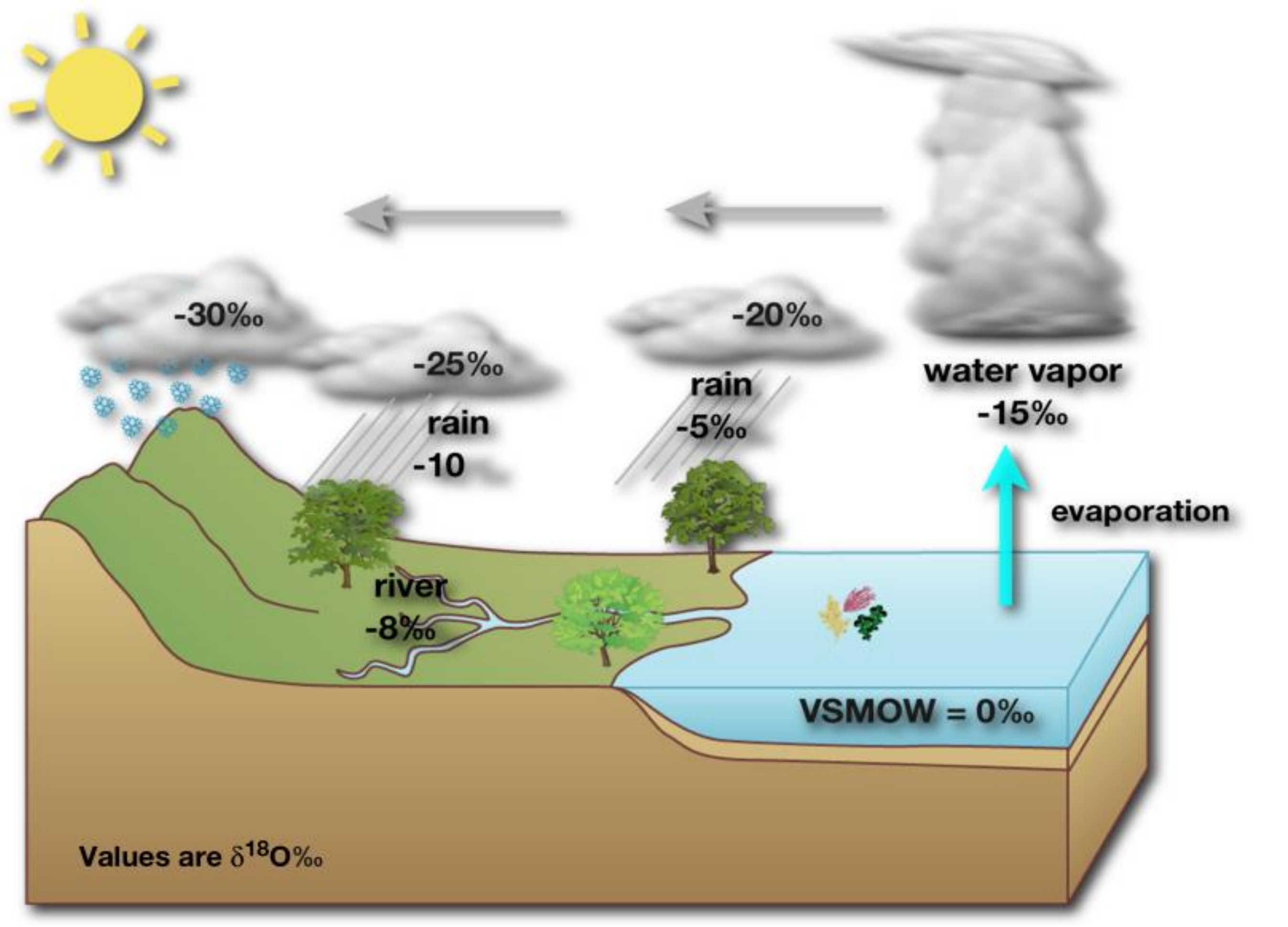

winter
(non-breeding)
summer
(breeding)
(a)
0.32
u
arrival date
0.40
u
first-egg date
0.36
number of
young fledged
δ13C
0.14
fledging date
u
u
(b)
0.01
u
arrival date
0.36
number of
young fledged
δ13C
0.66
fledging date
u
u



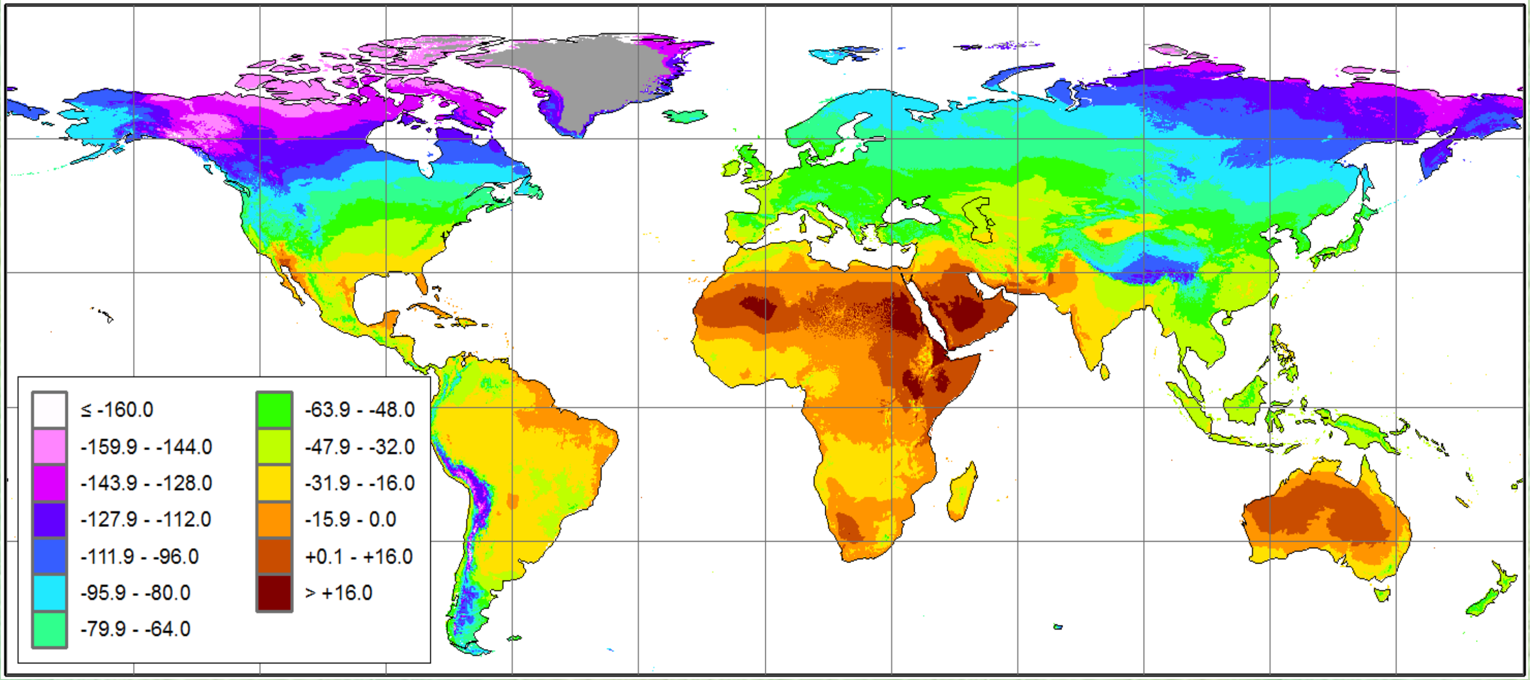


Gonzalez-Prieto and Hobson, *J. Ornith*. (2012)

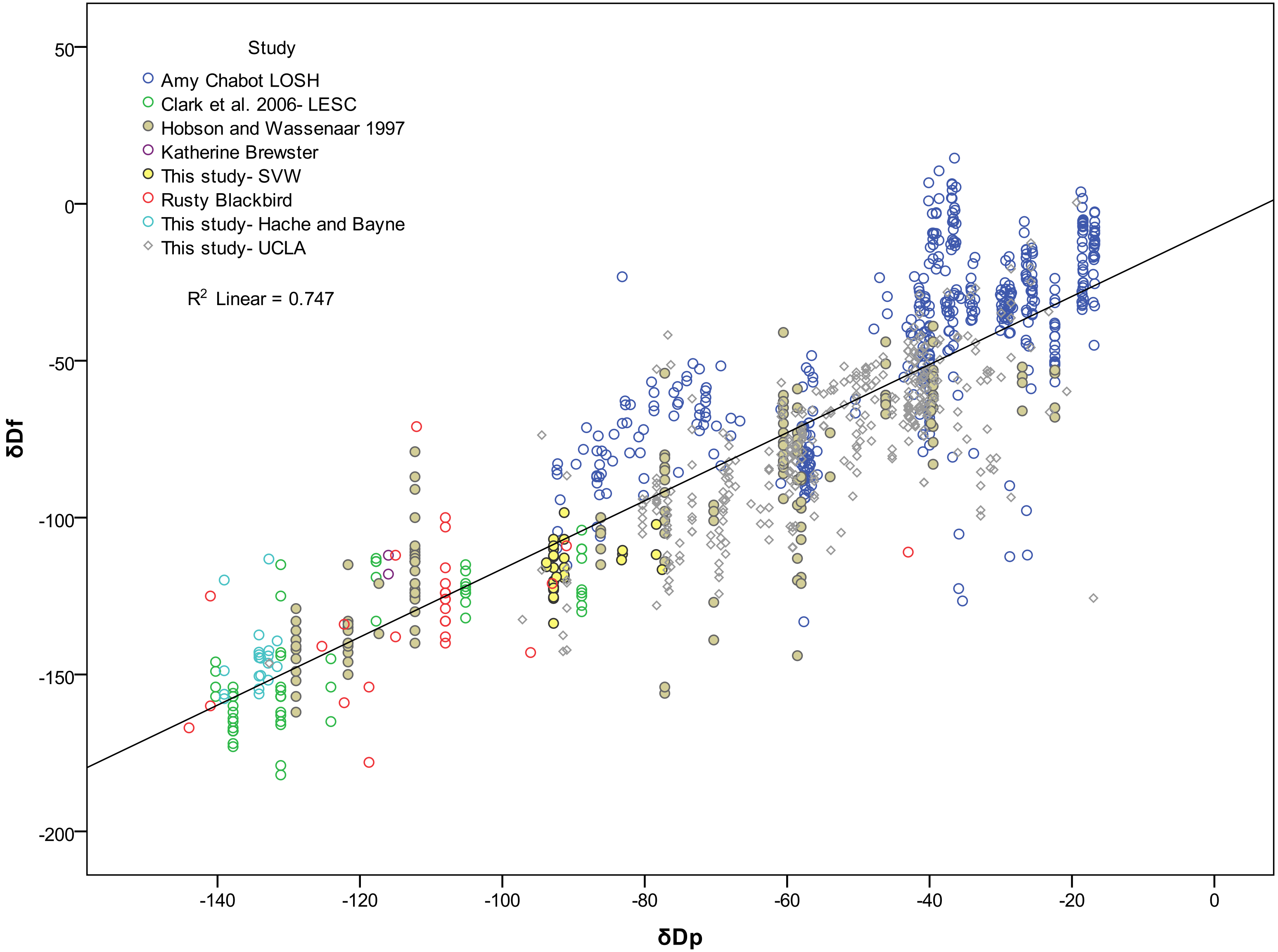
Breakthrough with water isotopes



Latest growing-season δ^2Hp

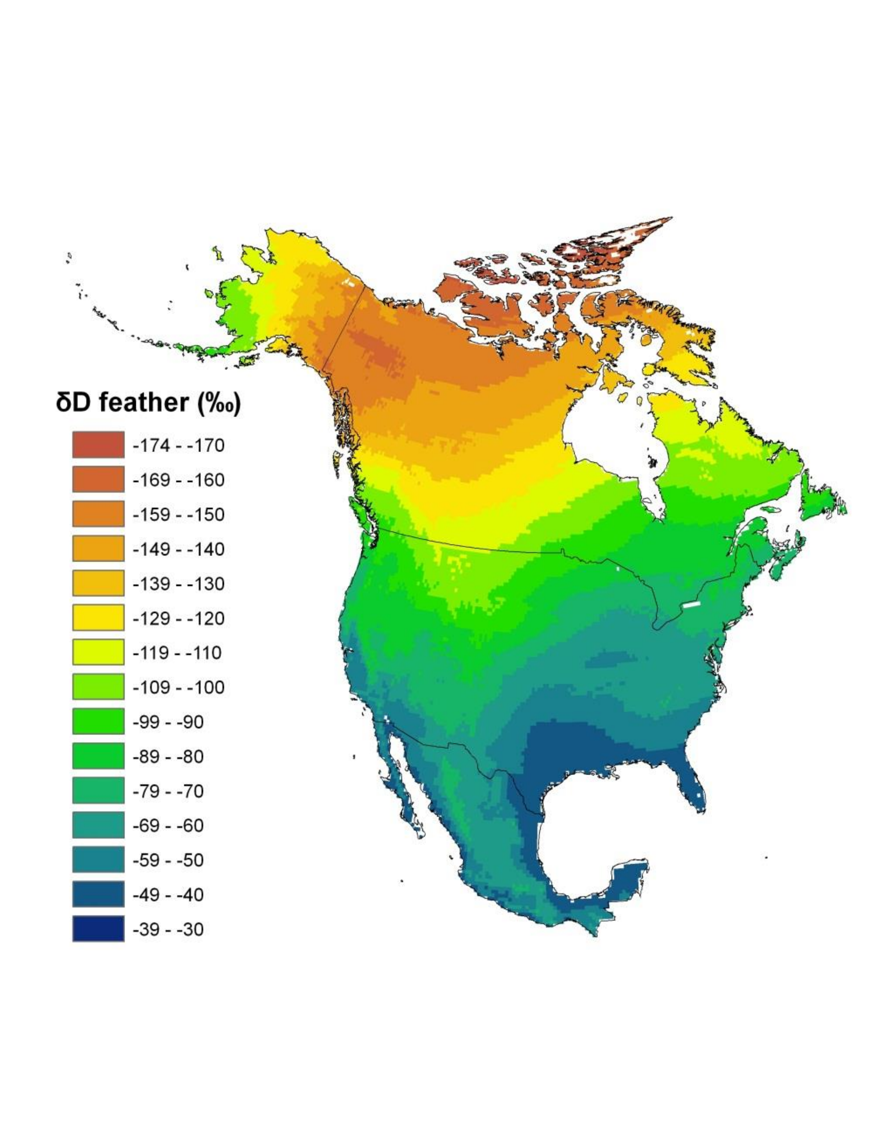


Wassenaar, IAEA.

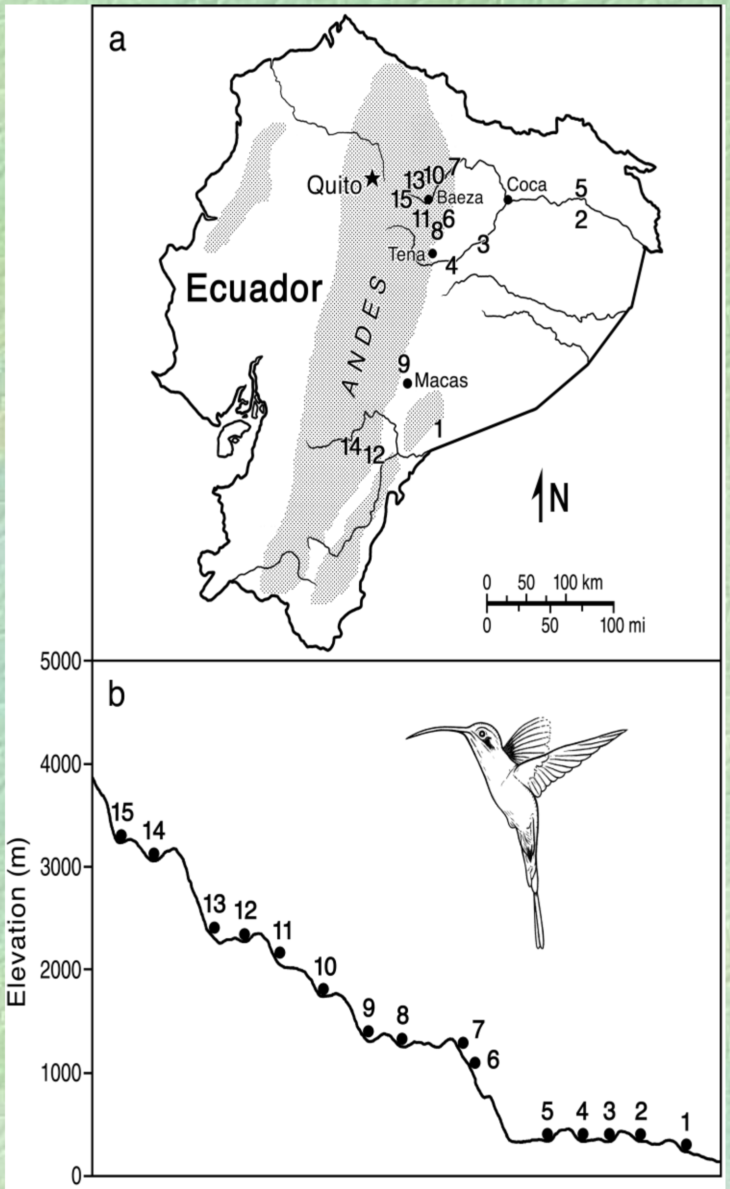


Study
Amy Chabot LOSH
Clark et al. 2006- LESC
Hobson and Wassenaar 1997
Katherine Brewster
This study- SVW
Rusty Blackbird
This study- Hache and Bayne
This study- UCLA
R^2 Linear = 0.747
50
0
-50
-100
-150
-200
δDf
-140
-120
-100
-80
-60
-40
-20
0
δDp

For most birds …

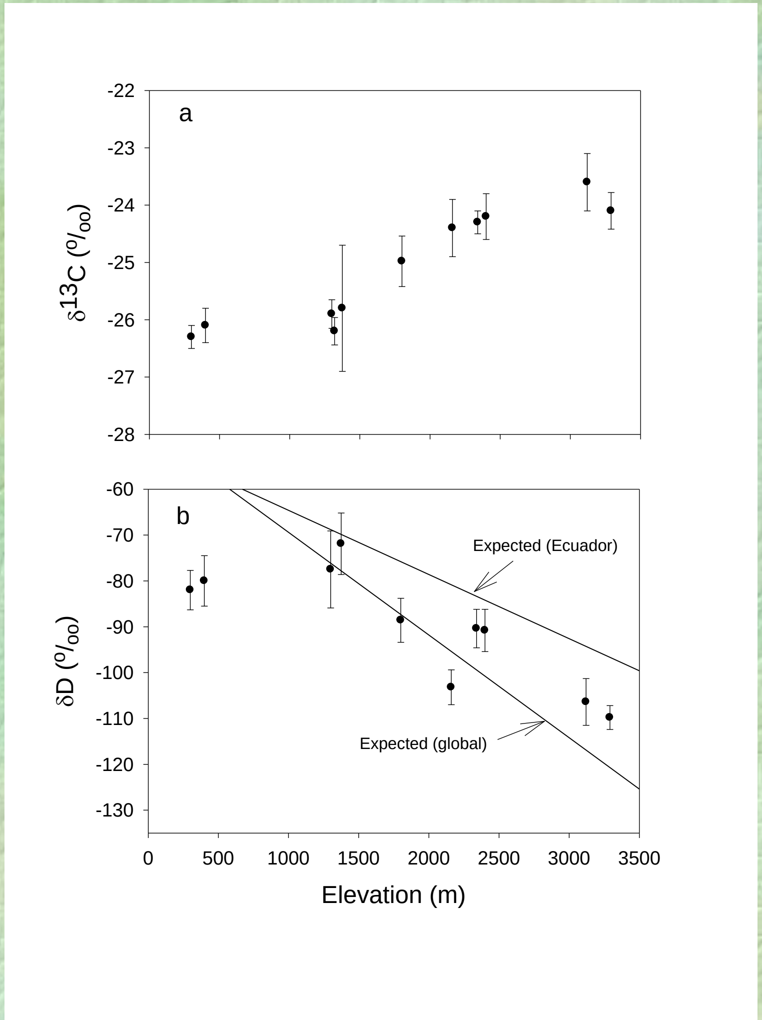


Altitudinal gradients are recorded in hummingbird feathers:



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

The feather isotopes follow large scale trajectories in precip δD

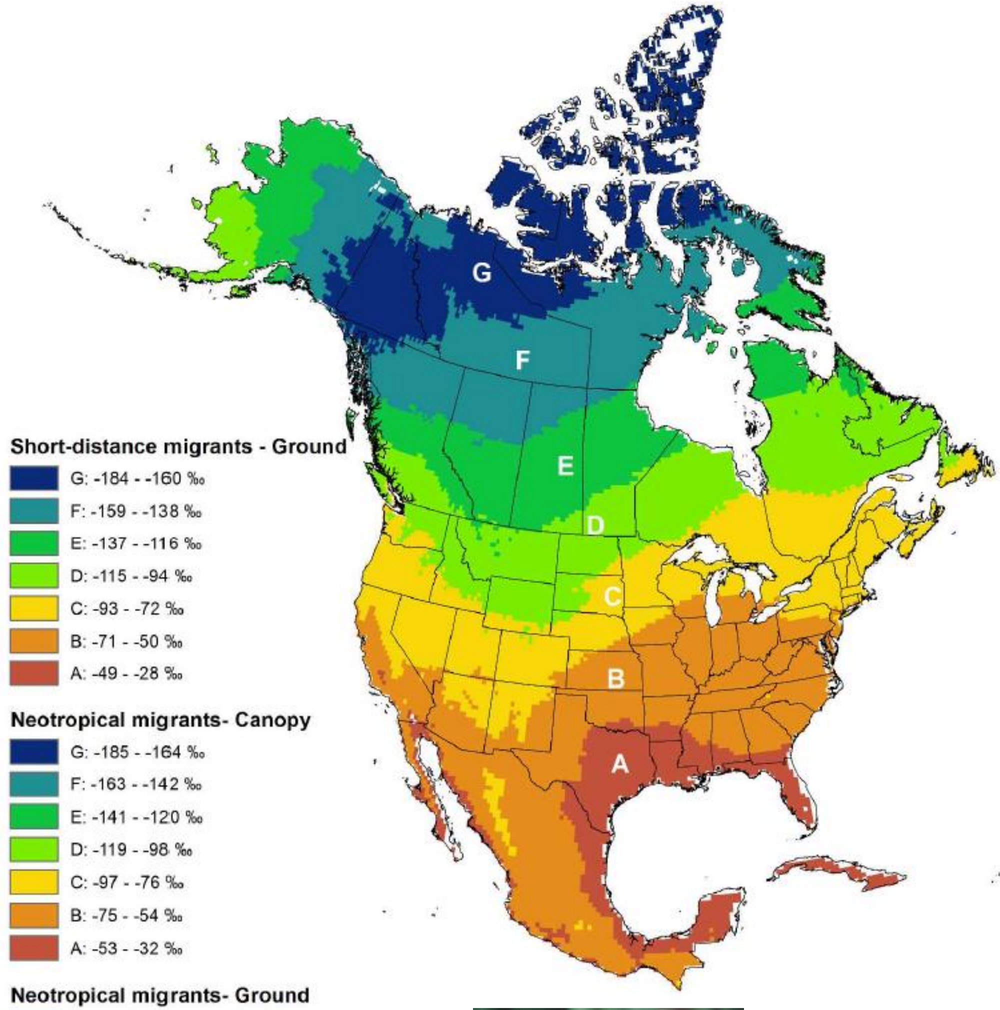


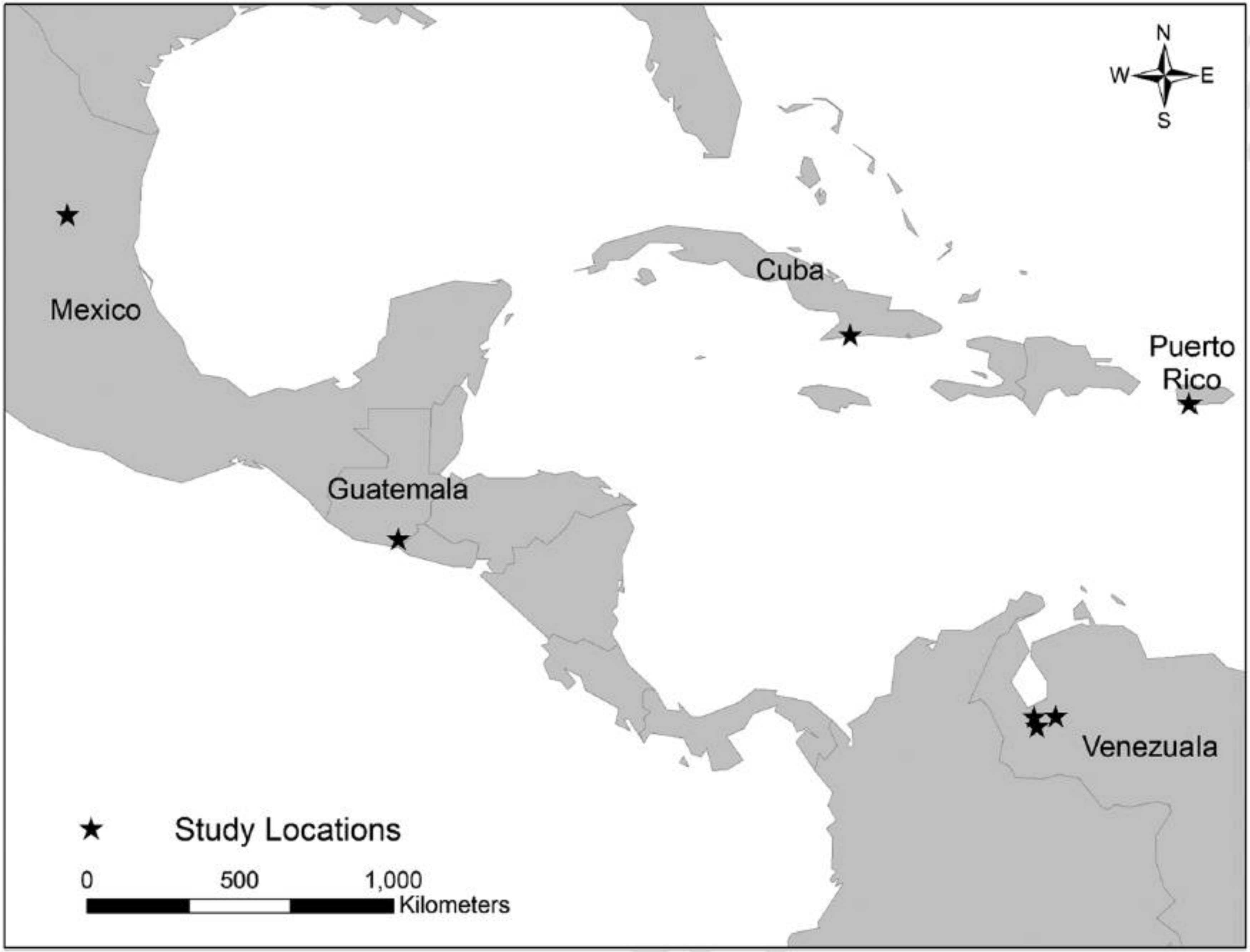
Ecuador:

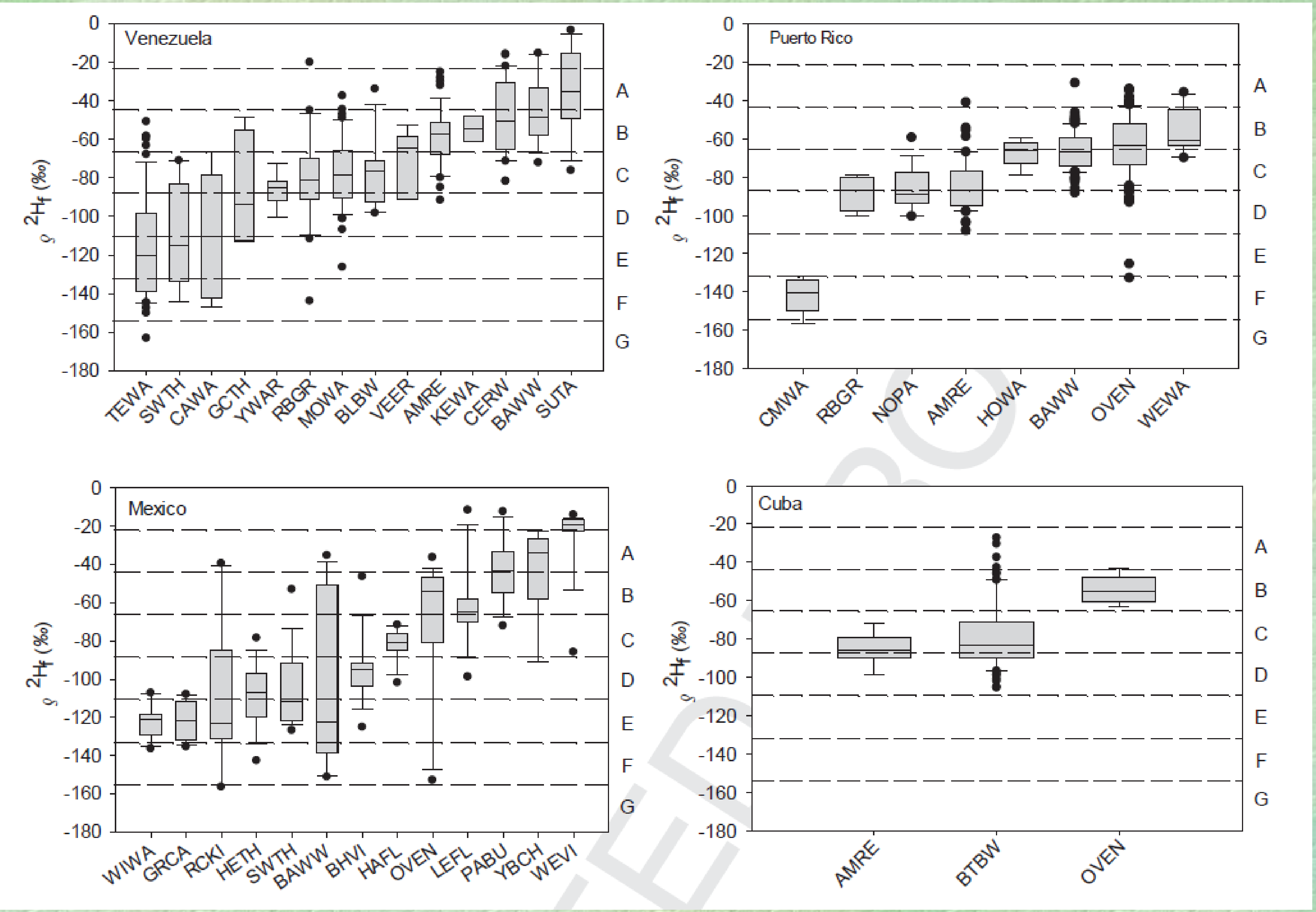
$\delta D_f = -25.6 + E(-0.014) -25\ ^o/oo$

Global:

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


G
F
E
D
C
B
A
Short-distance migrants - Ground
G: -184 - -160 ‰
F: -159 - -138 ‰
E: -137 - -116 ‰
D: -115 - -94 ‰
C: -93 - -72 ‰
B: -71 - -50 ‰
A: -49 - -28 ‰
Neotropical migrants- Canopy
G: -185 - -164 ‰
F: -163 - -142 ‰
E: -141 - -120 ‰
D: -119 - -98 ‰
C: -97 - -76 ‰
B: -75 - -54 ‰
A: -53 - -32 ‰
Neotropical migrants- Ground
G: -179 - -154 ‰
F: -153 - -132 ‰
E: -131 - -110 ‰
D: -109 - -88 ‰
C: -87 - -66 ‰
B: -65 - -44 ‰
A: -43 - -22 ‰


N
W
E
S
Mexico
Cuba
Puerto
Rico
Guatemala
Venezuala
Study Locations
0
500
1,000
Kilometers

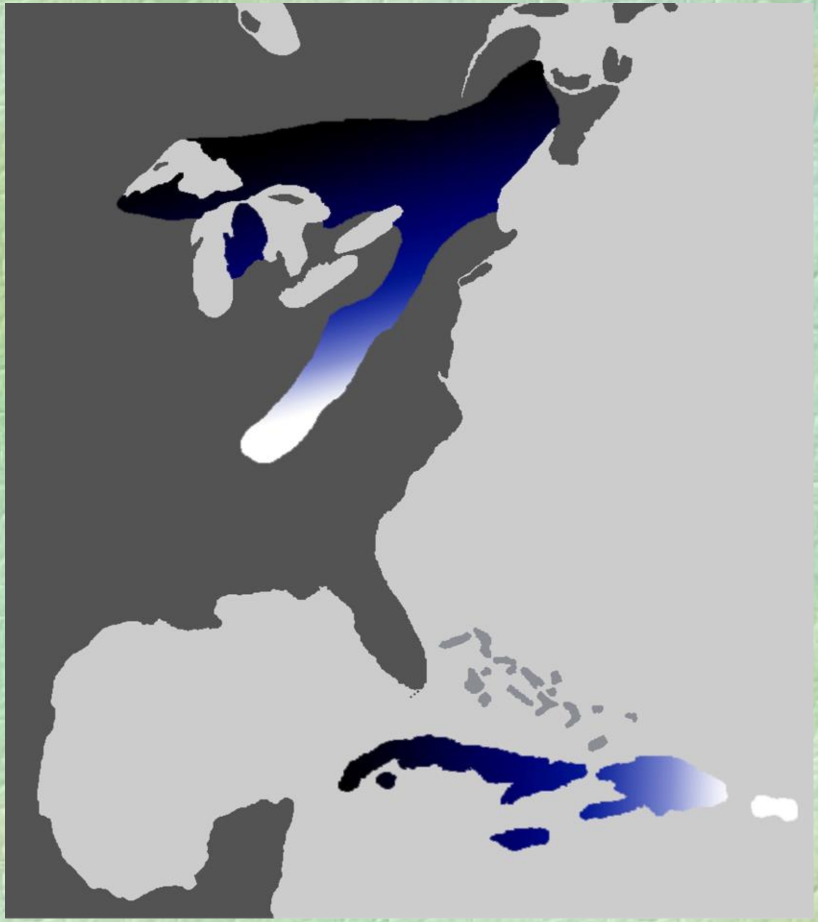


Venezuela
TEWA SWTH CAWA GCTH YWAR RBGR MOWA BLBW VEER AMRE KEWA CERW BAWW SUTA
Puerto Rico
CMWA RBGR NOPA AMRE HOWA BAWW OVEN WEWA
Mexico
WIWA GRCA RCKI HETH SWTH BAWW BHVI HAFL OVEN LEFL PABU YBCH WEVI
Cuba
AMRE BTBW OVEN
A
B
C
D
E
F
G
δ 2Hf (‰)

"Leapfrog" migration revealed ..

Kelly et al. (Oecologia 2002)

Other isotopic delineations of population structure …



Rubenstein et al. (Science 2002)

Incorporating uncertainty in assignments …..

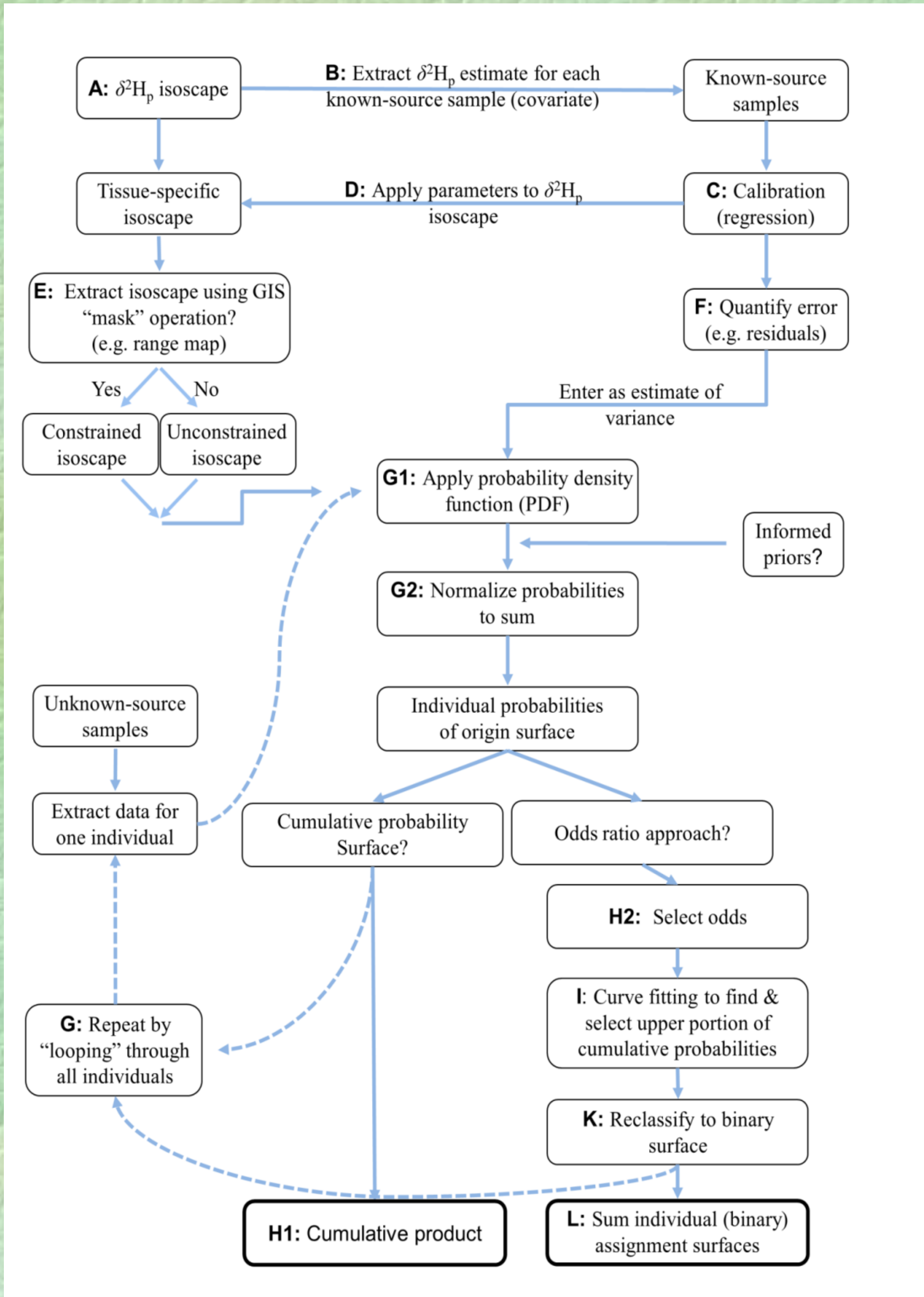
Chapter 12
Using Isoscapes to Model Probability Surfaces for Determining Geographic Origins

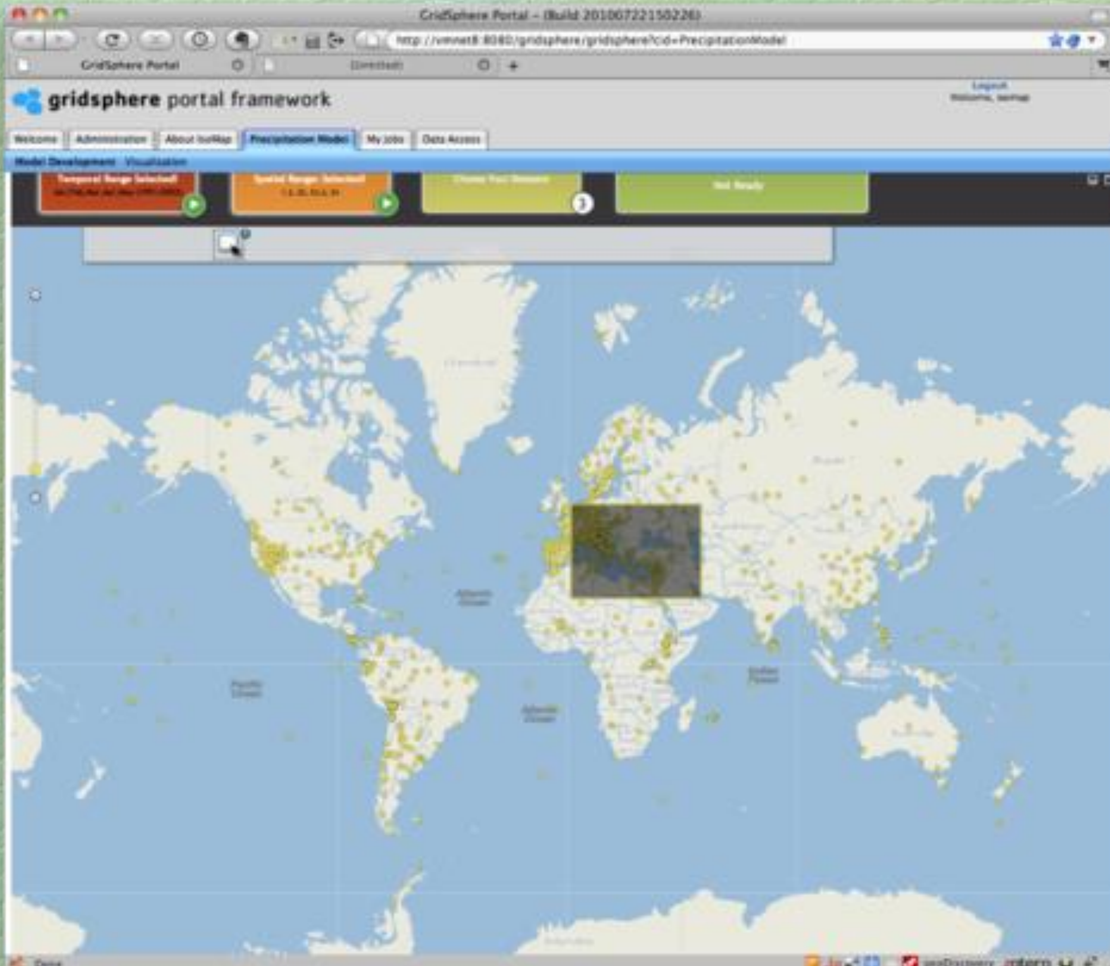
Michael B. Wunder

Ecological Applications, 18(2), 2008, pp. 549–559

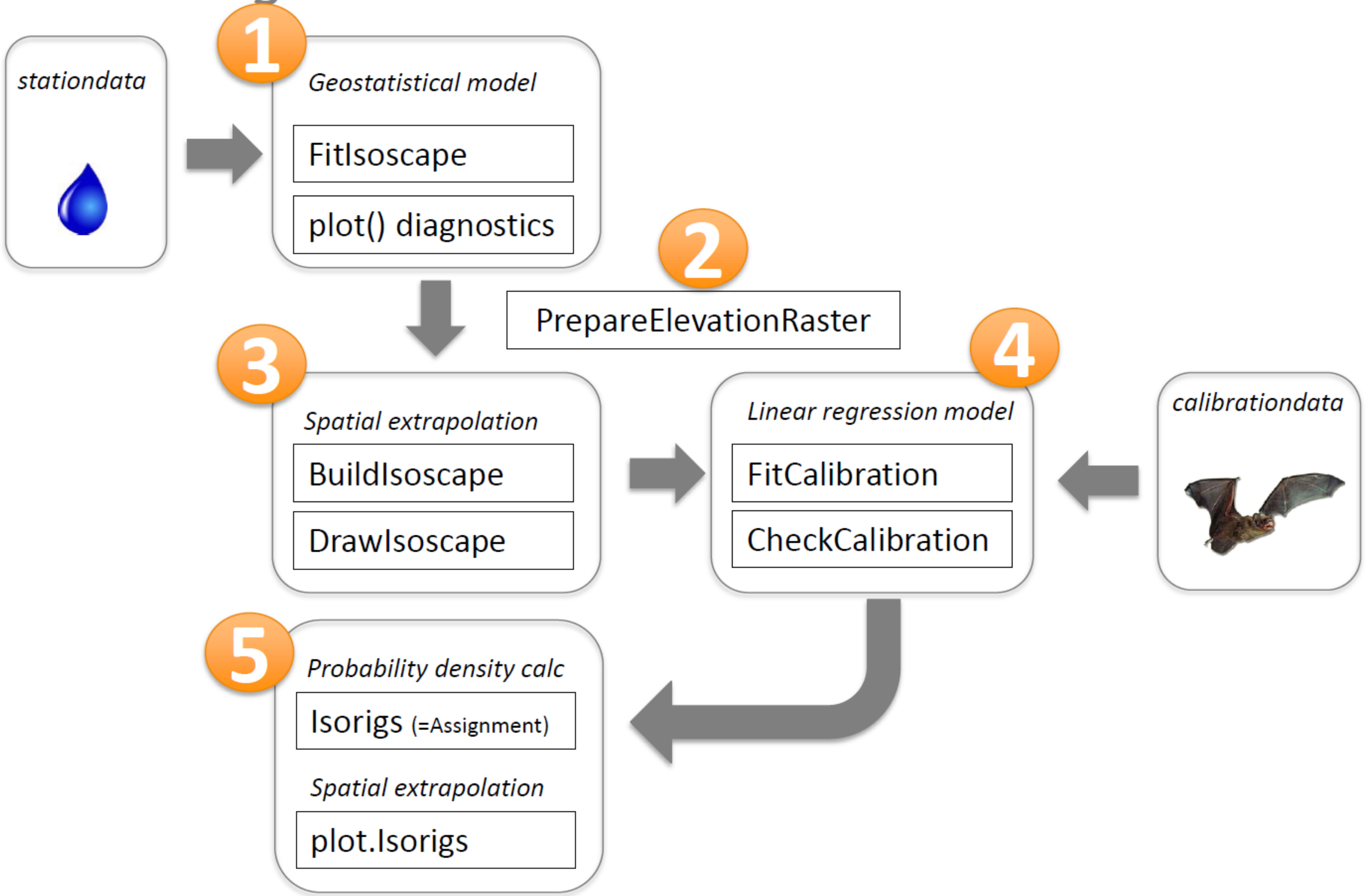
IMPROVED ESTIMATES OF CERTAINTY IN STABLE-ISOTOPE-BASED METHODS FOR TRACKING MIGRATORY ANIMALS

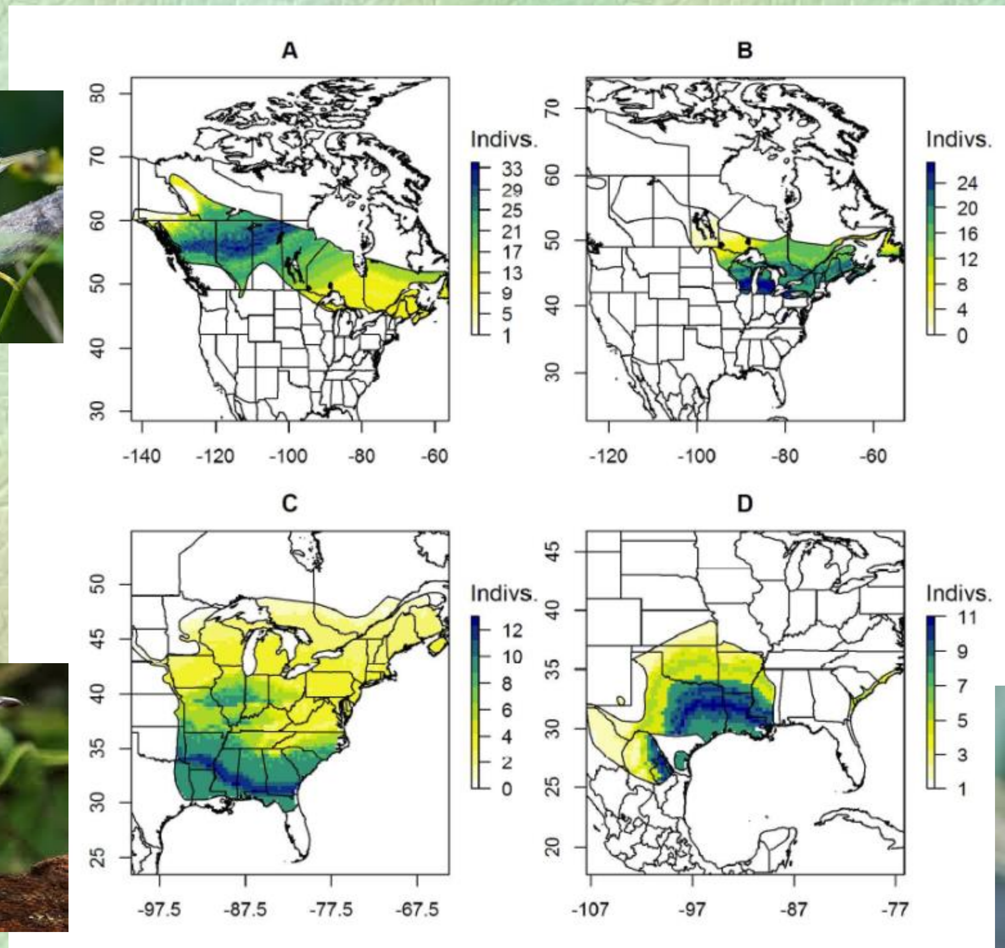
MICHAEL B. WUNDER[1,3] AND D. RYAN NORRIS[2]


A: δ^2H_p isoscape
B: Extract δ^2H_p estimate for each known-source sample (covariate)
Known-source samples
Tissue-specific isoscape
D: Apply parameters to δ^2H_p isoscape
C: Calibration (regression)
E: Extract isoscape using GIS "mask" operation? (e.g. range map)
F: Quantify error (e.g. residuals)
Yes
No
Enter as estimate of variance
Constrained isoscape
Unconstrained isoscape
G1: Apply probability density function (PDF)
Informed priors?
G2: Normalize probabilities to sum
Unknown-source samples
Individual probabilities of origin surface
Extract data for one individual
Cumulative probability Surface?
Odds ratio approach?
H2: Select odds
I: Curve fitting to find & select upper portion of cumulative probabilities
G: Repeat by "looping" through all individuals
K: Reclassify to binary surface
H1: Cumulative product
L: Sum individual (binary) assignment surfaces


GridSphere Portal – (Build 20100722150226)
http://vmnet8:8080/gridsphere/gridsphere?cid=PrecipitationModel
GridSphere Portal
gridsphere portal framework
Logout
Welcome
Administration
About IsoMap
Precipitation Model
My Jobs
Data Access
Model Development
Visualization
Done

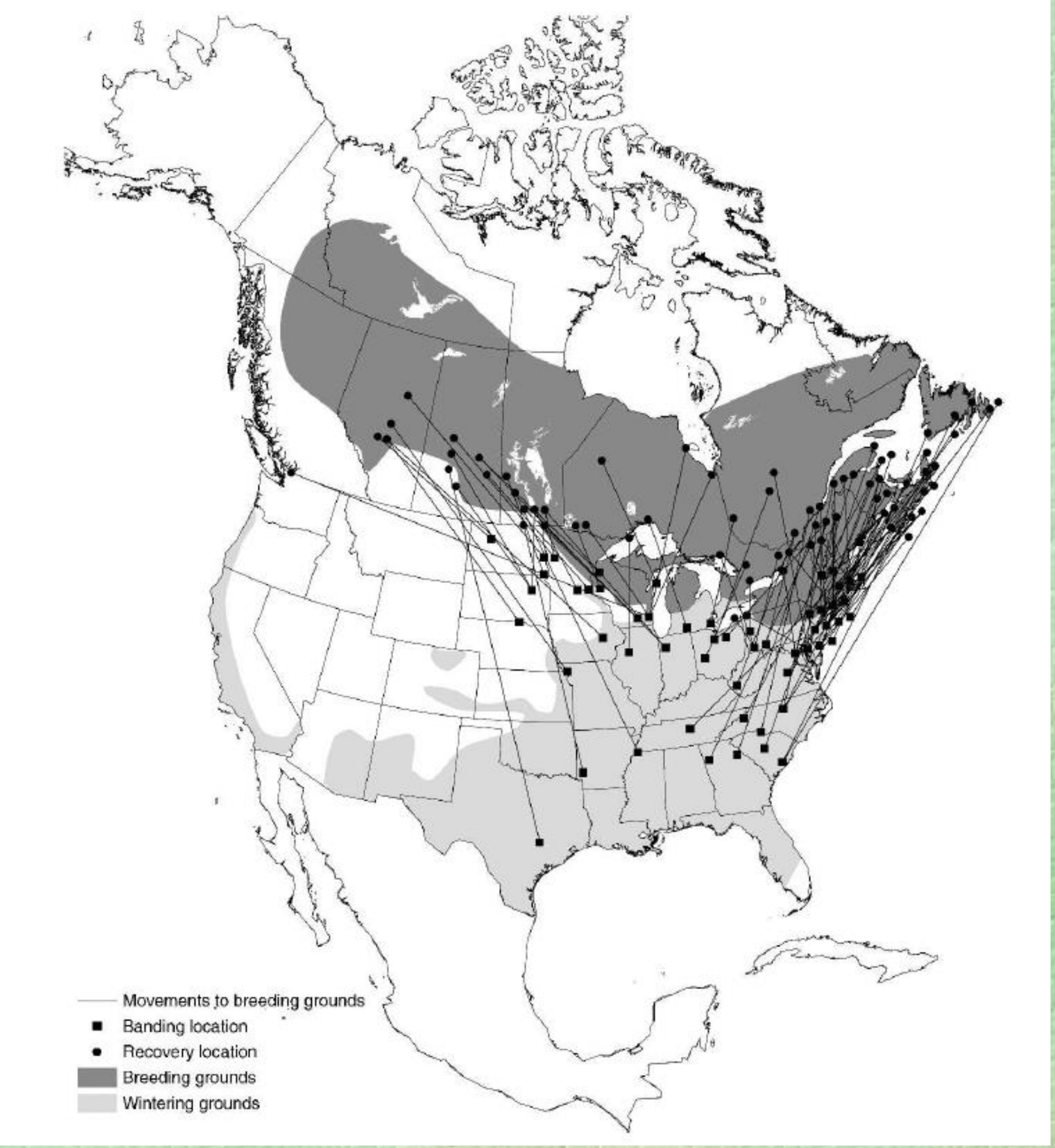
The assignment workflow in IsoriX

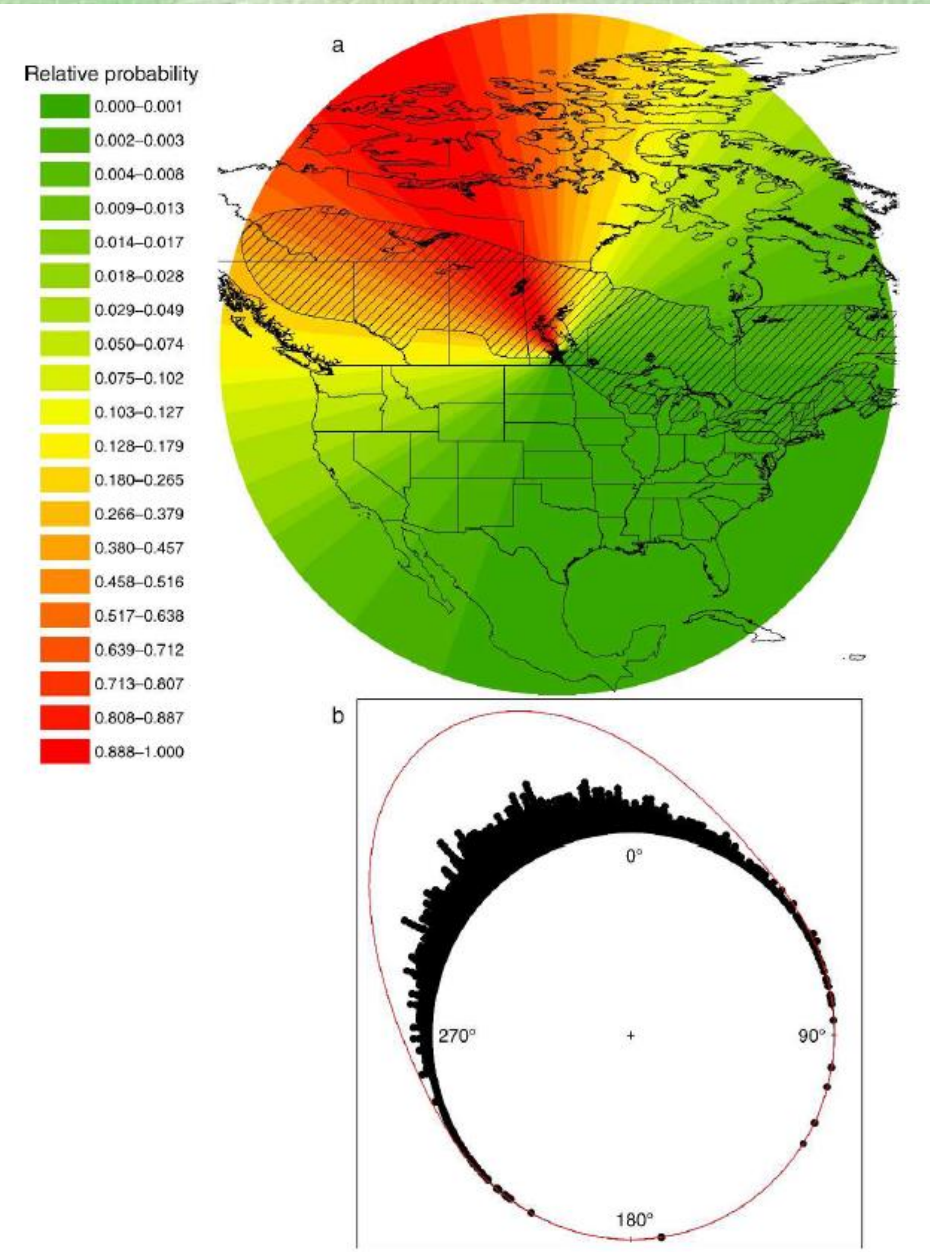


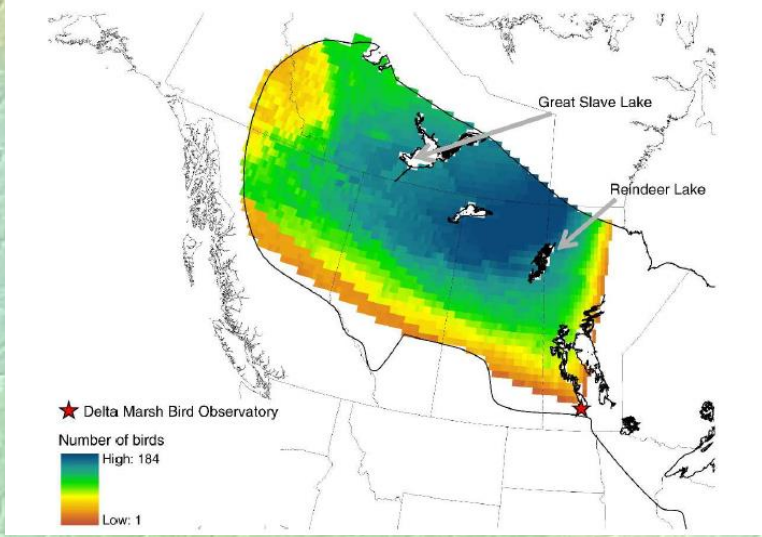


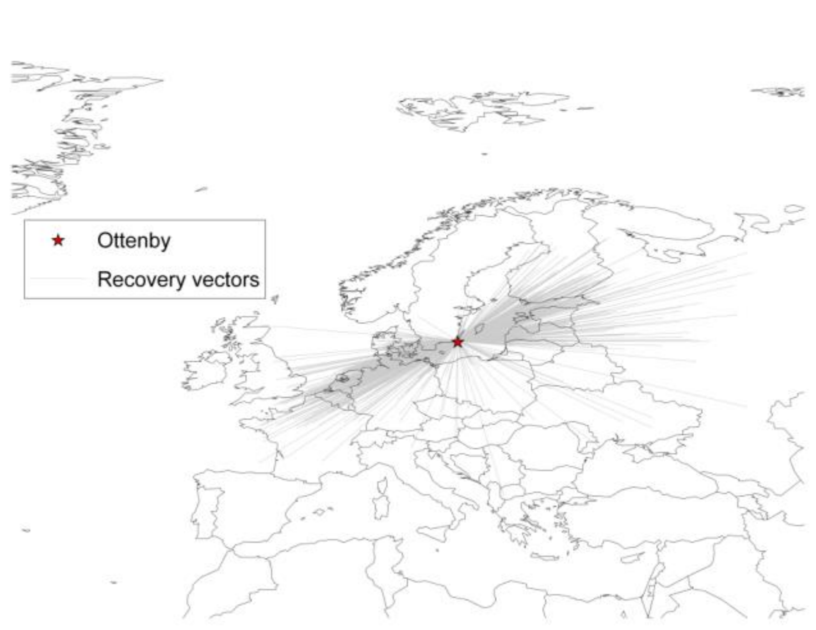
Hobson et al. *JFO* (2014)

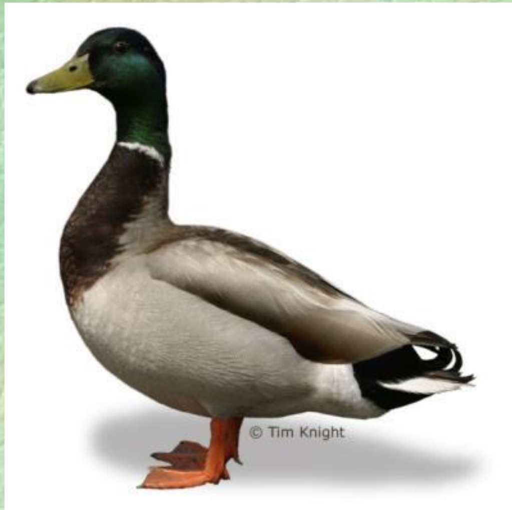
Applying prior probabilities

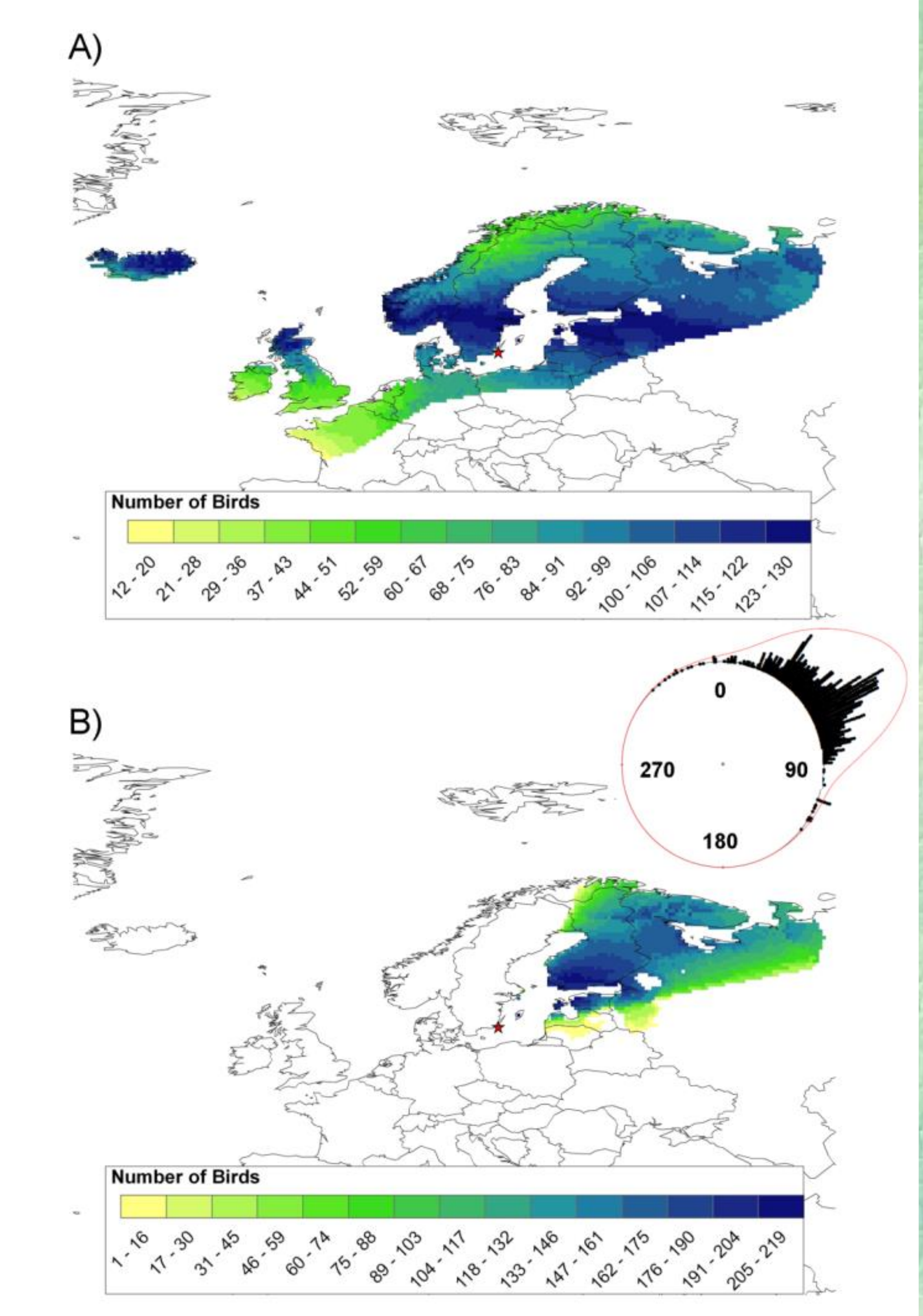


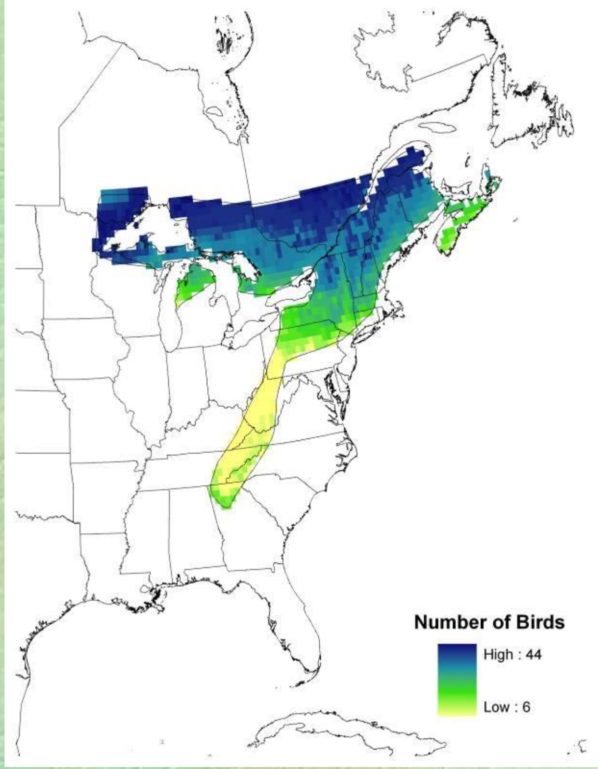

Relative probability
0.000–0.001
0.002–0.003
0.004–0.008
0.009–0.013
0.014–0.017
0.018–0.028
0.029–0.049
0.050–0.074
0.075–0.102
0.103–0.127
0.128–0.179
0.180–0.265
0.266–0.379
0.380–0.457
0.458–0.516
0.517–0.638
0.639–0.712
0.713–0.807
0.808–0.887
0.888–1.000
a
b
0°
270°
90°
180°


Great Slave Lake
Reindeer Lake
Delta Marsh Bird Observatory
Number of birds
High: 184
Low: 1

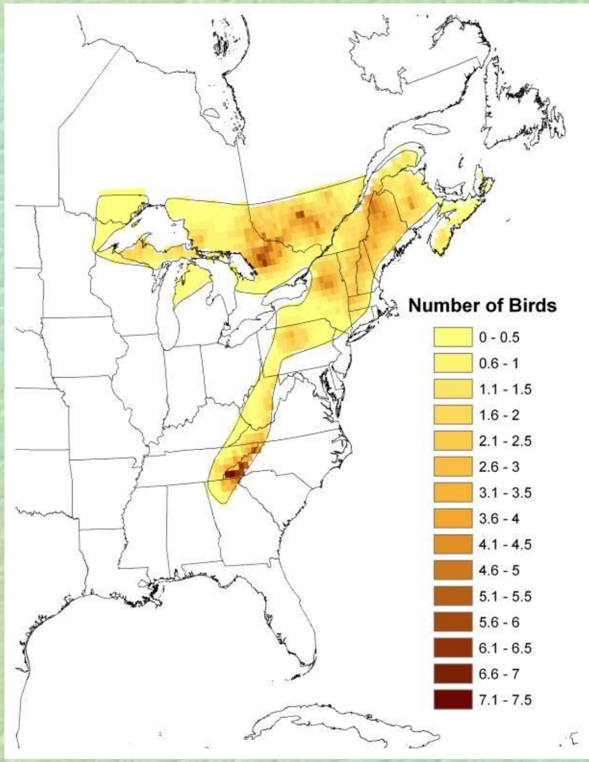

Ottenby
Recovery vectors


© Tim Knight

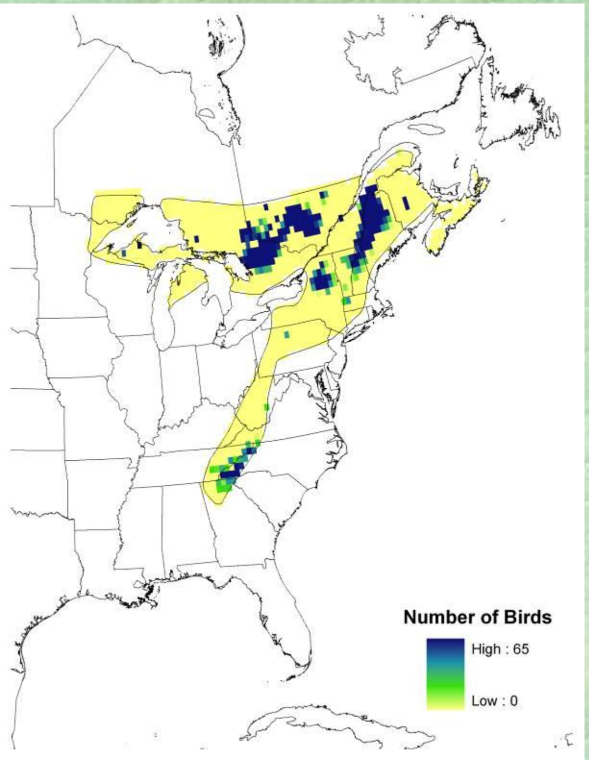

A)
Number of Birds
12 - 20
21 - 28
29 - 36
37 - 43
44 - 51
52 - 59
60 - 67
68 - 75
76 - 83
84 - 91
92 - 99
100 - 106
107 - 114
115 - 122
123 - 130
B)
0
90
180
270
Number of Birds
1 - 16
17 - 30
31 - 45
46 - 59
60 - 74
75 - 88
89 - 103
104 - 117
118 - 132
133 - 146
147 - 161
162 - 175
176 - 190
191 - 204
205 - 219



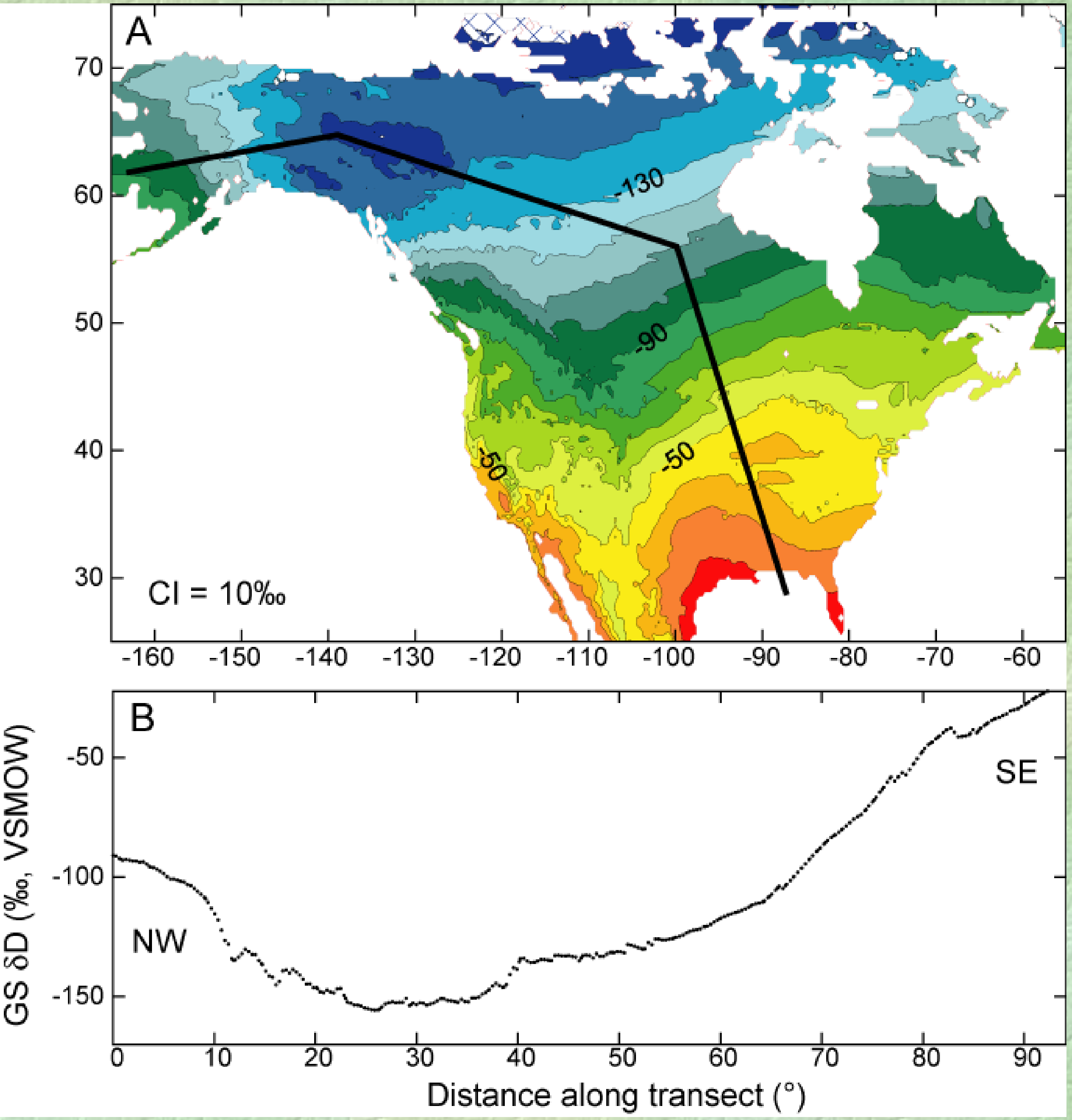
Raw Isotope Assignment



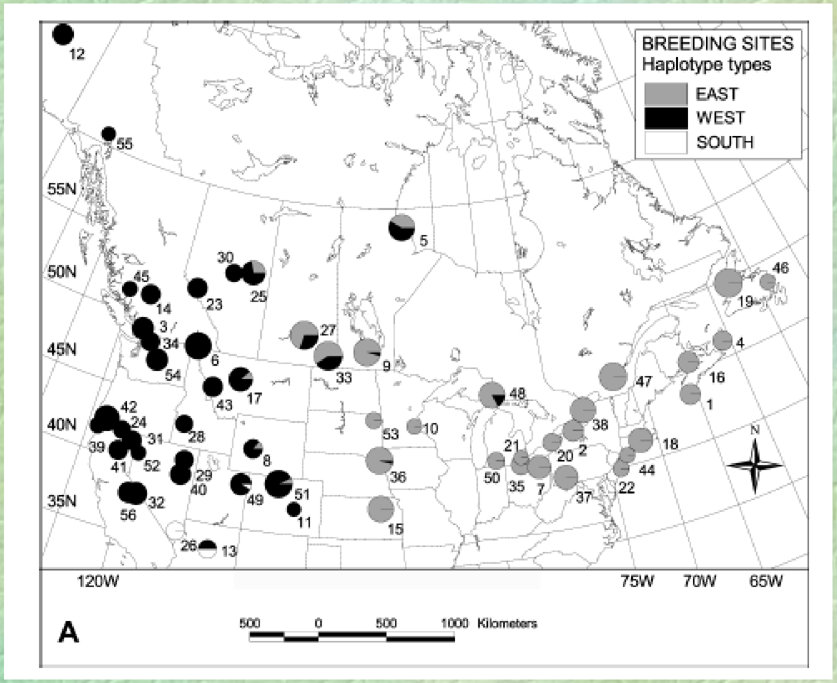
BBS Abundance



Assignment with Prior


A
70
60
50
40
30
-130
-90
-50
-50
CI = 10‰
-160
-150
-140
-130
-120
-110
-100
-90
-80
-70
-60
B
-50
-100
-150
GS δD (‰, VSMOW)
SE
NW
0
10
20
30
40
50
60
70
80
90
Distance along transect (°)

Combining genetics and δD



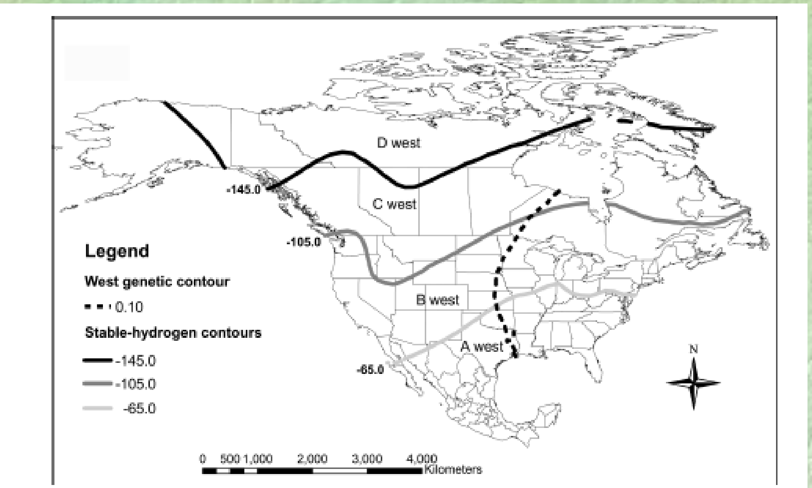
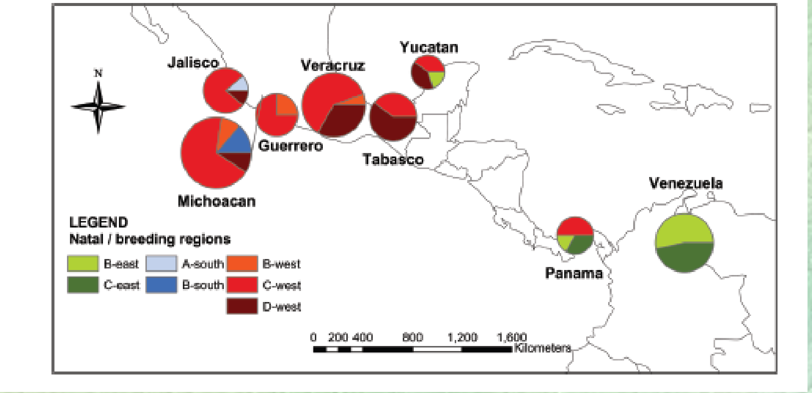
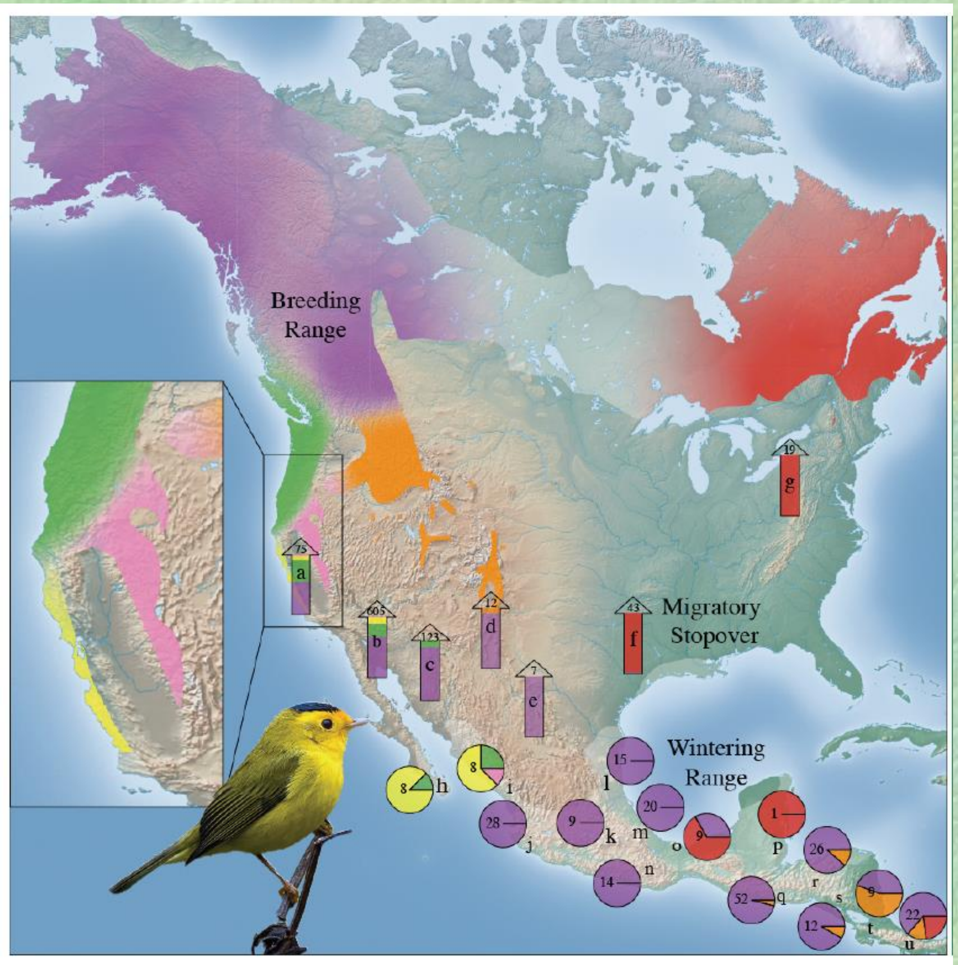
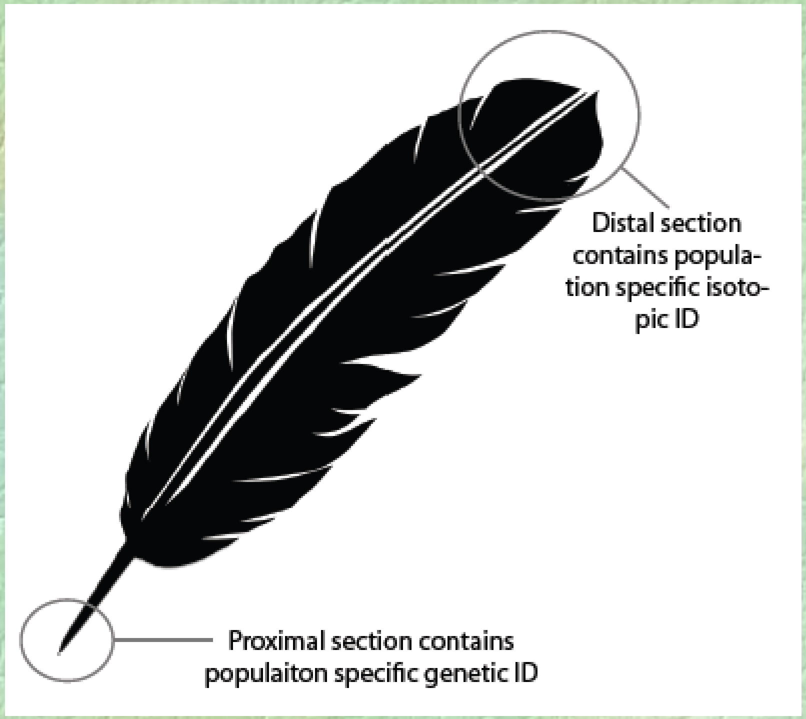


FIG. 10. Breeding subregions of western birds defined by stable hydrogen and genetic contours obtained by overlapping the kriging results of δD values for feathers with west predicted probabilities. The exclusion zone corresponds to the area east of the 10% west genetic contour (dashed black line).

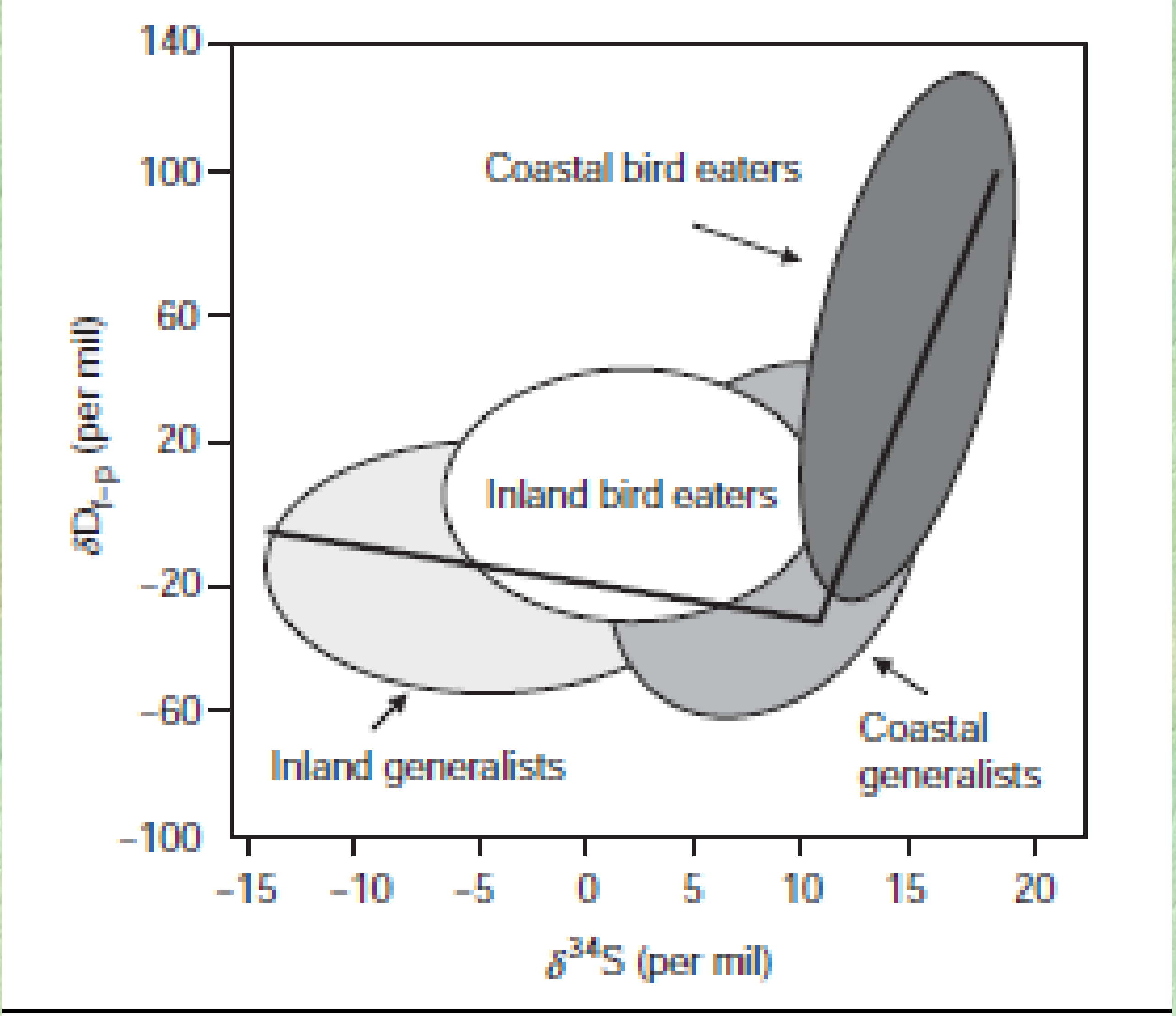


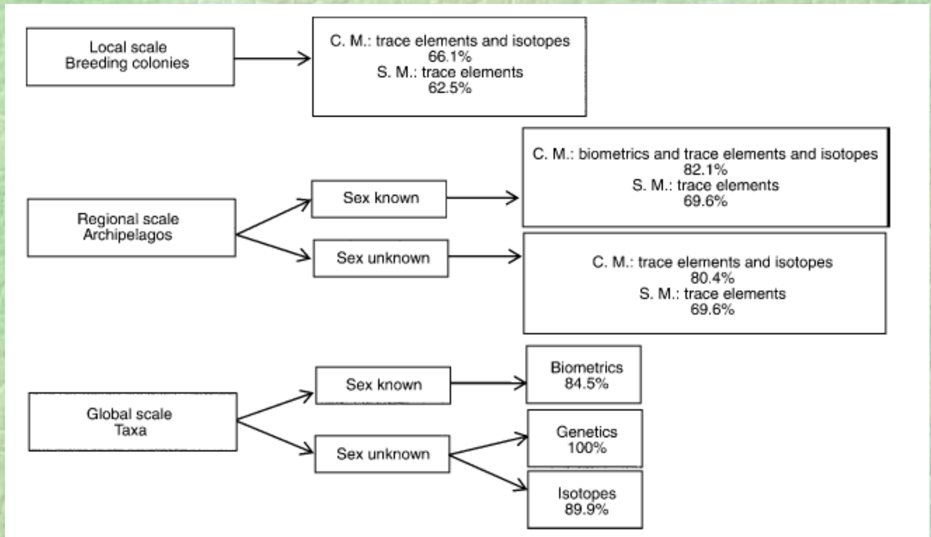
Boulet et al. (Ornithol Monogr)





Ruegg et al. 2014

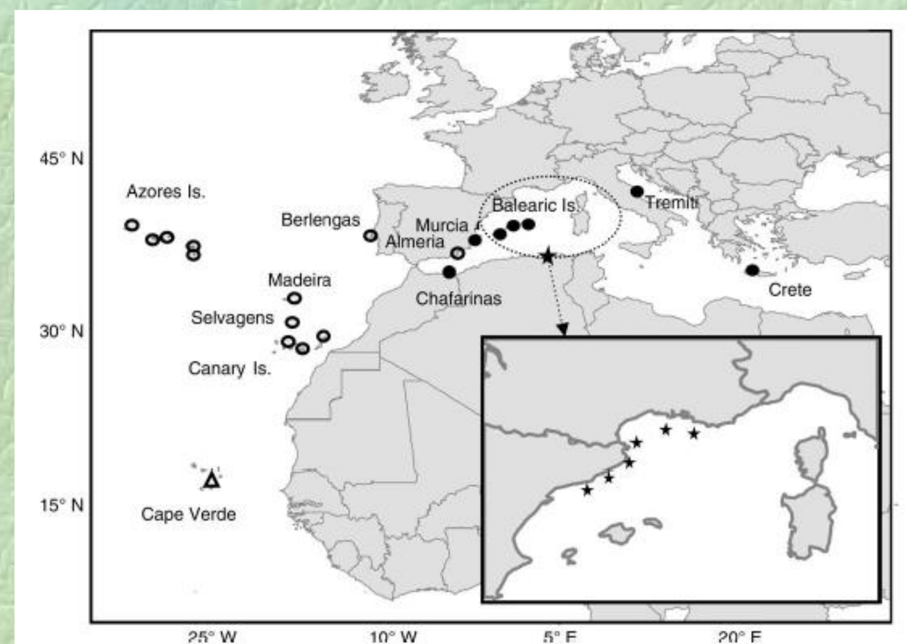

140
100
60
20
−20
−60
−100
δDf–p (per mil)
Coastal bird eaters
Inland bird eaters
Inland generalists
Coastal generalists
−15
−10
−5
0
5
10
15
20
δ34S (per mil)



Ecological Applications, 17(5), 2007, pp. 1484–1498

GEOGRAPHIC ASSIGNMENT OF SEABIRDS TO THEIR ORIGIN: COMBINING MORPHOLOGIC, GENETIC, AND BIOGEOCHEMICAL ANALYSES

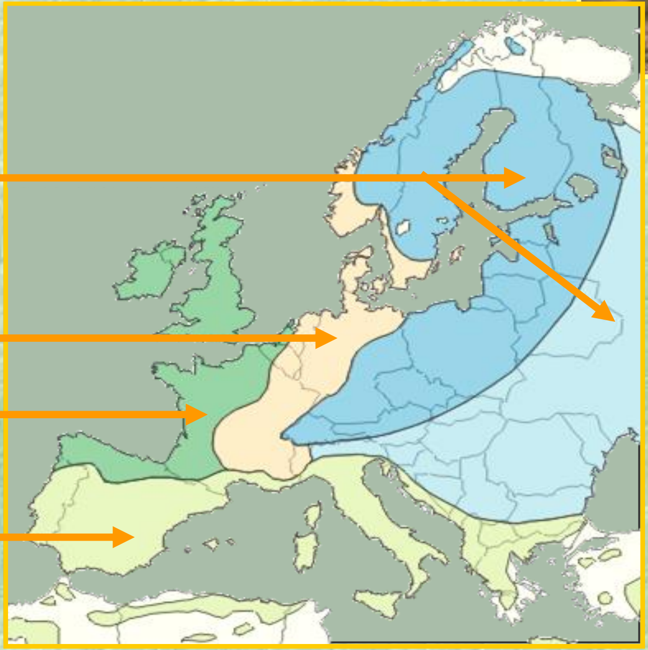
Elena Gómez-Díaz[1,2,3] and Jacob González-Solís[1]



Gómez-Diaz and González-Solis

Origins of Woodpigeons killed in France

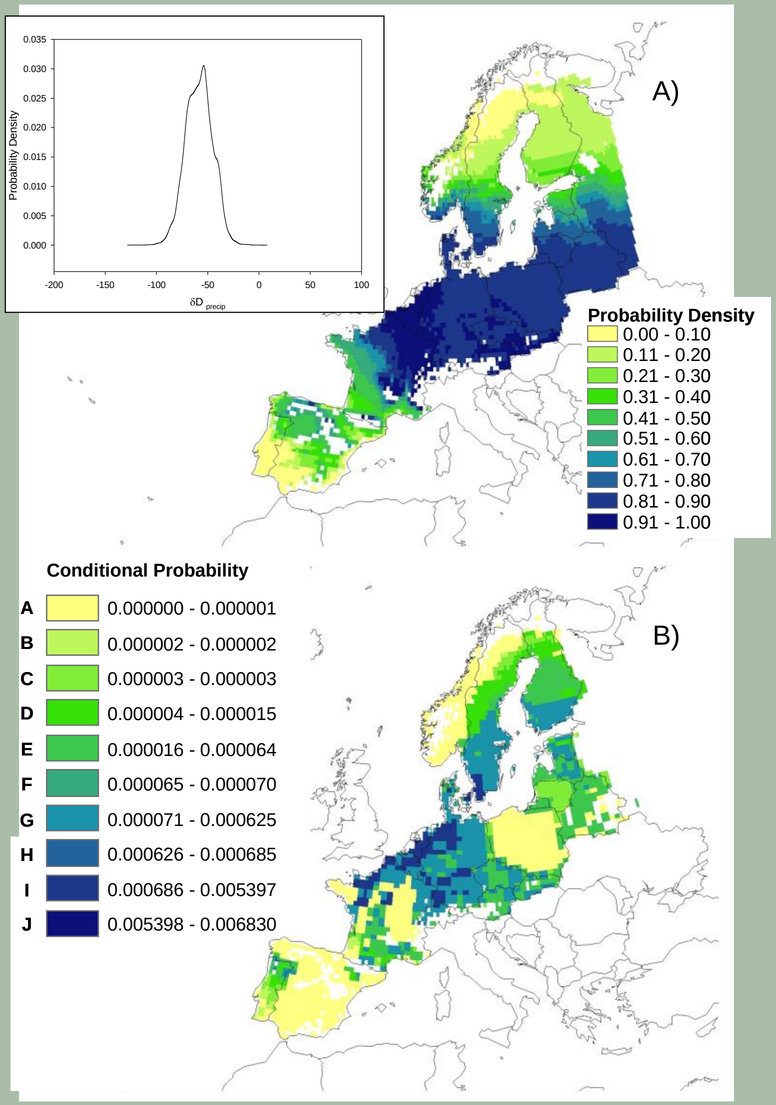
Several distinct populations with specific migratory traits



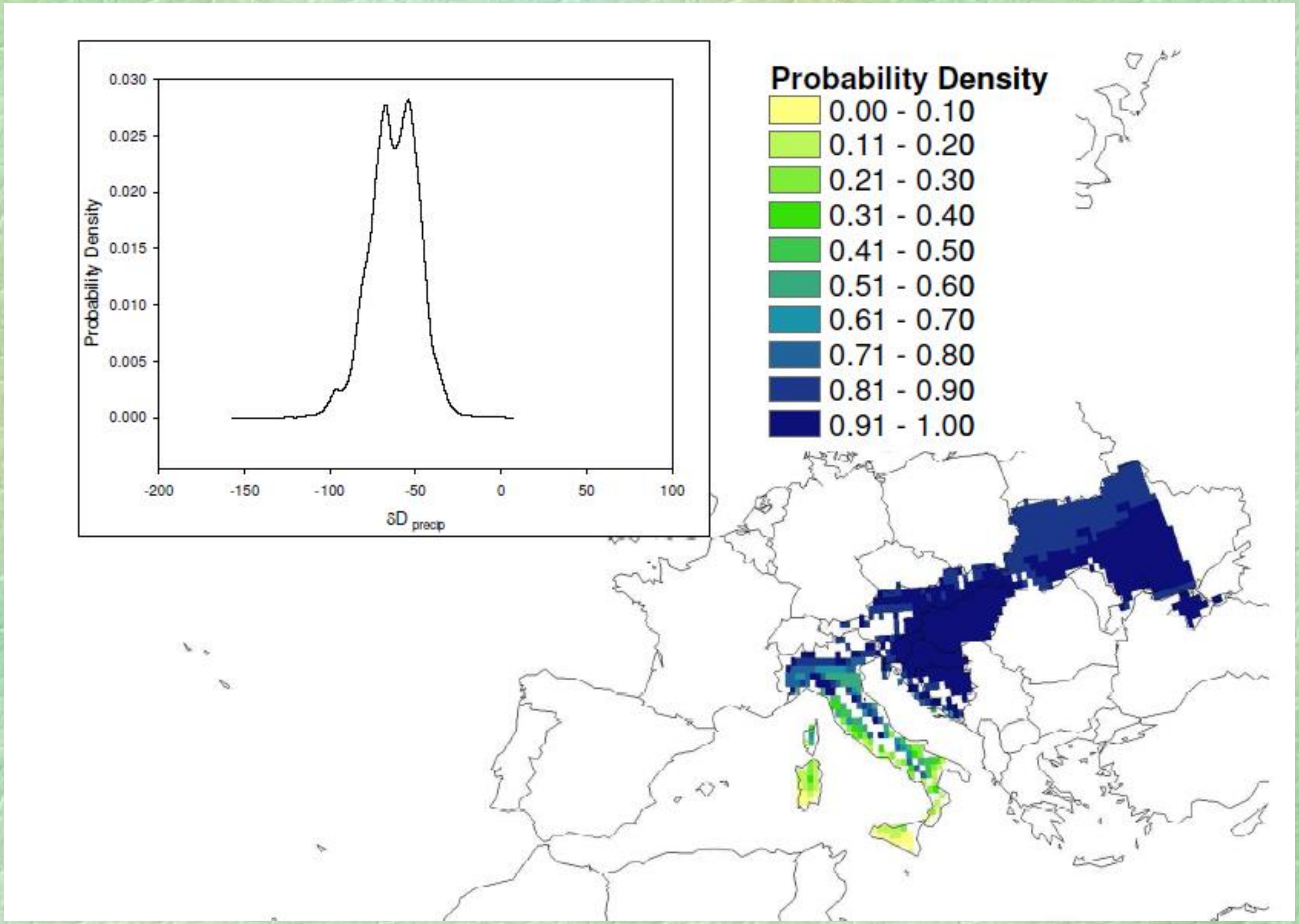
Long-range migrant (winter in southern range of Europe)

Medium-range migrant (winter in France)

sedentary



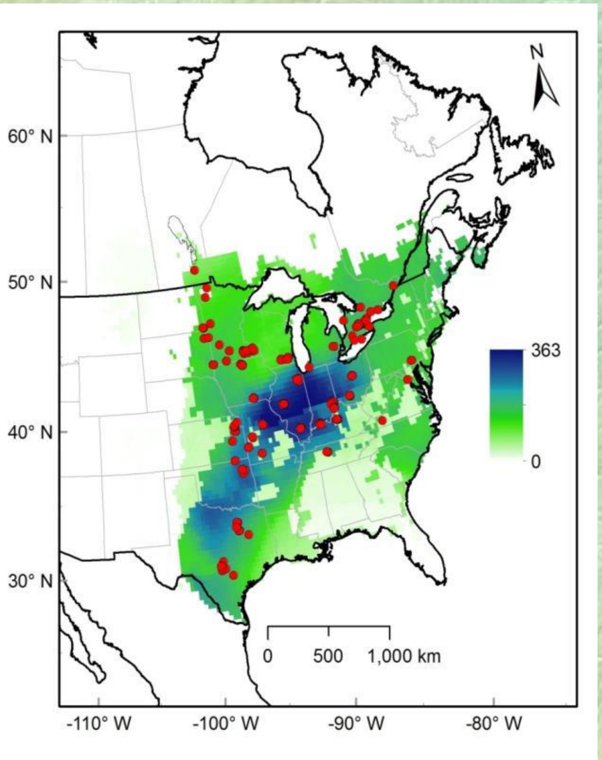
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
Probability Density
-200
-150
-100
-50
0
50
100
δD precip
A)
Probability Density
0.00 - 0.10
0.11 - 0.20
0.21 - 0.30
0.31 - 0.40
0.41 - 0.50
0.51 - 0.60
0.61 - 0.70
0.71 - 0.80
0.81 - 0.90
0.91 - 1.00
Conditional Probability
A 0.000000 - 0.000001
B 0.000002 - 0.000002
C 0.000003 - 0.000003
D 0.000004 - 0.000015
E 0.000016 - 0.000064
F 0.000065 - 0.000070
G 0.000071 - 0.000625
H 0.000626 - 0.000685
I 0.000686 - 0.005397
J 0.005398 - 0.006830
B)

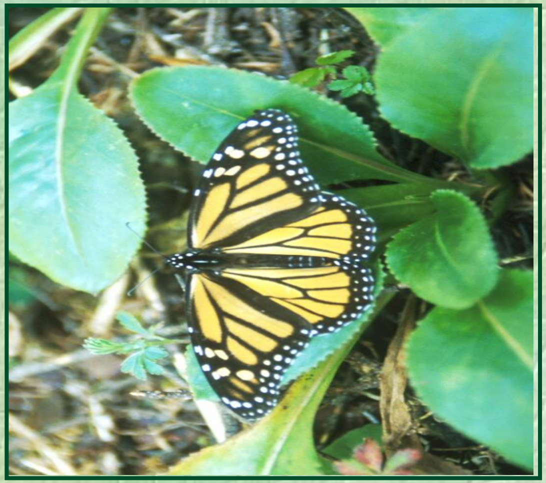


0.030
0.025
0.020
0.015
0.010
0.005
0.000
Probability Density
-200
-150
-100
-50
0
50
100
δD precip
Probability Density
0.00 - 0.10
0.11 - 0.20
0.21 - 0.30
0.31 - 0.40
0.41 - 0.50
0.51 - 0.60
0.61 - 0.70
0.71 - 0.80
0.81 - 0.90
0.91 - 1.00

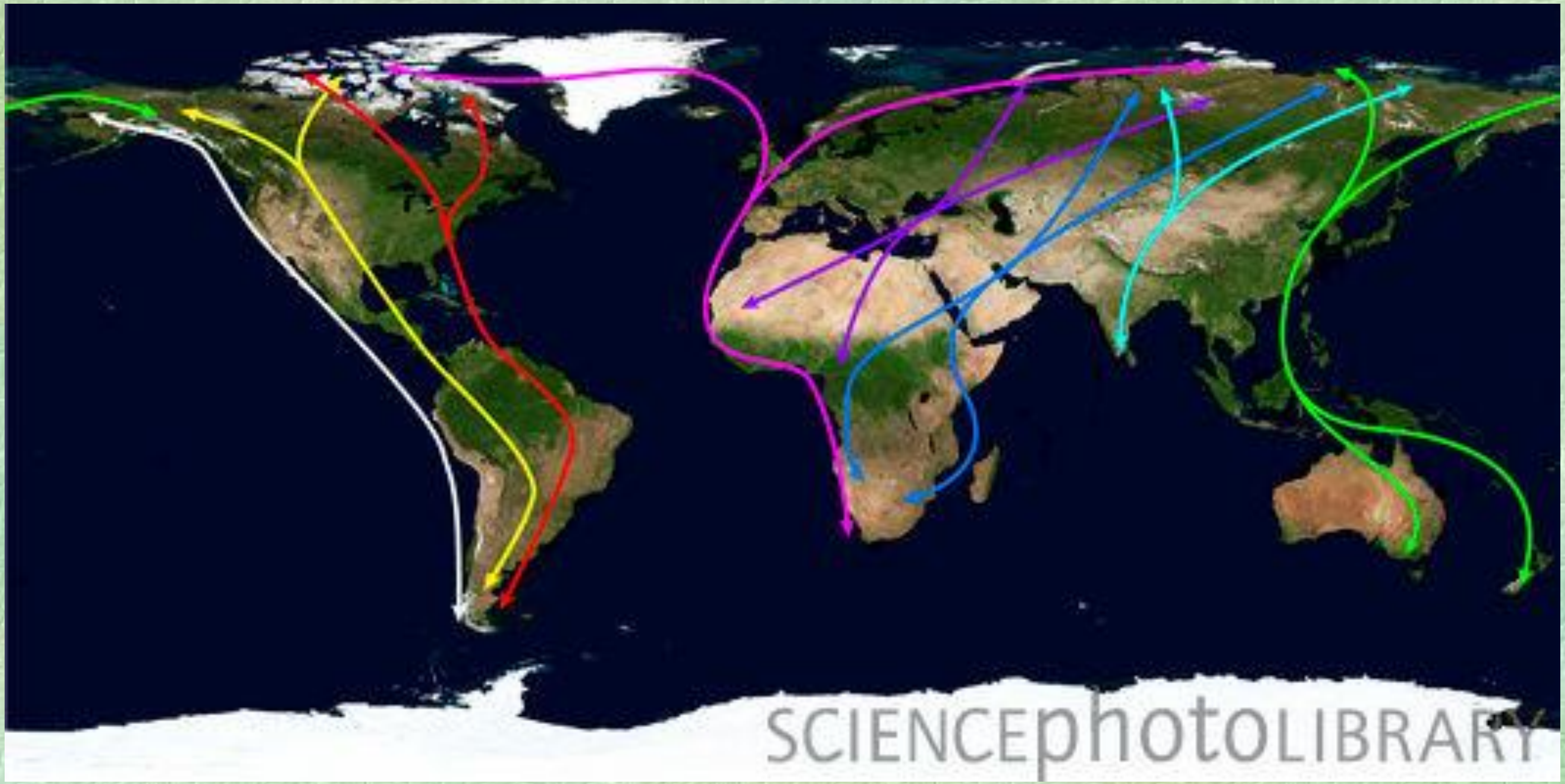
Modeling isoscapes and origins using multiple isotopes

- Assumes a multivariate normal distribution
  - All isotopes are orthogonal

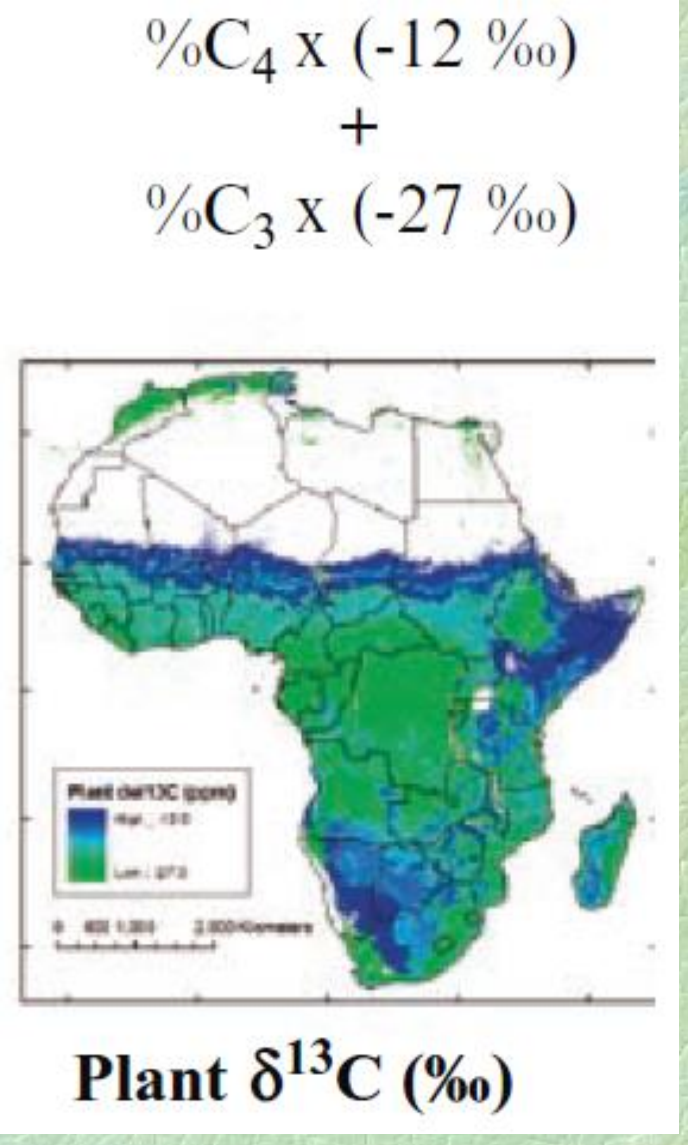




Major overwintering site for Palearctic-Aftrotopical migrants



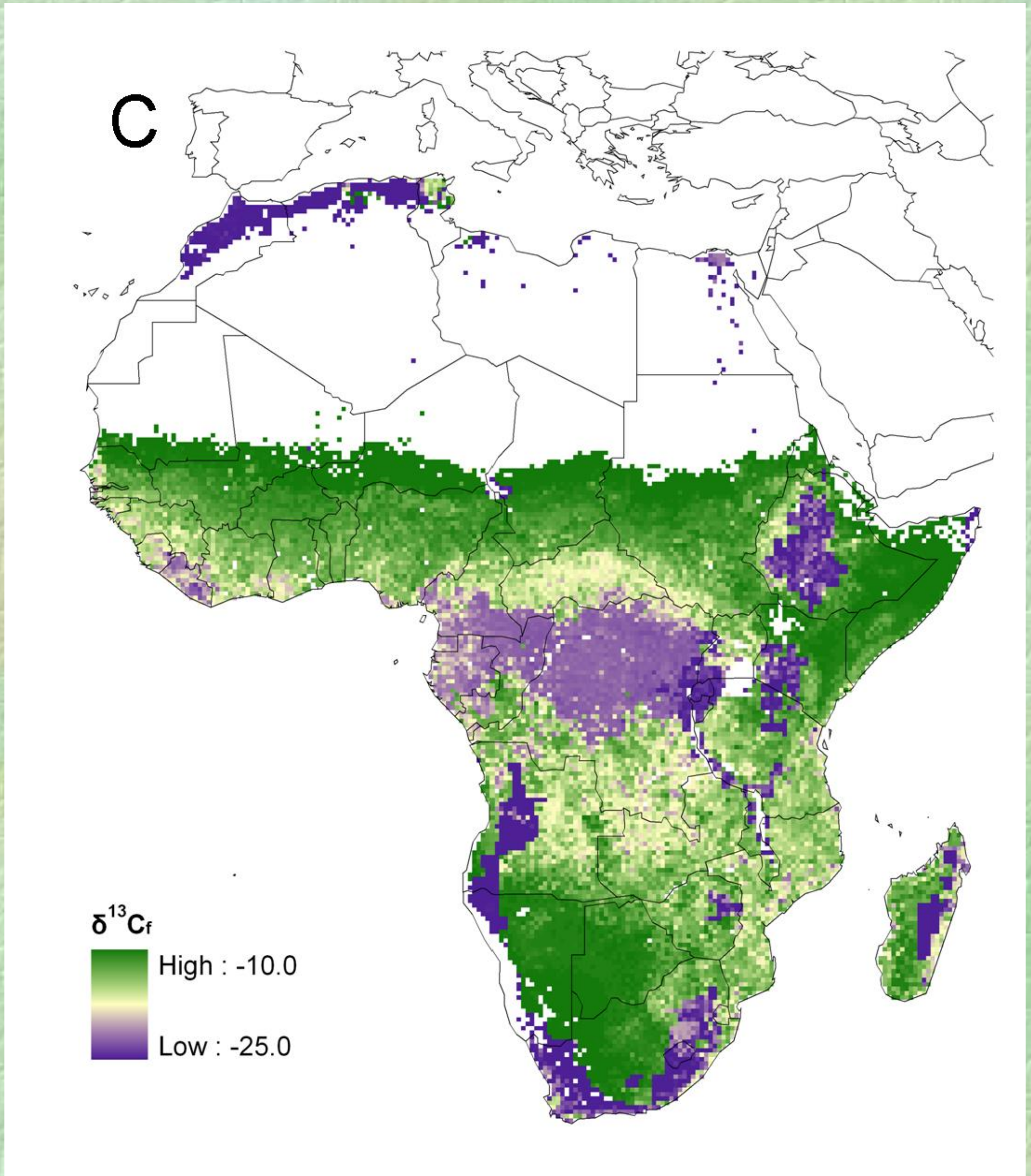
Plant isotope distribution models



- Plant isotope map based on predicted C3 vs. C4 plants

Still and Powell (2010)

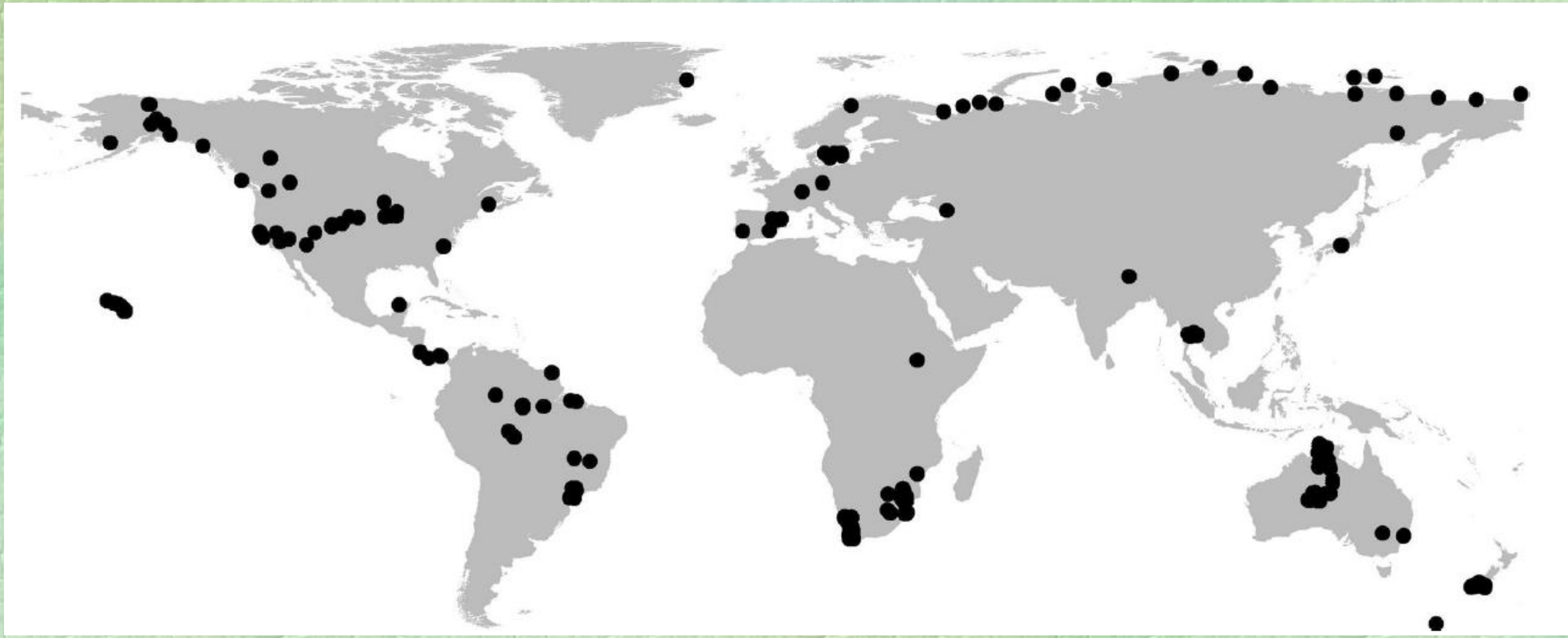
Feather $\delta^{13}C$ isoscape

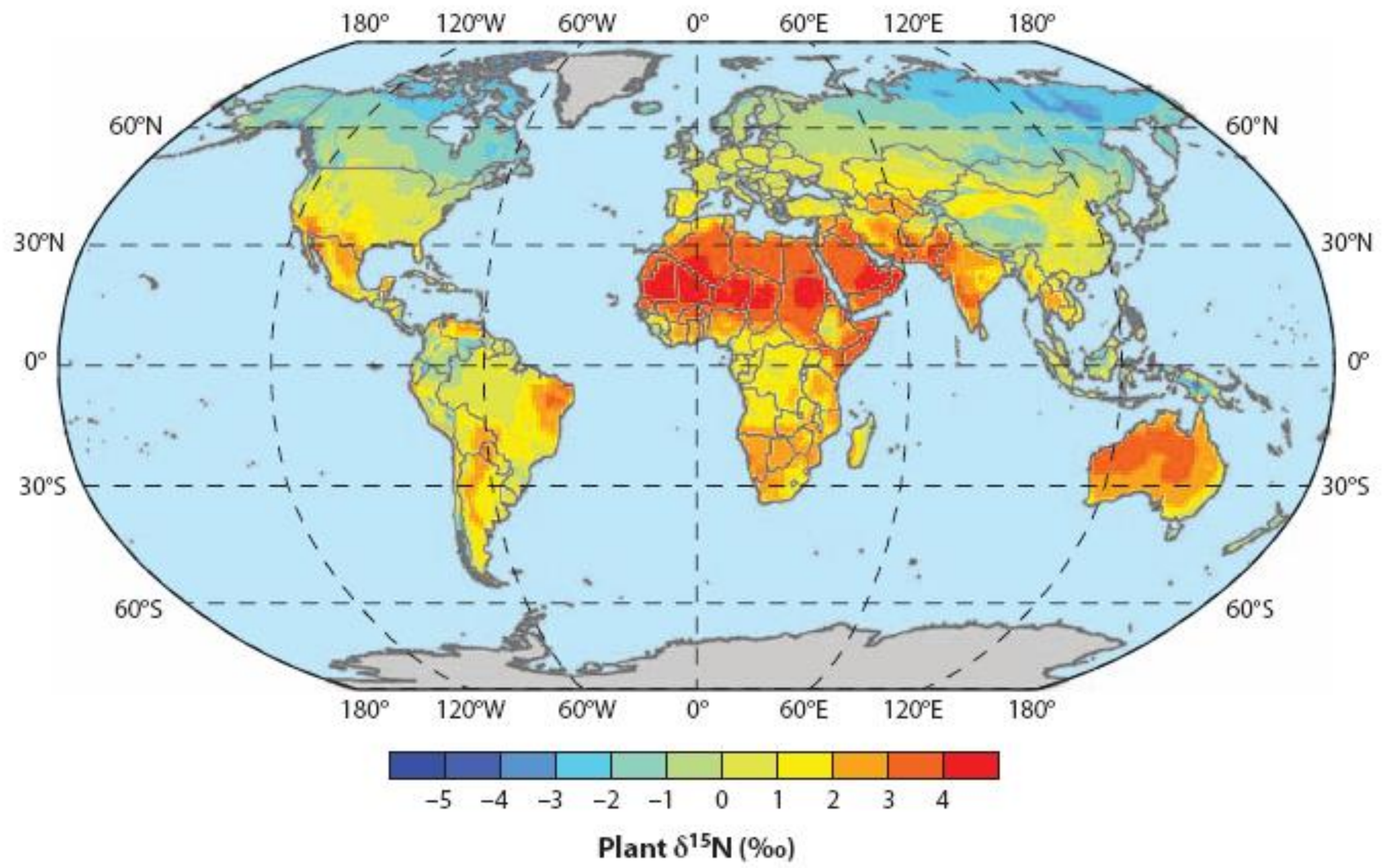


A feather $\delta^{15}N$ isoscape

Based on Craine et al. (2009, New Phytologist)

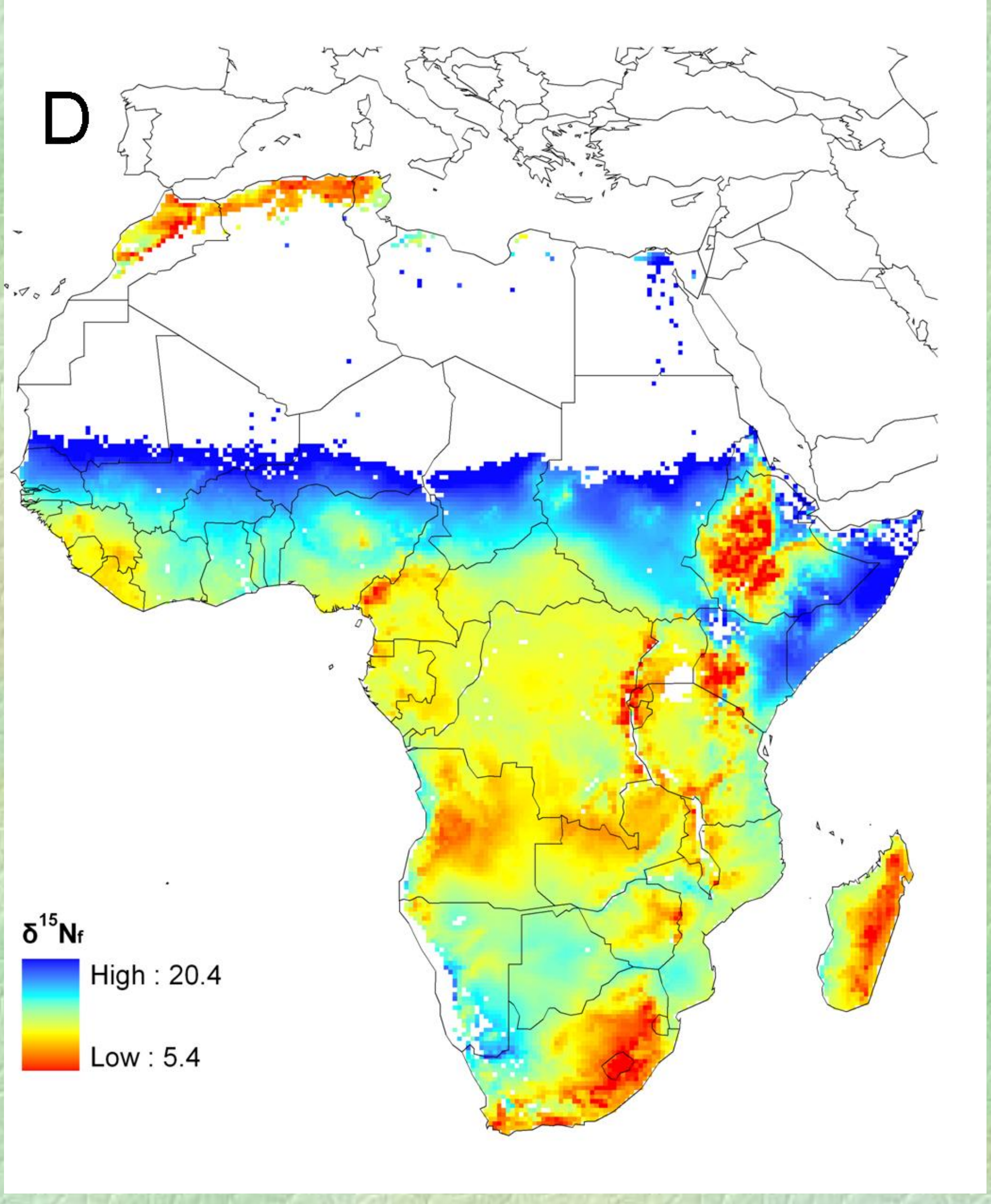
- Modeled MAT, MAP with foliar $\delta^{15}N$



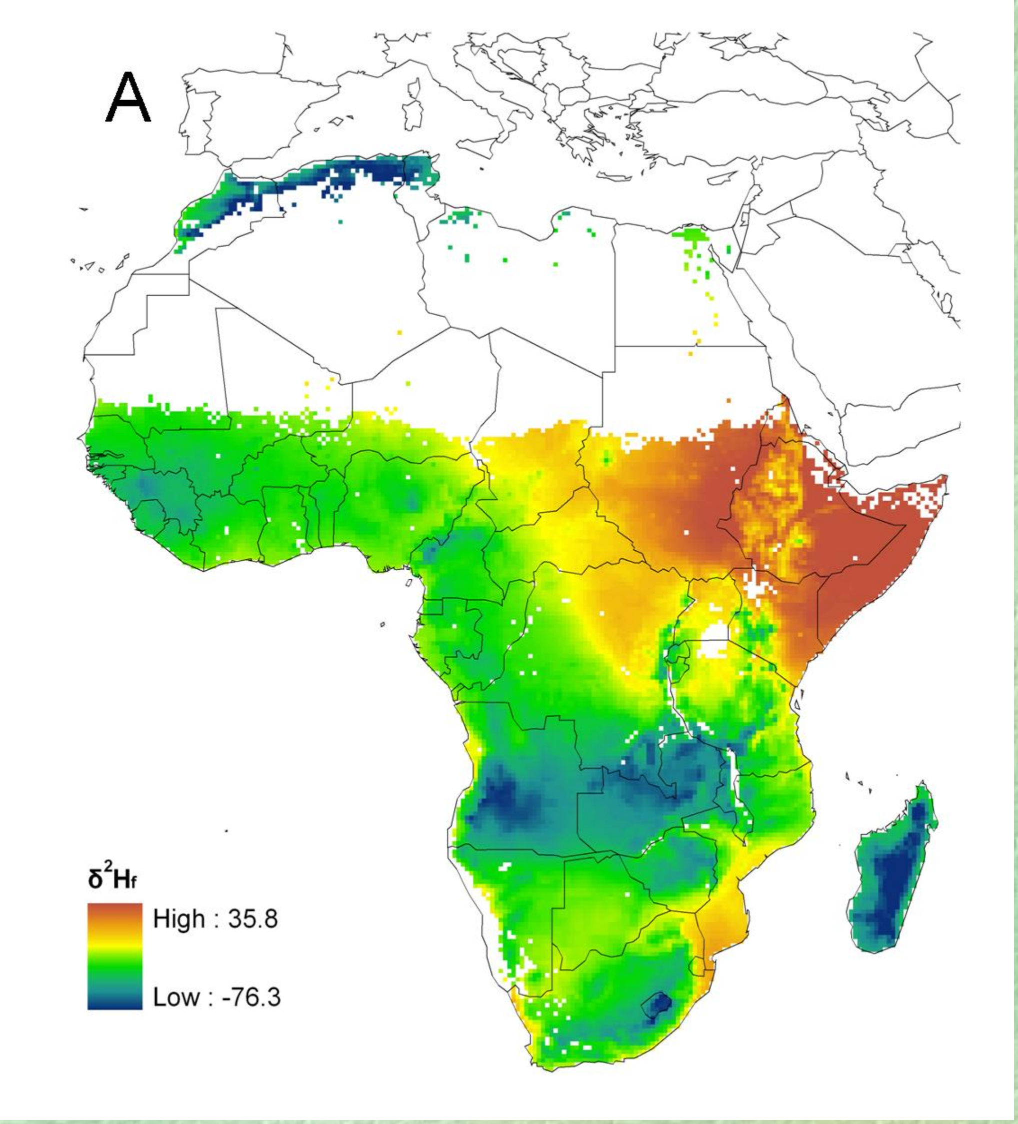


180°
120°W
60°W
0°
60°E
120°E
180°
60°N
30°N
0°
30°S
60°S
−5
−4
−3
−2
−1
0
1
2
3
4
Plant δ15N (‰)

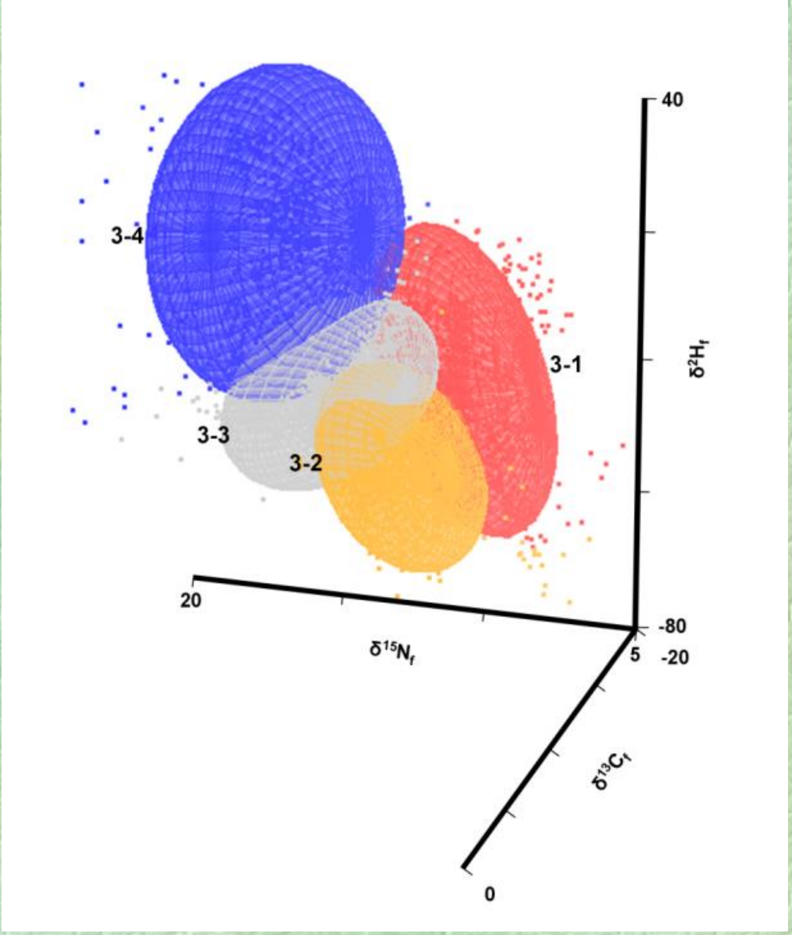
Feather $\delta^{15}N$ isoscape

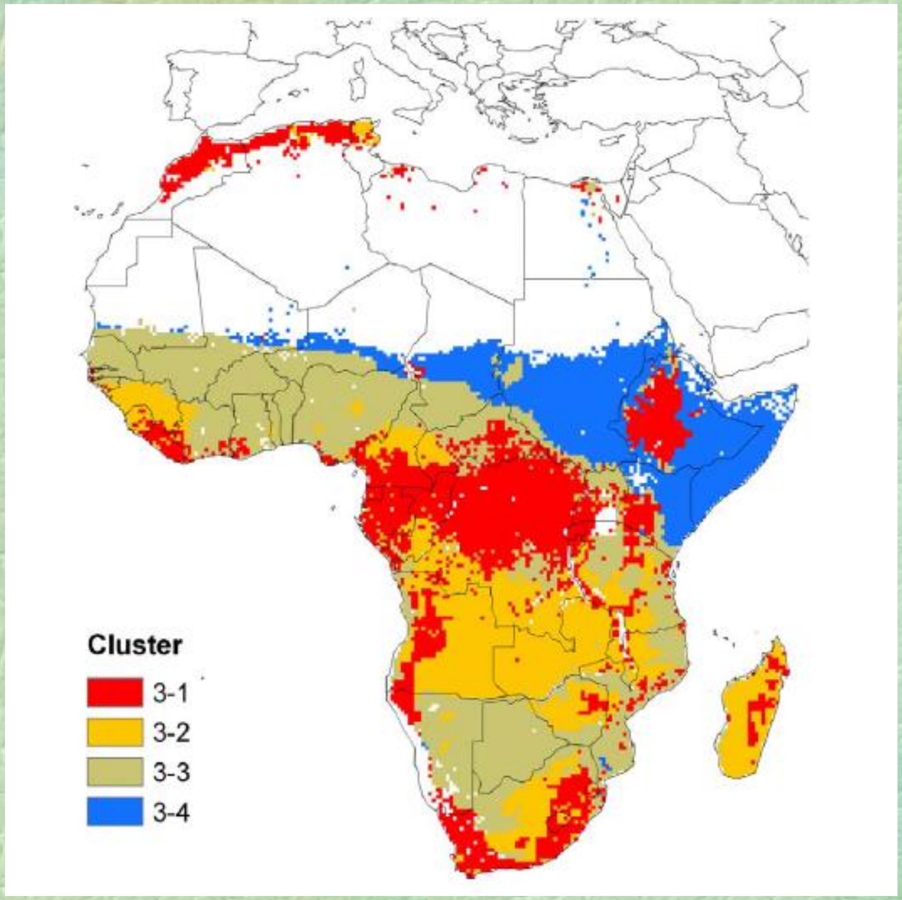


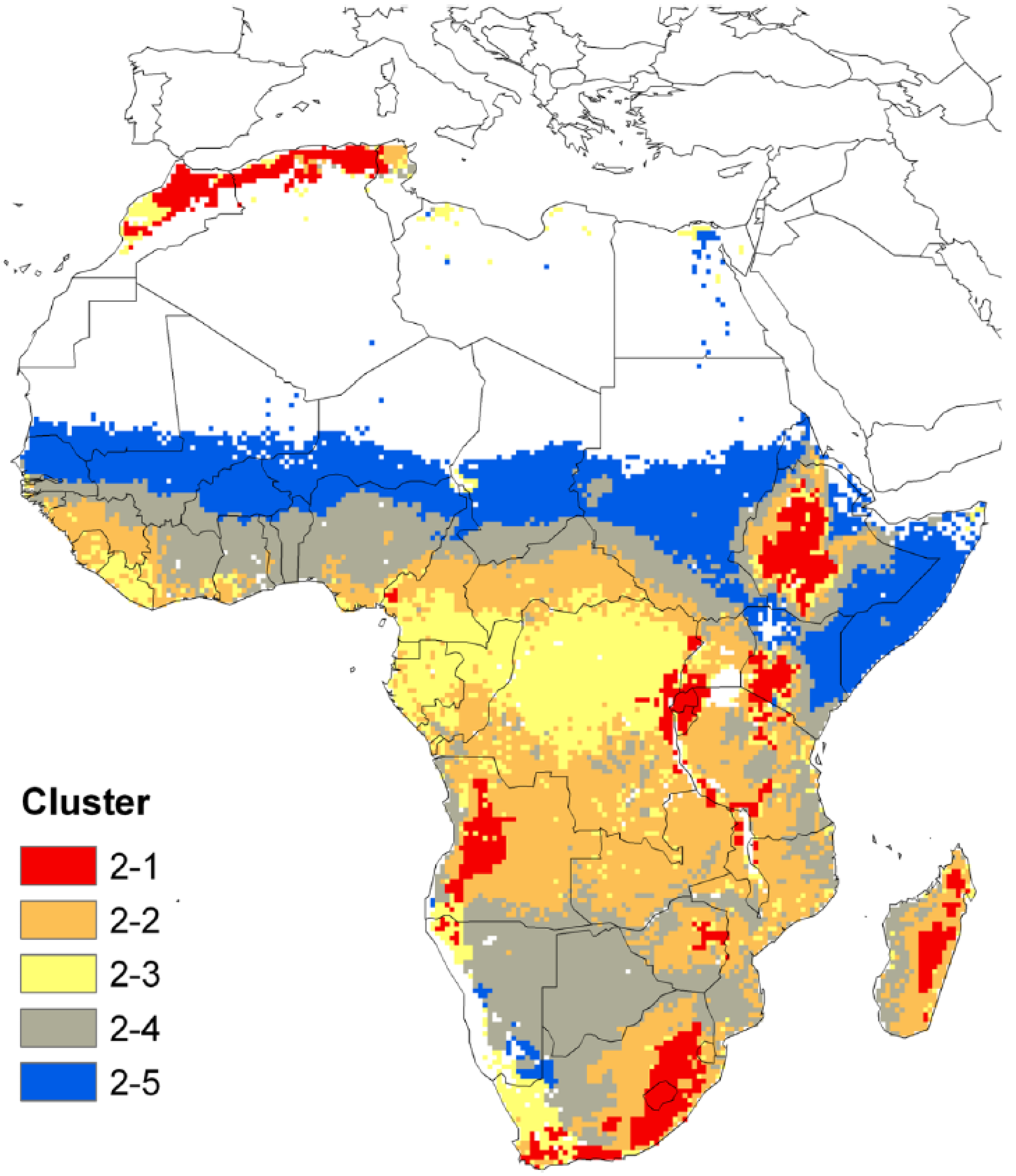
Feather δ^2H isoscape



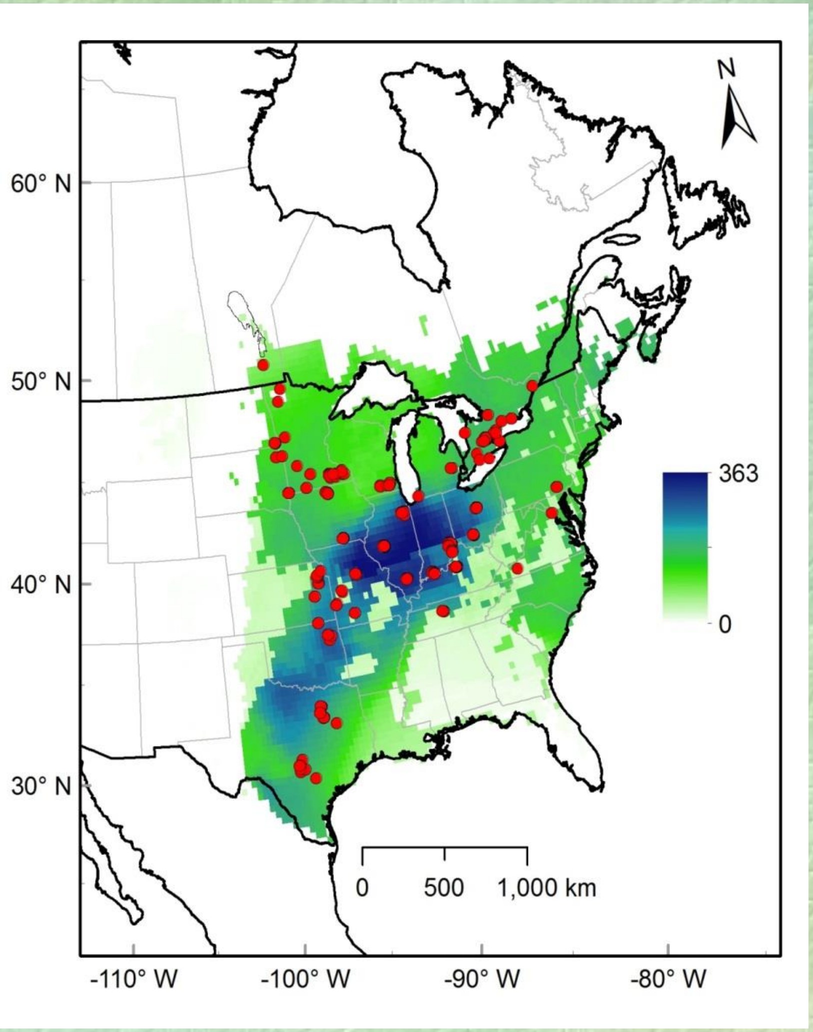
Combining $\delta^{13}C$, $\delta^{15}N$, $\delta^{2}H$ feather isoscapes

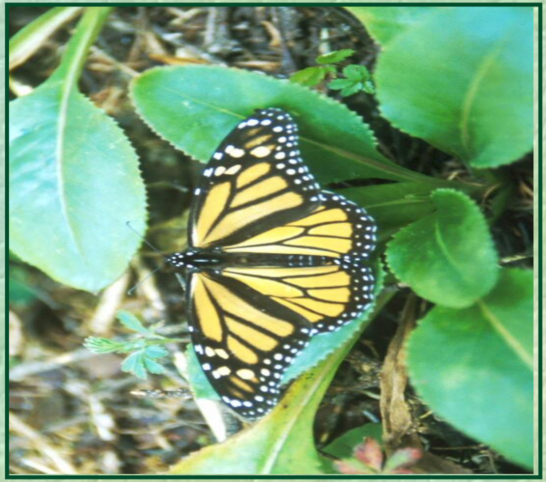




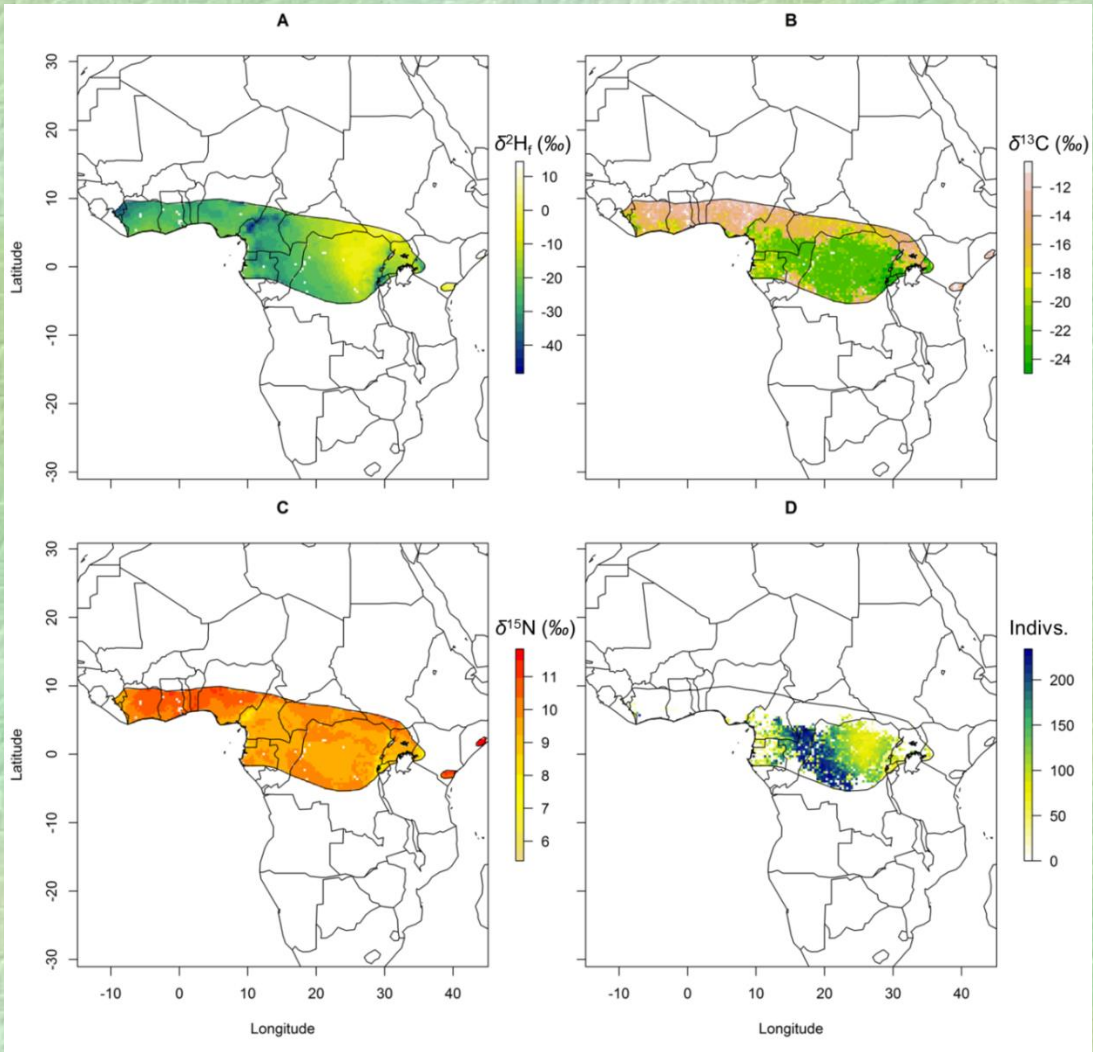

Cluster
2-1
2-2
2-3
2-4
2-5

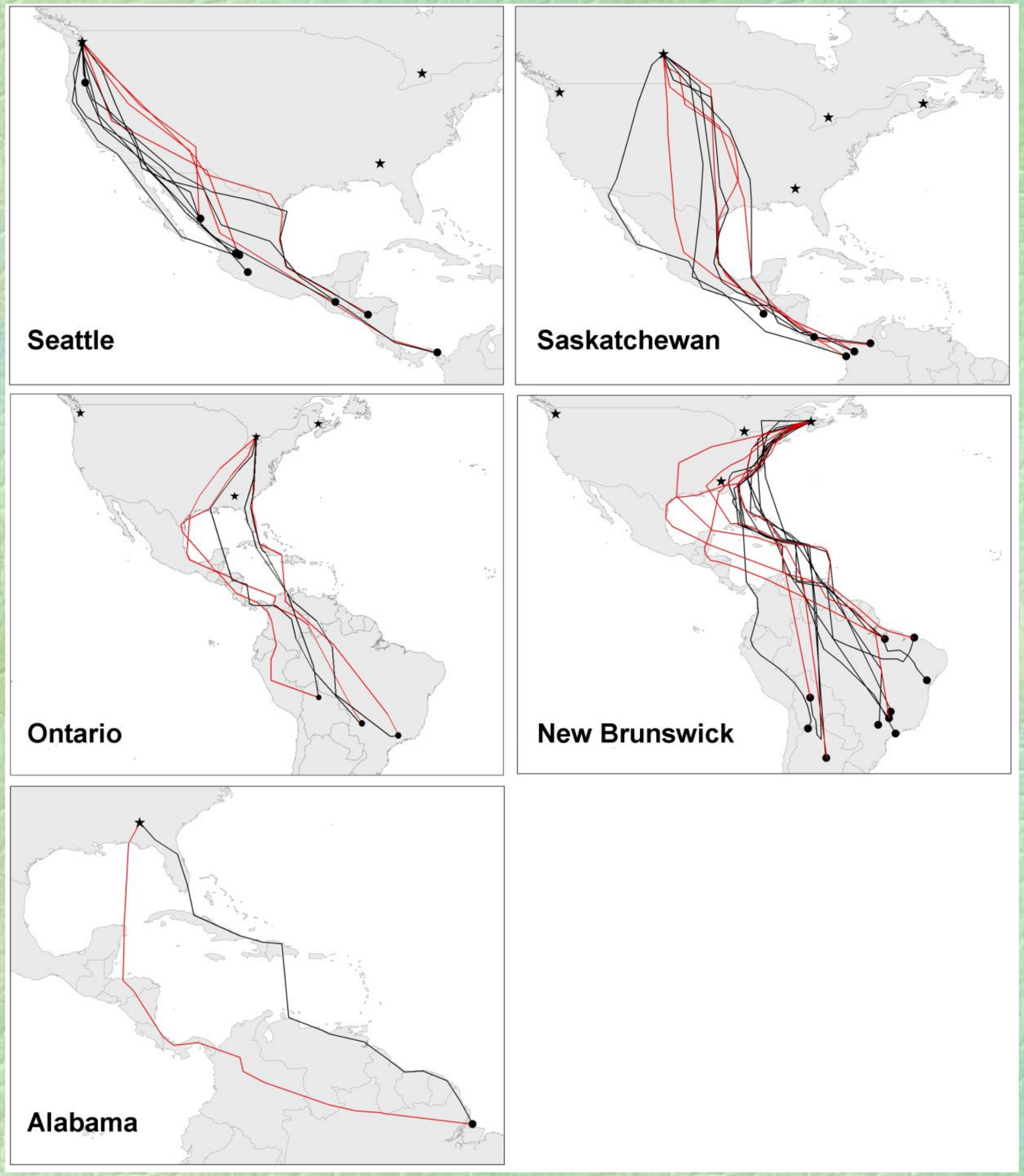
Combining two isotopes into a single probability surface

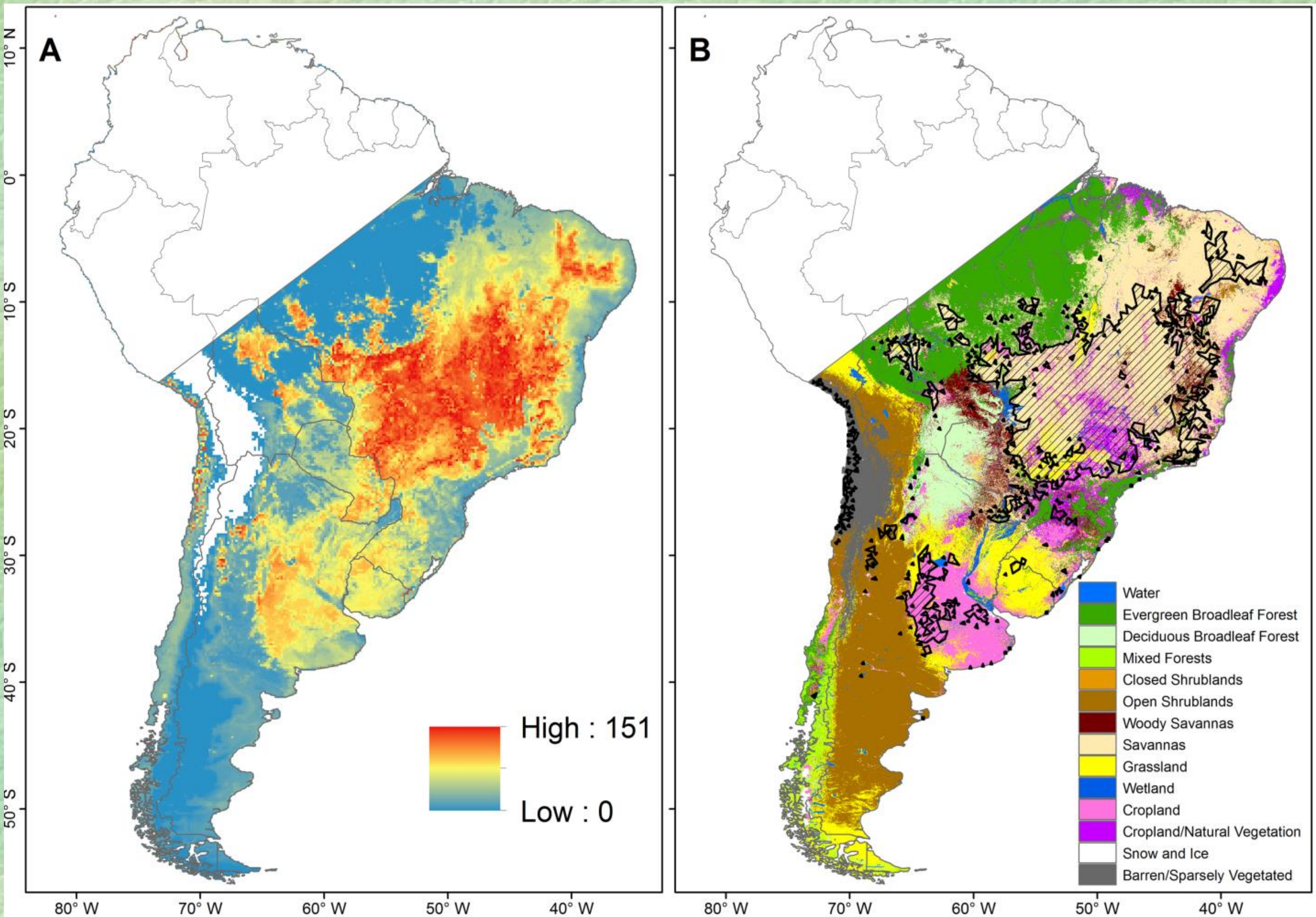




A multi-isotope (δ^2H,$\delta^{13}C$,$\delta^{15}N$) probability surface




Seattle
Saskatchewan
Ontario
New Brunswick
Alabama


A
B
High : 151
Low : 0
10° N
0°
10° S
20° S
30° S
40° S
50° S
80° W
70° W
60° W
50° W
40° W
Water
Evergreen Broadleaf Forest
Deciduous Broadleaf Forest
Mixed Forests
Closed Shrublands
Open Shrublands
Woody Savannas
Savannas
Grassland
Wetland
Cropland
Cropland/Natural Vegetation
Snow and Ice
Barren/Sparsely Vegetated

Some other considerations and future directions….

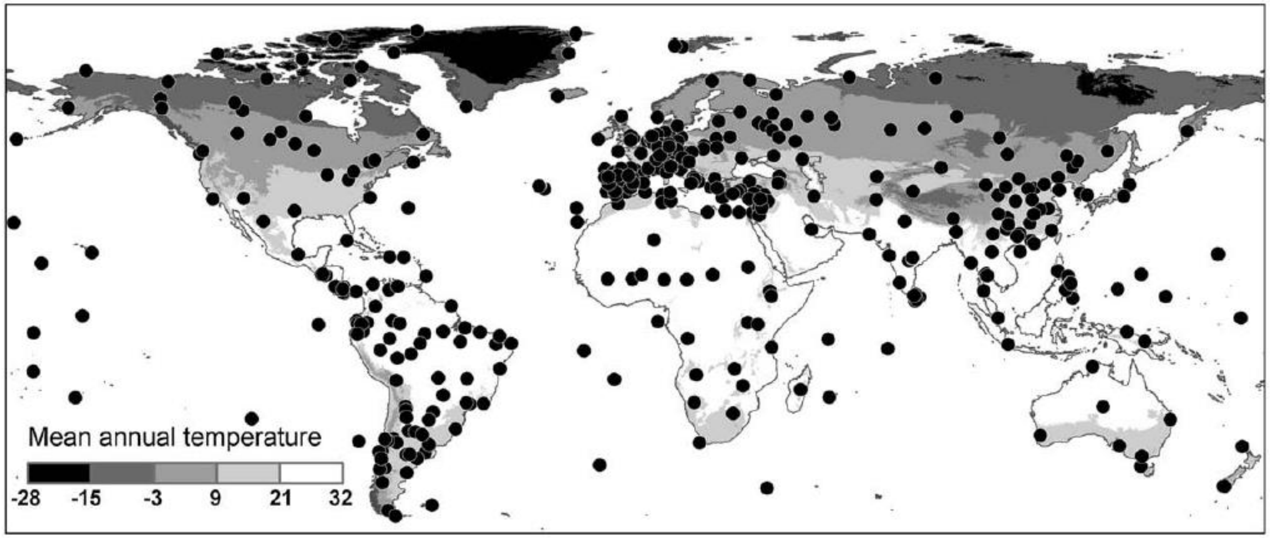
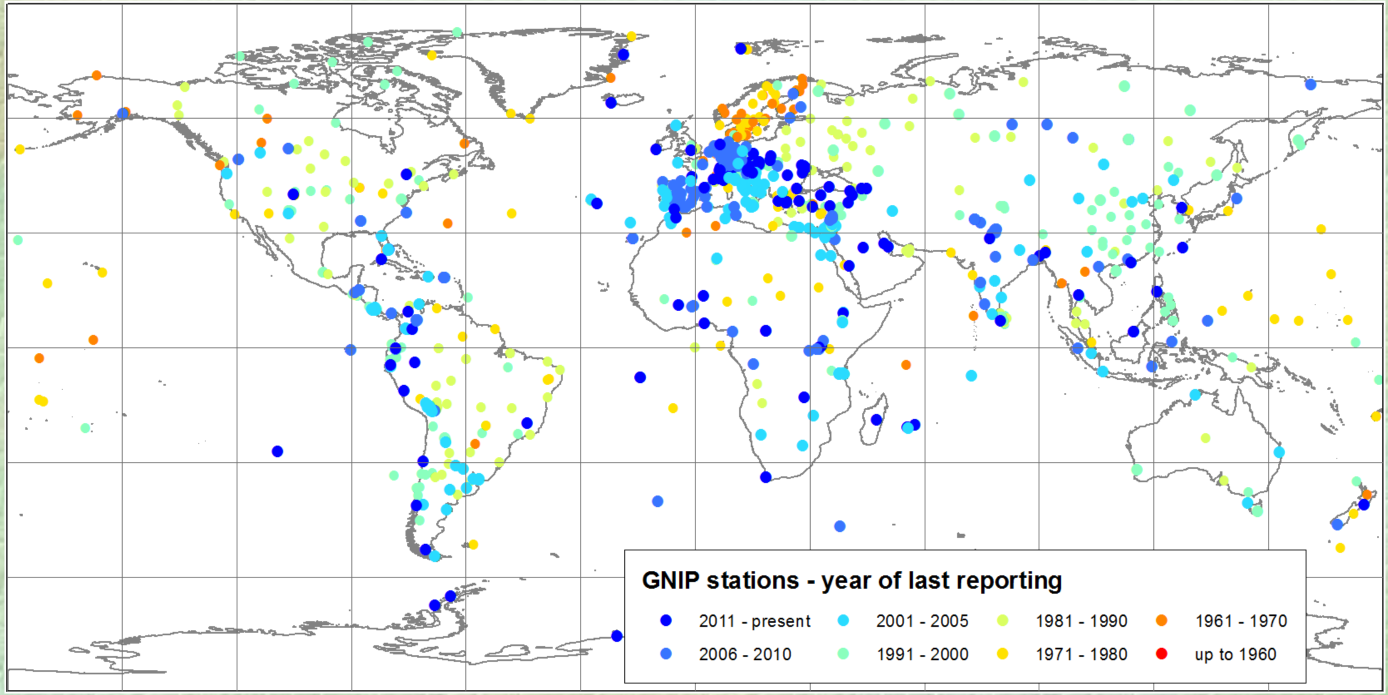
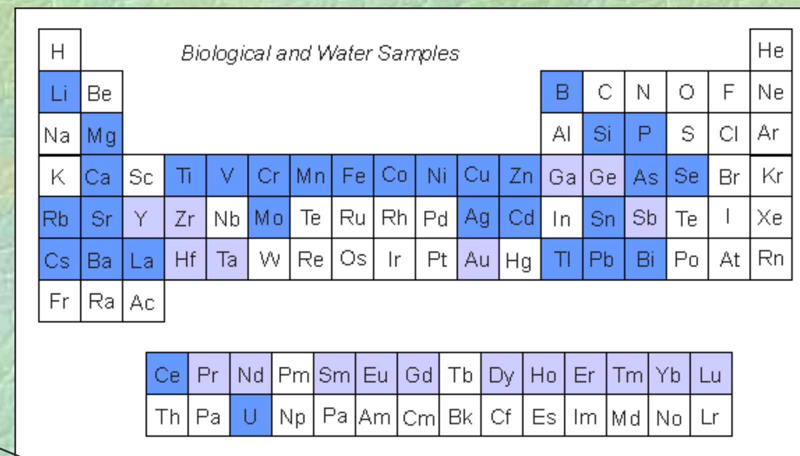


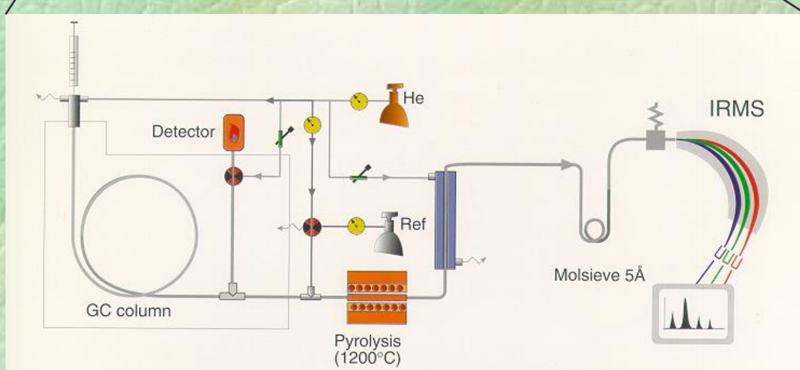
Fig. 1. Map showing the individual GNIP stations that measured the (weighted) annual mean δ^2H and $\delta^{18}O$ composition of precipitation for at least 1 year during 1960–2001 ($N = 467$). Background map shows the annual mean temperature (WorldClim data; see Hijmans et al., 2005).



Advances in water isoscapes

Trace element/heavy isotope





Compound specific
Mass spectrometry