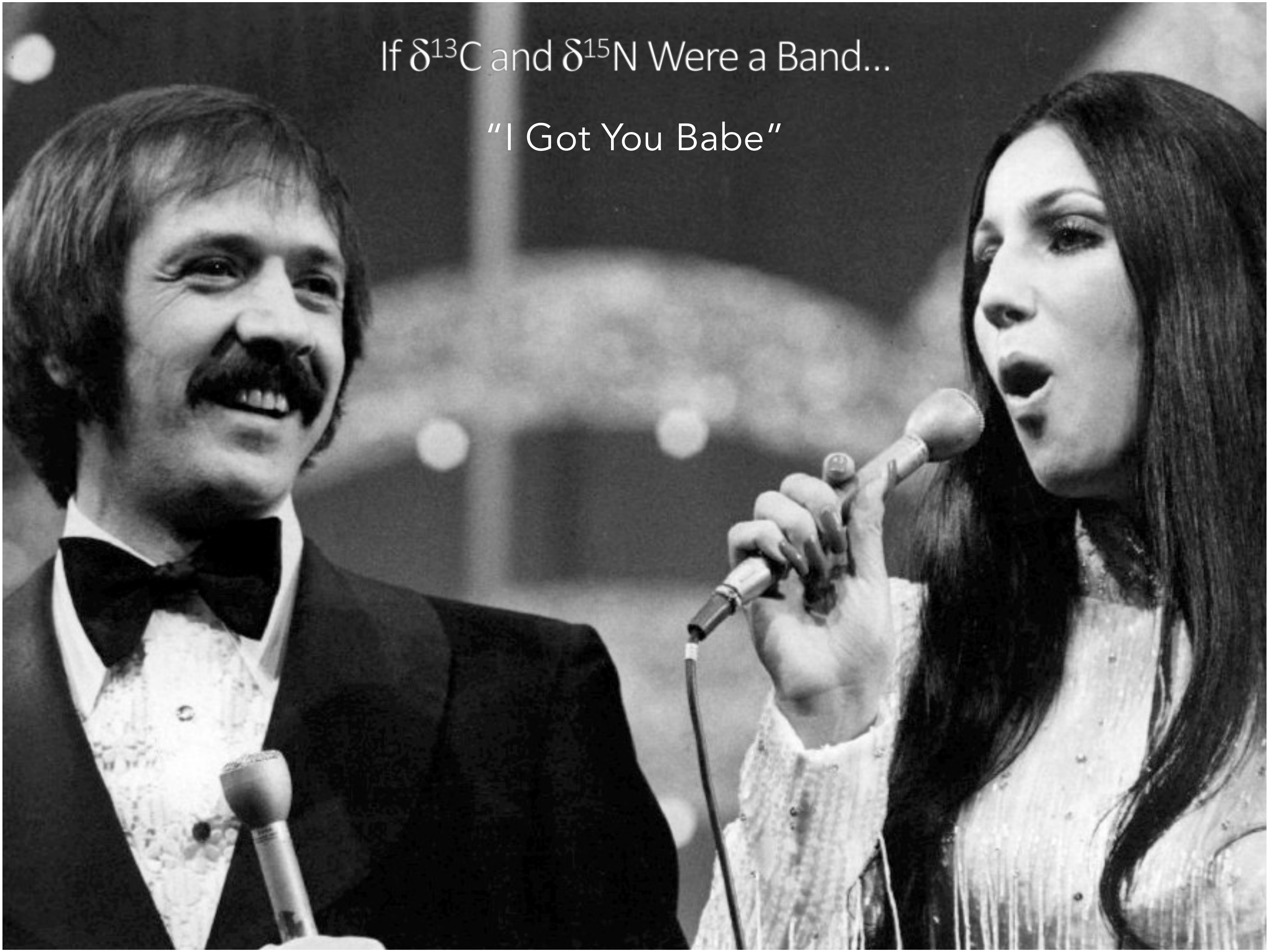
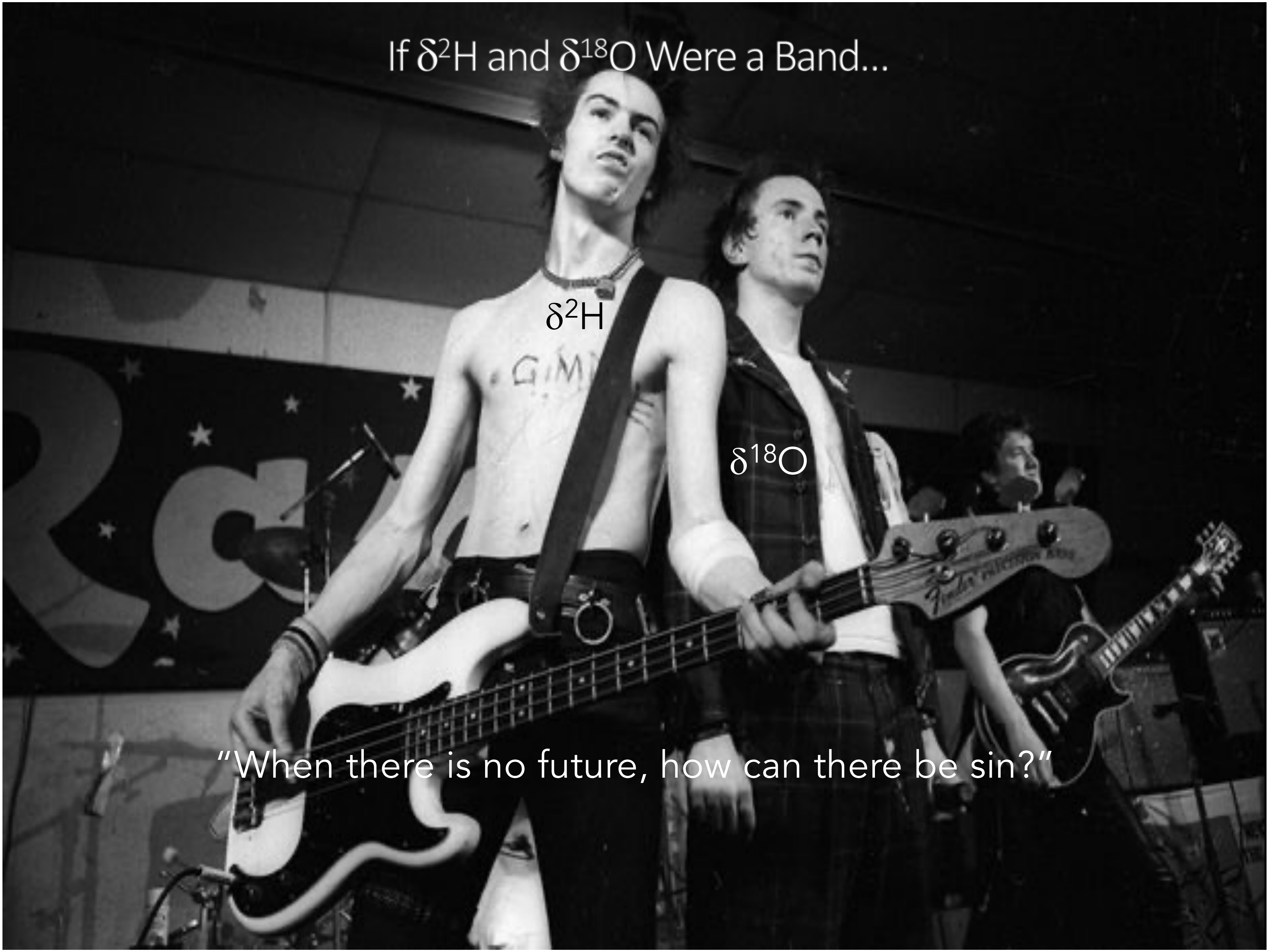

If $\delta^{13}C$ and $\delta^{15}N$ Were a Band…
"I Got You Babe"


If δ^2H and $\delta^{18}O$ Were a Band…
δ^2H
$\delta^{18}O$
"When there is no future, how can there be sin?"

Hydrogen in Animals

Rayleigh Distillation & Isoscapes

Tracking Avian Movement & Migration Patterns

Examples: Monarch Butterflies, Warblers, and Humminbirds

Intra-Population Variation in Tissue δ^2H

Using δ^2H to Trace Food

Refining the use of δ^2H as an Ecological Tool:
Analytical versus Eco-Physiological Sources of Error

Bands

Geolocators

MOTUS

Satellite Tags

North American Band Recoveries (1955-2000)

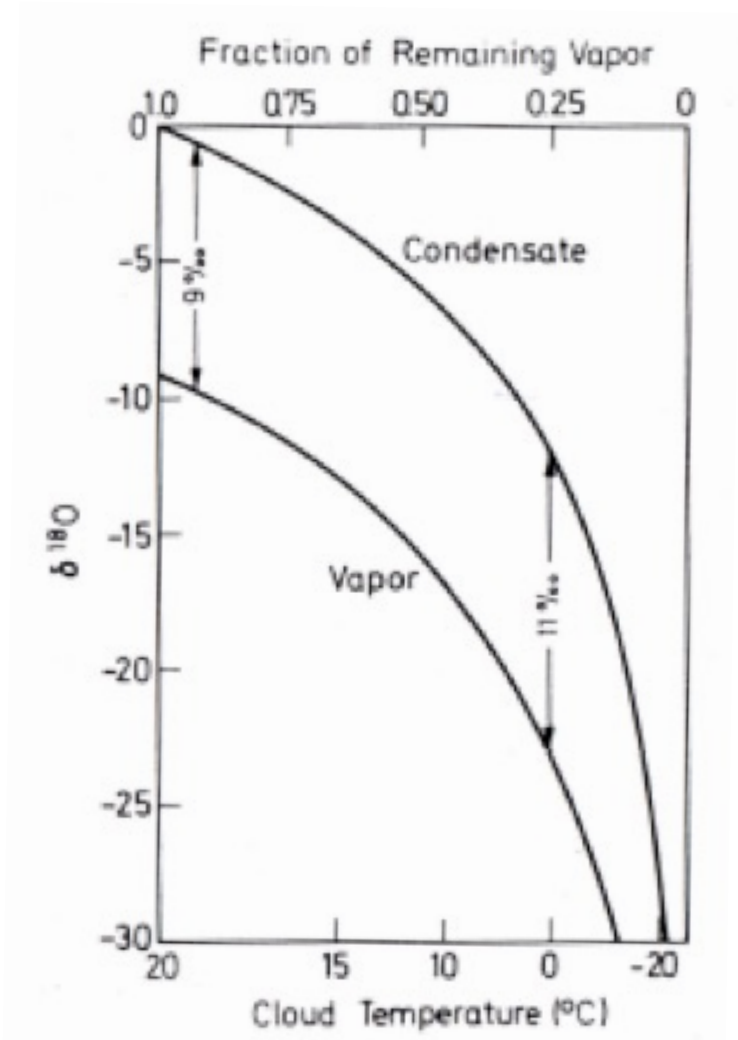
Species	*Banded*	*Recaptured*	*%*
Canada Goose	2,991,538	594,114	19.9
Mallard	5,935,960	878,704	14.8
Northern Pintail	1,286,499	142,449	11.1
Merlin	26,308	674	2.6
Loggerhead Shrike	22,897	196	0.86
Spotted Sandpiper	13.673	79	0.58
Red-Throated Hummingbird	54,218	53	0.10
American Redstart	275,222	256	0.09
Myrtle Warbler	824,013	704	0.09
Western Flycatcher	28,194	20	0.07
Swainson's Thrush	371,313	251	0.07

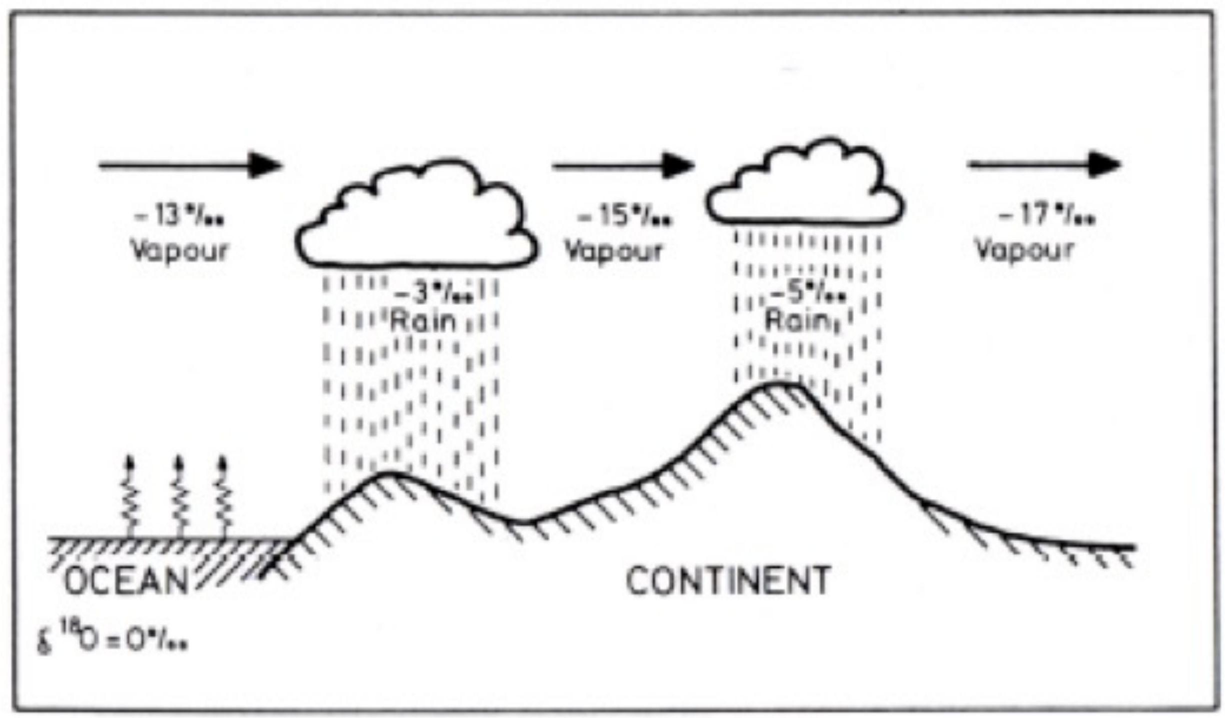
<1% recovery rate for most passerines

Can we use isotopes to better understand bird migration?

Remember Rayleigh Distillation

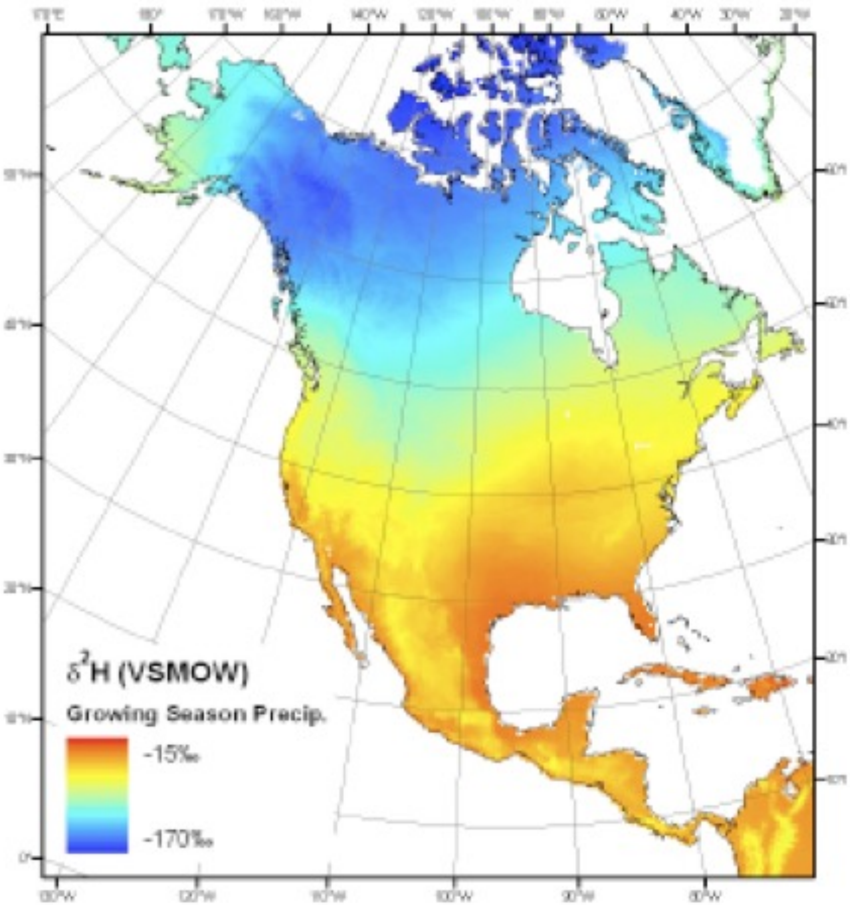
The water in clouds formed over the ocean tends to be "depleted" in ^{2}H (deuterium) and ^{18}O.

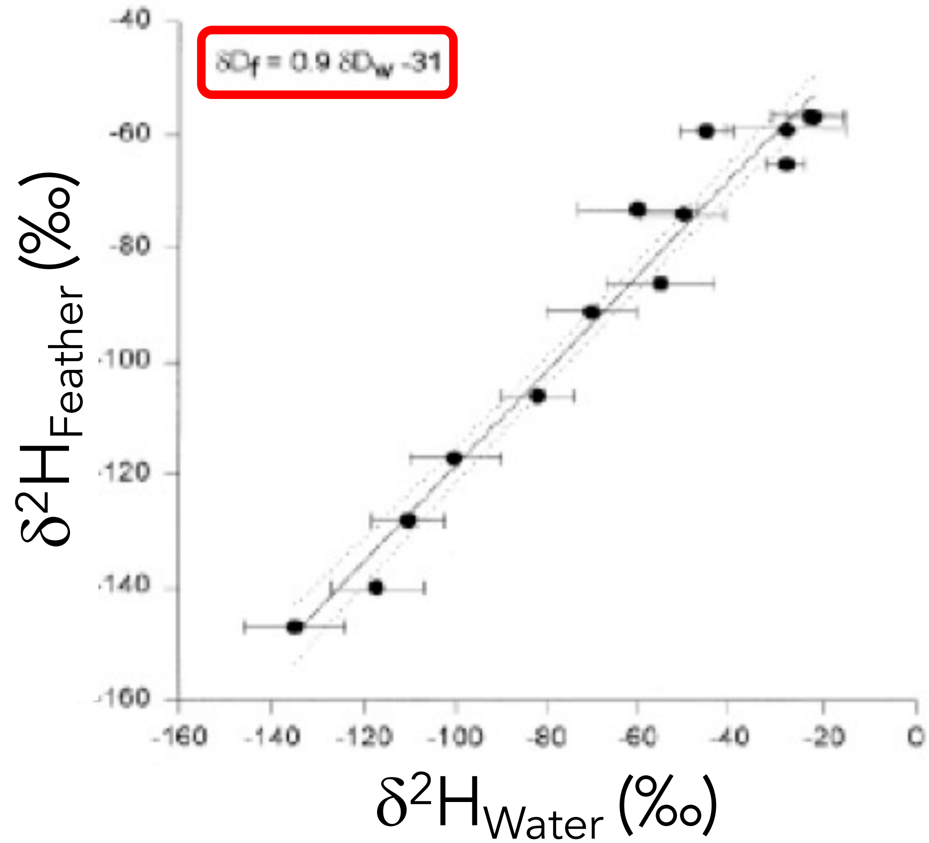




Rainwater, in contrast, is "enriched" in both ^{2}H and ^{18}O

In North America, rainwater and bird feathers become more depleted in δ^2H with increasing latitude of collection.





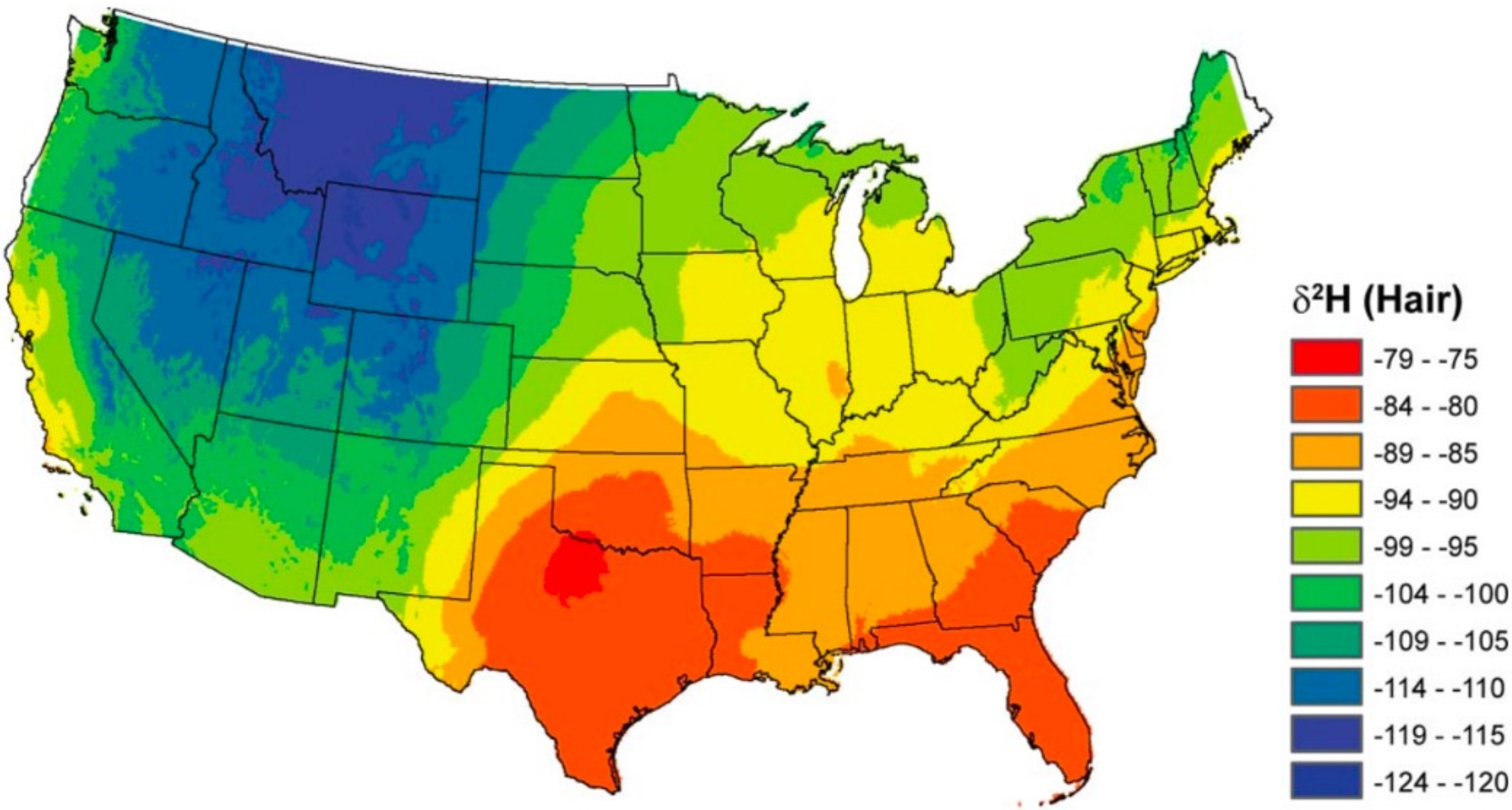
$\Delta^2H_{feather\text{-}precipitation} \approx -30‰$

100s of publications have used this approach to study animal movement/migration.

www.waterisotopes.org

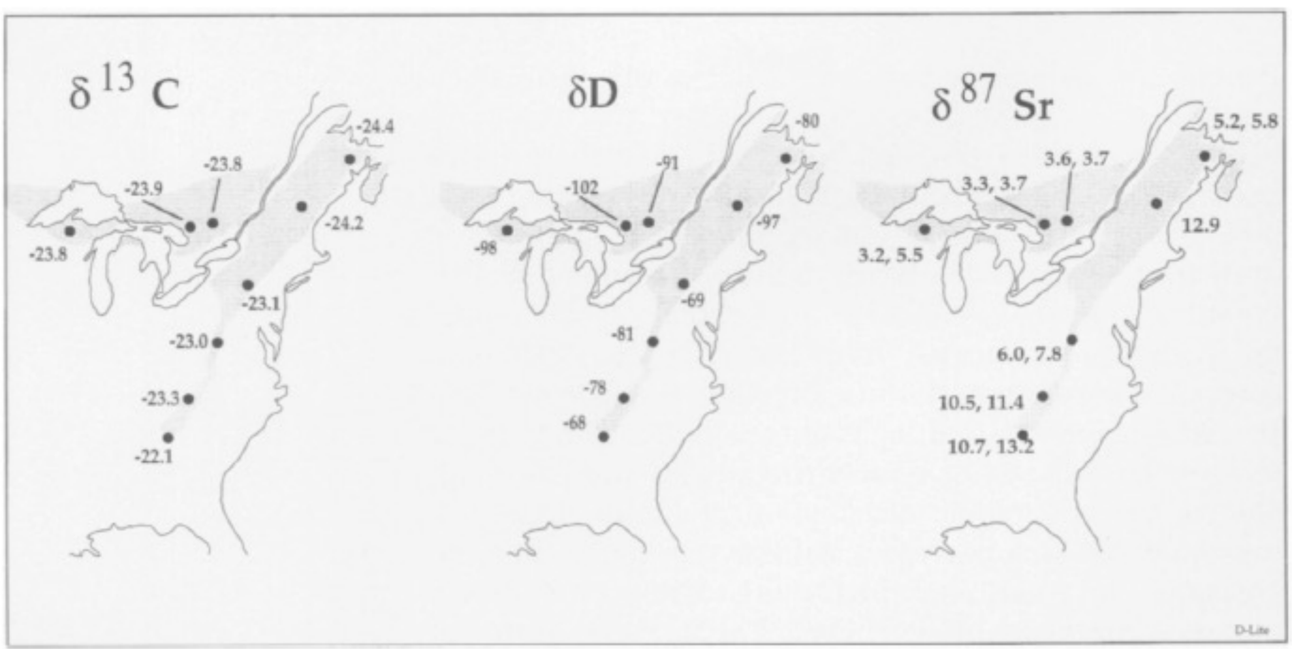
Hobson and Wassenaar 1997

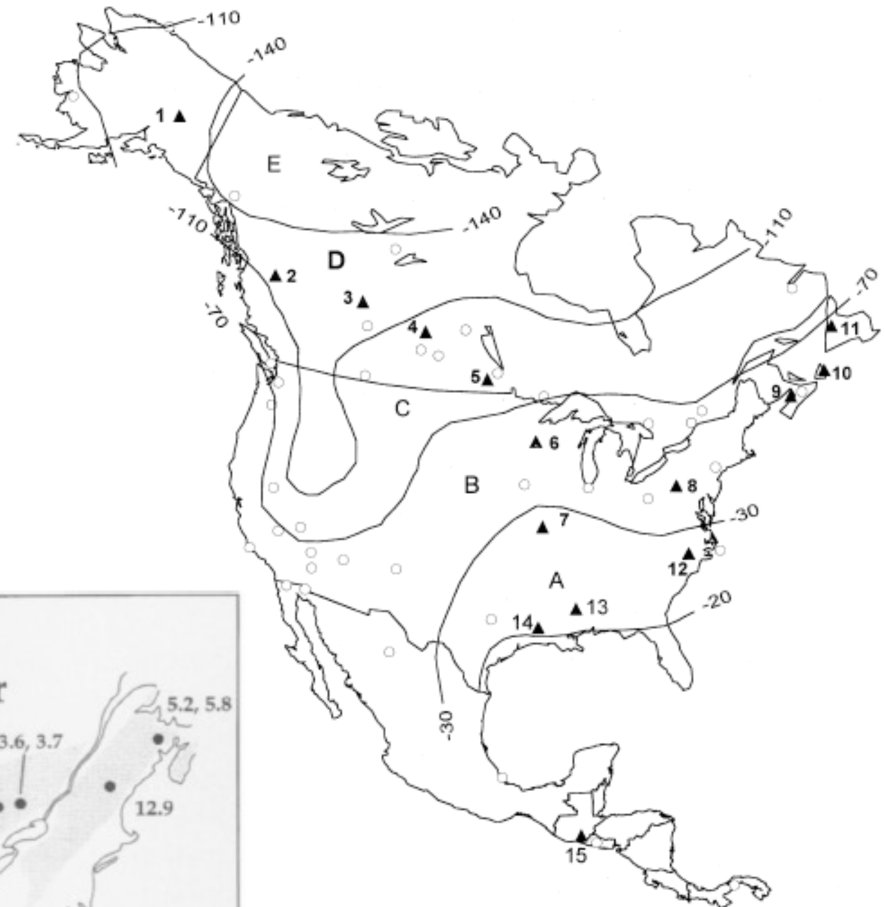
δ^2H: Geographic Assignment of Humans



Ehleringer et al. 2008

Origins of Using δ²H to Track Avian Movement





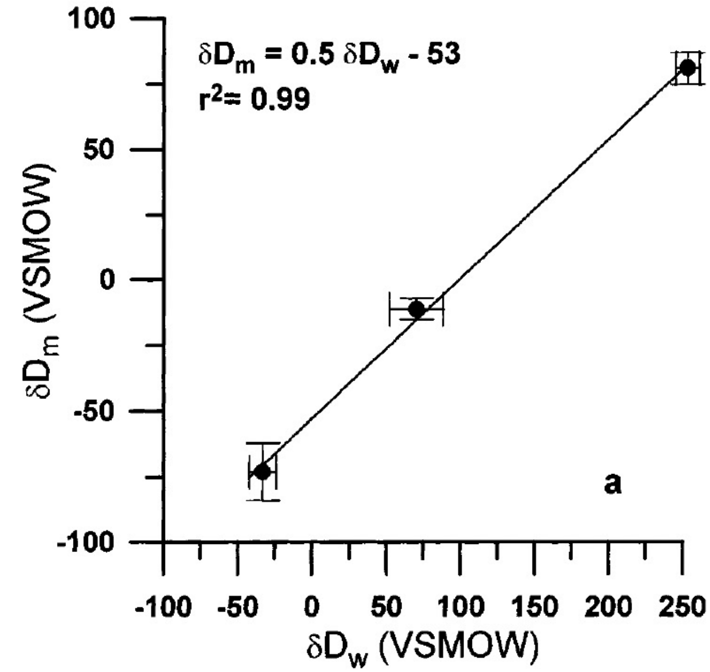
Chamberlain et al. 1996

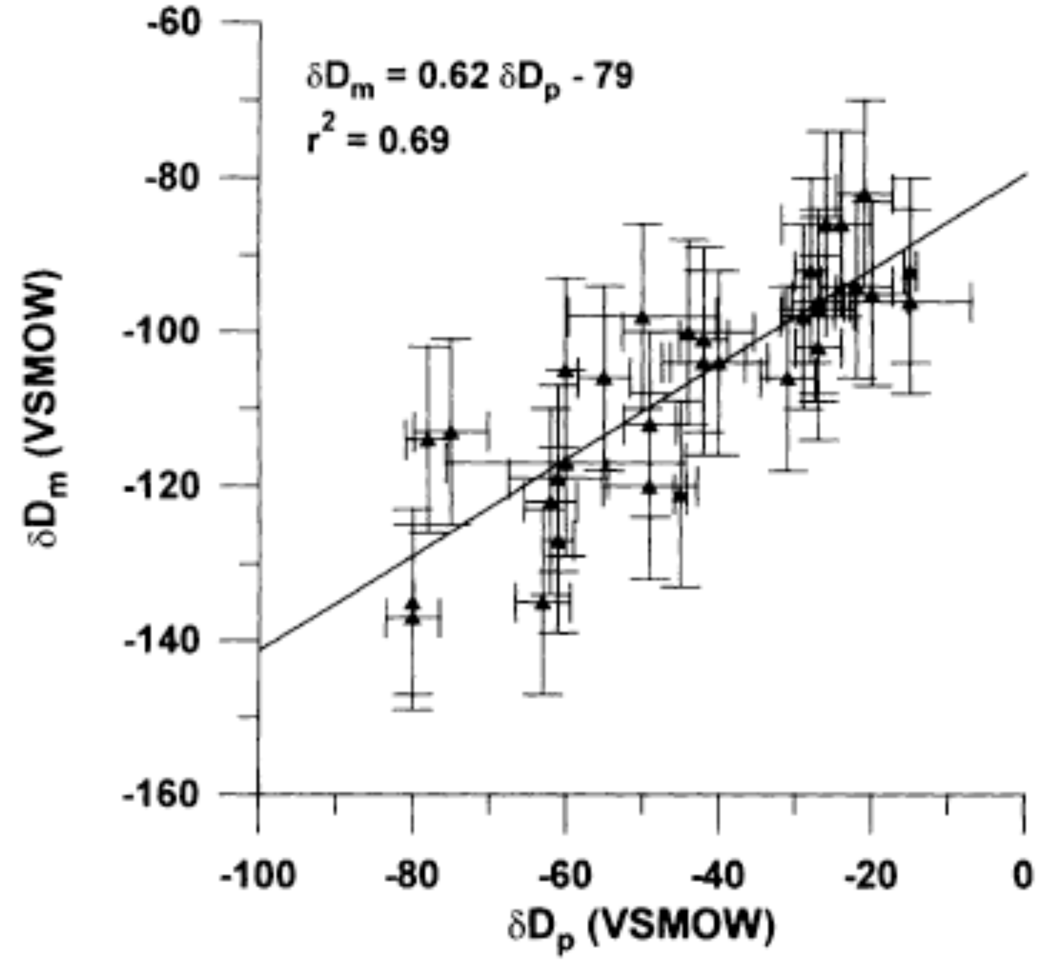
Hobson and Wassenaar 1996

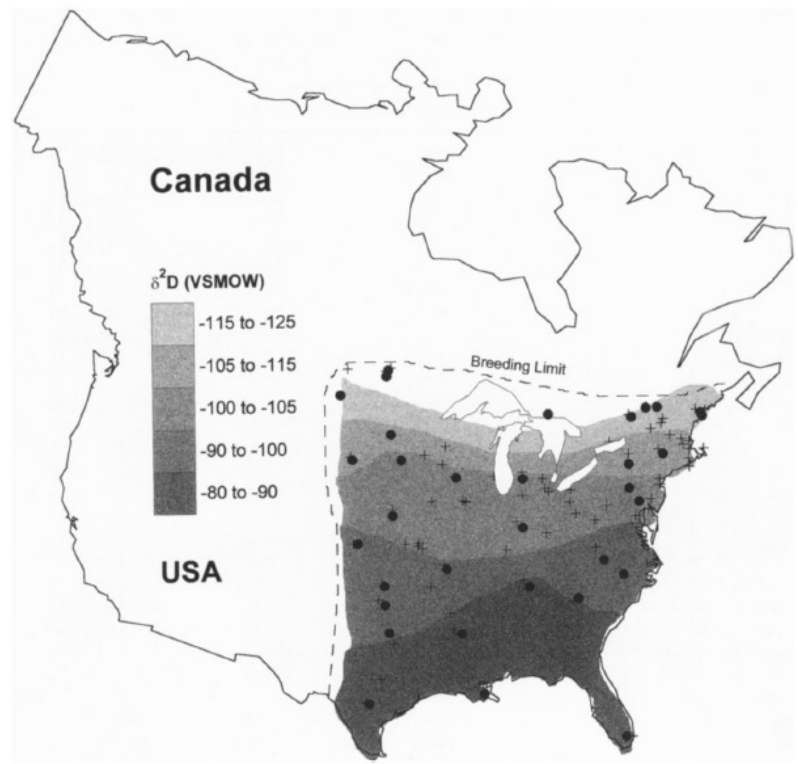
Tagging Butterflies?

Butterfly Isoscapes

Stable isotopes (δ^2H and $\delta^{13}C$) are geographic indicators of natal origins of monarch butterflies in eastern North America



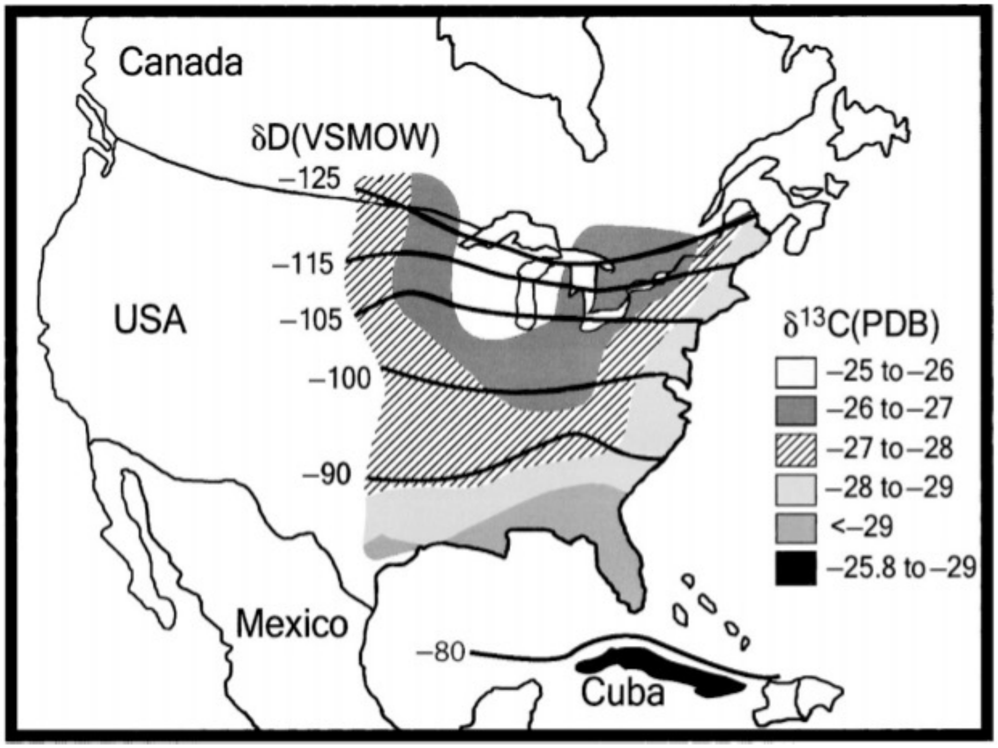


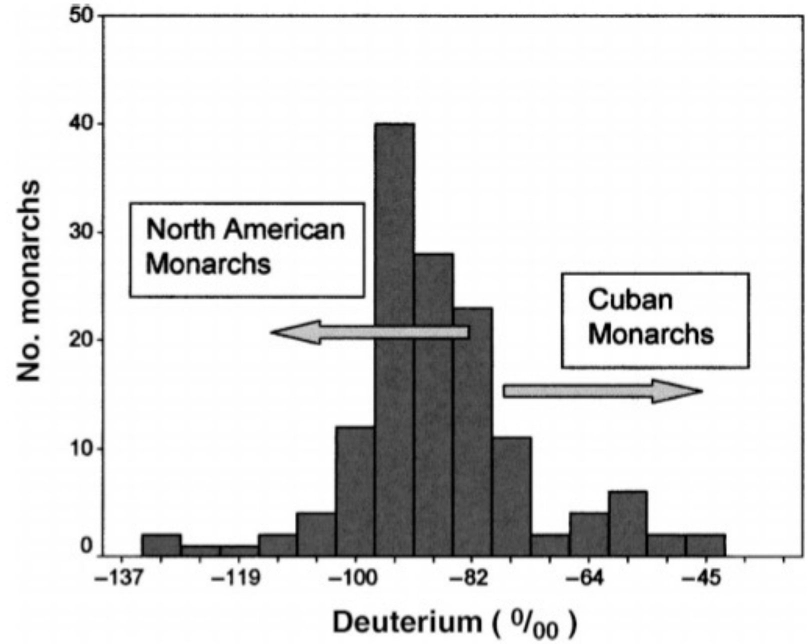


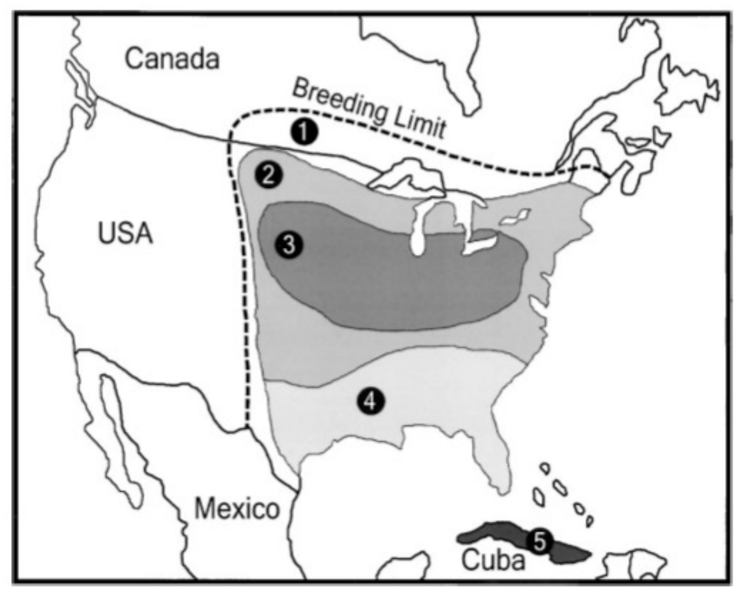
Hobson et al. 1999

Do North American monarch butterflies travel to Cuba?

“δ^2H and δ^{13}C “Monarch Isoscape”



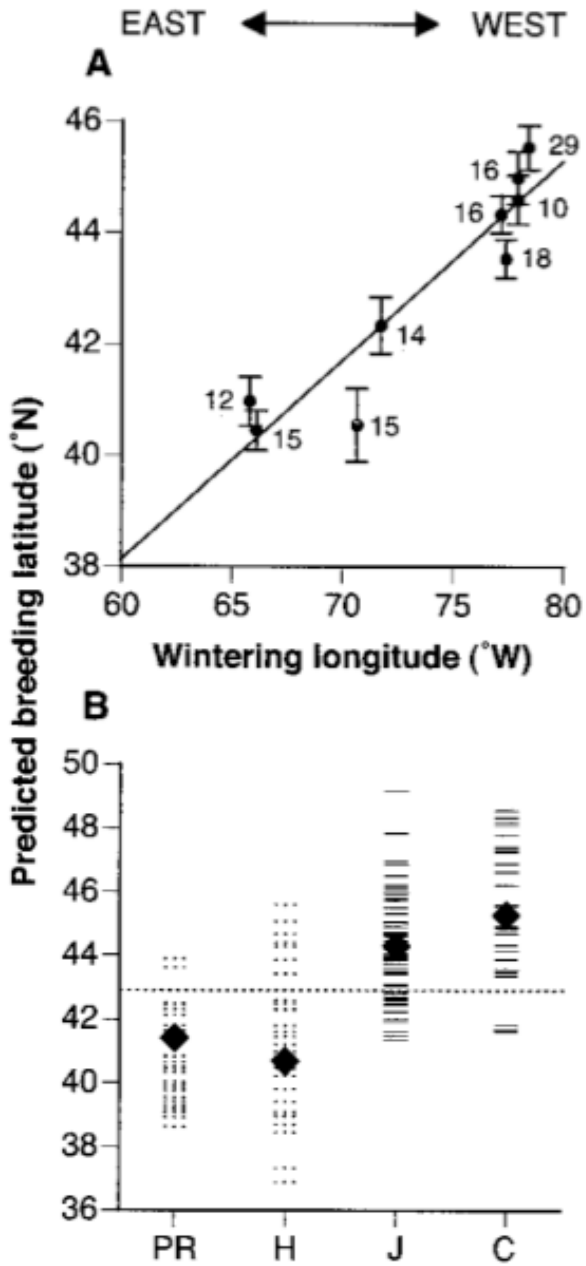


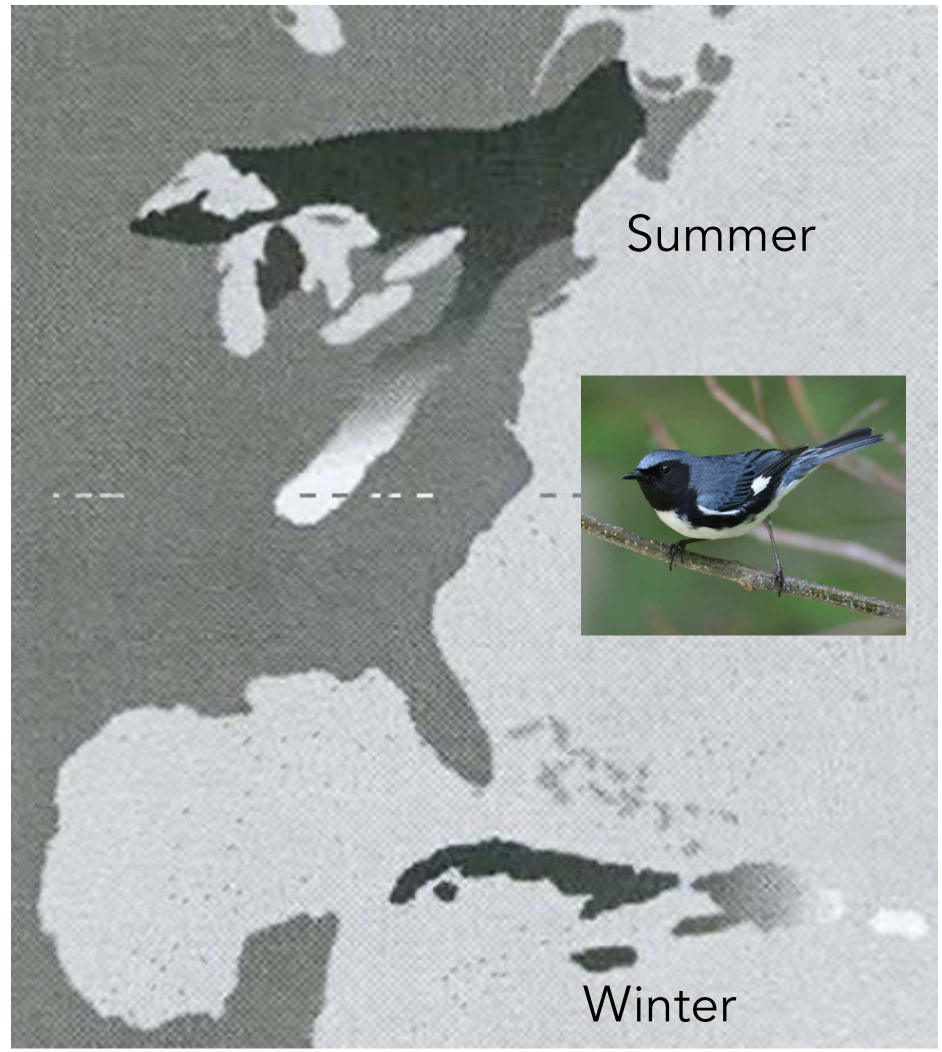


Dockx et al. 2004

Population Structure and Migratory Connectivity

Linking breeding and wintering ranges of a migratory songbird using stable isotopes

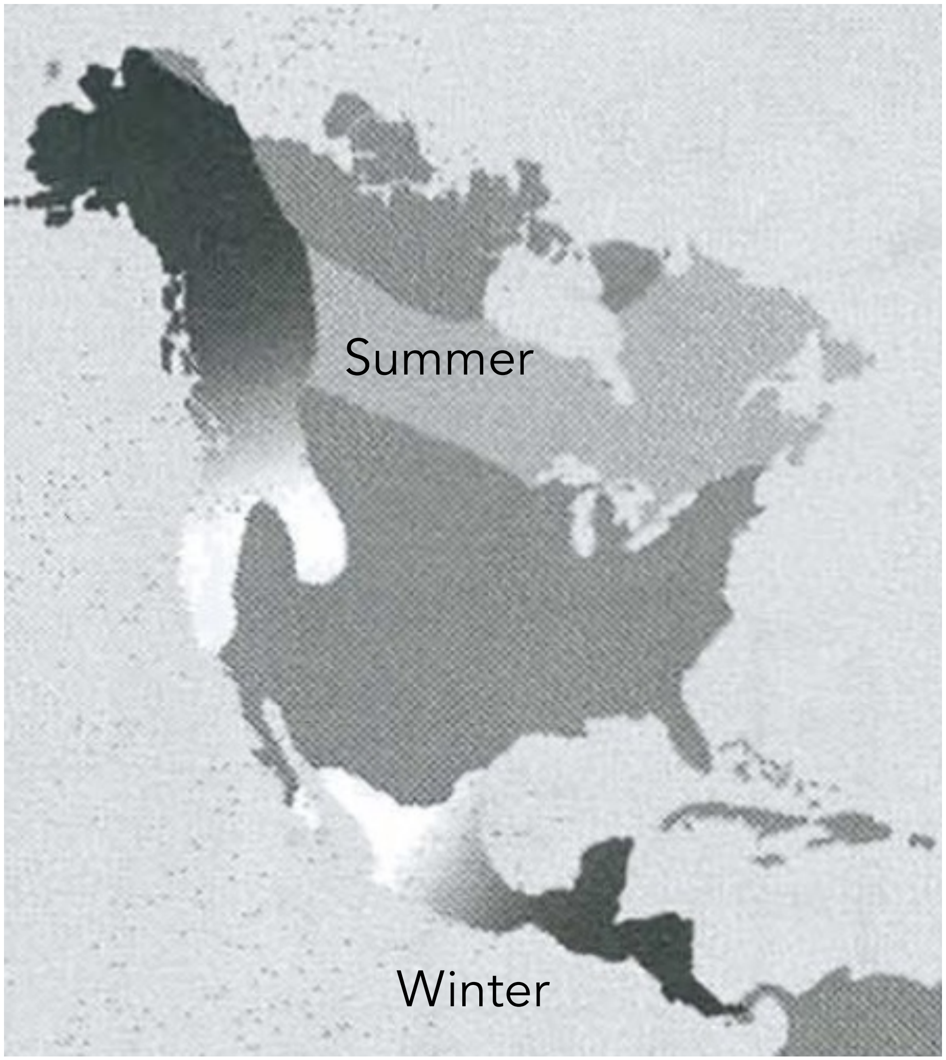


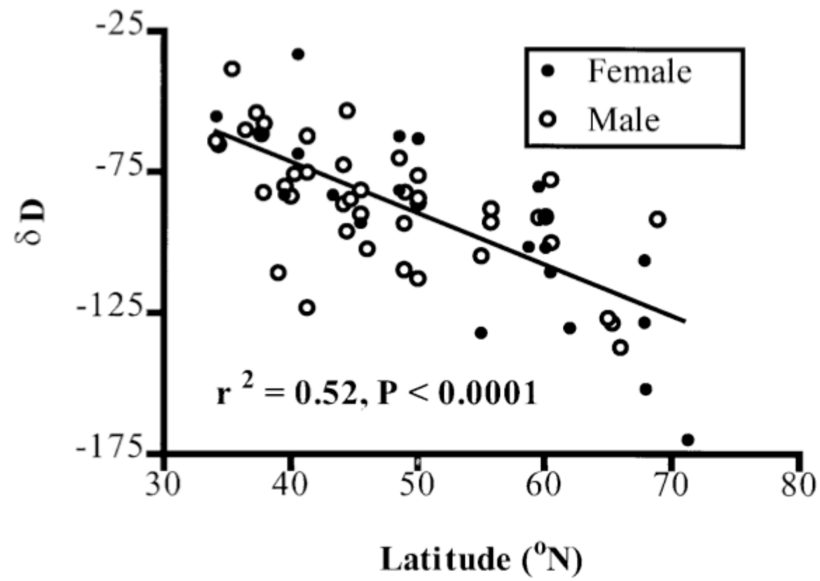


Rubenstein et al. 2002

Insights into Wilson's Warbler migration from analyses of hydrogen stable isotopes

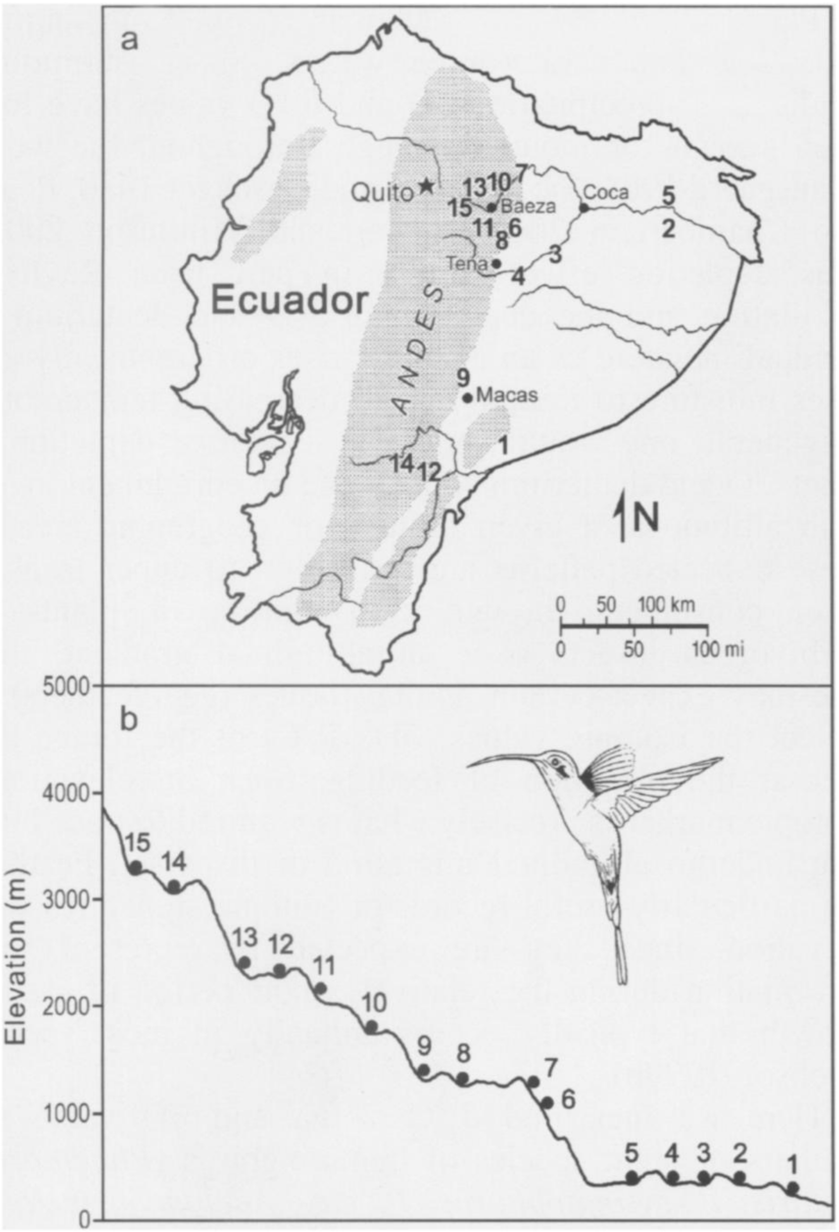
"Leapfrog Migration"



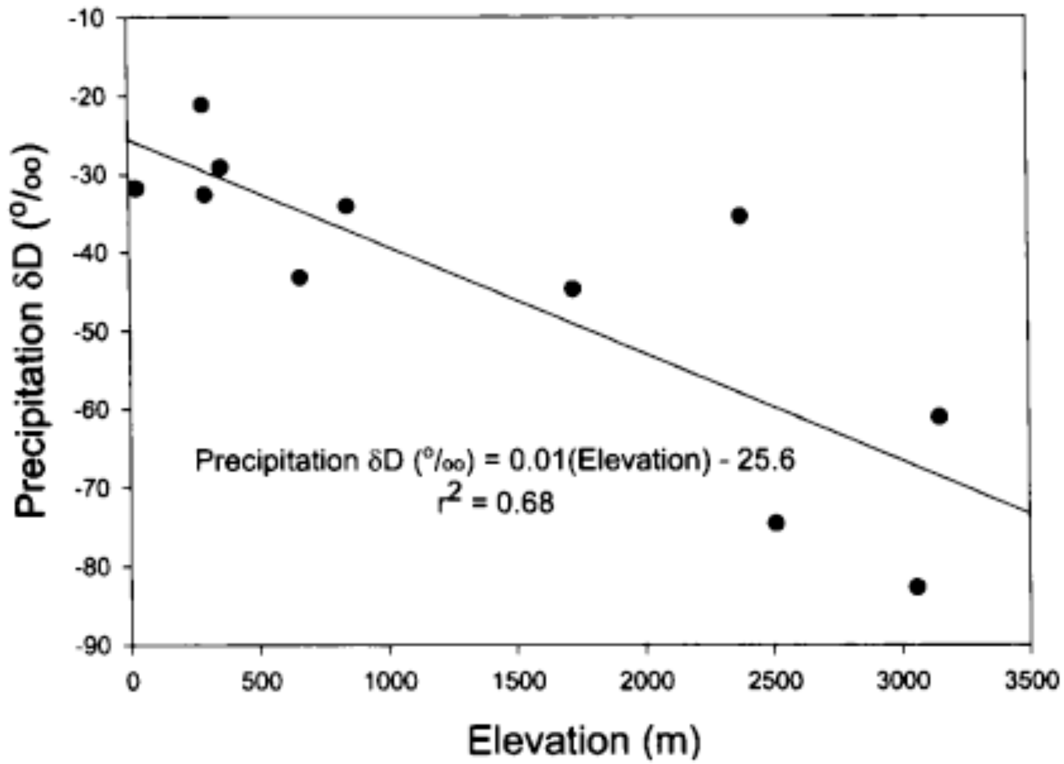


Kelly et al. 2002

Elevational Movements and Residency



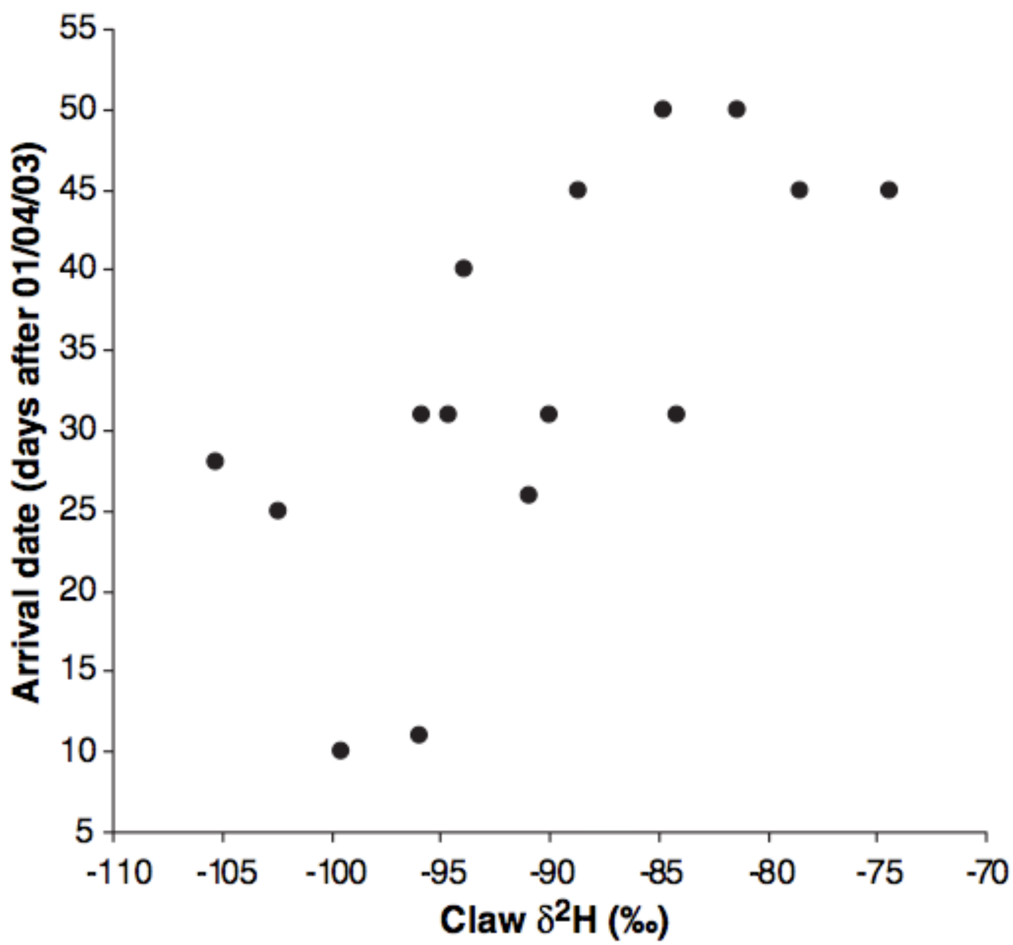
Stable isotopes as indicators of altitudinal distributions and movements in an Ecuadorean hummingbird community

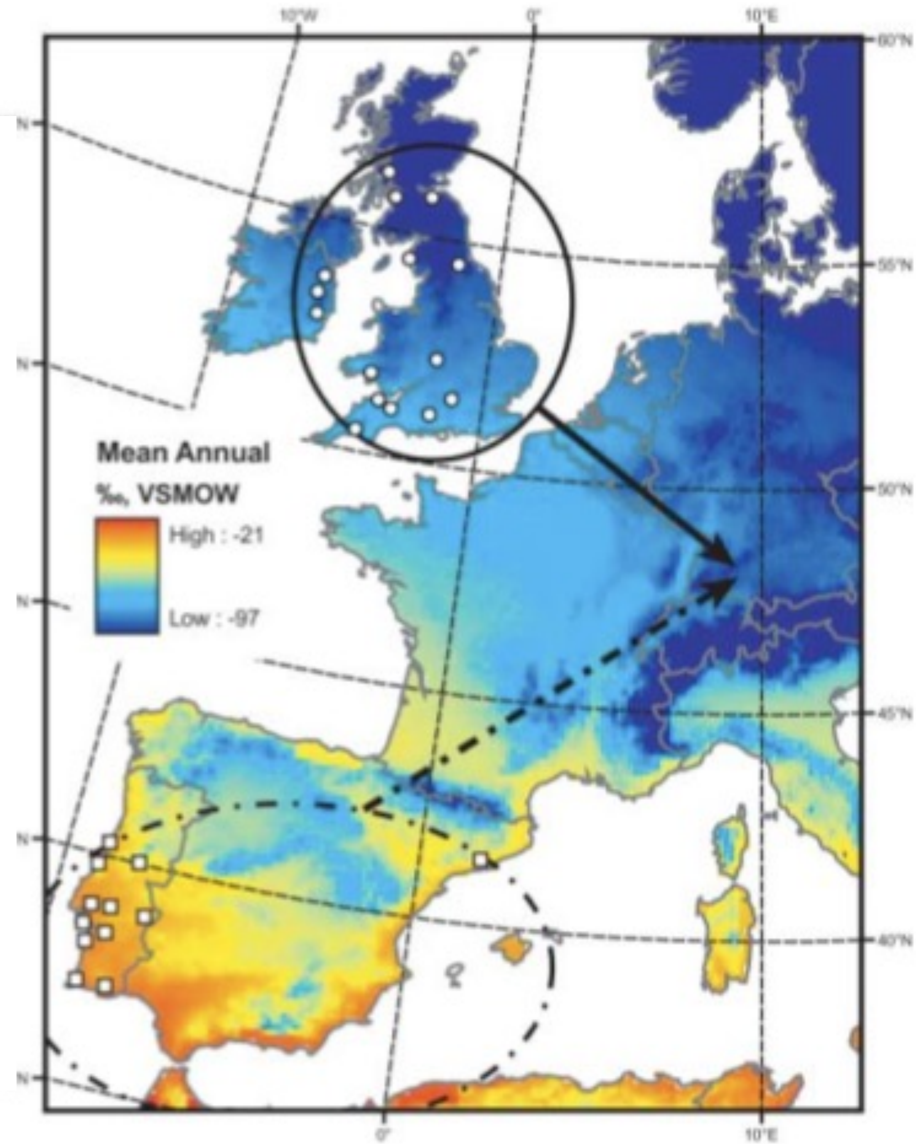


Hobson et al. 2003

Sympatric Evolution?

Assortative mating as a mechanism for rapid evolution of a migratory divide

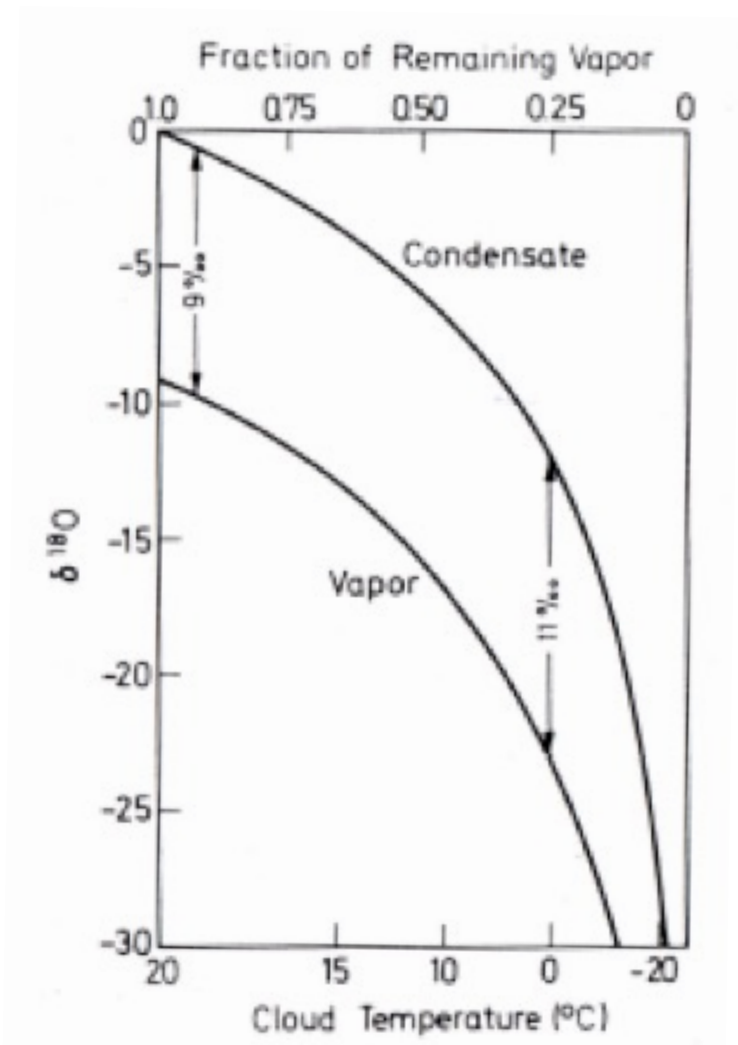


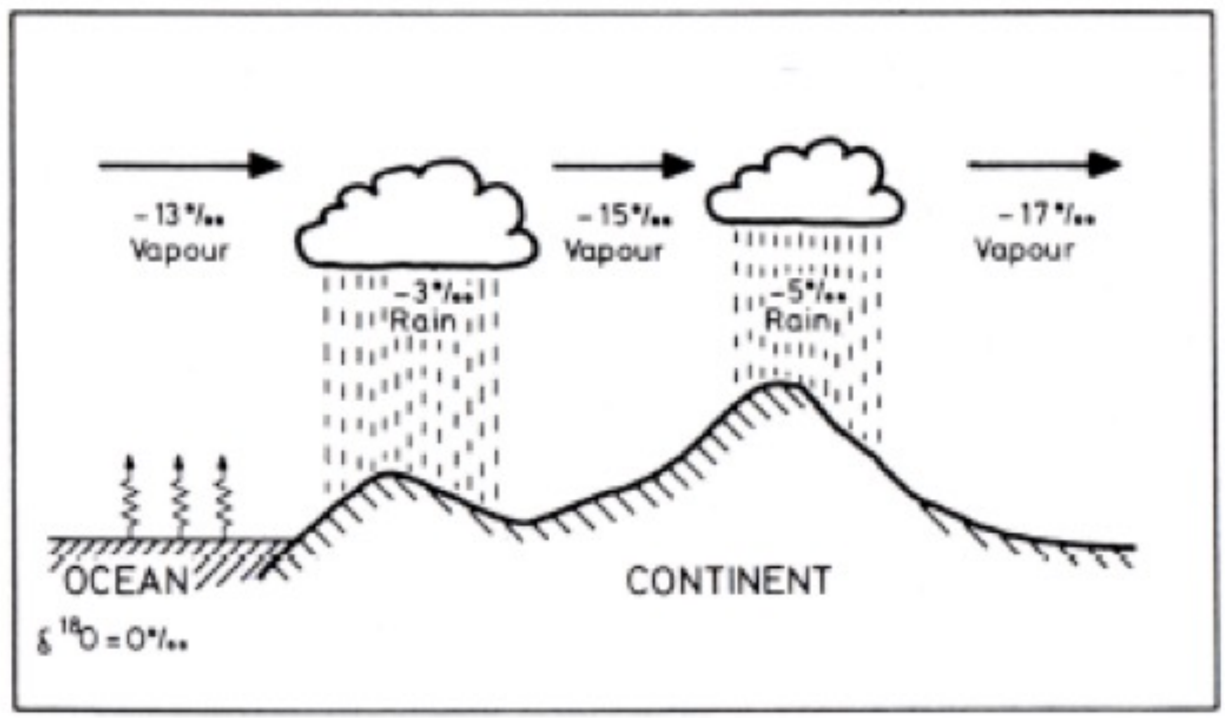


Bearhop et al. 2005

Remember Rayleigh Distillation

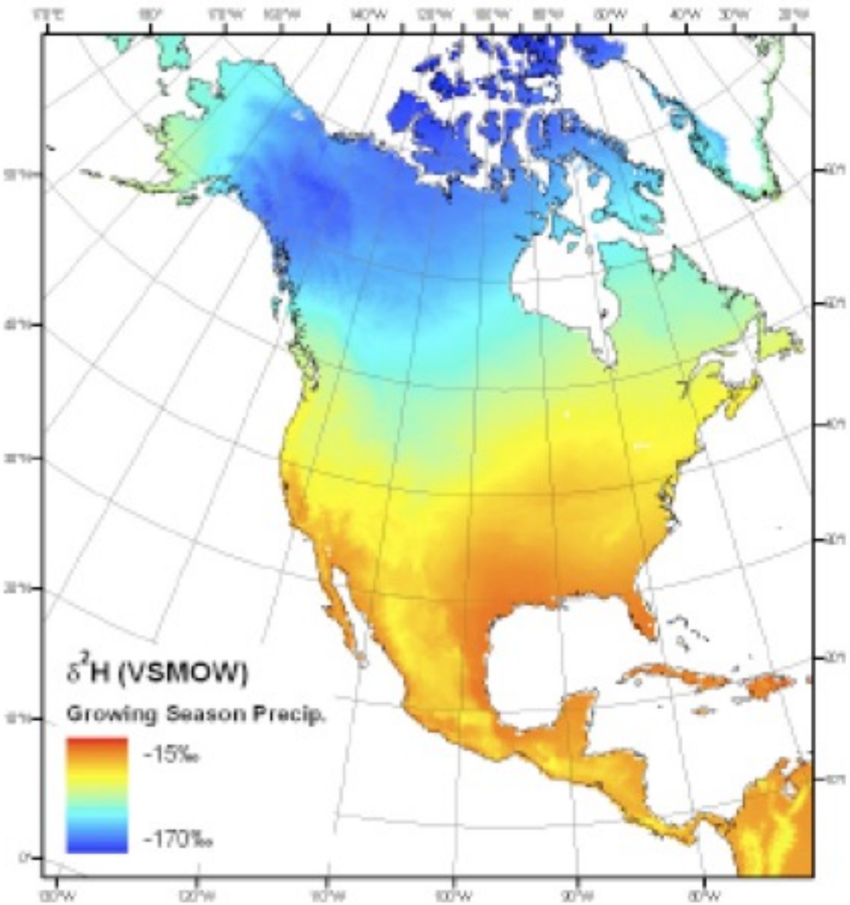
The water in clouds formed over the ocean tends to be "depleted" in ^2H (deuterium) and ^{18}O.

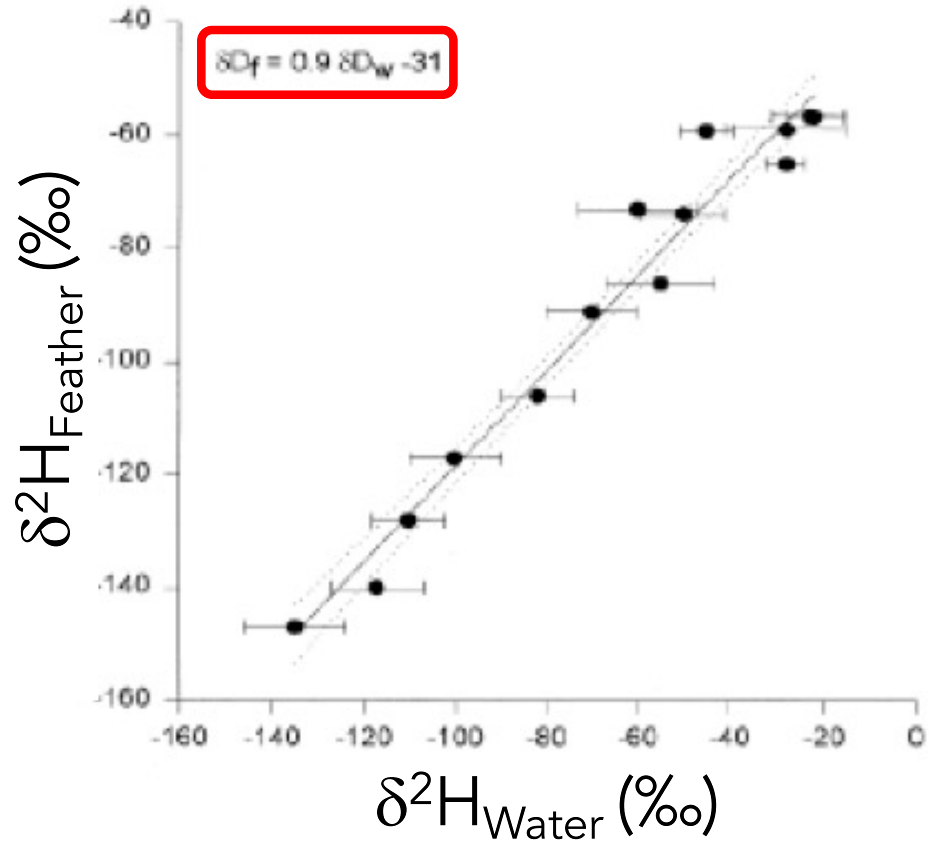




Rainwater, in contrast, is "enriched" in both ^2H and ^{18}O

In North America, rainwater and bird feathers become more depleted in δ^2H with increasing latitude of collection.





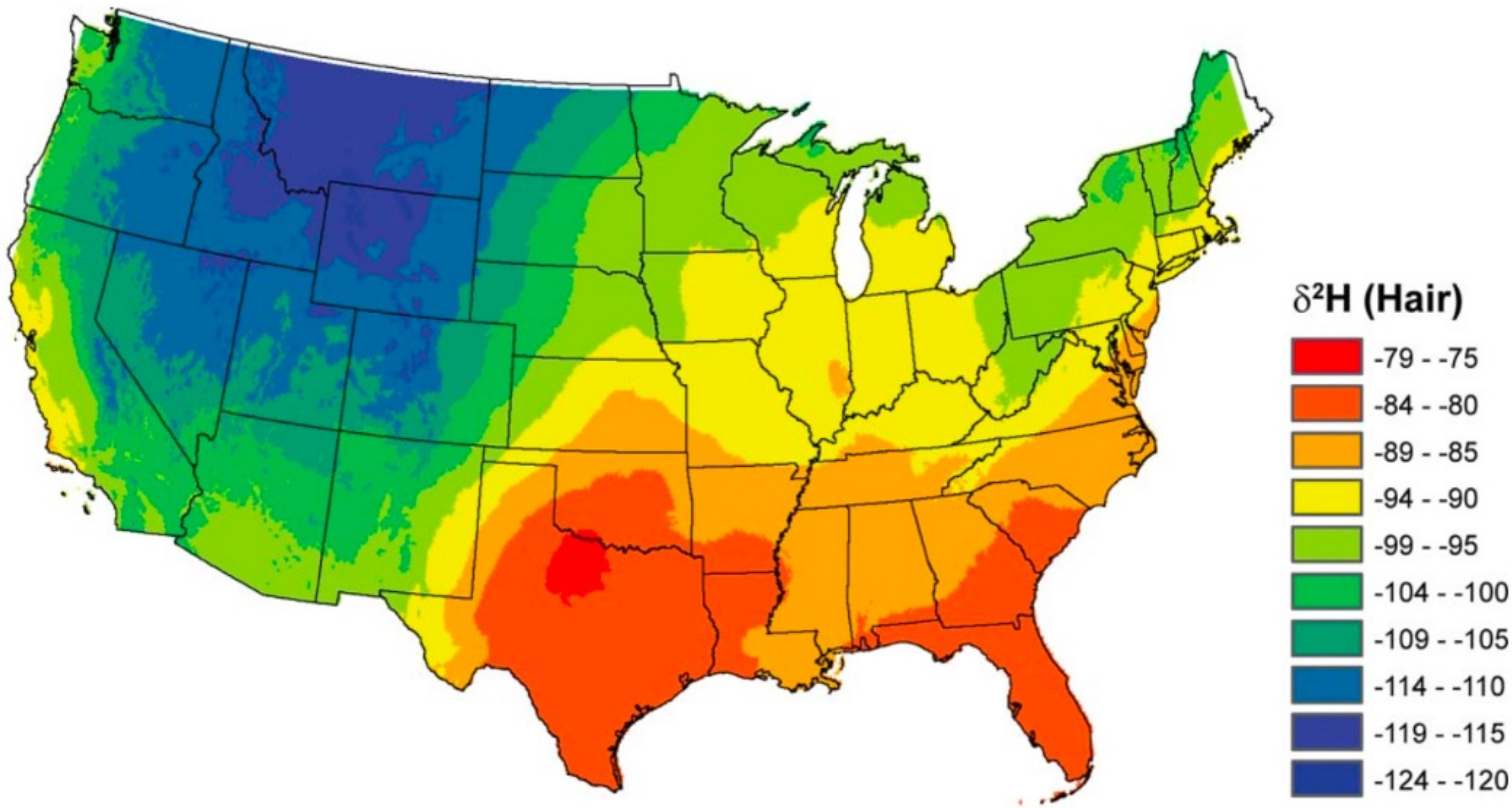
$\Delta^2H_{feather\text{-}precipitation} \approx -30‰$

100s of publications have used this approach to study animal movement/migration.

www.waterisotopes.org

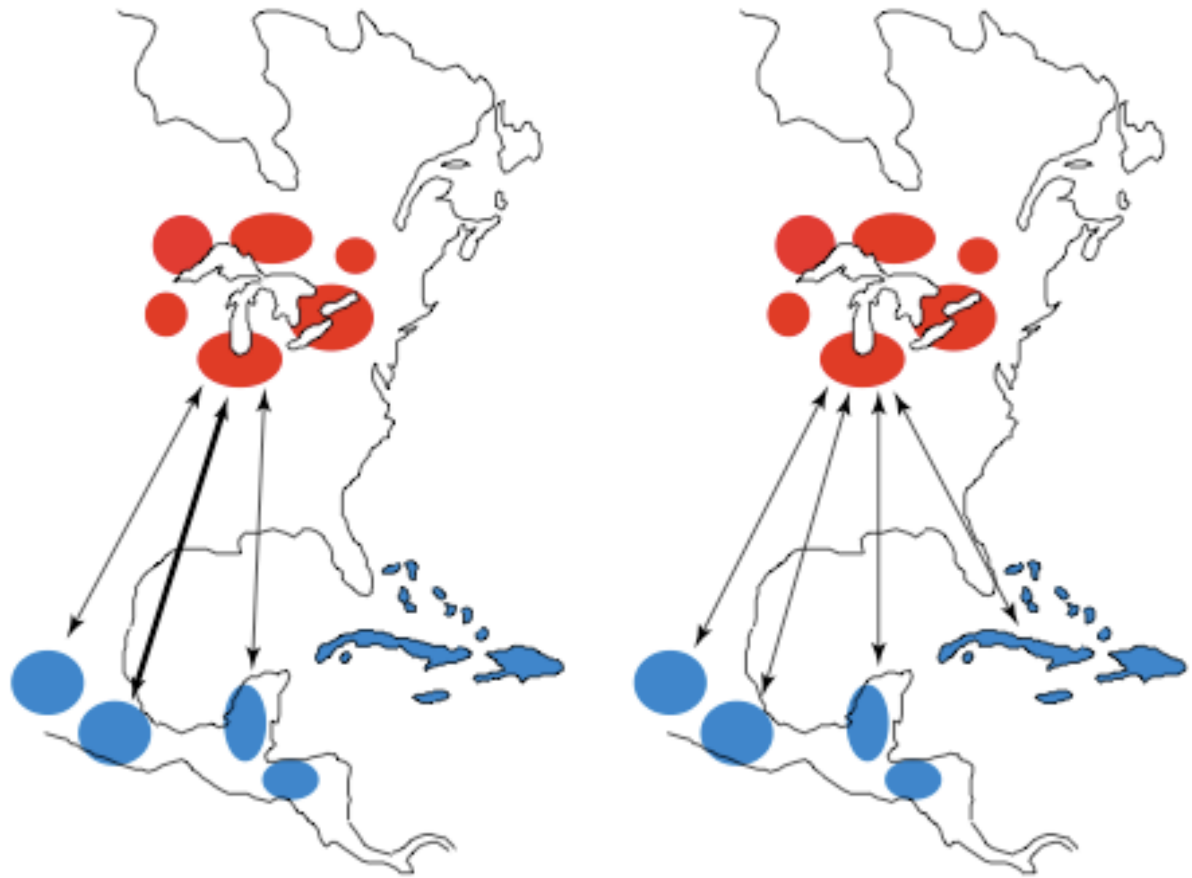
Hobson and Wassenaar 1997

δ^2H: Geographic Assignment of Humans

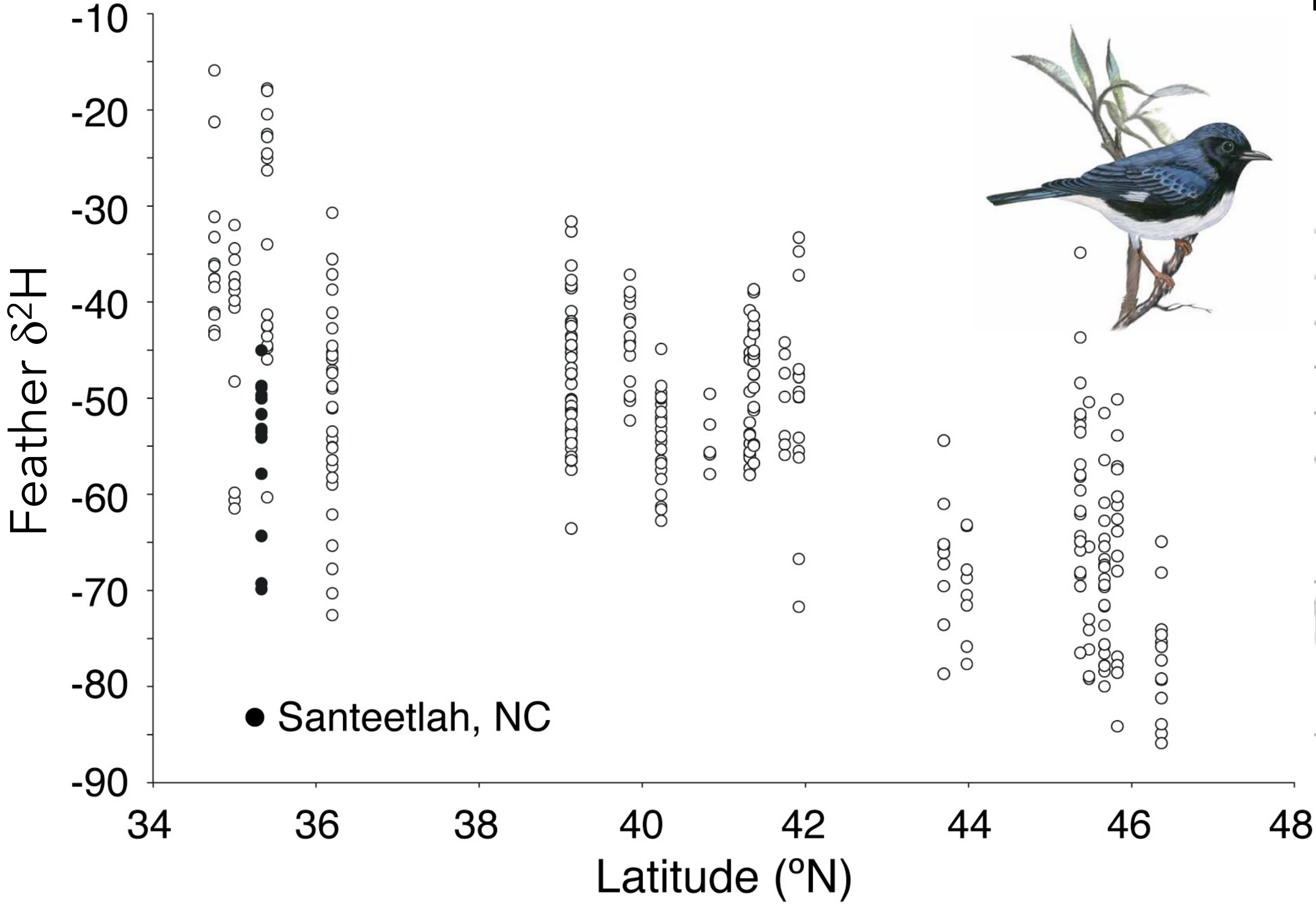


Ehleringer et al. 2008

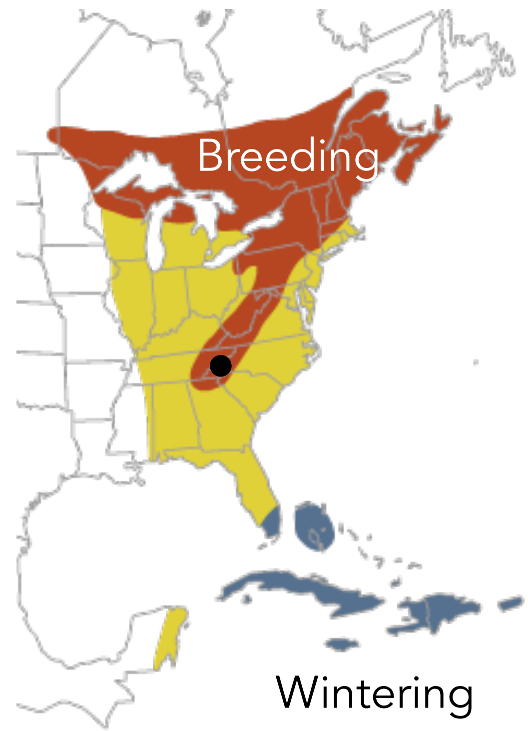
Population Structure and Migratory Connectivity



Intra-Population δ^2H Variation

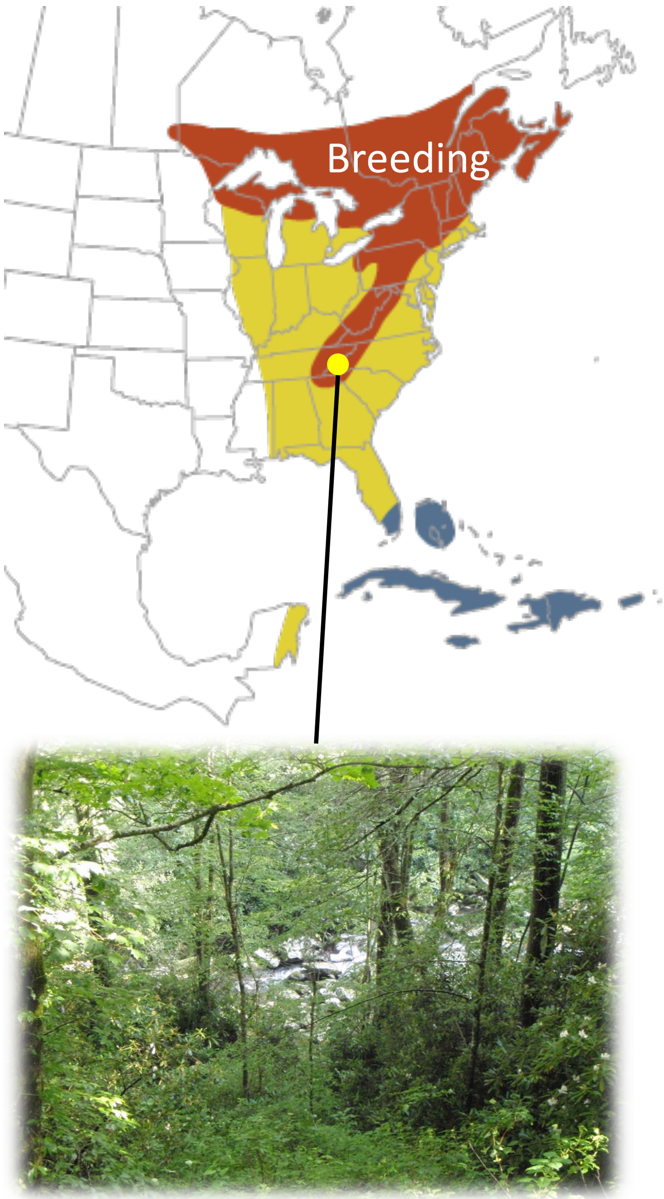


Black-Throated Blue Warbler
(*Setophaga caerulescens*)

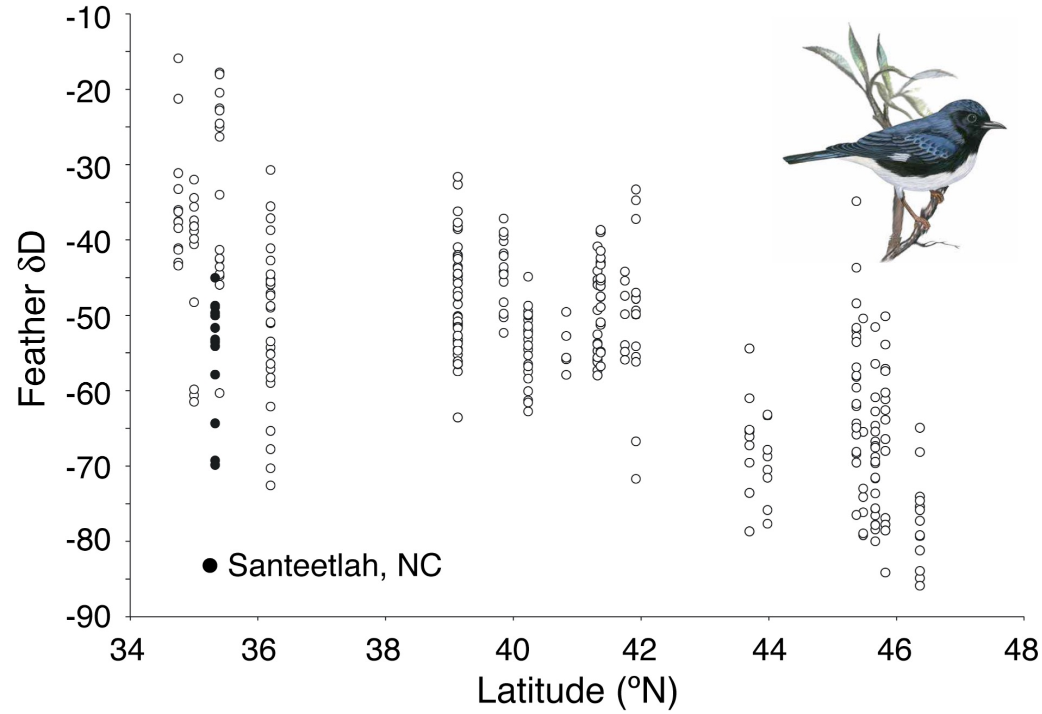


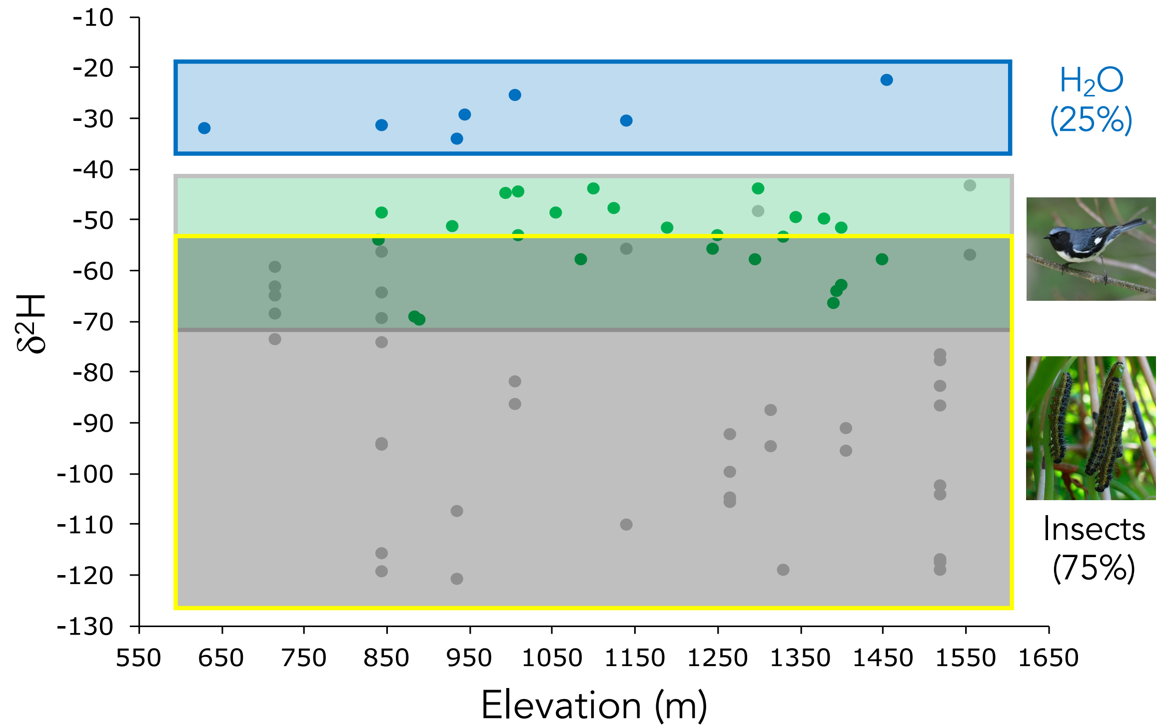
Newsome et al. (unpublished)

Water and Food δ²H

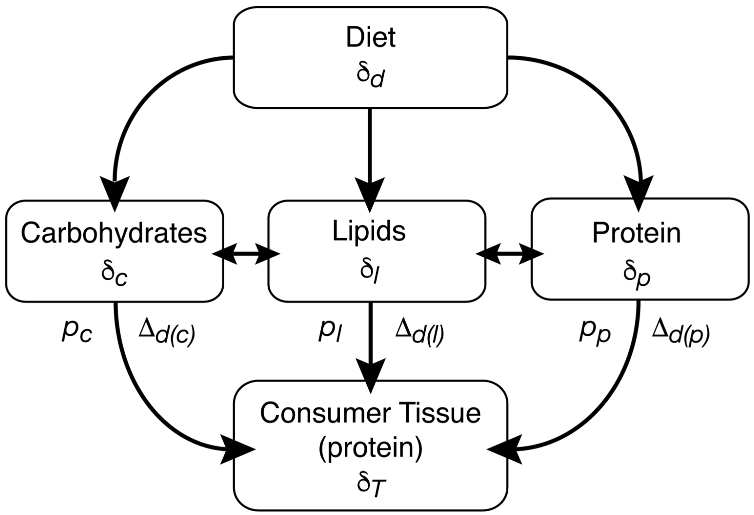


Santeetlah National Forest

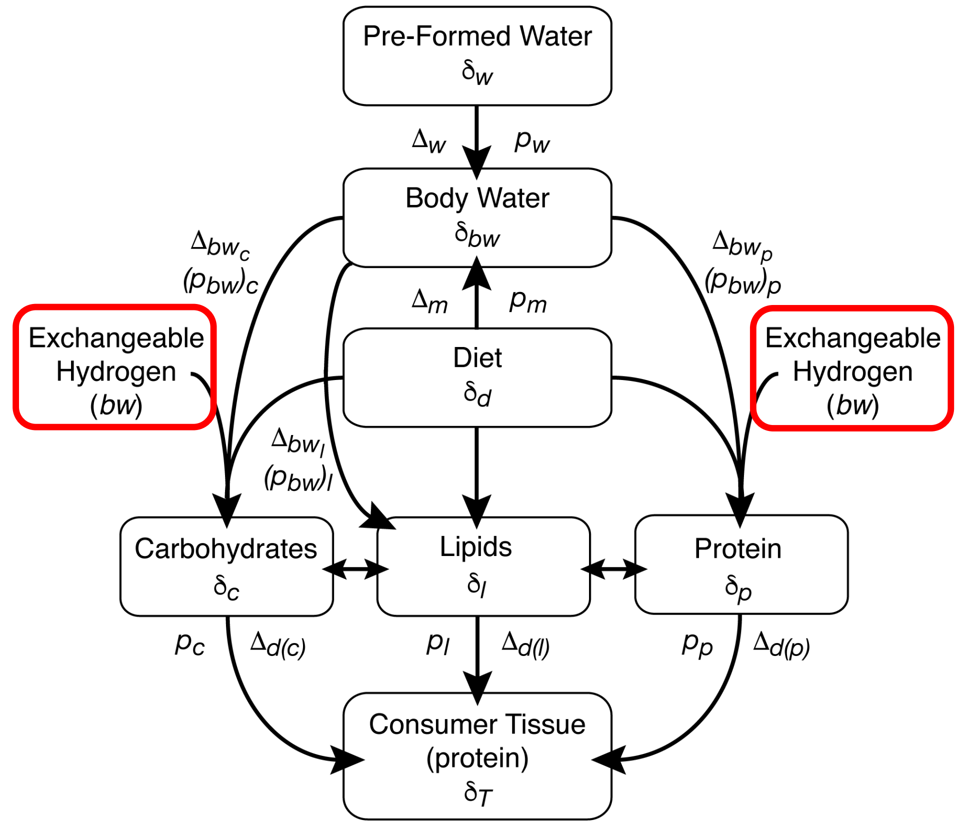




δ^{13}C and δ^{15}N: Food



δ^2H: Food and Water



$$\delta^{13}C_{tissue} = p_{food}(\delta^{13}C_{food} + \Delta^{13}C_{tissue\text{-}food})$$

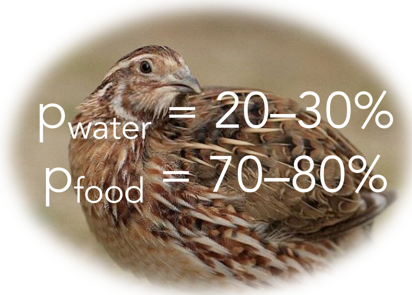
$$\delta^{2}H_{tissue} = p_{water}(\delta^{2}H_{water} + \Delta^{2}H_{tissue\text{-}water}) + p_{food}(\delta^{2}H_{food} + \Delta^{2}H_{tissue\text{-}food})$$

$$\delta^{2}H_{tissue} = p_{water}(\delta^{2}H_{water}) + p_{food}(\delta^{2}H_{food}) + \Delta^{2}H_{net}$$

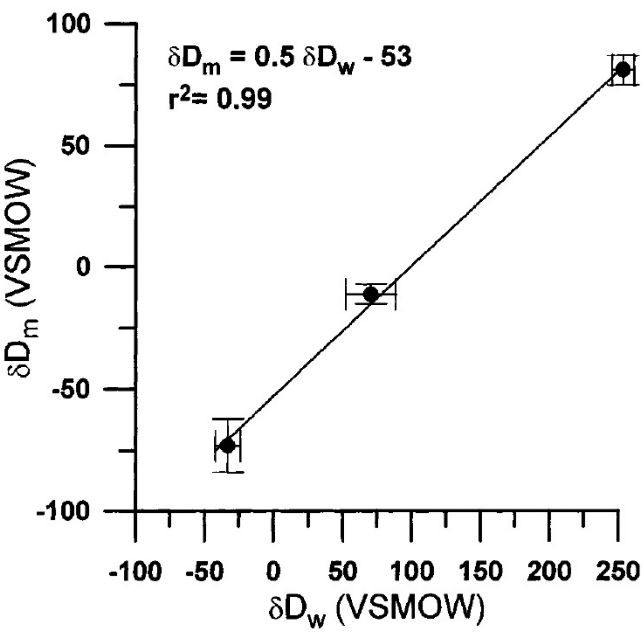
Two Sources: Diet and Drinking Water

$$\delta^2H_{tissue} = p_{water}(\delta^2H_{water}) + p_{food}(\delta^2H_{food}) + \Delta^2H_{net}$$

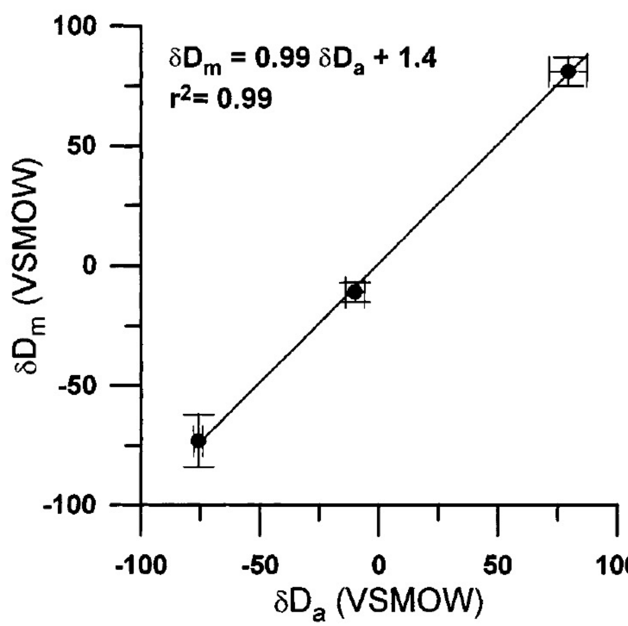
25% 75%



Tissue	Diet 1: Water 1	n	Diet 1: Water 2	n	Diet 1: Water-derived hydrogen, %	Diet 2: Water 1	n	Diet 2: Water 2	n	Diet 2: Water-derived hydrogen, %
Blood	−142 ± 6	7*	−69 ± 3	7*	22	−162 ± 3	3*	−94 ± 5	3*	21
Muscle	−137 ± 2	7*	−68 ± 3	7*	21	−158 ± 1	3*†	−99 ± 3	2*	18
Liver	−127 ± 2	7†	−50 ± 2	7†	24	−151 ± 4	4†	−84 ± 1	3†	21
Lipids	−198 ± 3	7‡	−141 ± 3	7‡	18	−256 ± 5	3‡	−194 ± 5	3‡	19
Feather	−134 ± 2	5*	−29 ± 2	3§	32	−152 ± 1	3*	−72 ± 1	5§	26
Nail	−118 ± 3	7¶	−31 ± 3	7§	27	—	—	—	—	—



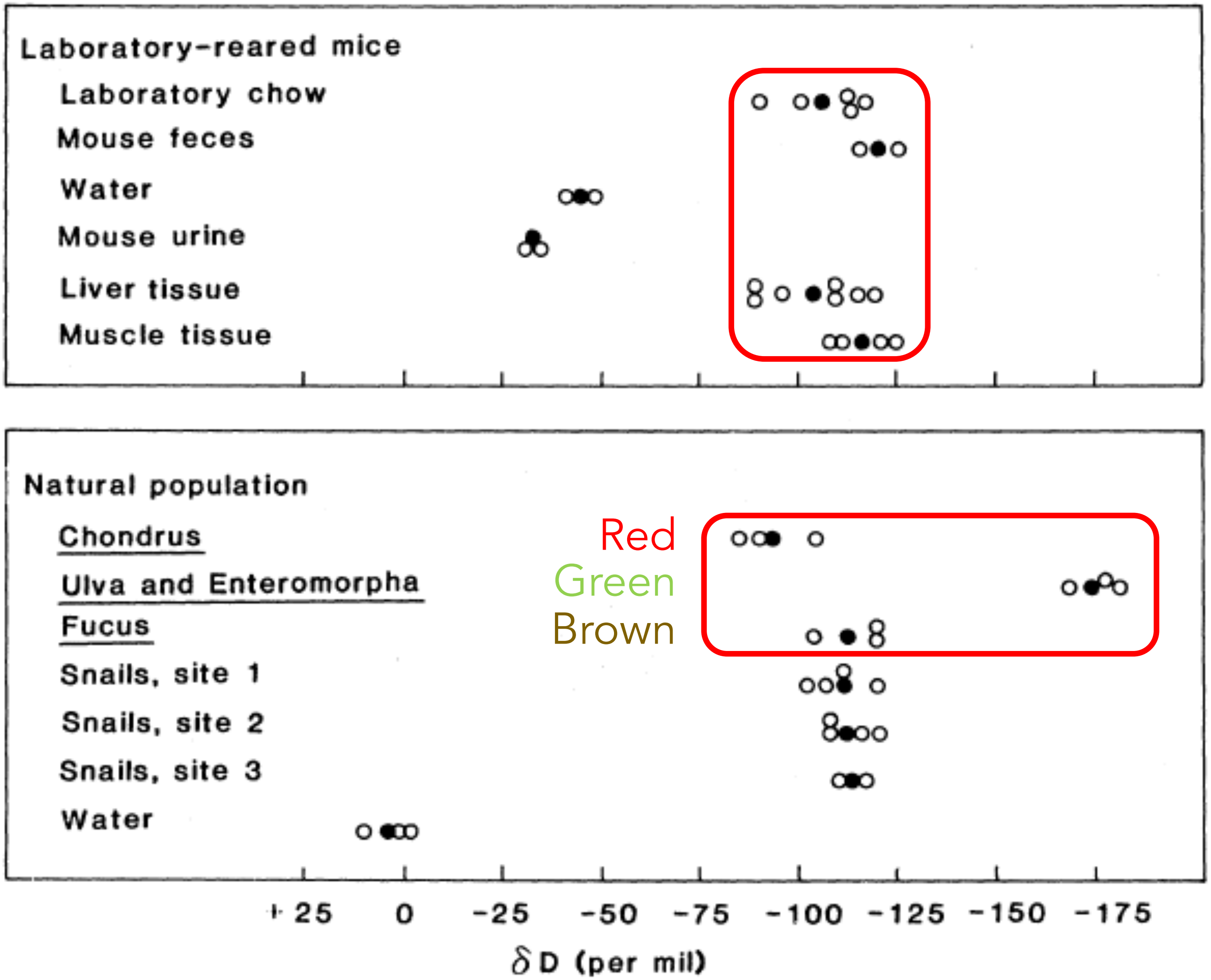
Milkweed Water



Milkweed Leaves

Hobson et al. 1999a, 1999b

Using δ²H to Trace Resource and Habitat Use



<10 publications have used this approach to study animal resource and habitat use.

Estep and Dabrowski 1980

A ‘Simple’ Two Source Mixing Problem

Assumptions:

p_{water} = 25% and p_{food} = 75%

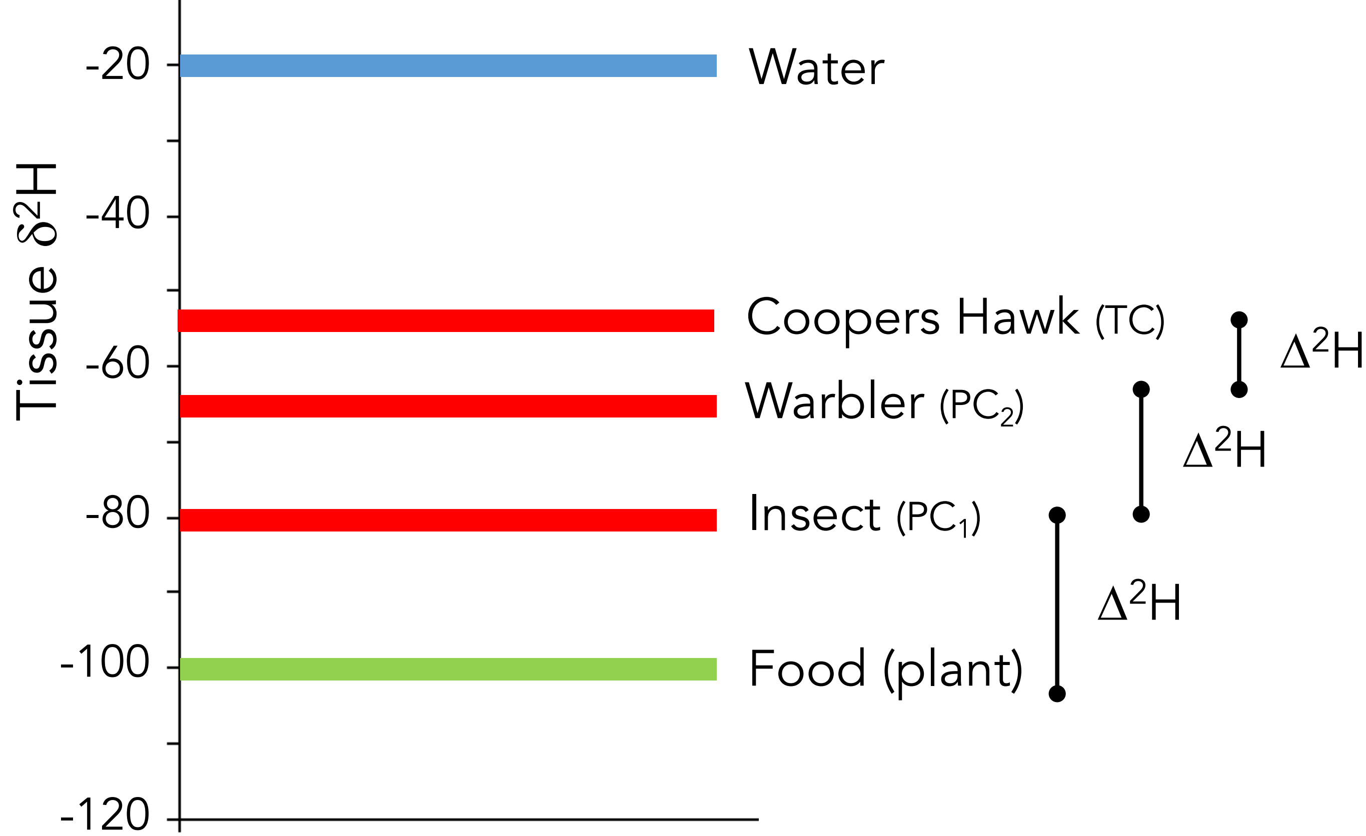
No isotopic discrimination associated with tissue synthesis (Δ^2H_{net} = 0)

Observations:

Consumer δ^2H increases with trophic level

Tertiary consumers look more like water than primary consumers

Apparent tissue-diet discrimination decreases with increasing trophic level



Solomon et al. 2009

Experimental Design

Ingredient	Macromolecule	Diet 1	Diet 2	Diet 3	δ^2H (SD)	[H] (SD)	δ^{13}C (SD)	[C] (SD)	δ^{15}N (SD)	[N] (SD)
Casein	Protein	0.05	0.20	0.35	-107 ± 4.2	6.0 ± 0.02	-24.8 ± 0.2	48.4 ± 0.32	5.5 ± 0.3	14.1 ± 0.35
Sucrose	Carbohydrates	0.45	0.30	0.15	-14 ± 4.1	6.3 ± 0.04	-11.7 ± 0.8	41.9 ± 0.15	–	–
Corn Meal	Carbohydrates	0.15	0.15	0.15	-18 ± 4.4	5.8 ± 0.05	-10.8 ± 0.2	47.2 ± 0.05	1.5 ± 0.8	0.8 ± 0.05
Corn Oil	Lipids	0.02	0.02	0.02	-154 ± 4.6	9.6 ± 0.21	-15.5 ± 0.2	73.9 ± 2.65	–	–
Cellulose	Binder	0.25	0.25	0.25	-25 ± 4.0	5.8 ± 0.02	-25.6 ± 0.2	41.9 ± 0.41	–	–
Fortified Salt	Salt	0.04	0.04	0.04	–	–	–	–	–	–
Brewer's Yeast	Yeast	0.02	0.02	0.02	-66 ± 4.1	5.8 ± 0.05	-21.4 ± 0.3	44.0 ± 0.30	3.2 ± 0.2	7.3 ± 0.15
Vitamin Mix	Vitamins	0.01	0.01	0.01	1 ± 4.4	6.3 ± 0.05	-12.9 ± 0.3	39.9 ± 0.38	–	–
	Protein:Carb Ratio	5:60	20:45	35:30						
	Bulk δ^2H	-26.0 ± 3.0	-41.0 ± 3.0	-56.0 ± 3.0						
	Bulk δ^{13}C	-16.2 ± 0.2	-18.3 ± 0.2	-20.3 ± 0.2						
	Bulk δ^{15}N	2.6 ± 0.7	3.8 ± 0.6	4.3 ± 0.5						

Mauriel Rodriguez Curras

Dietary protein (casein) varied from 5% to 35%; low δ^2H: -108‰

Dietary carbohydrates varied from 30% to 60%; high δ^2H: -16‰

Drinking water δ^2H varied from -95‰ to -50‰ to +5‰

Dietary fat was low and did not vary among diet treatments

Rodriguez Curras et al. 2018

Bulk Tissue δ^2H Results

P_{Water}: 15–26%

P_{Carbs}: 10–35%

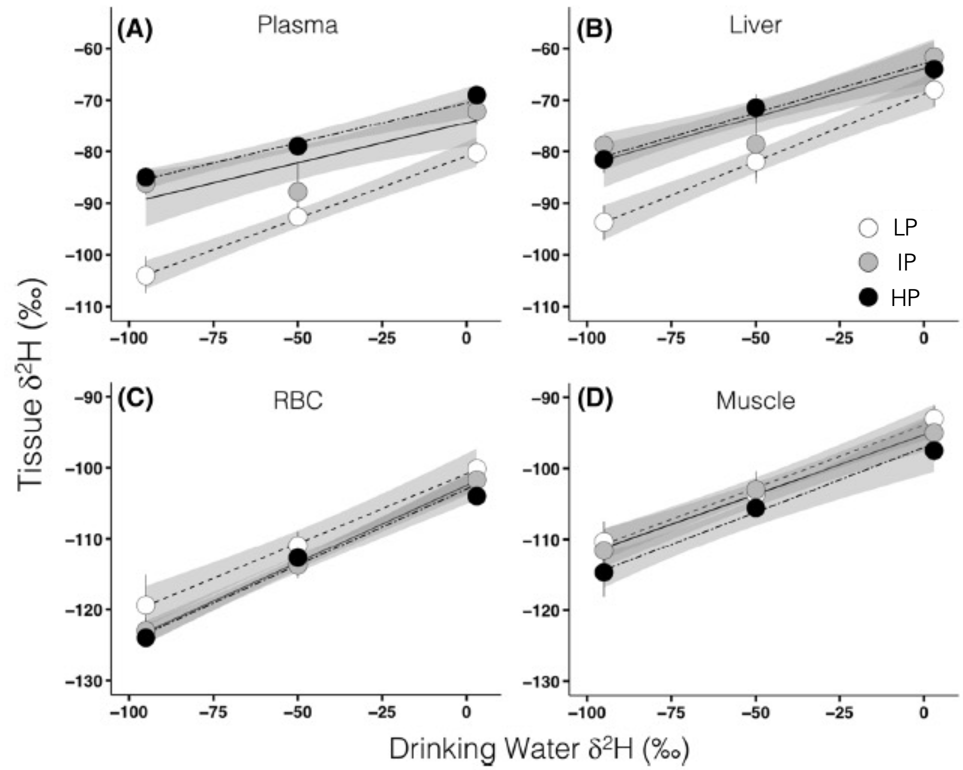
$P_{Protein}$: 41–69%

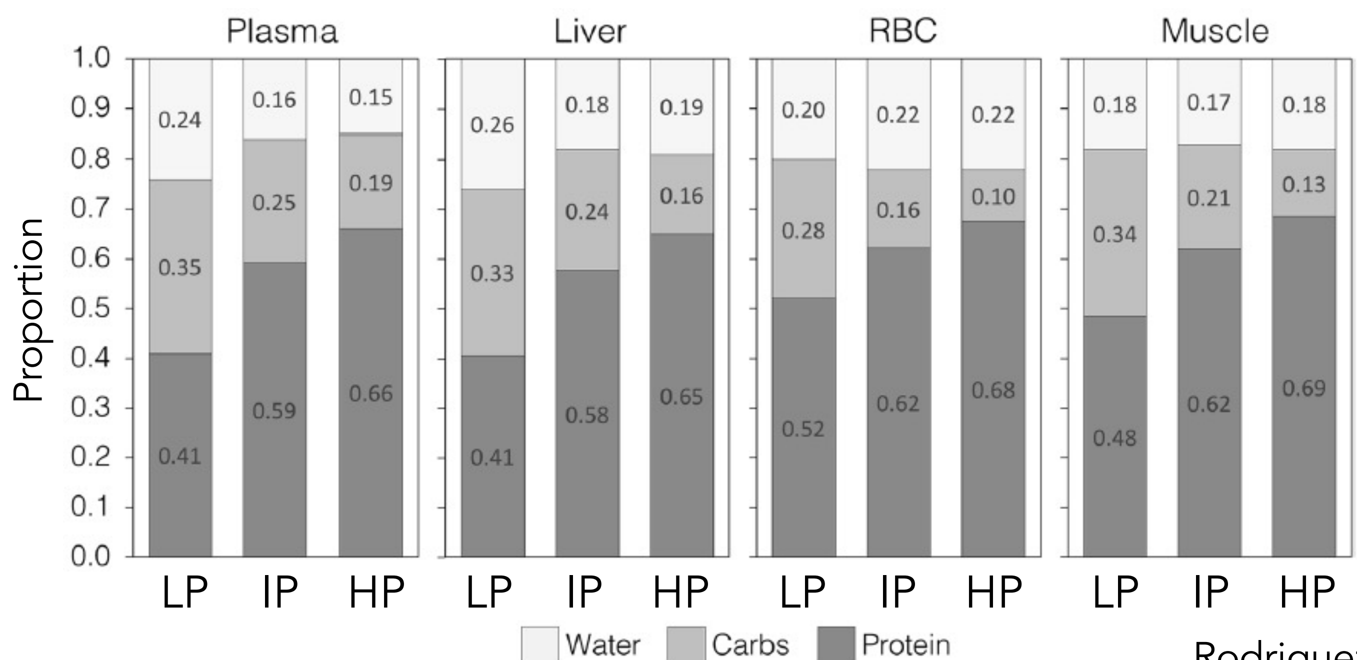
Larger P_{carbs} in low protein diet

Larger $P_{protein}$ in high protein diet

More AA *de novo* synthesis in low protein diet

More AA routing in high protein diet





Rodriguez Curras et al. 2018

Take Home Message(s): Bulk Tissue δ^2H

Unlike carbon and nitrogen, there are two major sources of hydrogen utilized by animals to build and maintain tissues: food and water.

Food contributes ~75% of the hydrogen in (protein-rich) tissues, with (drinking/food) water supplying the remainder.

Variation in tissue δ^2H variation among individuals in a population is likely driven by variability among dietary sources of hydrogen and physiology.

Non-protein dietary macromolecules (e.g., carbohydrates) can contribute ~2X more hydrogen to tissue synthesis than drinking water.

δ^2H analysis is a promising tool to study animal diet and habitat use, but a better understanding of isotopic discrimination is needed.