Vector-borne Disease Control & Taylor's Law of Fluctuation Scaling: Chagas Disease in Argentina

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Outline

1. ➔ Taylor's law (TL)
2. Empirical examples
3. Empirical counterexamples

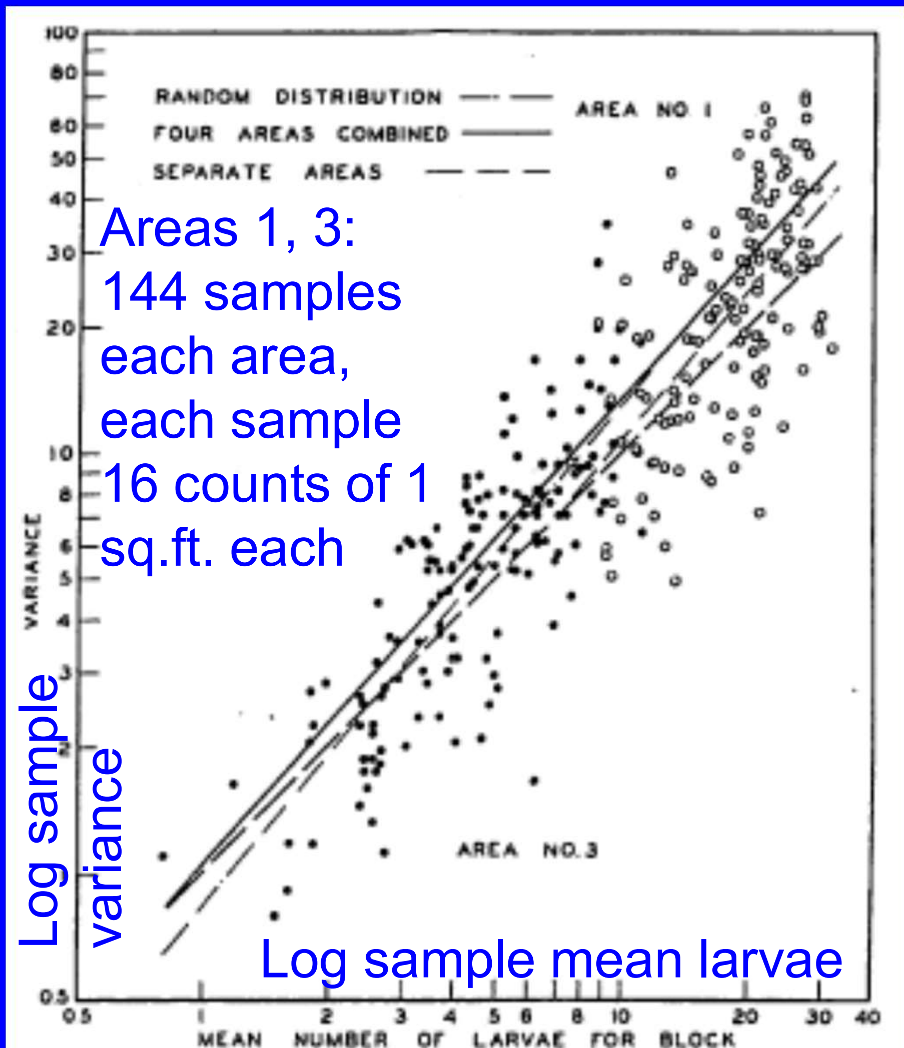
4. Chagas disease & TL
5. Spraying insecticides & TL
6. Using TL for more efficient fixed-precision estimation of insect vector populations

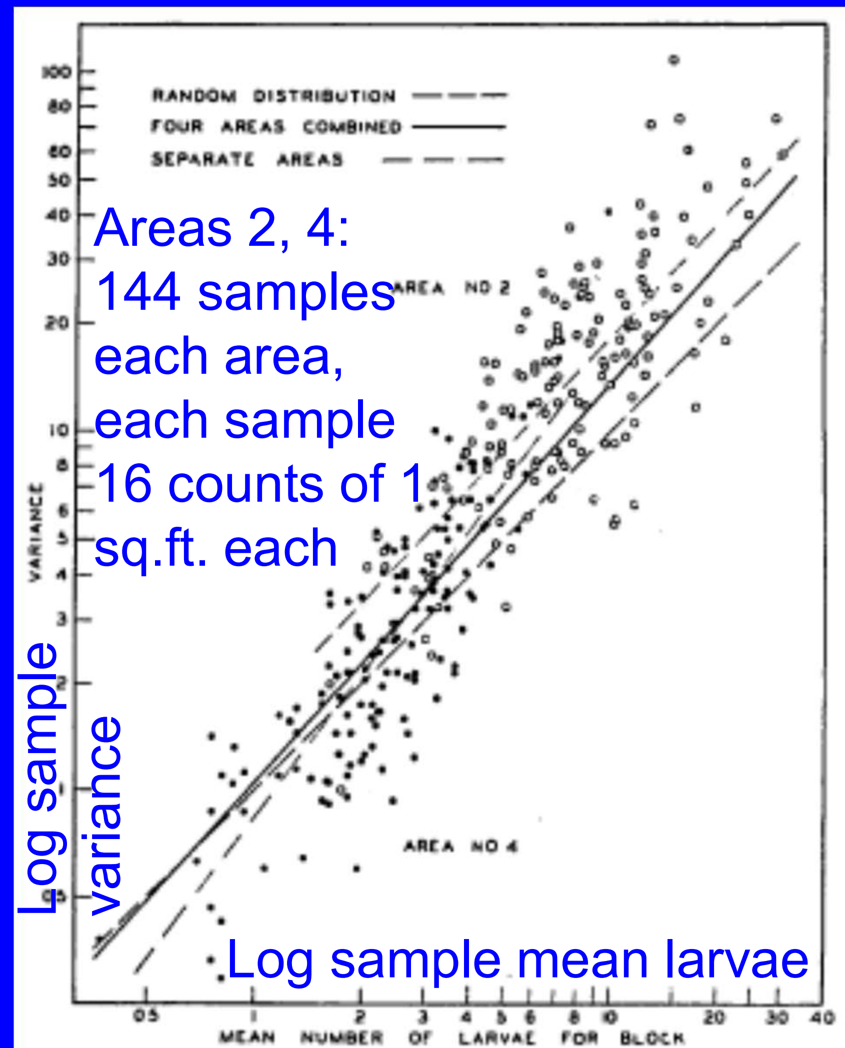
TL data structure: multiple samples, each with multiple observations

Sample number →	*j*=1	*j*=2	*j*=3	*j*=…
Population size or density in units (quadrats, plots, transects, counties, states, years, days)	x_{11}	x_{12}	x_{13}	$x_{...}$
	x_{21}	x_{22}	x_{23}	…
	x_{31}	x_{32}	x_{33}	…
		x_{42}	x_{43}	…
		x_{52}		…
Mean (weighted)	m_1	m_2	m_3	m…
Variance (weighted)	v_1	v_2	v_3	v…

Japanese beetle larvae $v_j = am_j^b$

Chester I. Bliss *J. of Economic Entomology* 1941





Taylor's law *Nature* 1961

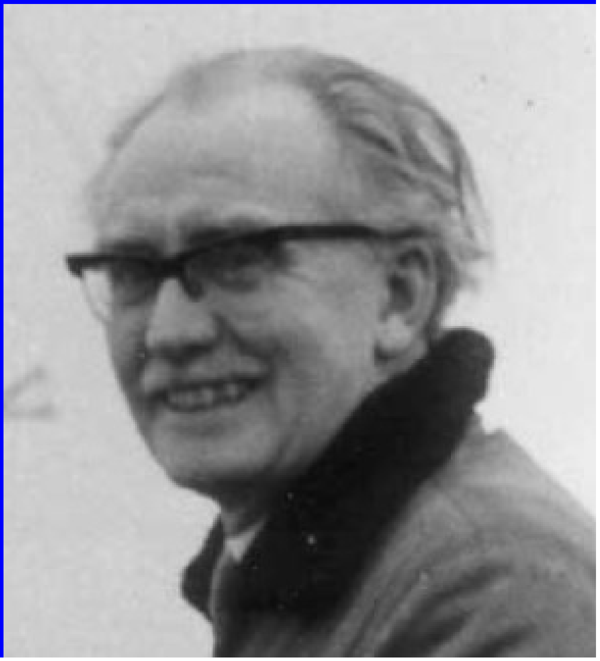
In multiple sets of samples, the variance of population density is proportional to a power of the mean population density.

$\text{variance} = a(\text{mean})^b, a > 0.$

$\log(\text{variance}) = \log(a) + b \cdot \log(\text{mean}).$

$\text{variance}/(\text{mean})^b = a, \quad a > 0.$

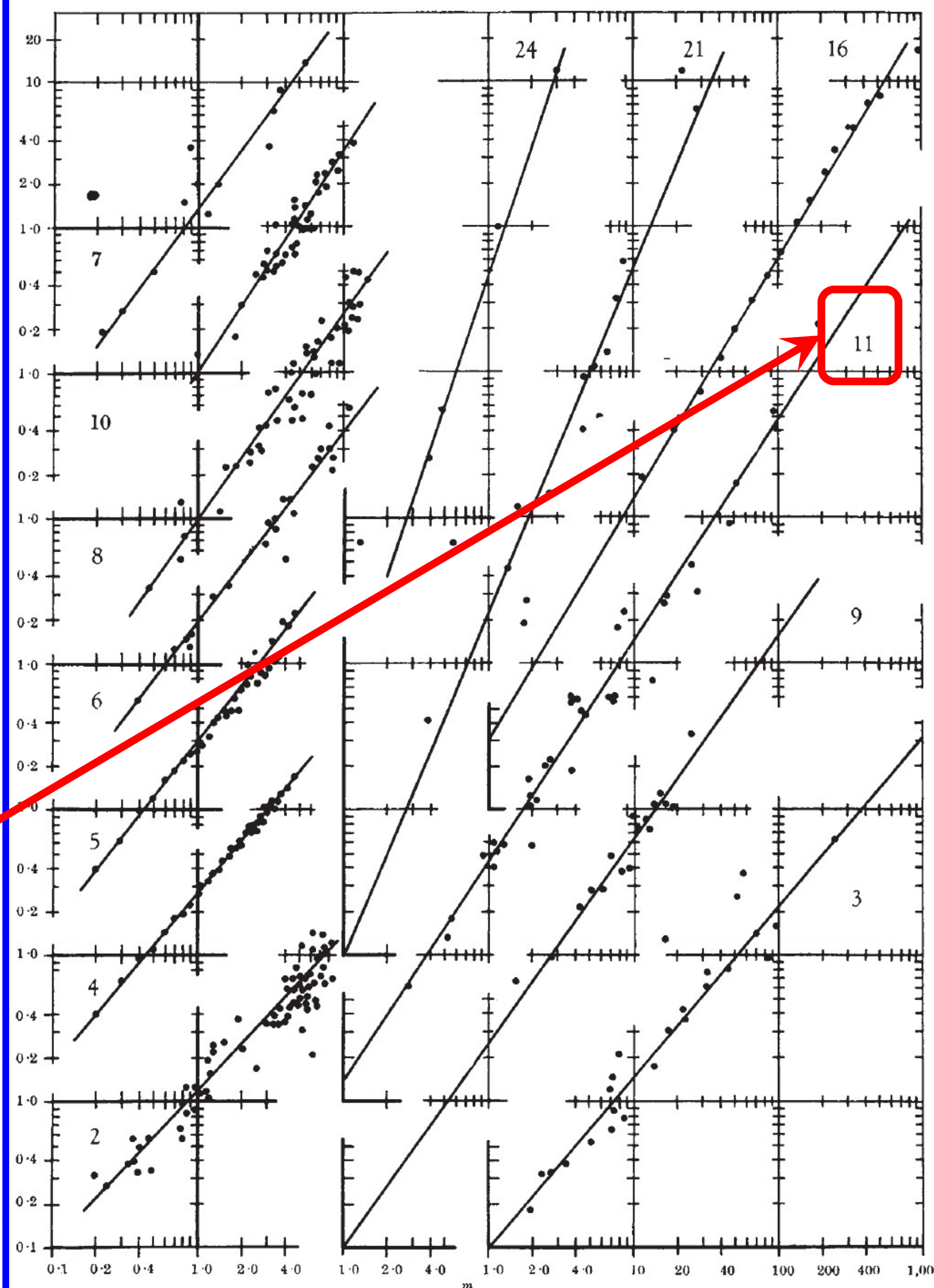
Taylor stated no model of error (deviations from exact equality).



Lionel Roy Taylor
(1924–2007)

2019-09-10

	Name	Site and sample
1	Shellfish on seashore, *Tellina tenuis* da Costa, Eulamellibranchiata : Mollusca	Sand, 63 units, various sizes
2	European chafer larvæ, *Amphimallon majalis* Raz. (= *Melolontha melolontha* L.), Coleoptera : Insecta	Pasture soil, 25 units, each 1 ft. sq.
3	Flying insects, various orders : Insecta	Open air, 16–104 units aerial density
4	Wireworms, *Agriotes* spp. mainly *obscurus*, Coleoptera : Insecta	Grassland soil 20 units, 4 in. cores
5	Wireworms, *Agriotes* as above	Arable land soil 20 units, 4 in. cores
6	Wireworms, *Limonius* spp., Coleoptera : Insecta	Arable land soil, 175 units, each 1 ft. sq.
7	Gall midge larvæ, *Jaapiella medicaginis* (Rub.), Diptera : Insecta	Lucerne field soil, 10 units, 4 in. cores
8	Spruce budworm larvæ, *Choristoneura fumifera* (Clem.), Lepidoptera : Insecta	Fir foliage, 25 units, larvæ/twig
9	Virus lesions, tobacco necrosis virus	Bean leaves, 4 units, lesions/half leaf
10	Colorado beetle adults, *Leptinotarsa decemlineata* Say., Coleoptera : Insecta	Potato foliage, 2,304 counts : insects/2 ft. row
11	Japanese beetle larvæ, *Popillia japonica* New., Coleoptera : Insecta	Soil, 10,000 units each 1 ft. sq.*
12	Macro-zooplankton	Water, net collection, slide count, 10 areas
13	Macro-zooplankton	As above, 50 areas
14	Ticks, *Ixodes ricinus* L., Acarina : Arachnida	Sheep, 20–86 units, ticks/sheep
15	Enchytraeid worms, mainly *Fridericia bisetosa* (Lev.), Enchytraeidae : Annelida	Pasture, 60–150 units, 3·6 cm. cores
16	Corn borer larvæ, *Pyrausta nubilalis* (Hubn.), Lepidoptera : Insecta	Maize stalks, 2 stage†
17	Thrips, *Thrips imaginis* (Bagnall), Thysanoptera : Insecta	Rose flowers, 20 units, thrips/rose
18	Leather-jackets, *Tipula* spp., Diptera : Insecta	Soil, 2 units, Nos./sq. ft.
19	Earthworms, all stages, *Allolobophora chlorotica* (Sav.), Oligochaeta : Annelida	Grassland, 4 units, 18 in. sq.
20	Red spider mite, eggs and adults, *Metatetranychus ulmi* (Koch), Acarina : Arachnida	Apple leaves, 20 units, mites/leaf
21	Haddock, *Melanogrammus aeglefinus*, Gadidae : Pisces	Sea, 4–47 units, Nos./trawl
22	Earthworms, all stages, *Allolobophora caliginosa* (Sav.), Oligochaeta : Annelida	Grassland, 4 units, 18 in. sq.
23	Symphyla, *Symphylella* spp., Symphyla : Myriapoda	Various soils, 60–120 units, 2½ in. cores
24	Symphyla, *Scutigerella* spp., Symphyla : Myriapoda	Various soils, 60–140 units, 2½ in. cores



TL matters practically because variability is fundamental.

Fluctuations of forests, fisheries, infectious diseases, disease vectors, tornados

Conservation of endangered species

Sampling insect pests of cotton & soybeans, fishery stocks

Linking levels of biological organization: variance-body mass allometry

Evaluation of human population projections

Slope *b* in TL is "elasticity."

Taylor's law says: variance ≈ $a(\text{mean})^b$.

Then $b \approx \dfrac{d \log variance}{d \log mean} = \dfrac{\frac{1}{var} \times d\, var}{\frac{1}{mean} \times d\, mean}$

≈ % change in variance for 1% change in mean.

b = "elasticity of variance with respect to mean" (in economists' use of "elasticity").

b = 2 iff coefficient of variation (SD/mean) & signal-to-noise ratio (mean/SD) are the same for all values of the mean.

Spatial & temporal Taylor's laws

Suppose we measure population density at *s* in space & at *t* in time.

Spatial TL: for each t, mean & variance average over space *s.*

Temporal TL: for each s, mean & variance average over time *t.*

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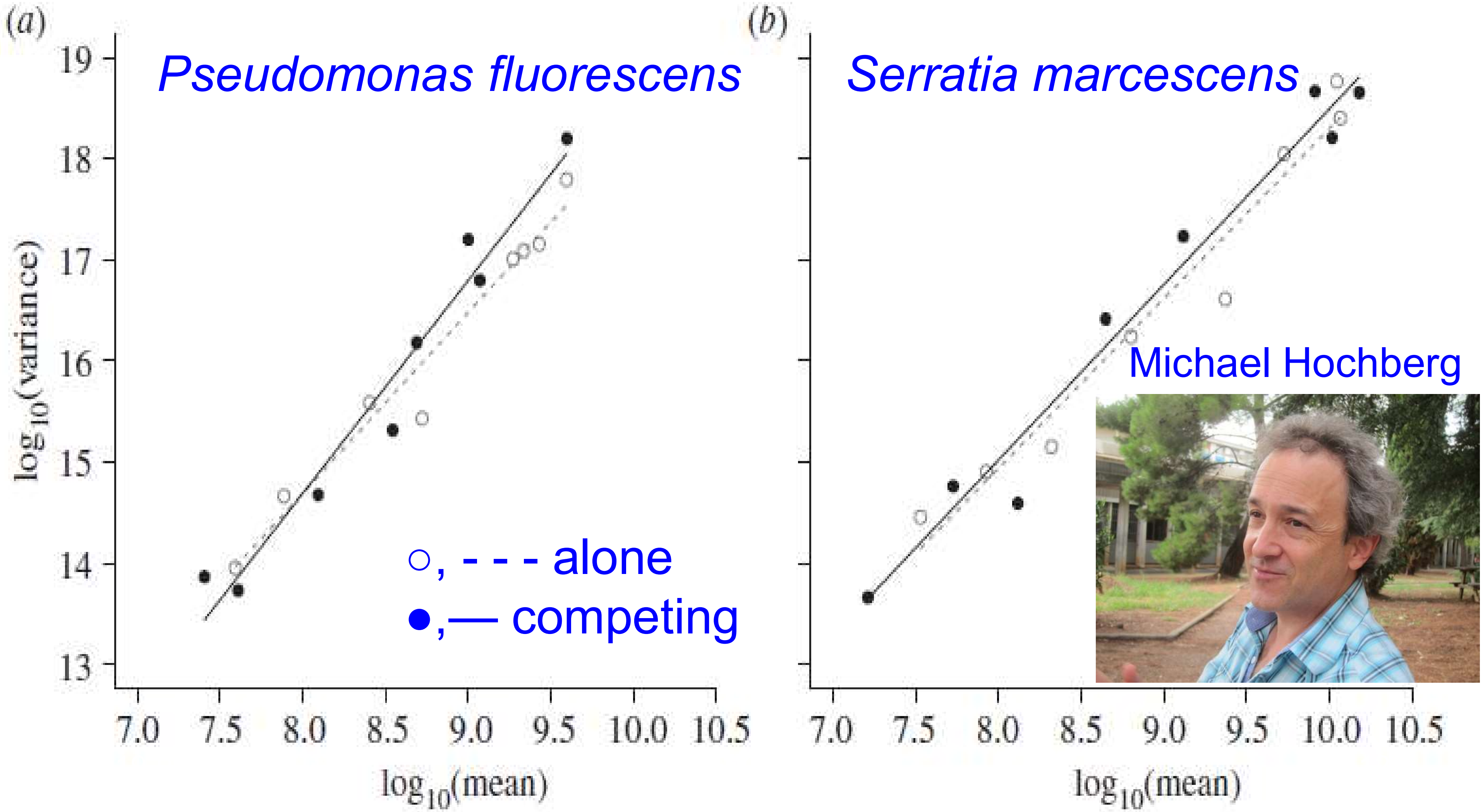
Competing bacteria satisfy spatial TL with slope ≈ 2

Ramsayer, Fellous, Cohen, Hochberg *Biology Letters* 2011; 8 replicates per treatment

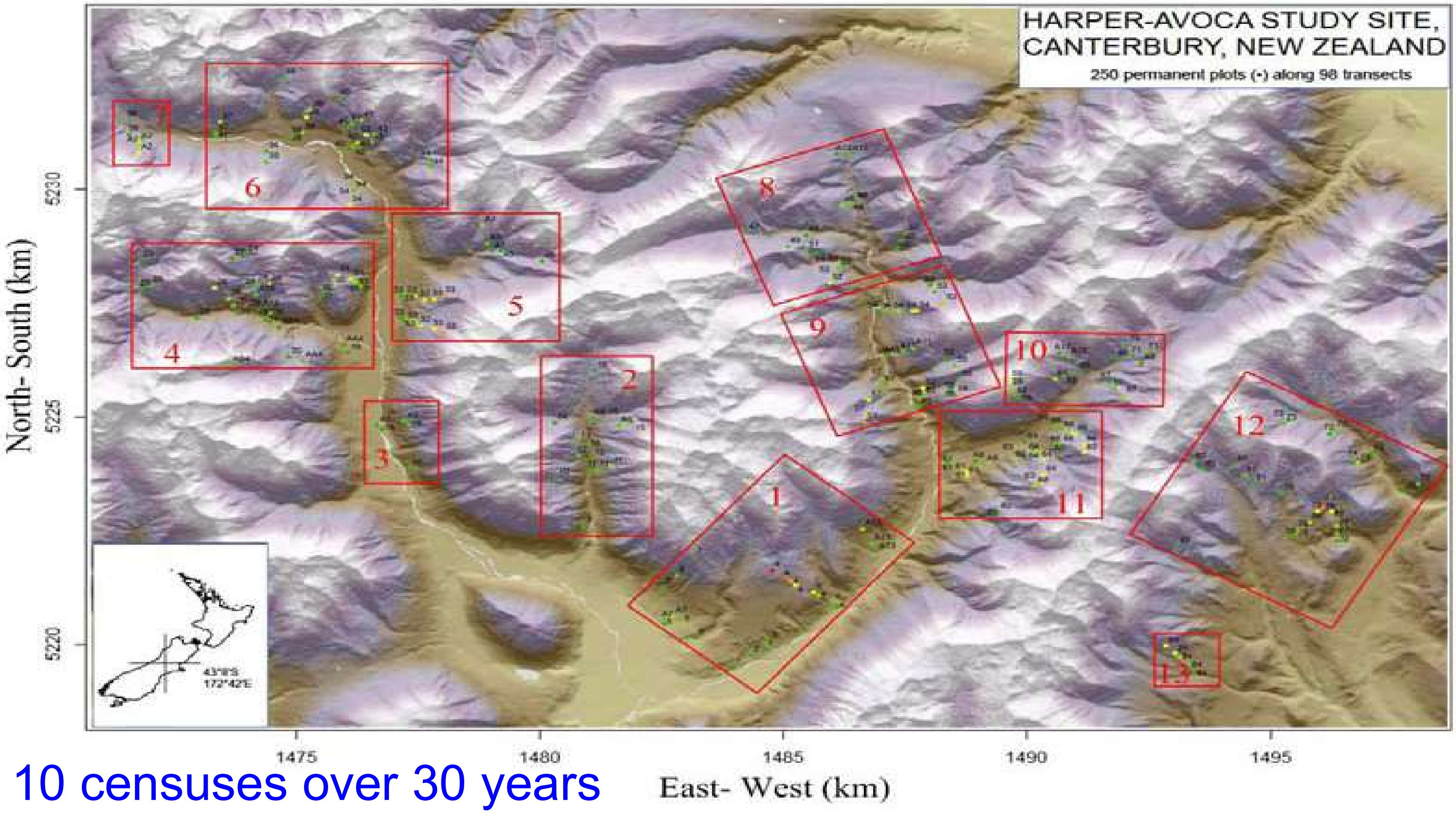


Michael Hochberg


20120323 Arthurs Pass, New Zealand

New Zealand mountain beech

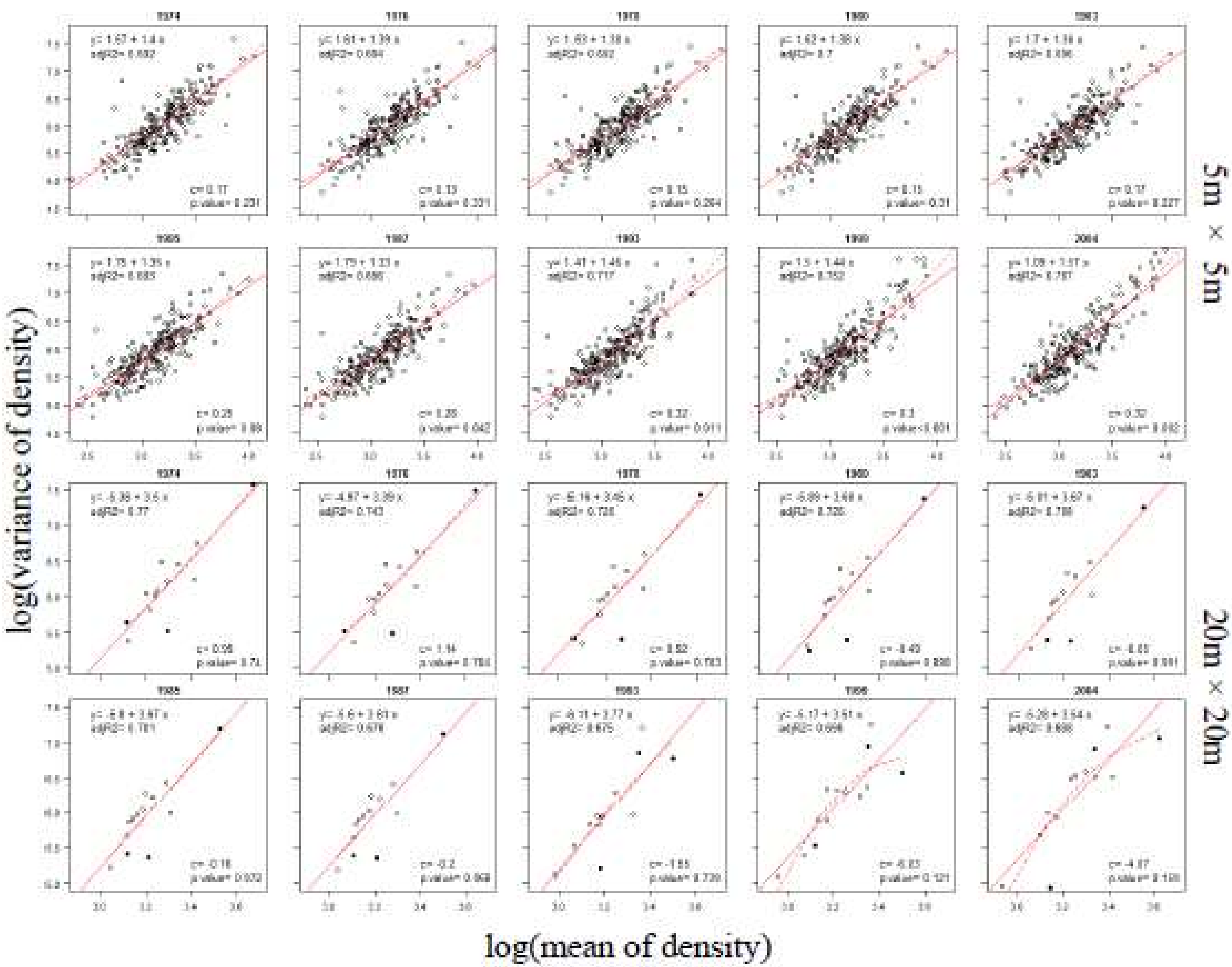
Cohen, Lai, Coomes, Allen, *Oikos* 2016
3 spatial scales: subplots 5x5m, plots 20x20m, blocks
16 subplots/plot, 5-33 plots/block, 13 blocks



10 censuses over 30 years

New Zealand mountain beech

Cohen, Lai, Coomes, Allen, *Oikos* 2016



David Coomes
2013

10 censuses
1974-2004

TL slope *b* is much greater at larger spatial scale than small.

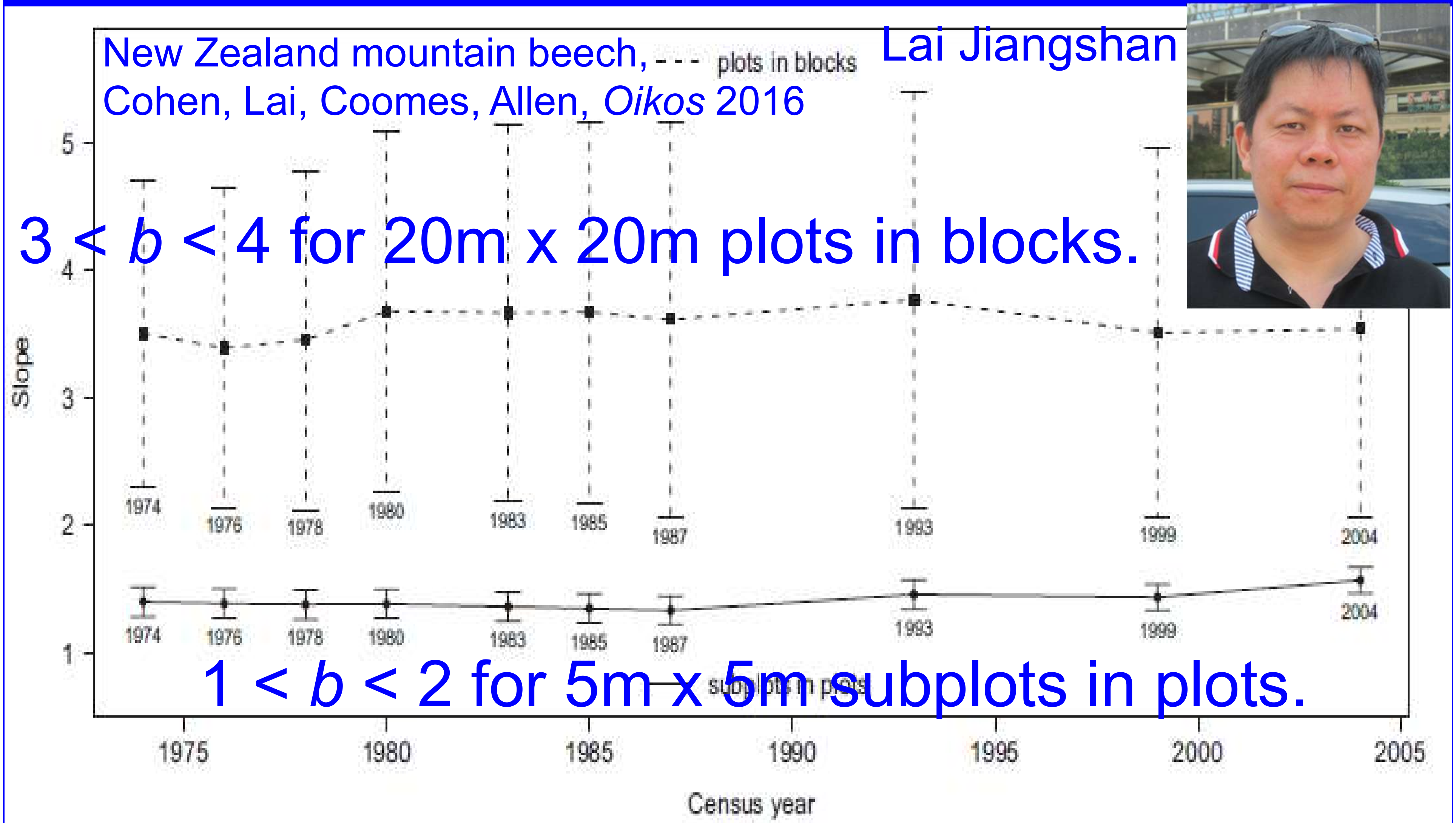
Slope cannot be species-specific characteristic.

New Zealand mountain beech,
Cohen, Lai, Coomes, Allen, *Oikos* 2016

Lai Jiangshan

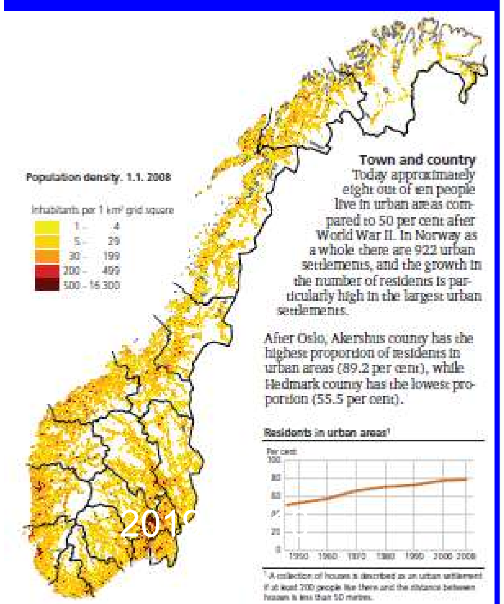
3 < *b* < 4 for 20m x 20m plots in blocks.

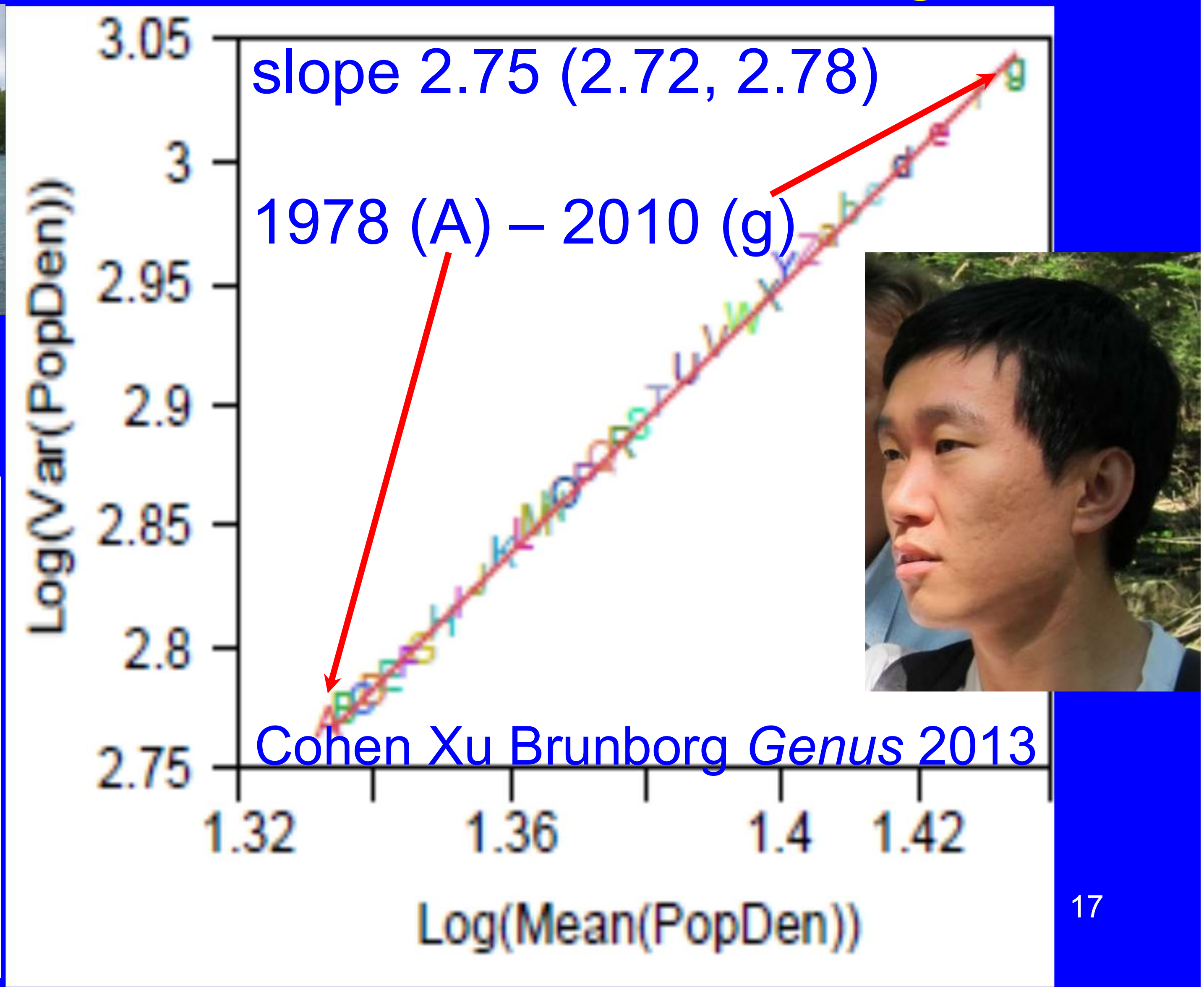
1 < *b* < 2 for 5m x 5m subplots in plots.



Norway: spatial mean & spatial variance of people/km^2 in 18 counties excluding Oslo

Helge Brunborg



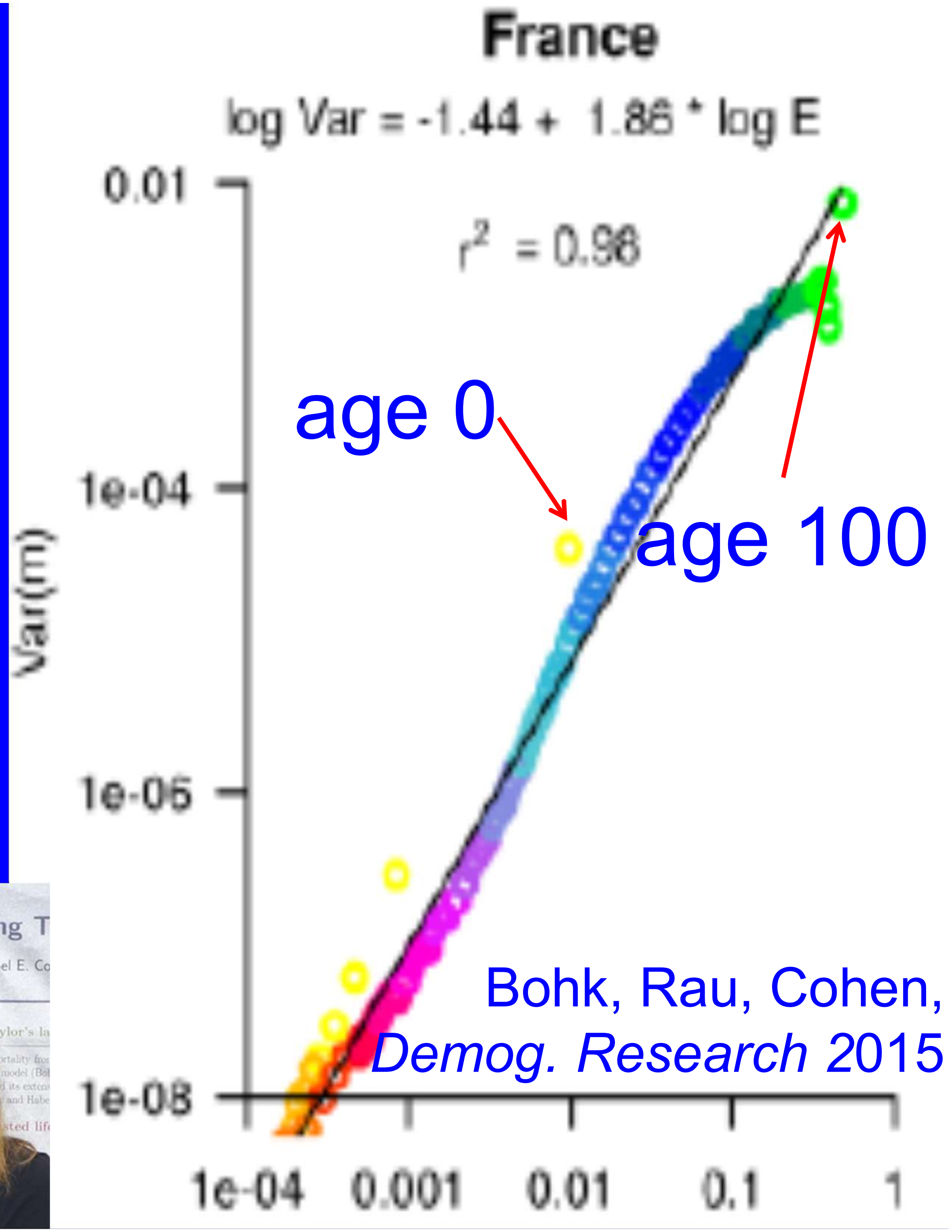


Age-specific death rates, France

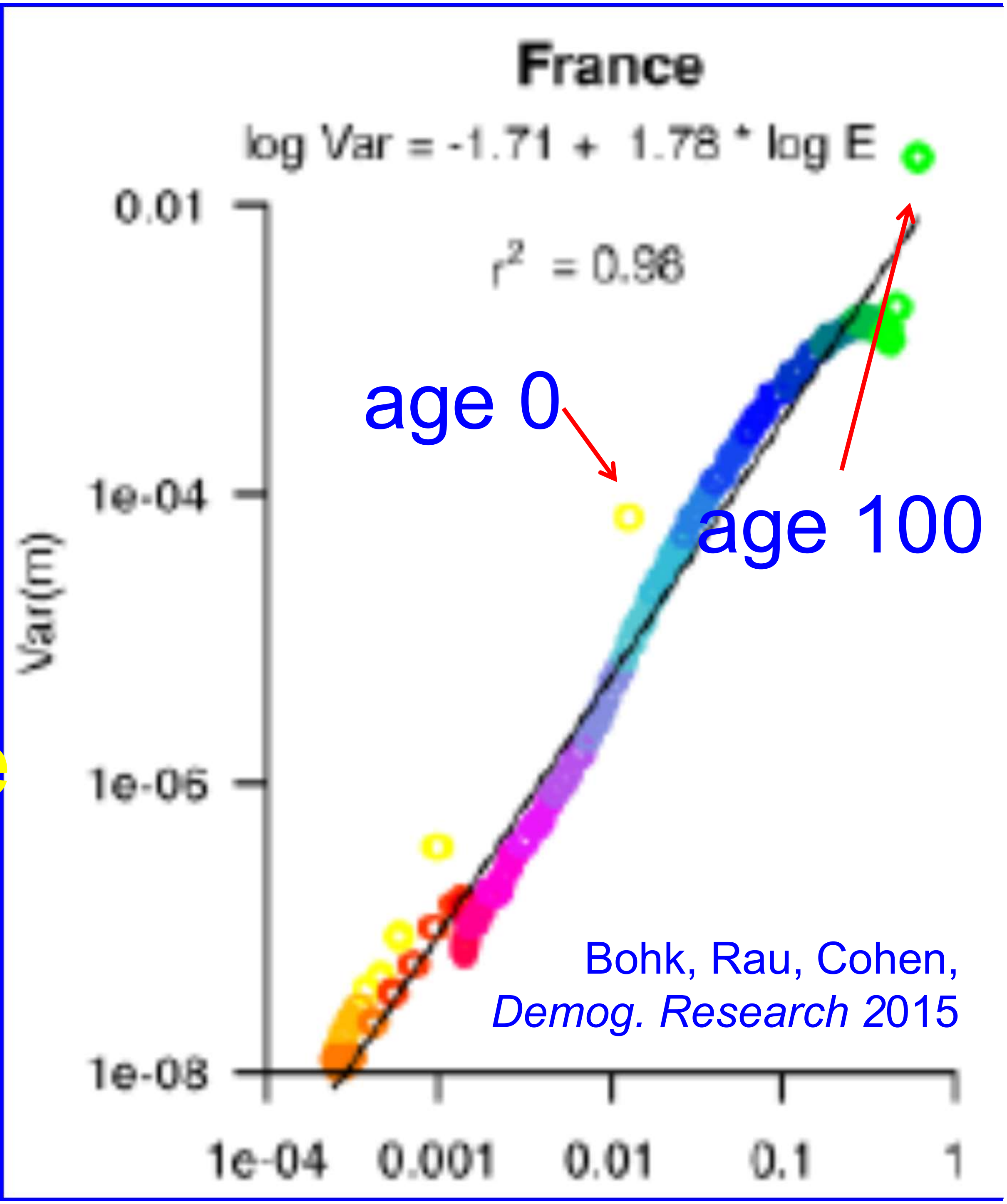
Human Mortality Database

Year t ↓ Age x→	0	1	x	100
1960			…	
1961			…	
t			$m_{t,x} = \frac{d_{t,x}}{L_{t,x}}$	
2008			…	
2009			…	
Mean			Mean(x)	
Variance			Var(x)	

Female death rates for each year of age, mean & variance over 1960-2009, France



Male death rates for each year of age, mean & variance over 1960-2009, France



Female death rates by age, mean & variance over time 1960-2009

Bohk, Rau, Cohen, *Demographic Research* 2015

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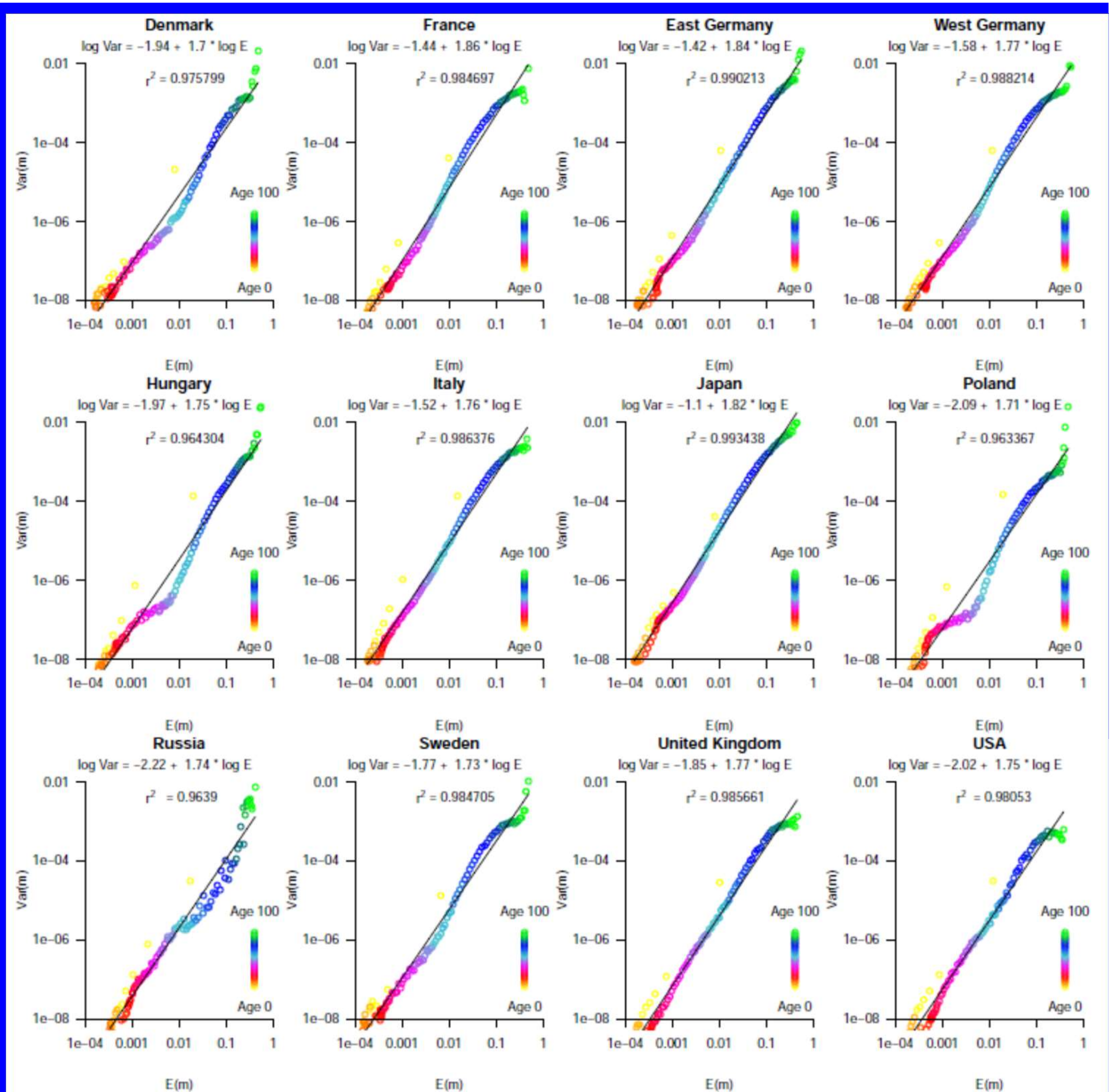

Male death rates by age, mean & variance over time 1960-2009

Bohk, Rau, Cohen, *Demographic Research* 2015

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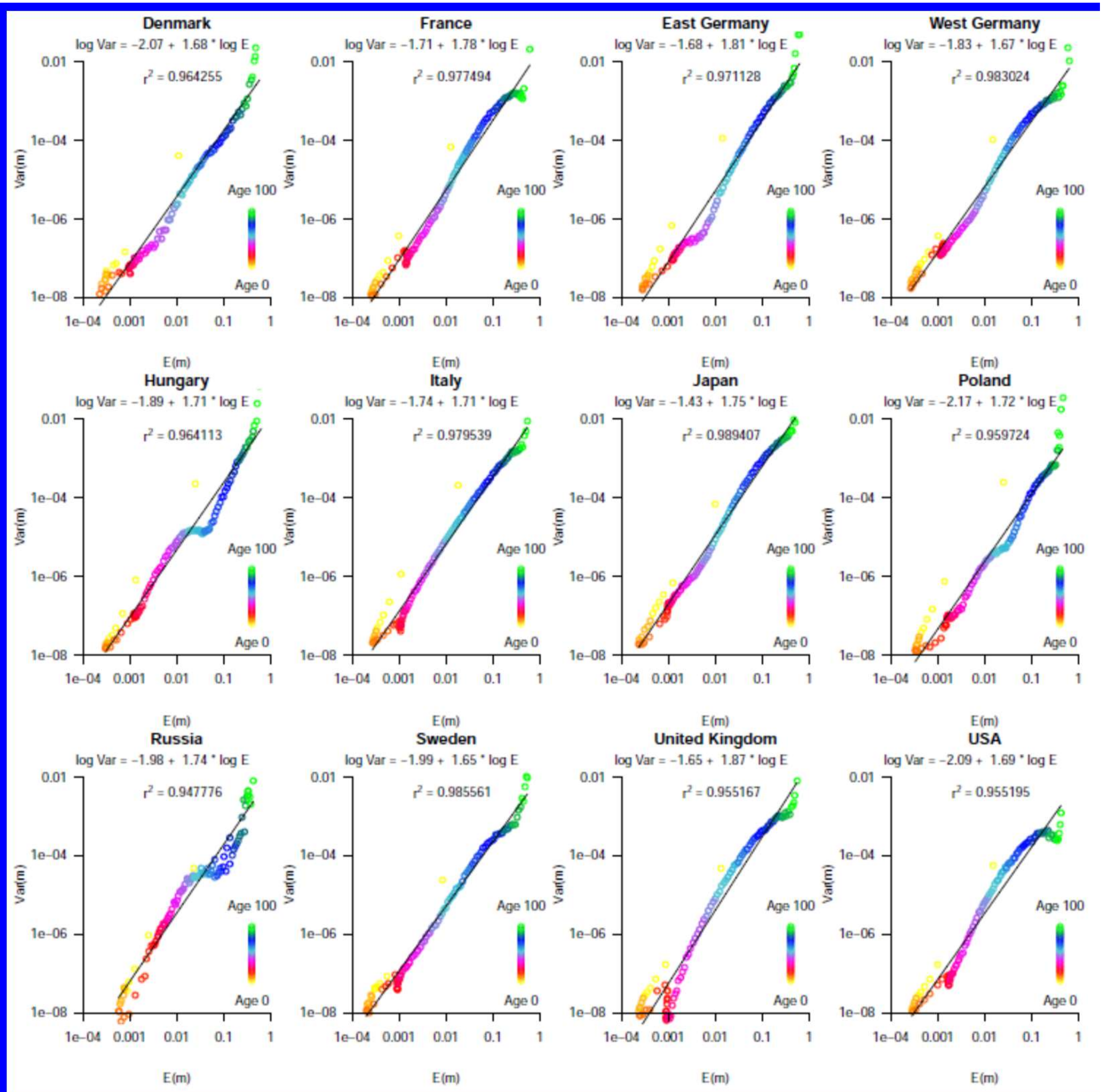
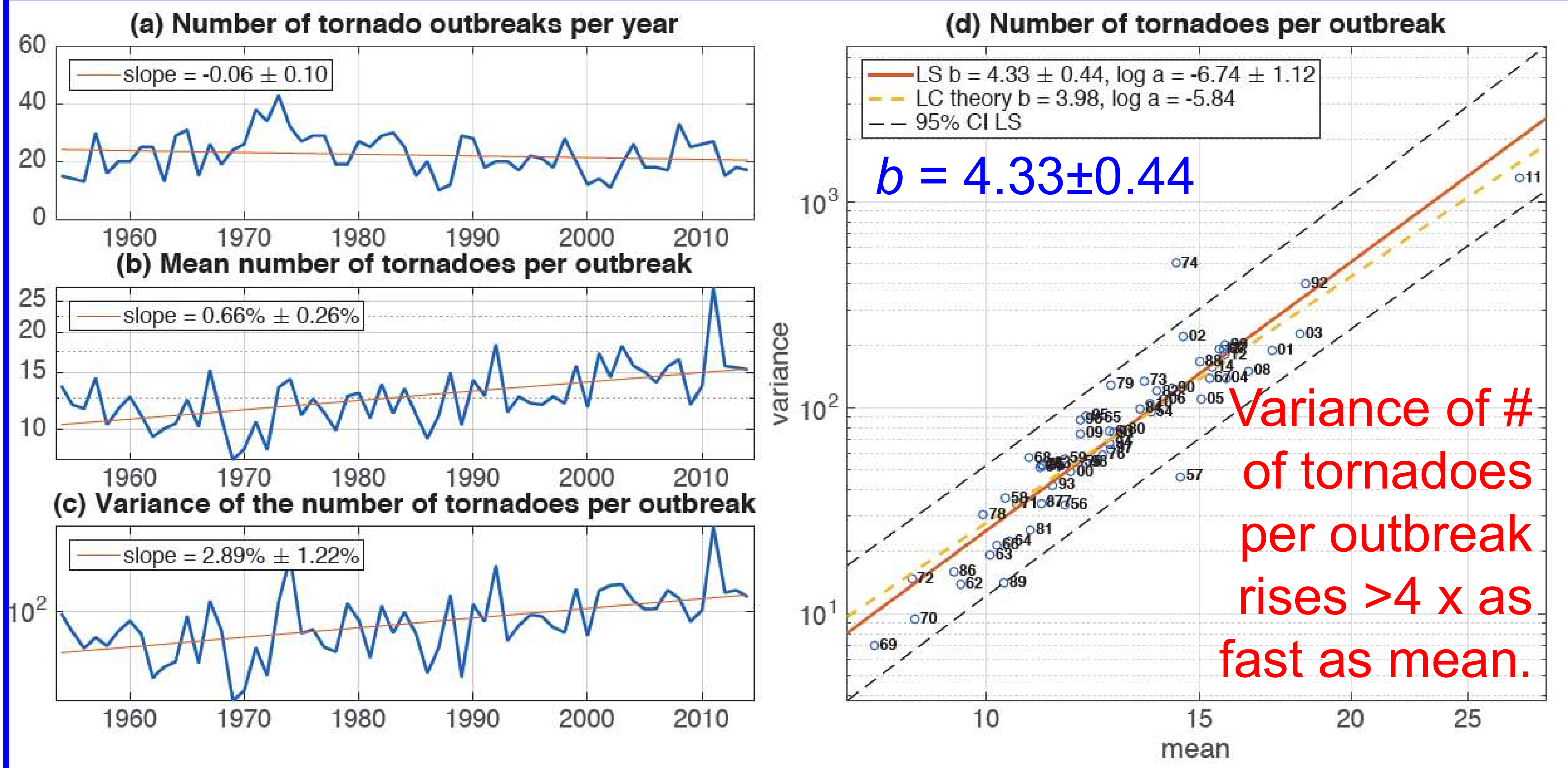


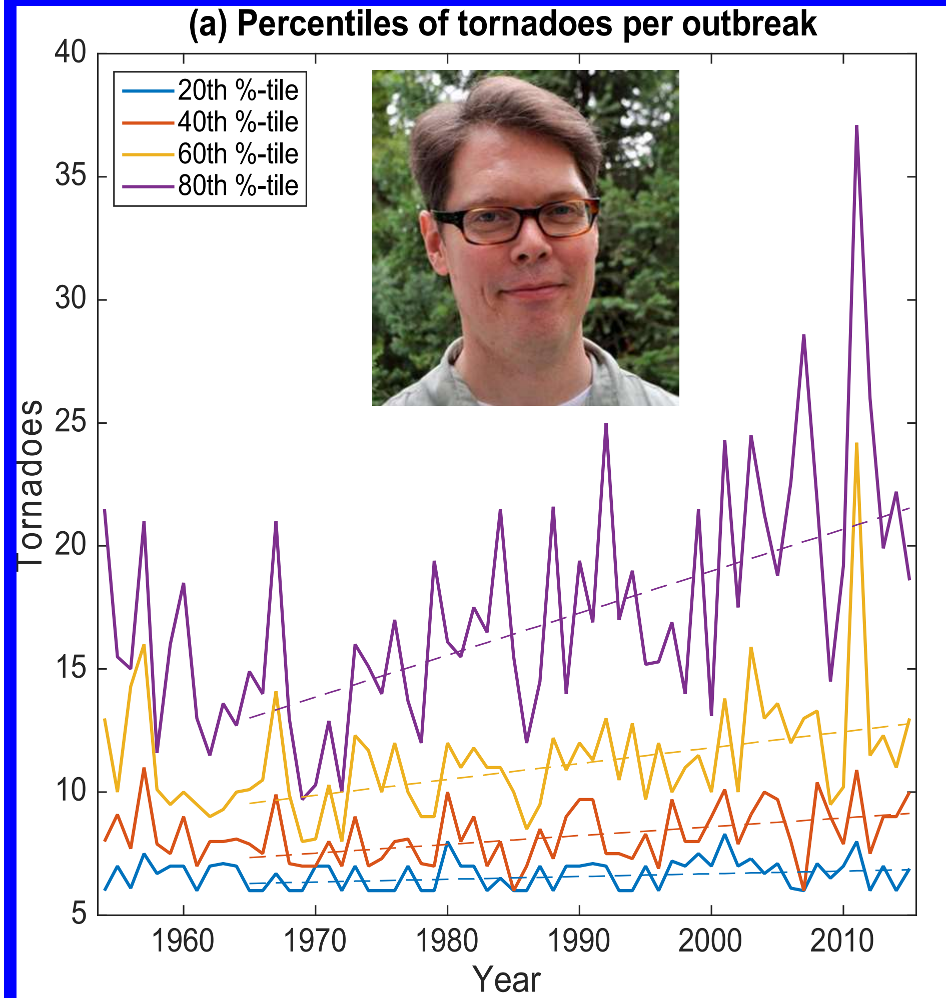
F1+ tornadoes per outbreak in USA: variance~(mean)$^{4.3}$

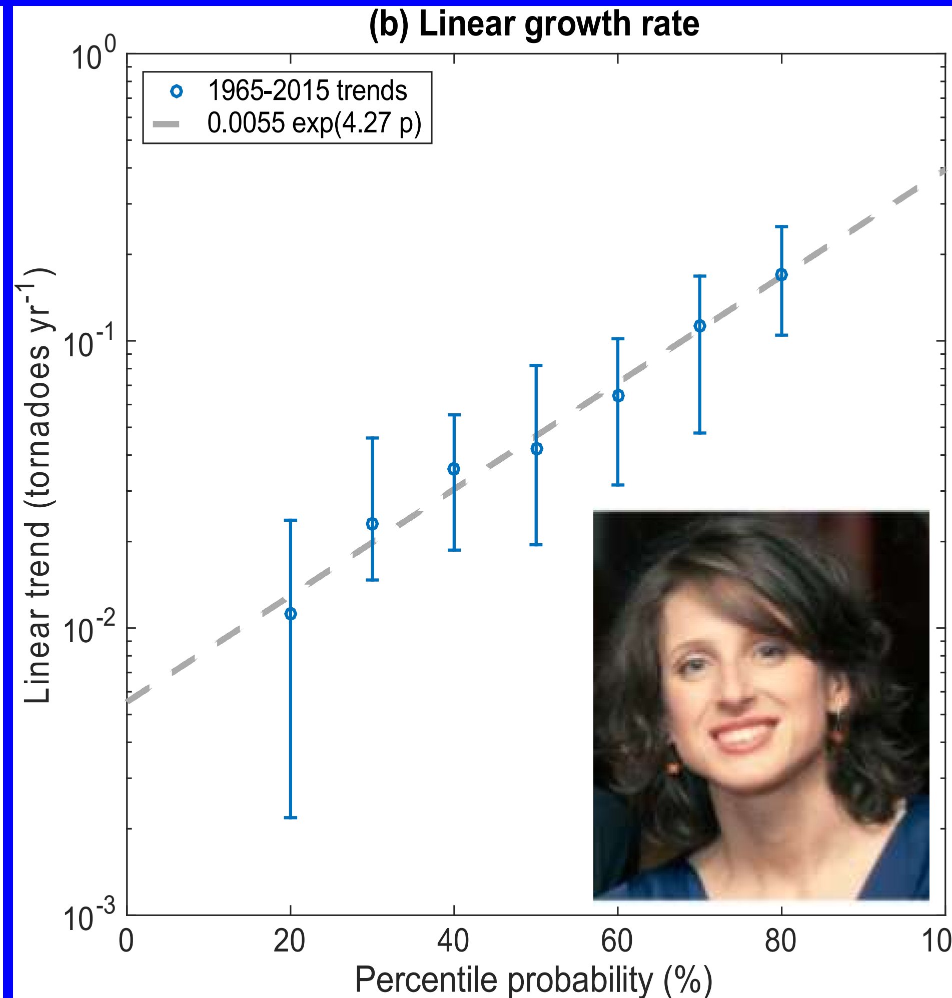
Tippett & Cohen, *Nature Communications* 2016



Higher percentiles increased faster.

“quantile regression”





Tippett, Lepore, Cohen *Science* 2016

Extreme outbreaks (12+ tornadoes) increased extremely.

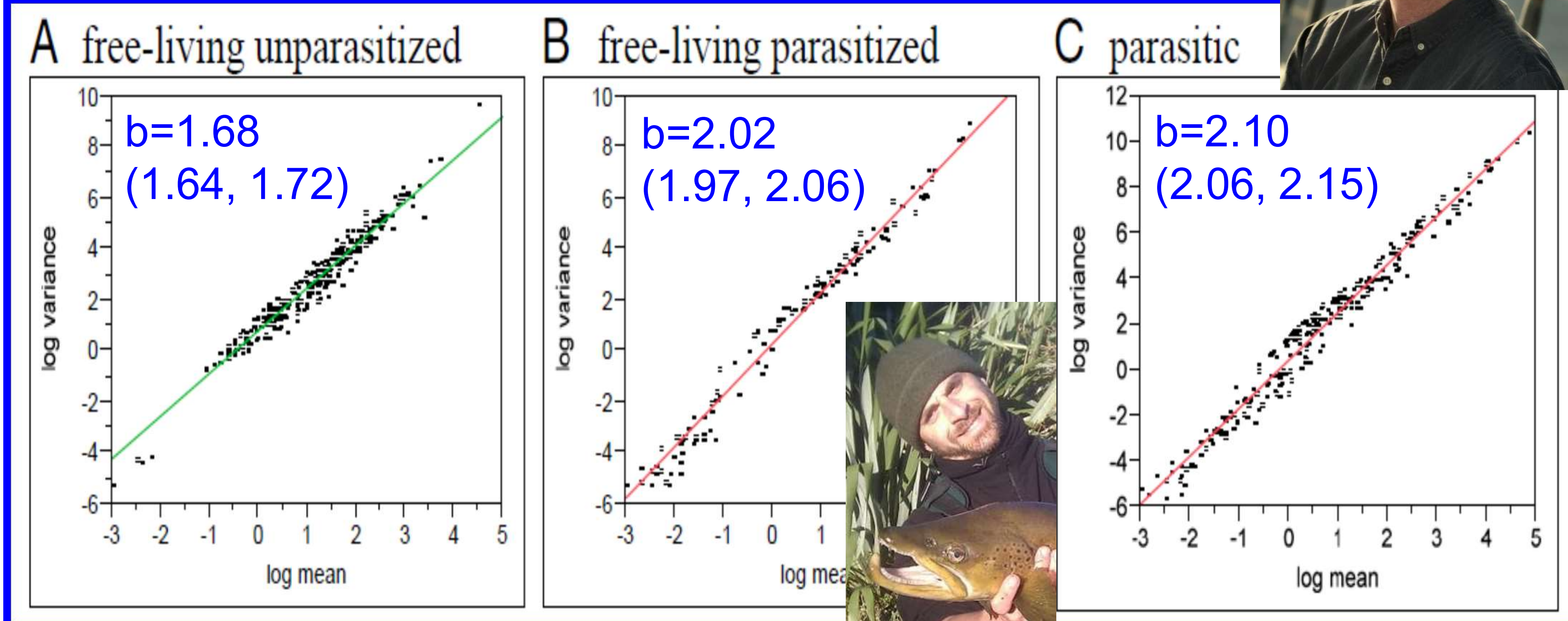
- “Once in 5 years” extreme outbreak increased from 40 tornadoes in 1965 to 80 tornadoes in 2015.
- “Once in 25 years” extreme outbreak more than doubled from 1965 to 2015.

Tippett, Lepore, Cohen *Science* 2016

Metazoan population density (individuals m^{-2}) obey spatial TL. Parameters differ by life style.

Lagrue, Poulin, Cohen PNAS 2015

First demonstration that the parameters of TL depend on lifestyle within a given metazoan community



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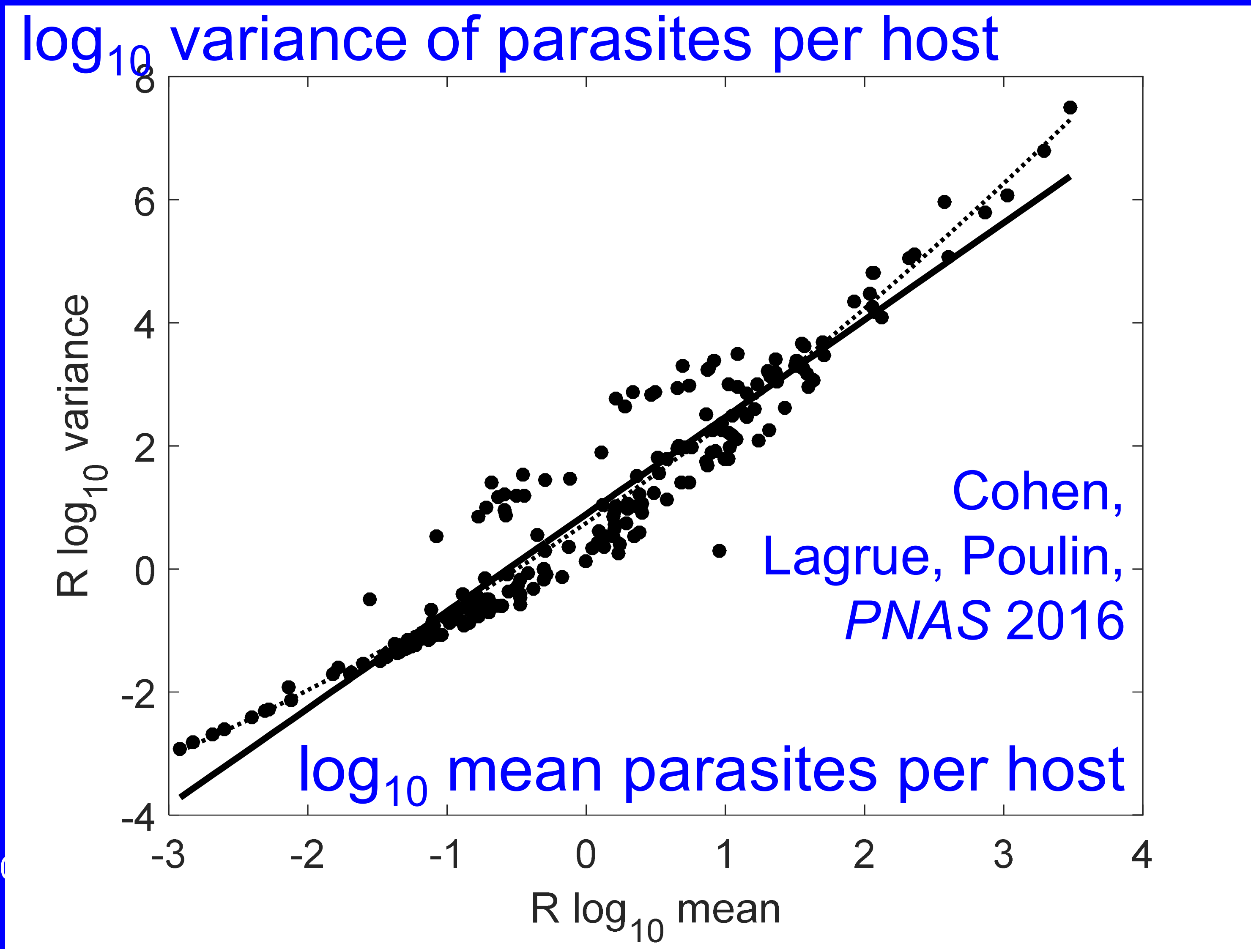
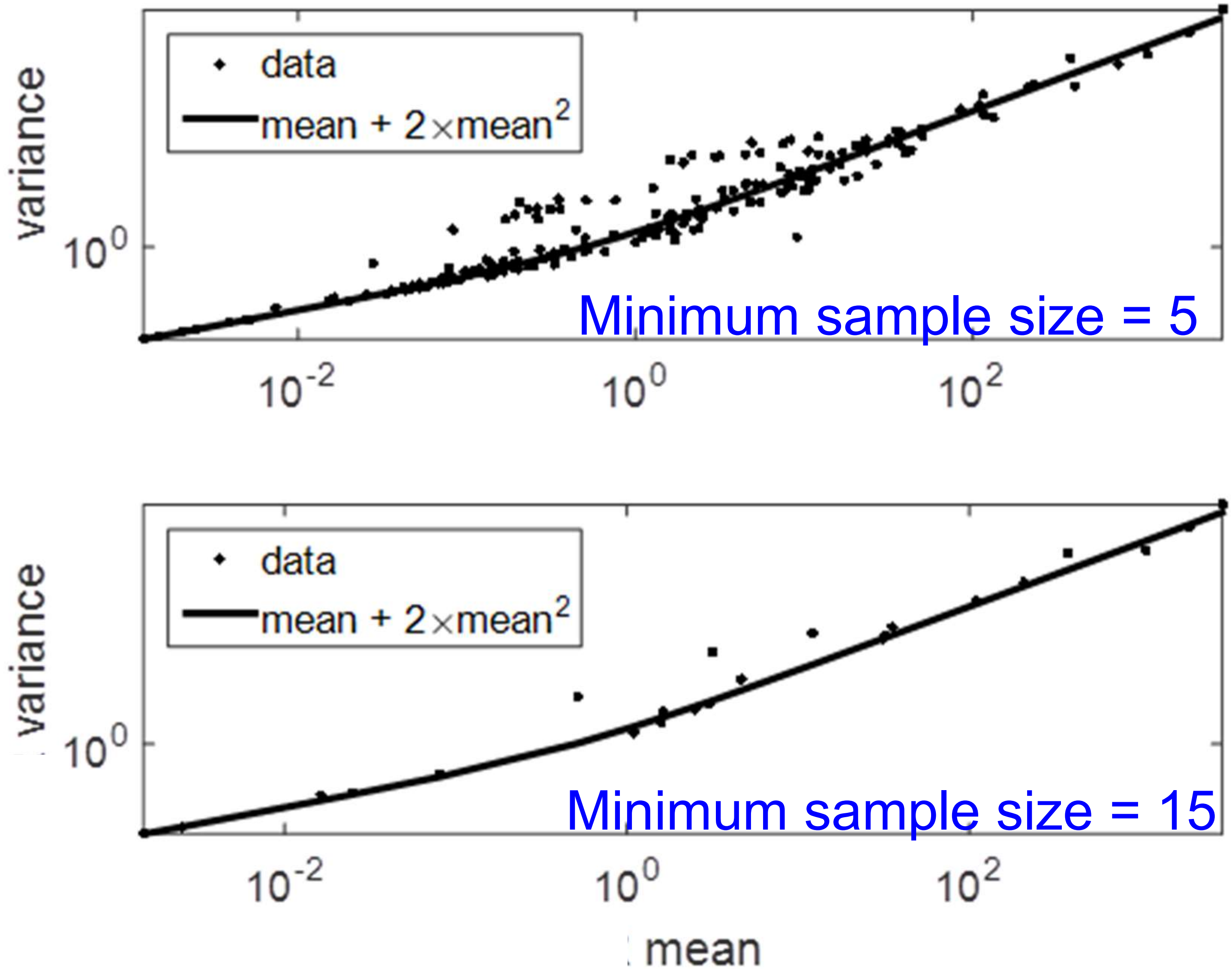
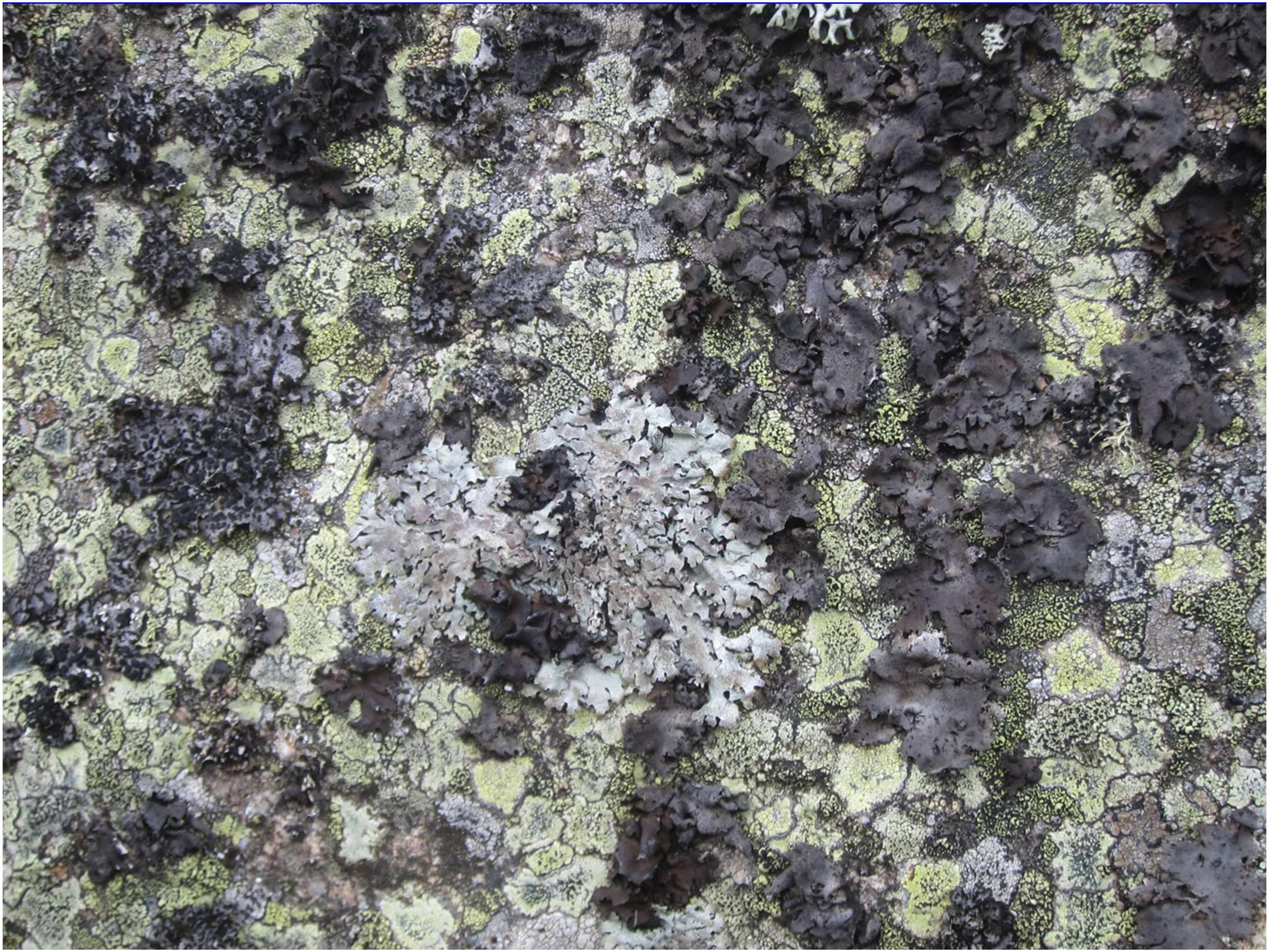
Quadratic model beats Taylor's law for parasite number per host.



Parasites/host follow negative binomial: variance=mean+2(mean^2).

Cohen, Lagrue, Poulin, *PNAS* 2016





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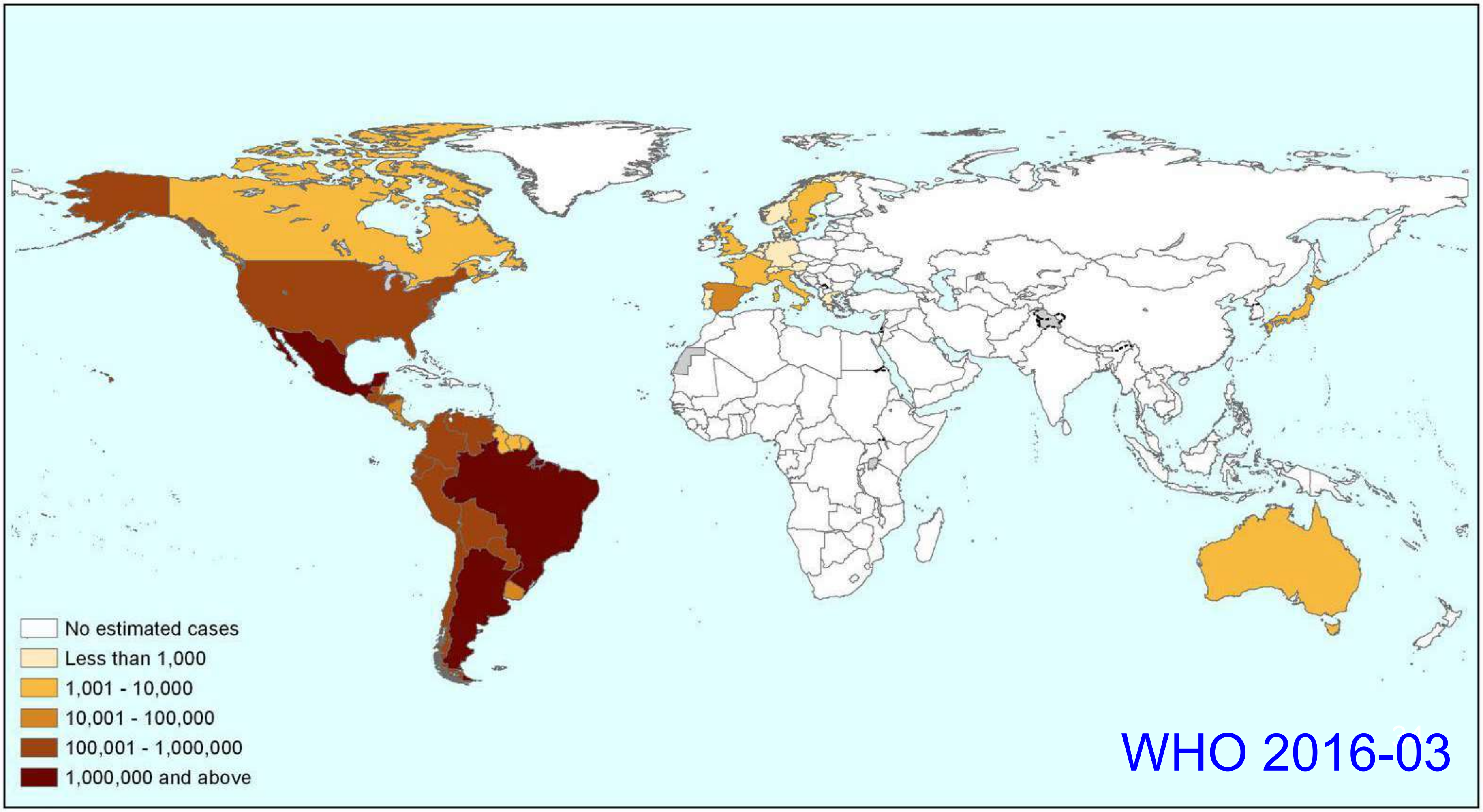
Chagas disease

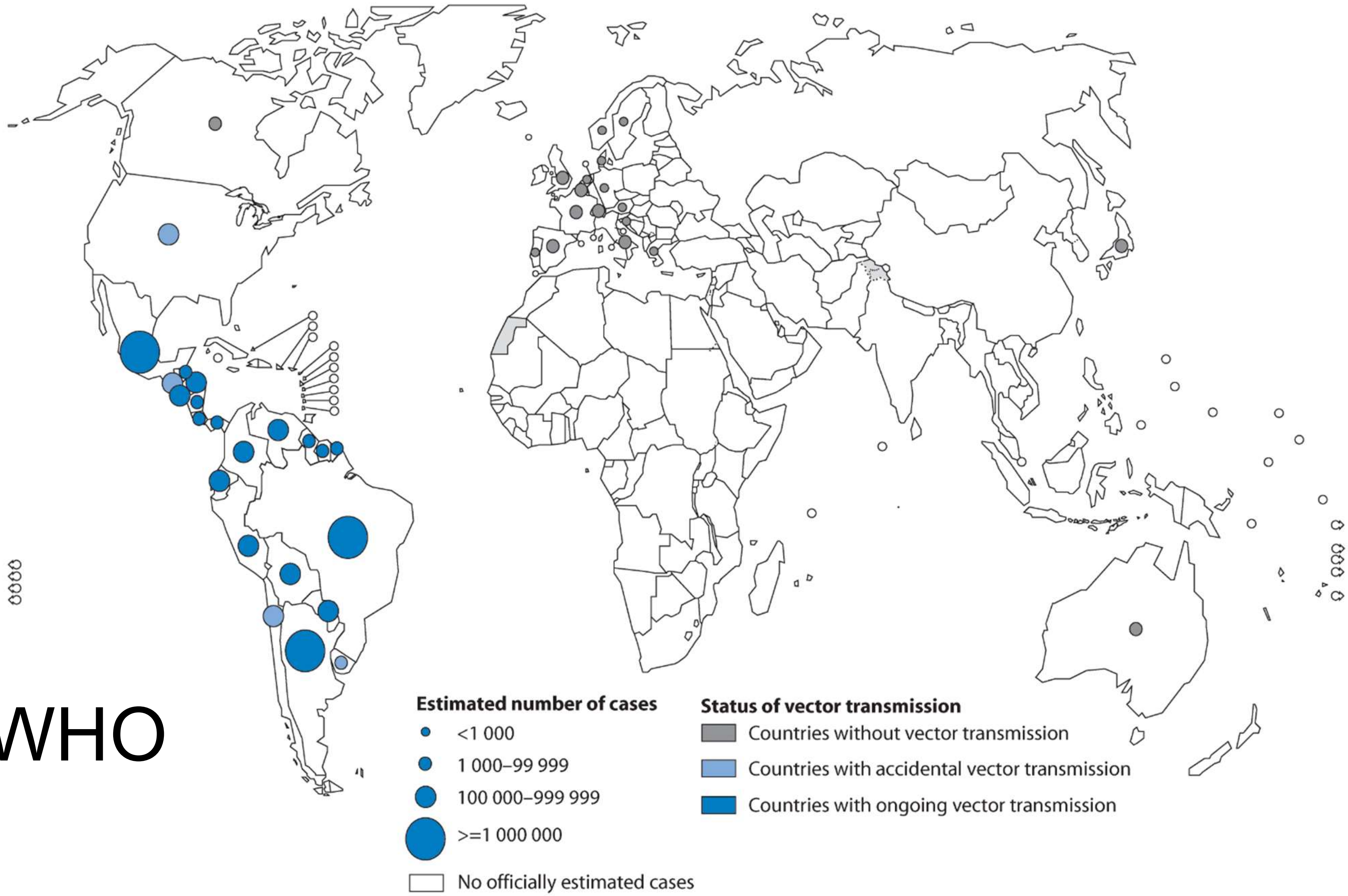
Carlos Chagas discovered infectious agent 1909

Estimated global population infected by *Trypanosoma cruzi*, 2009



6-7 million cases of Chagas disease 2019

Distribution of cases of *Trypanosoma cruzi* infection, based on official estimates and status of vector transmission, worldwide, 2006–2009

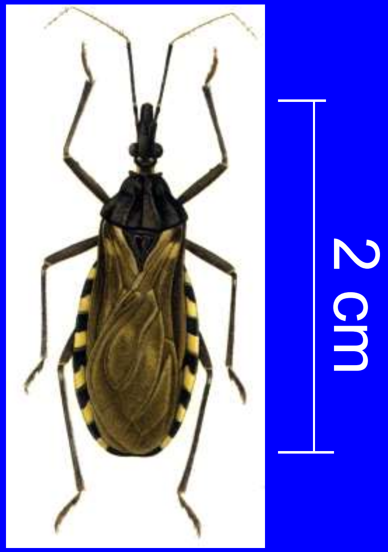


WHO

Parasite & vectors are widespread.

Parasite:
Trypanosoma cruzi

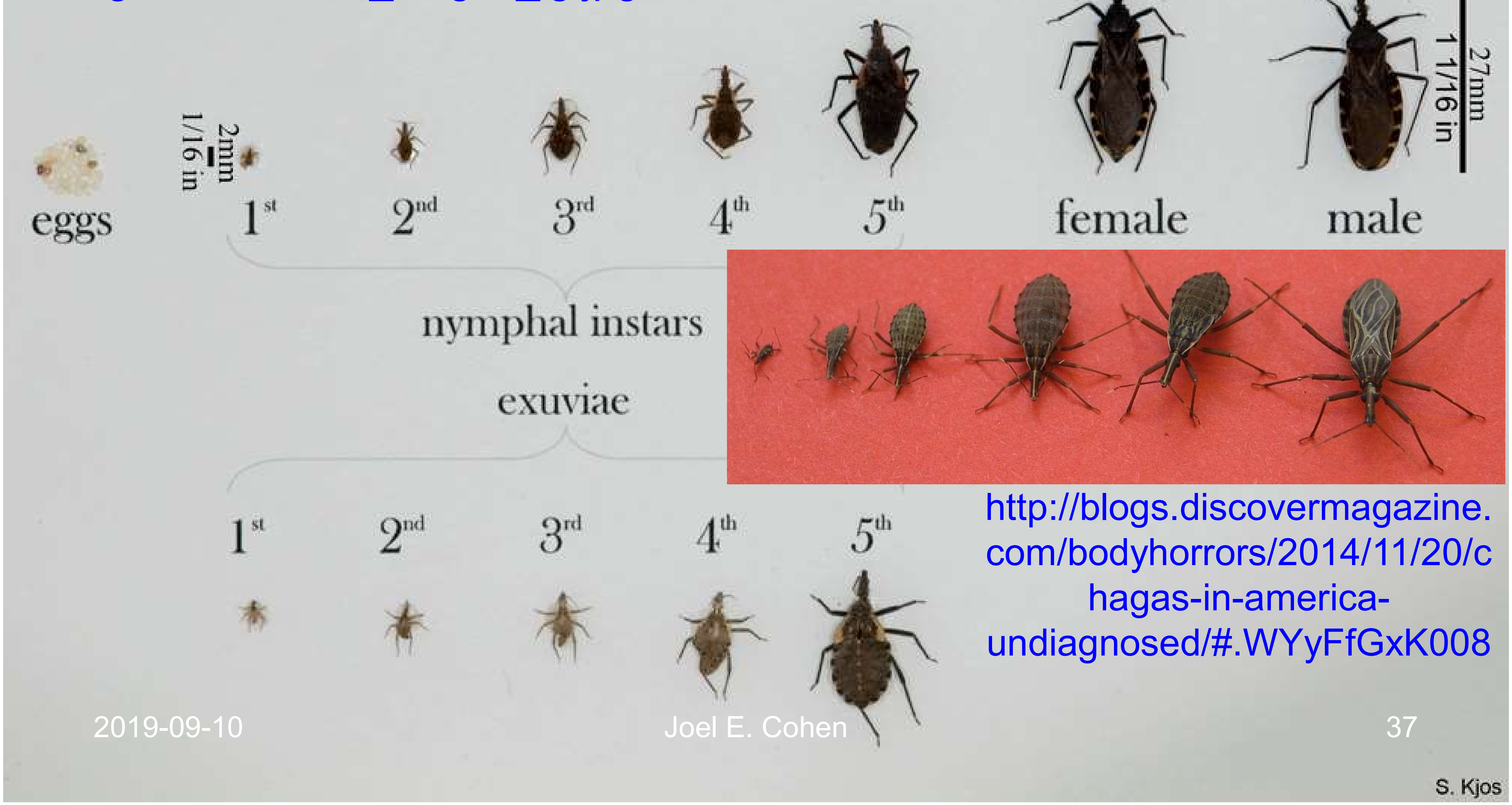
Vectors: multiple species, mainly *Triatoma infestans*



Source:
http://www.cpqrr.fiocruz.br/laboratorios/lab_triato/TriatoInfestans.html

Triatomine bug needs a blood meal to moult & lay eggs.

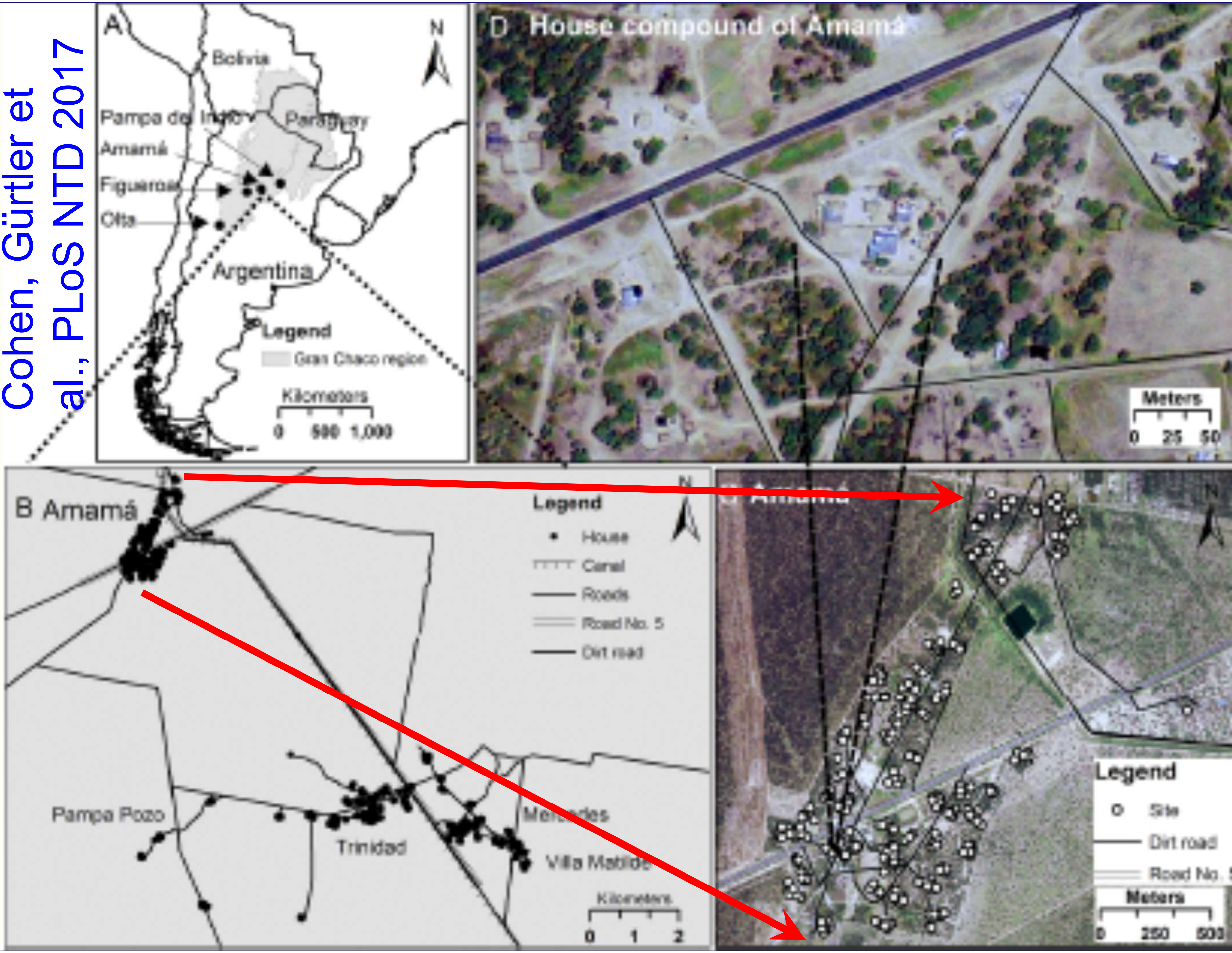
https://www.cdc.gov/parasites/images/chagas/triatomine_stages_lg.jpg

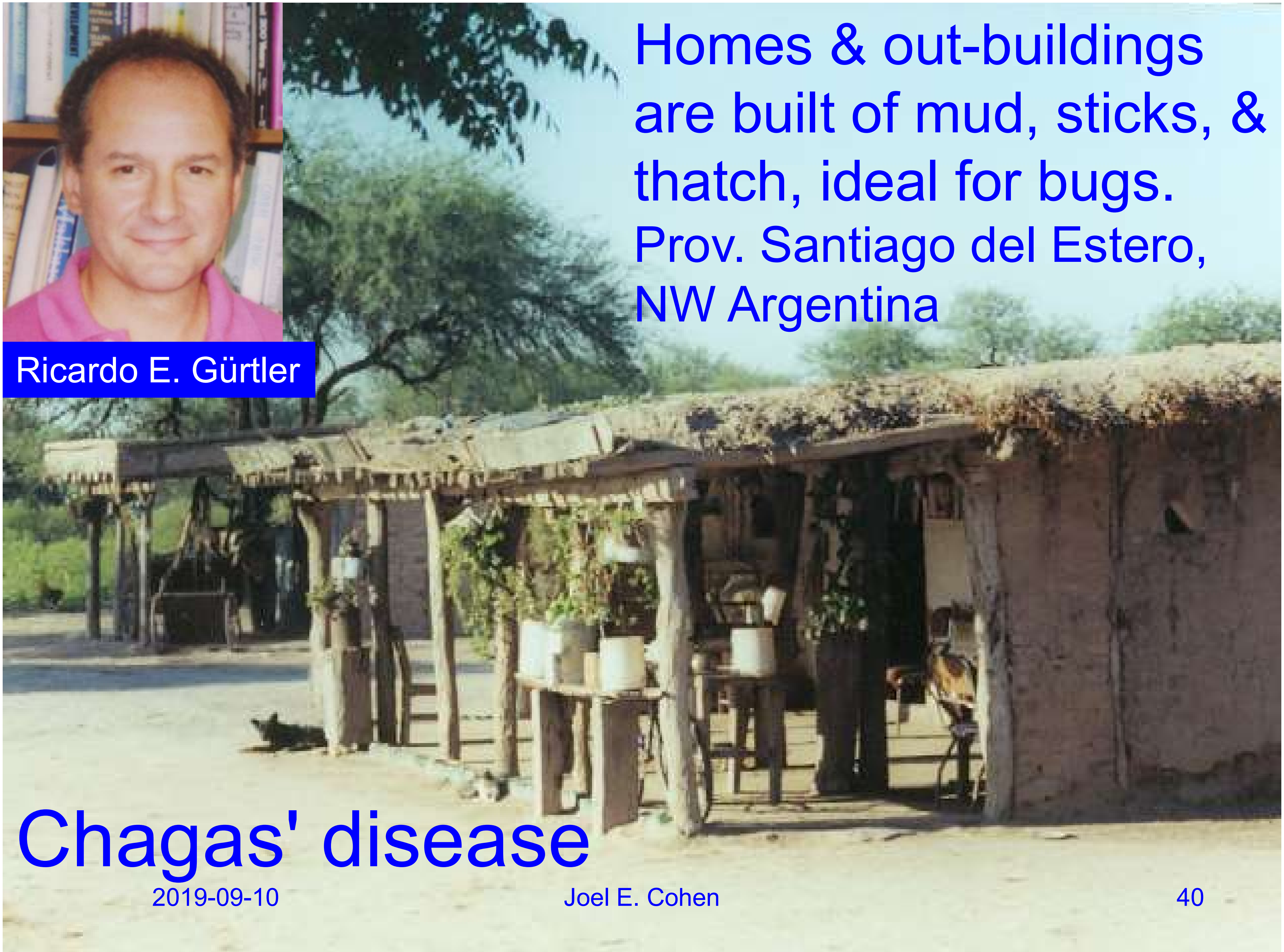


http://blogs.discovermagazine.com/bodyhorrors/2014/11/20/chagas-in-america-undiagnosed/#.WYyFfGxK008

Distribución aparente de *Triatoma infestans*

Cohen, Gürtler et al., PLoS NTD 2017





Ricardo E. Gürtler

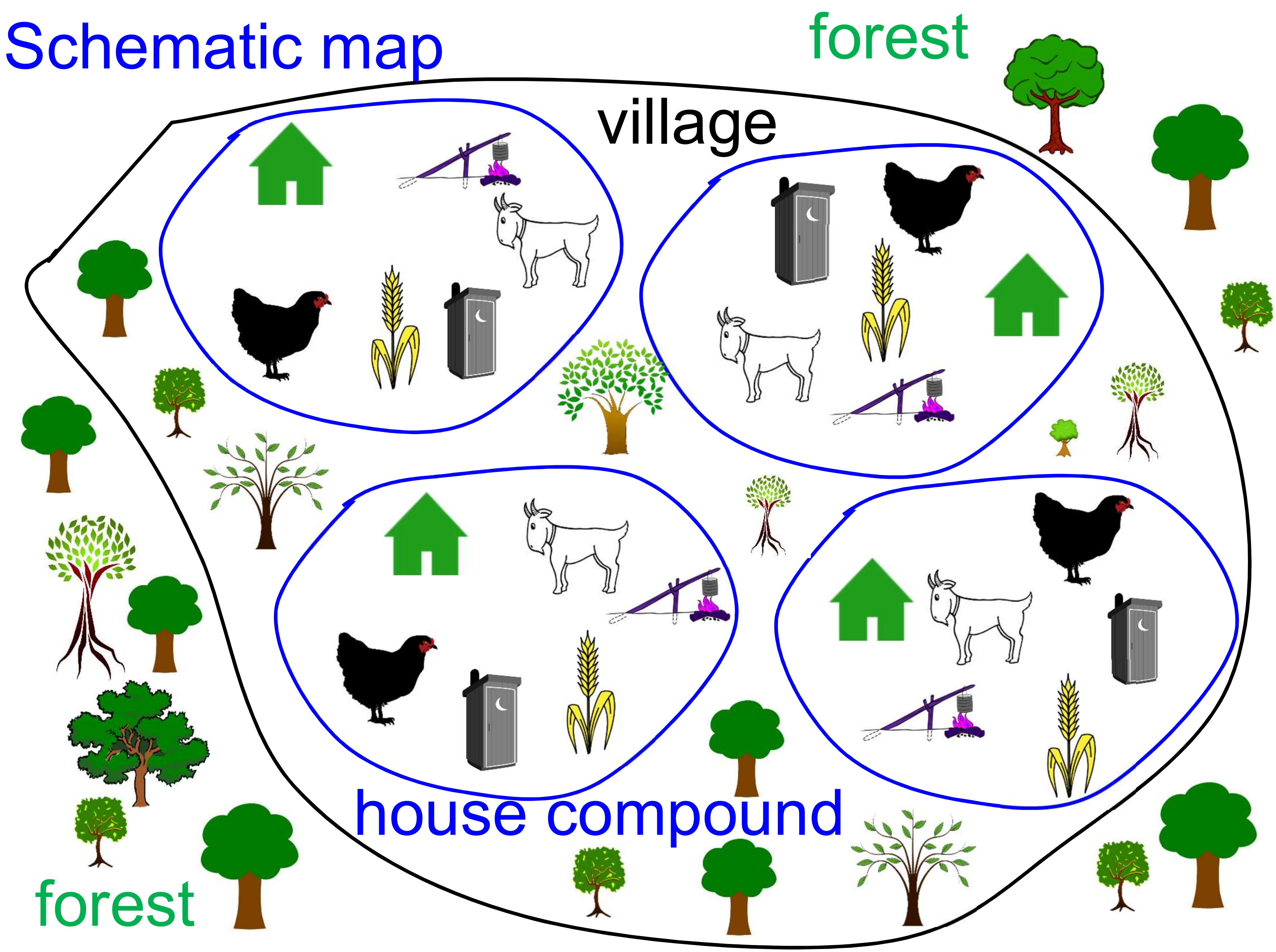
Homes & out-buildings are built of mud, sticks, & thatch, ideal for bugs.

Prov. Santiago del Estero, NW Argentina

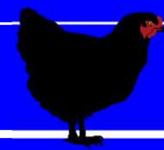
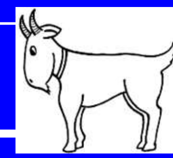
Chagas' disease

Bug bites dog infected with *T. cruzi*, infected bug bites boy.

Outbuildings surround domiciles, Pampa del Indio, 2007-2011.

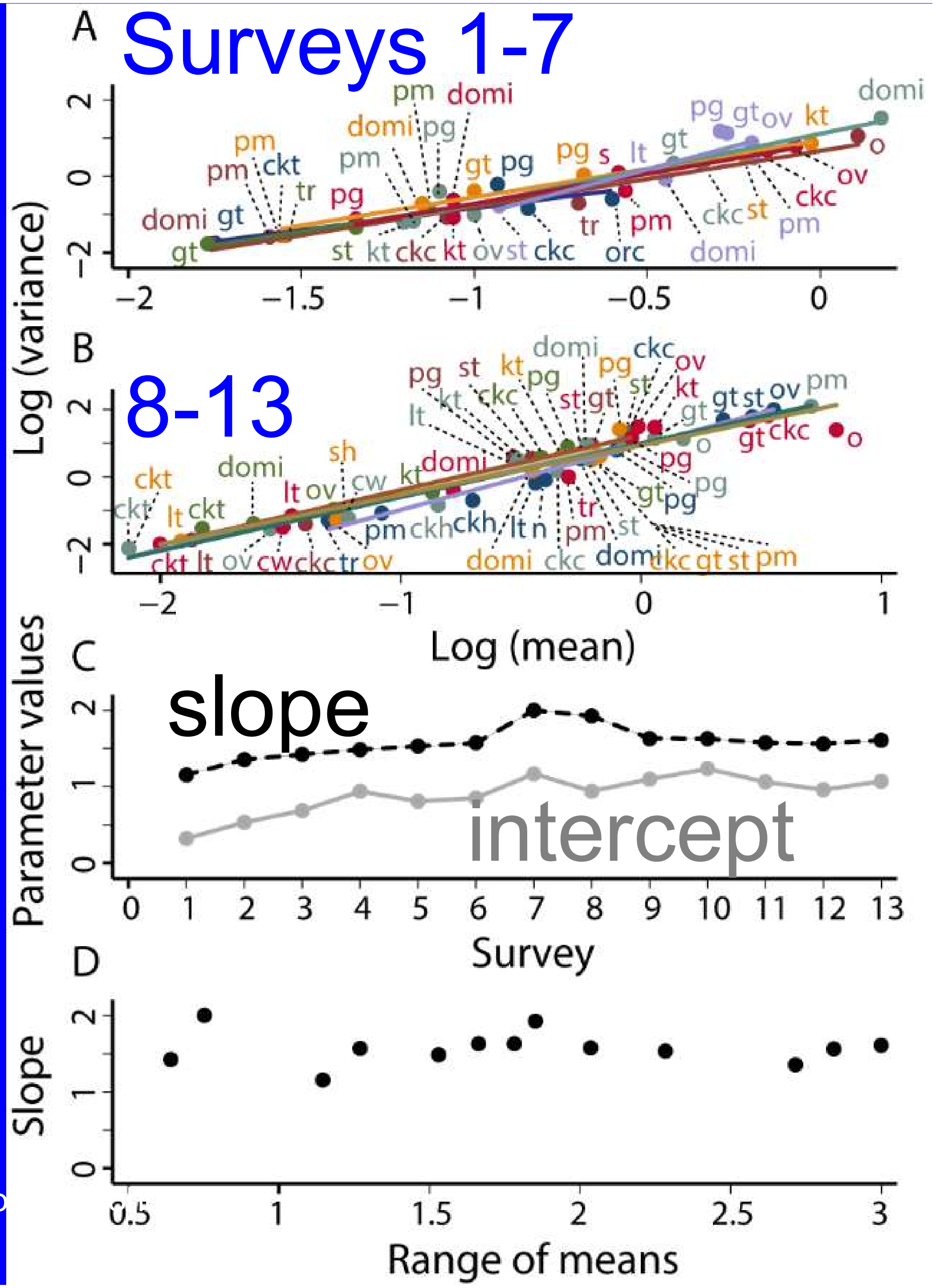

Schematic map
forest
village
house compound
forest

Each habitat (domicile, chicken coop, goat corral, granary) defines one sample.

Habitat→				
Bug population density (per hour of search) in exemplars of this habitat	x_{11}	x_{12}	x_{13}	$x_{...}$
	x_{21}	x_{22}	x_{23}	…
	x_{31}	x_{32}	x_{33}	…
		x_{42}	x_{43}	…
		x_{52}		…
Mean	m_1	m_2	m_3	m…
Variance	v_1	v_2	v_3	v…

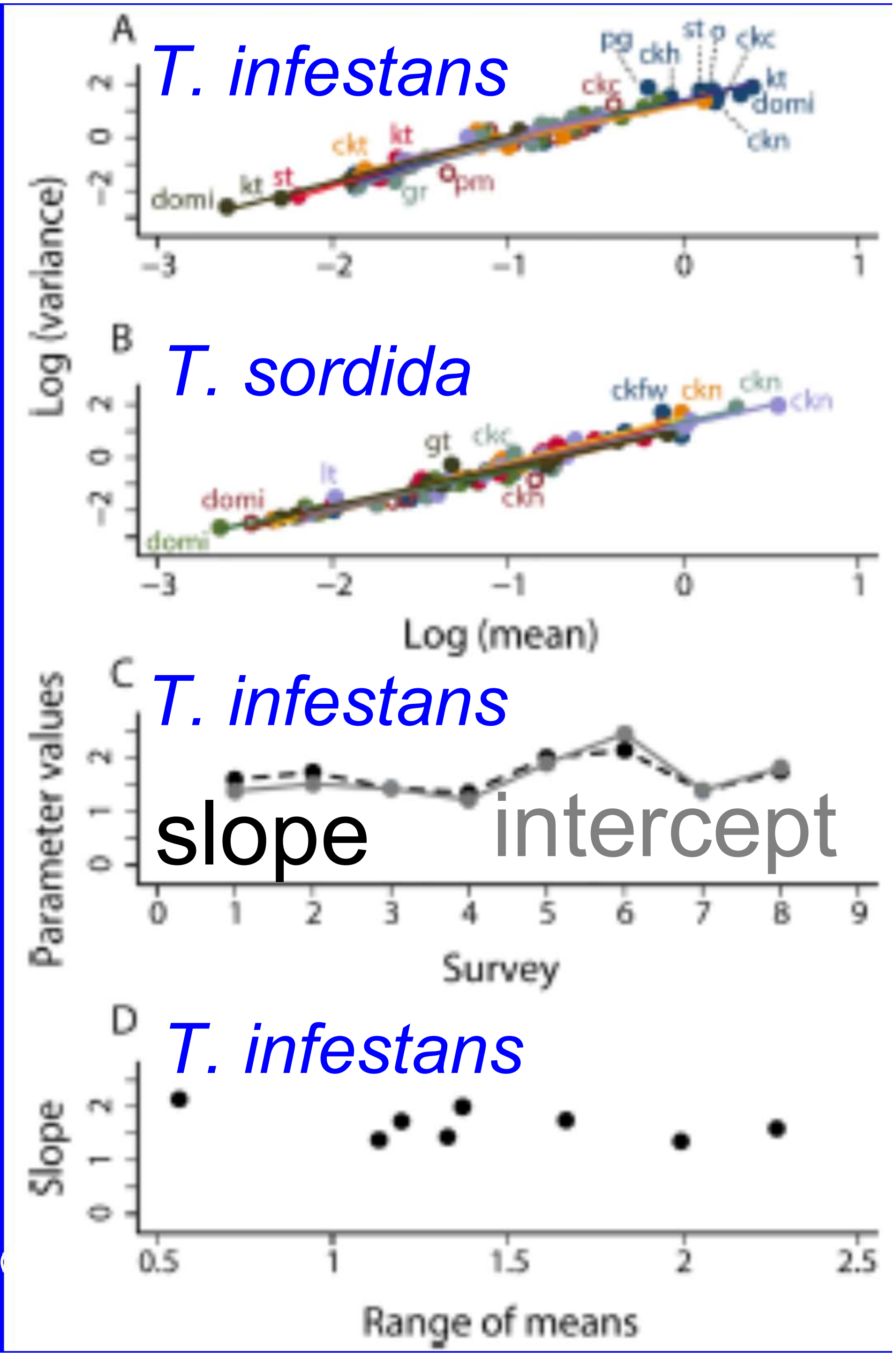
Amamá core (sustained surveillance & control): *T. infestans* obeys spatial TL in 13 surveys 1993-2002.

Cohen, Rodríguez-Planes, Gaspe, Cecere, Cardinal, Gürtler, *PLoS Neglected Tropical Diseases* 2017



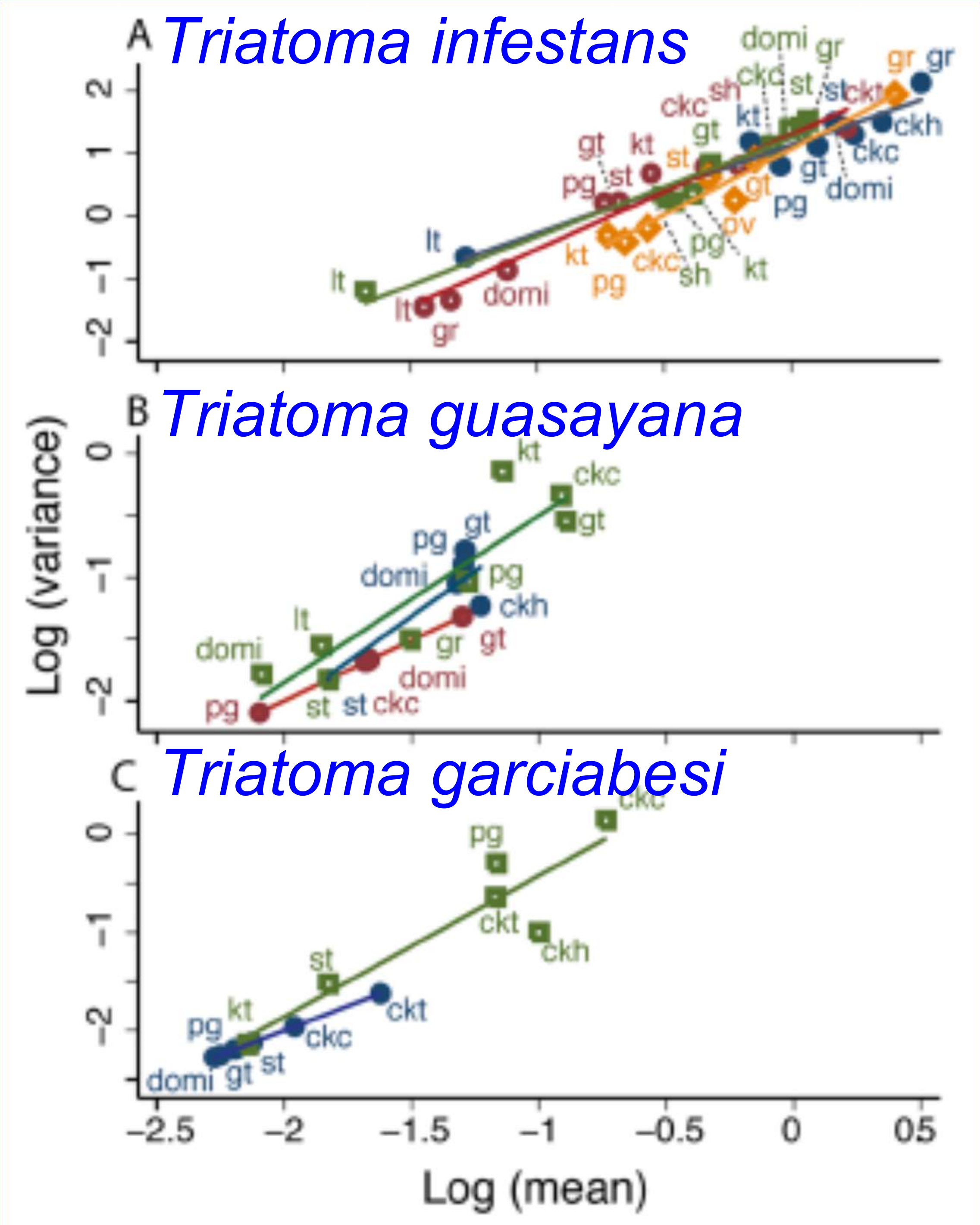
Pampa del Indio: *T. infestans* & *T. sordida* obey spatial TL in 8 surveys 2007-2010.

Cohen, Rodríguez-Planes, Gaspe, Cecere, Cardinal, Gürtler, *PLoS Neglected Tropical Diseases* 2017



Figueroa: Vectors of Chagas disease obey spatial TL.

Cohen, Rodríguez-Planes, Gaspe, Cecere, Cardinal, Gürtler, *PLoS Neglected Tropical Diseases* 2017



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Uses of TL in Chagas vector control

Flagging errors in data

Identifying habitats of unusually high or unusually low variability

Designing sequential sampling to reach specified precision, using stopping line derived from TL

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TL before & after spraying

Suppose TL holds before the house compounds (including all (peri)domestic structures) are sprayed with insecticides to kill the vectors: for relative population density of a single vector species,

$$\log \text{variance} = \log a + b \log \text{mean}.$$

What would be the effect of spraying? Would TL hold after spraying? If so, with what intercept and slope?

Model of spraying & TL: notation

Cohen, Gürtler et al., PLoS NTD 2017

Habitats are labeled $h = 1, 2, \ldots, H$.

$B(h)$ = random number of vectors of one *Triatoma* species in the various sites of habitat h in study area *Before* spraying.

$A(h)$ = random number of vectors of one *Triatoma* species in the various sites of habitat h in study area *After* spraying.

Assume $\log_{10} Var(B(h))$
$= \log_{10} a + b \log_{10} E(B(h)),\ h = 1, 2, \ldots, H$.

Model of spraying & TL: key assumptions, key result

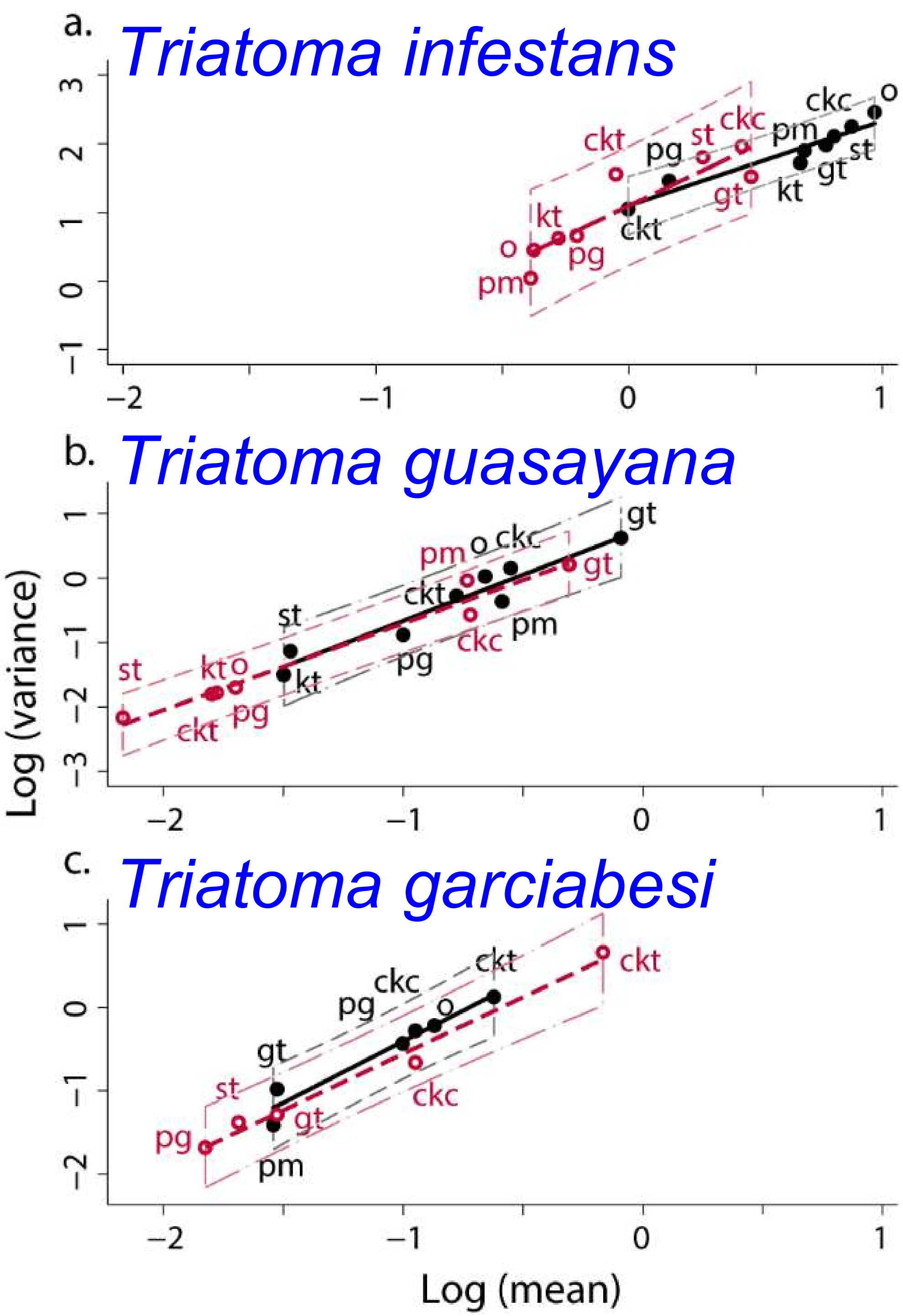
Suppose that a fraction s, $0<s<1$, of vectors survive spraying in every site of every habitat. s = *Survive Spraying*.

If $\log_{10} Var(B(h)) = \log_{10} a + b \log_{10} E(B(h))$, then $\log_{10} Var(A(h)) = \log_{10} a + (2-b) \log_{10} s + b \log_{10} E(A(h))$, $h = 1, 2, \ldots, H$.

After spraying, TL holds for the relative population density of vectors with the same exponent b as before spraying. Intercept changes, but little if $b \approx 2$ or $s \approx 1$.

Olta: Vectors of Chagas disease obey spatial TL before (black) & after (red) community-wide spraying.

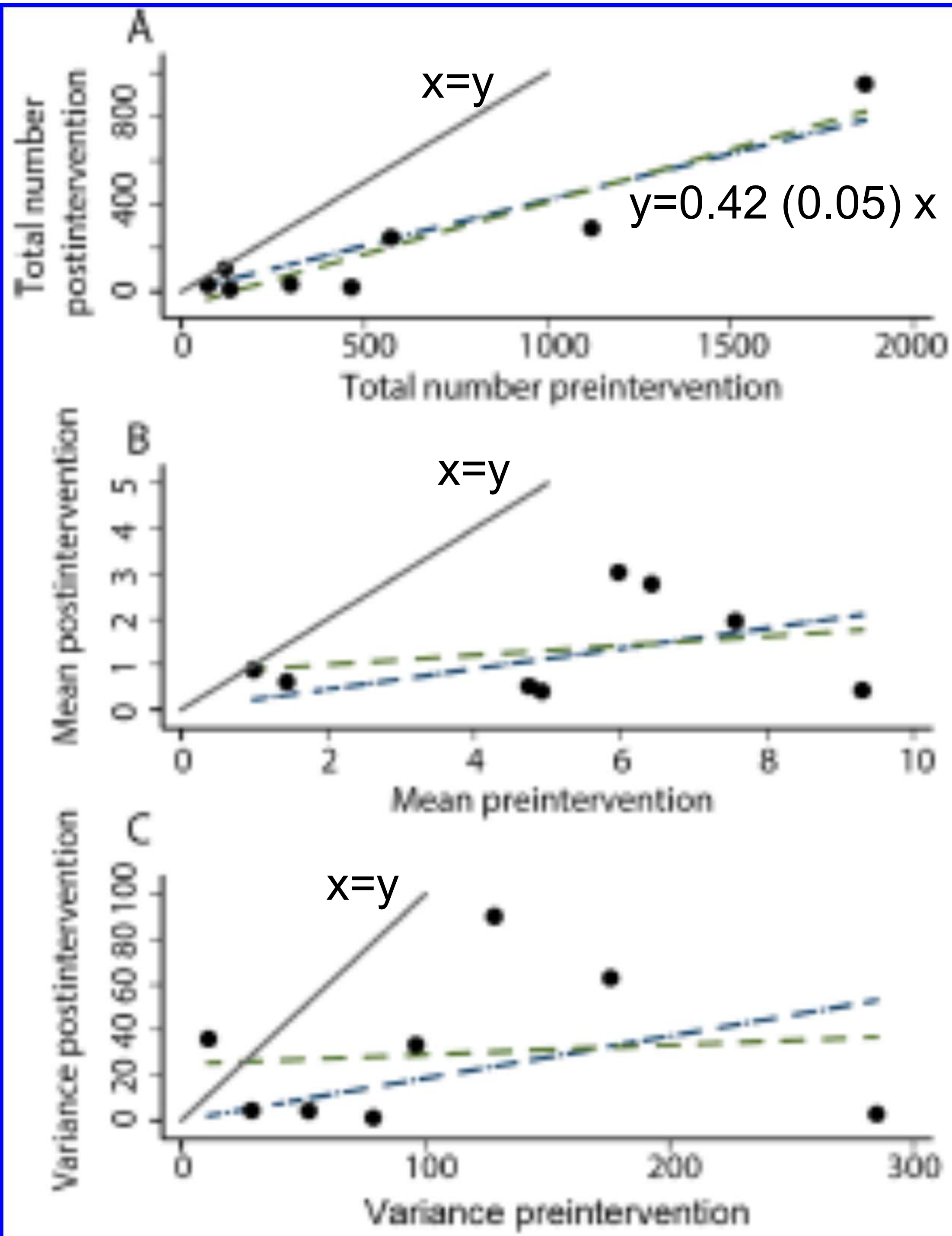
Cohen, Rodríguez-Planes, Gaspe, Cecere, Cardinal, Gürtler, *PLoS Neglected Tropical Diseases* 2017



2019-09-10 Joel E. Cohen

Direct tests of model of spraying for *T. infestans*

Cohen, Rodríguez-Planes, Gaspe, Cecere, Cardinal, Gürtler, *PLoS Neglected Tropical Diseases* 2017



2019-09-10

Slope *b* in TL is independent of scale of measurement.

If $s^2 = am^b$ for r.v. X, & $Y = kX, k > 0$, then mean of Y is $\mu = km$, variance of Y is

$$\sigma^2 = k^2 s^2 = k^2 a m^b = k^2 a \left(\frac{\mu}{k}\right)^b = k^{2-b} a \mu^b.$$

Y obeys TL power law with same exponent *b*, coefficient ak^{2-b}.

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Using TL to design sampling with fixed precision

Suppose we collect multiple samples on each day of a sequence of days $t = 1, 2, ...$

We want to stop sampling when the mean population density can be estimated with a fixed "precision" defined as

$$C = \frac{standard\ deviation\ of\ mean\ density}{mean\ density}.$$

$C = 0.1$ when std. dev. of mean density (SEM) is 10% of mean density.

Data structure: multiple samples, each with multiple observations

Sample day →	t=1	t=2	t=3
Number of individuals in samples on day t	x_{11}	x_{12}	x_{13}
	x_{21}	x_{22}	x_{23}
	x_{31}	x_{32}	x_{33}
Daily abundance	a_1	a_2	a_3
Cumulative abundance	$A_1 = a_1$	$A_2 = A_1 + a_2$	$A_3 = A_2 + a_3$
Daily no. samples	n_1	n_2	n_3

Notation & definitions

x_{jt} = number of individuals in sample *j*, day *t*

Data on day t: $\{x_{jt} | j = 1, \ldots, n_t\}, t = 1, \ldots$

Daily samples on day t: n_t

Daily abundance on day *t*: $a_t = \sum_{j=1}^{n_t} x_{jt}$

Cumulative number of samples, abundance, mean, variance by day *T*:

$$N_T = \sum_{t=1}^{T} n_t\,, \quad A_T = \sum_{t=1}^{T} a_t\,, \quad M_T = \frac{A_T}{N_T}$$

$$V_T = \boldsymbol{var}\{x_{jt} | j = 1, \ldots, n_t,\ t = 1, \ldots, T\}$$

Cumulative precision by day *T*: $C_T = \frac{\sqrt{V_T/N_T}}{M_T}$

Cumulative precision & sample size

Cumulative precision by day T: $C_T = \frac{\sqrt{V_T/N_T}}{M_T}$

Hence $C_T M_T = \sqrt{V_T/N_T}$, $(C_T M_T)^2 = V_T/N_T$,

$$N_T = V_T/(C_T M_T)^2.$$

For fixed V_T, M_T, increasing required precision from 50% to 10% increases required sample size by factor of 25.

Precision, sample size, & TL

When TL holds, $V_T = a(M_T)^b$ so

$N_T = V_T/(C_T M_T)^2 = \left(a(M_T)^{b-2}\right)/(C_T)^2$, so

$\log N_T = \log a + (b-2)\log M_T - 2\log C_T$.

Since $M_T = A_T/N_T$, we have (Green 1970),

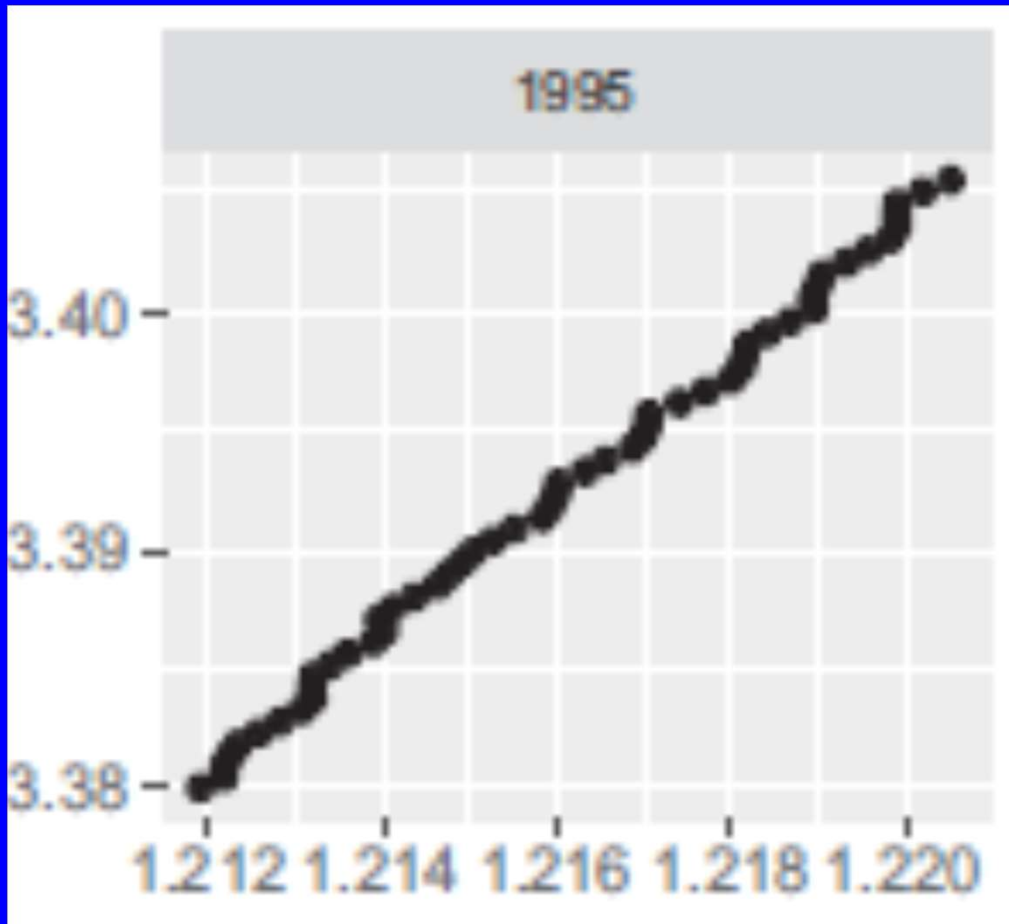
$$\log A_T = \frac{\log\left((C_T)^2/a\right)}{b-2} + \frac{b-1}{b-2}\log N_T.$$

Slope of this "stopping line" is <0 if & only if $1 < b < 2$. Slope is >0 iff $b < 1$ or $b > 2$.

Stopping lines with positive or negative slopes & positive or negative intercepts exist in data.

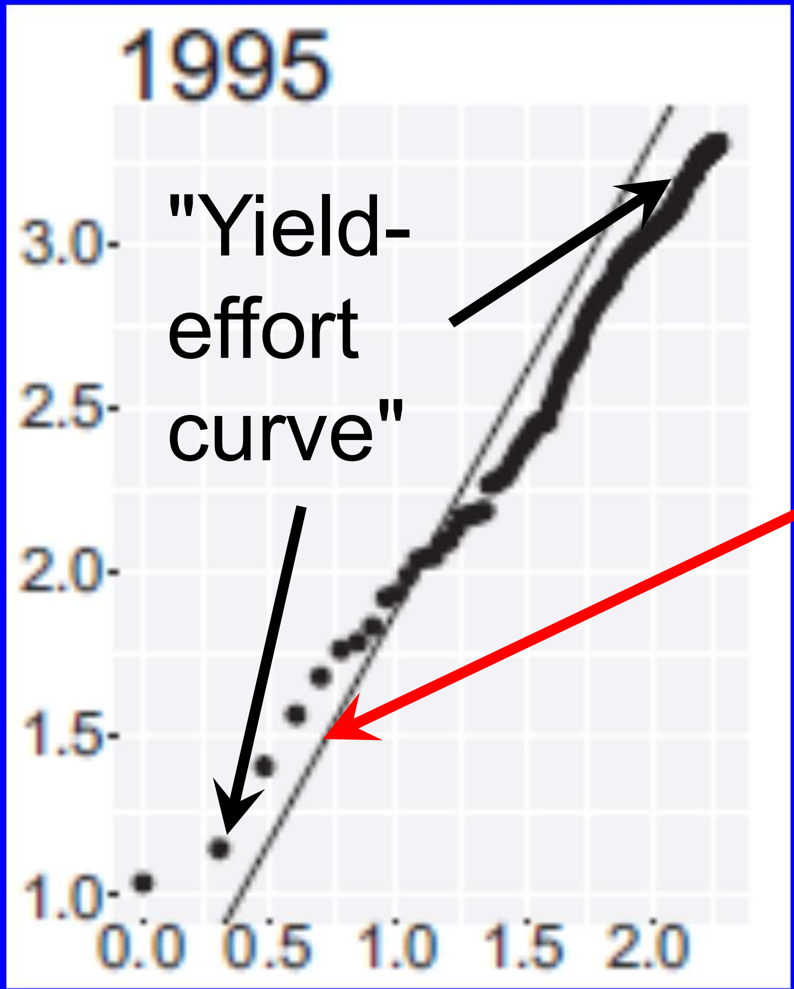
Example: Lake Kariba fisheries, fished area (Xu, Kolding, Cohen 2019, CJFAS)

Log$_{10}$ cumulative variance of number of individuals



Log$_{10}$ cumulative mean number of individuals

Example: Lake Kariba fisheries, fished area (Xu, Kolding, Cohen 2019, CJFAS)



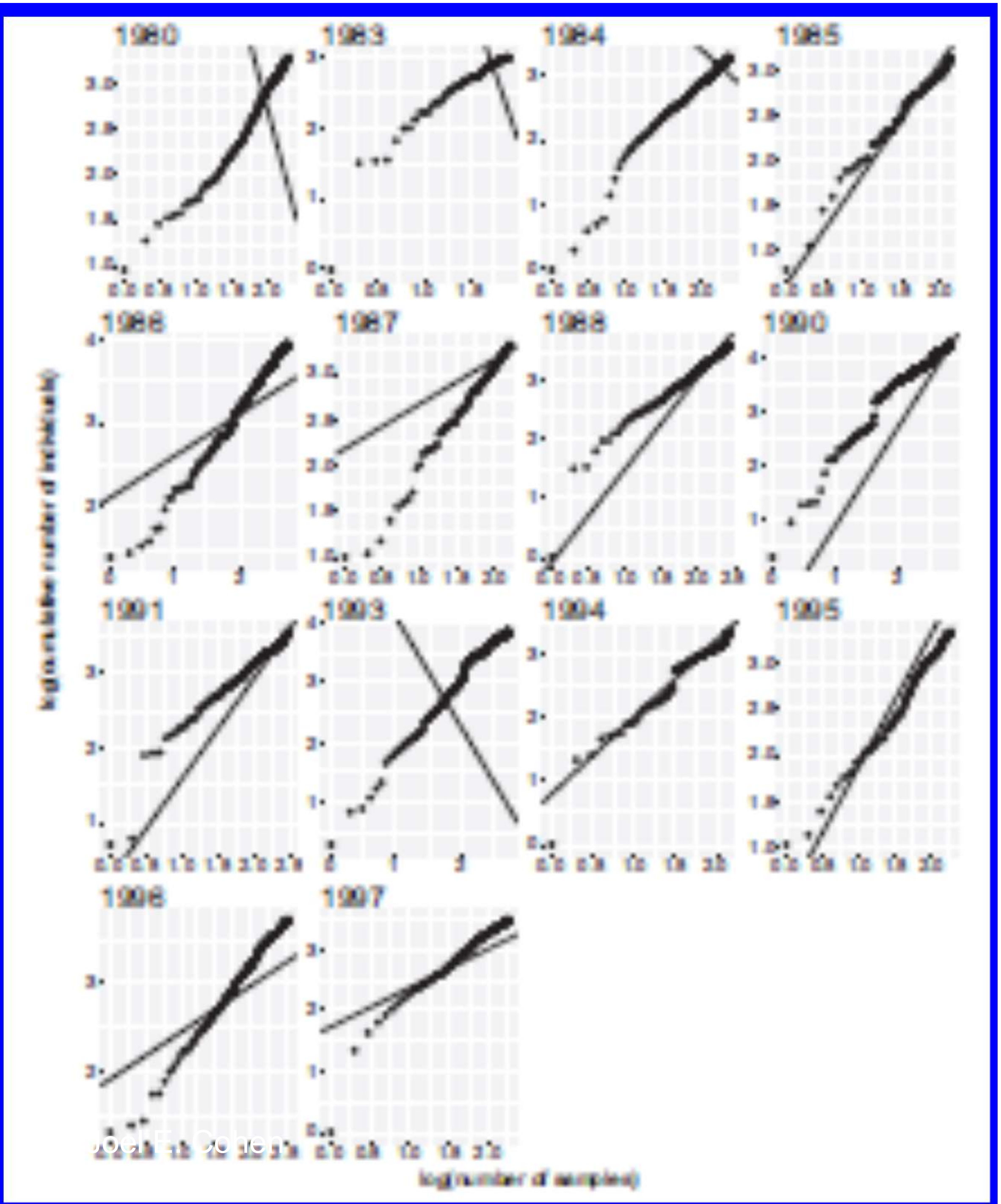
Log$_{10}$ cumulative number of individuals

Stopping lines were updated each day. Shown is **first stopping line with $C = 0.1$ that intersected cumulative abundance plot.**

Log$_{10}$ cumulative number of samples

Example: Lake Kariba fisheries, fished area

Xu, Kolding, Cohen 2019, Canadian J Fisheries & Aquatic Sciences



When does stopping line intercept yield-effort curve?

(Xu, Kolding, Cohen 2019, CJFAS)

From TL: $\log A_T = \frac{\log\left((c_T)^2/a\right)}{b-2} + \frac{b-1}{b-2}\log N_T$

Empirical approximation to yield-effort curve:

$\log A_T = L + K \log N_T$, & $K < 1, = 1, > 1$

Stopping line intersects yield-effort curve iff

$\left(L < \frac{\log\left((c_T)^2/a\right)}{b-2}\right.$ & $\left.K > \frac{b-1}{b-2}\right)$ or

$\left(L > \frac{\log\left((c_T)^2/a\right)}{b-2}\right.$ & $\left.K < \frac{b-1}{b-2}\right)$.

This method could save work.

In Lake Kariba data, using updated stopping lines of fixed precision 0.1 after each new sample, updated stopping-line method required 21% to 41% of the number of sampling days & 19% to 40% of number of samples that were planned a priori under systematic sampling, depending on sampling area (fished vs unfished) & abundance measure (number vs weight).

Mean abundance estimates were similar to those from systematic sampling.

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Merci!
Questions?

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