When do “the details” matter?

The promise of DEB for climate change adaptation

Brian Helmuth

Marine Science Center and School of Public Policy and Urban Affairs

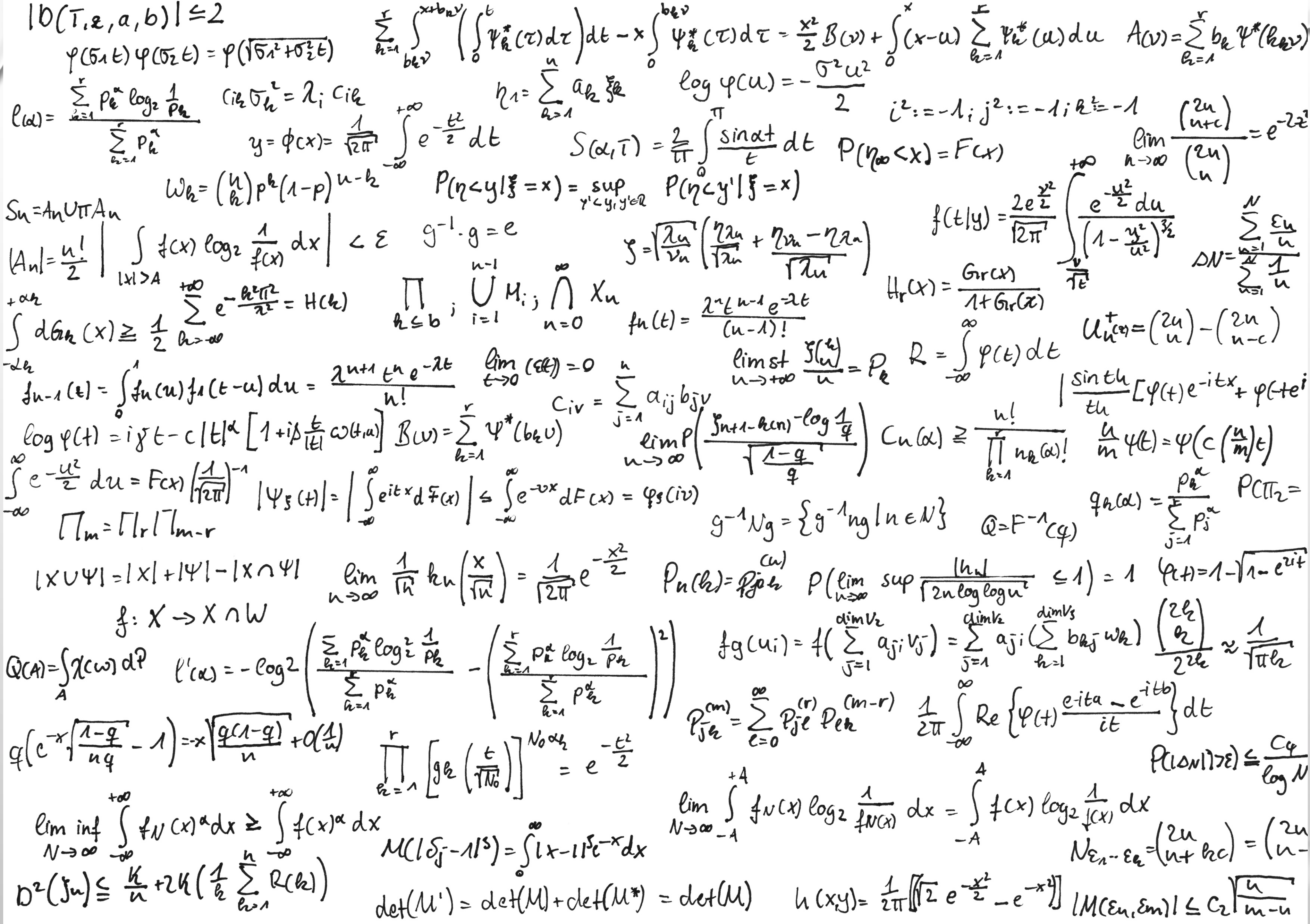
Northeastern University

b.helmuth@northeastern.edu

@aquanaut1967

DEB2019 1-12 April 2019 / Brest (France)

Sixth International Symposium and Thematic School on DEB theory for metabolic organization

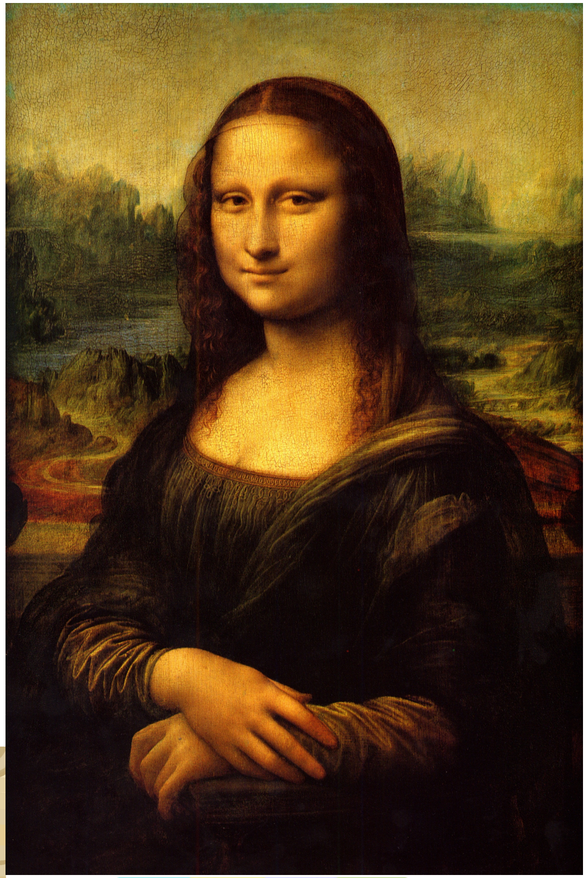


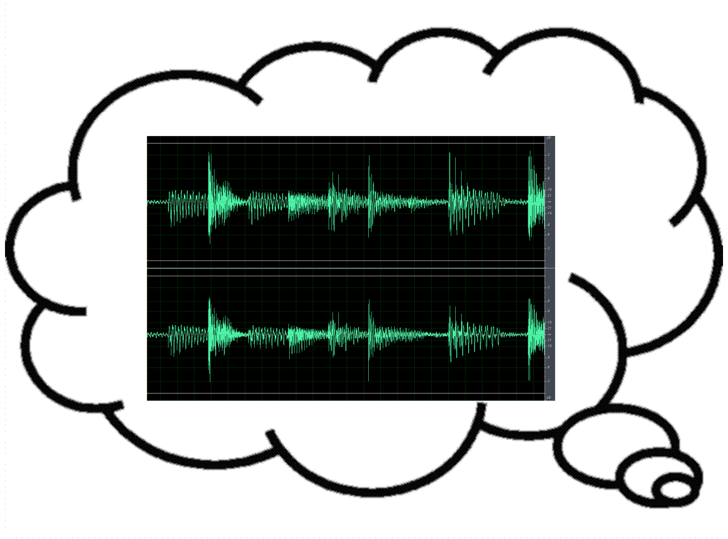

HOW ABOUT
A GREASEY
PORK SANDWICH
SERVED IN A
DIRTY ASHTRAY?


REGRET...
Ugghhh...
WineFolly


IT'S NOT A HANGOVER.
IT'S WINE FLU.

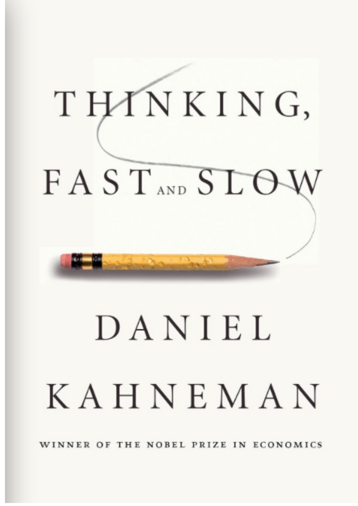
Pattern Recognition

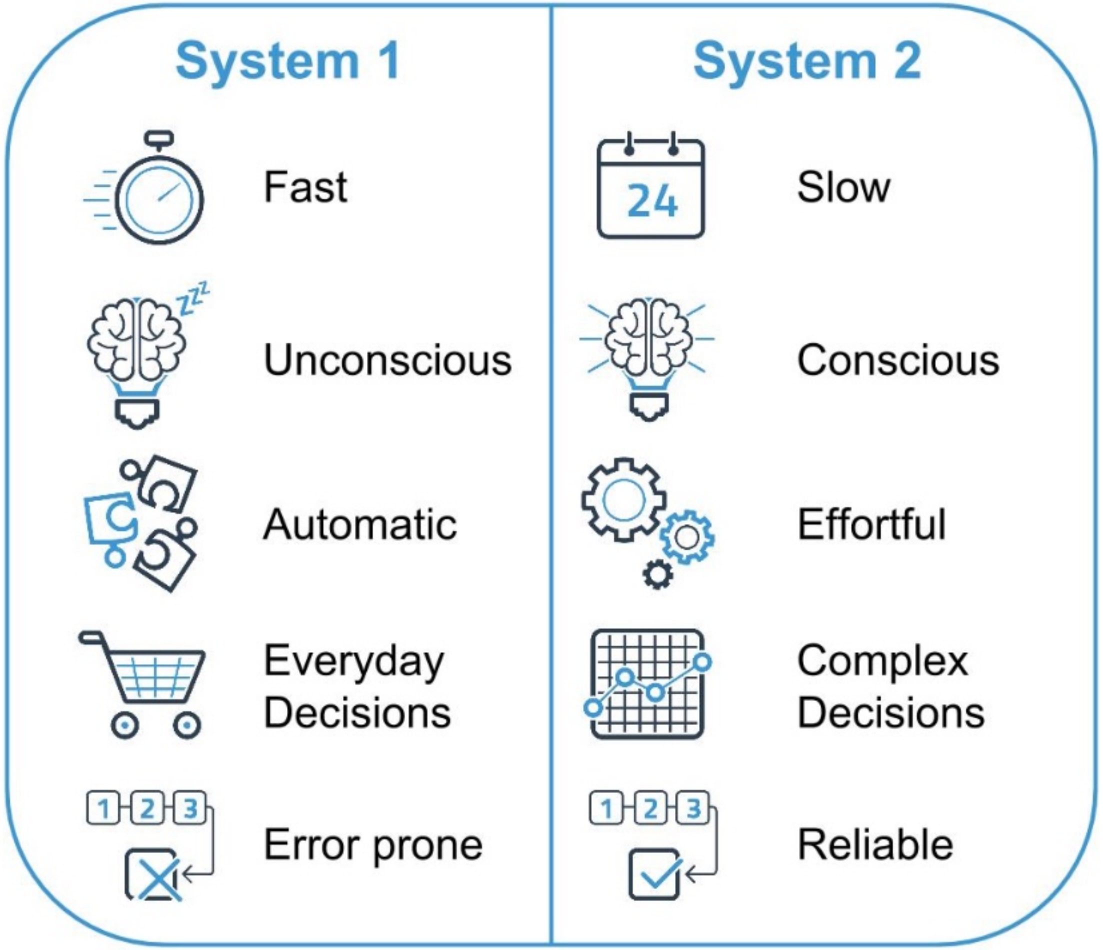




http://mapadetalentos.com.br/portal/images/9303.jpg

"Fast" (system 1) and "slow" (system 2) decision-making responses

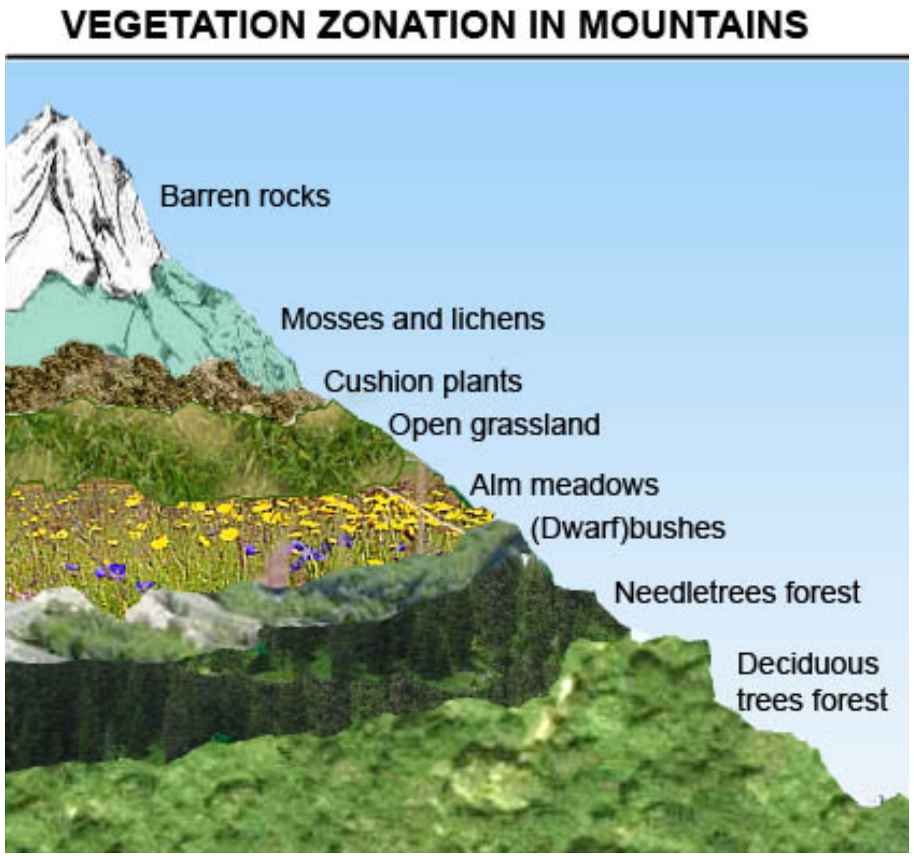




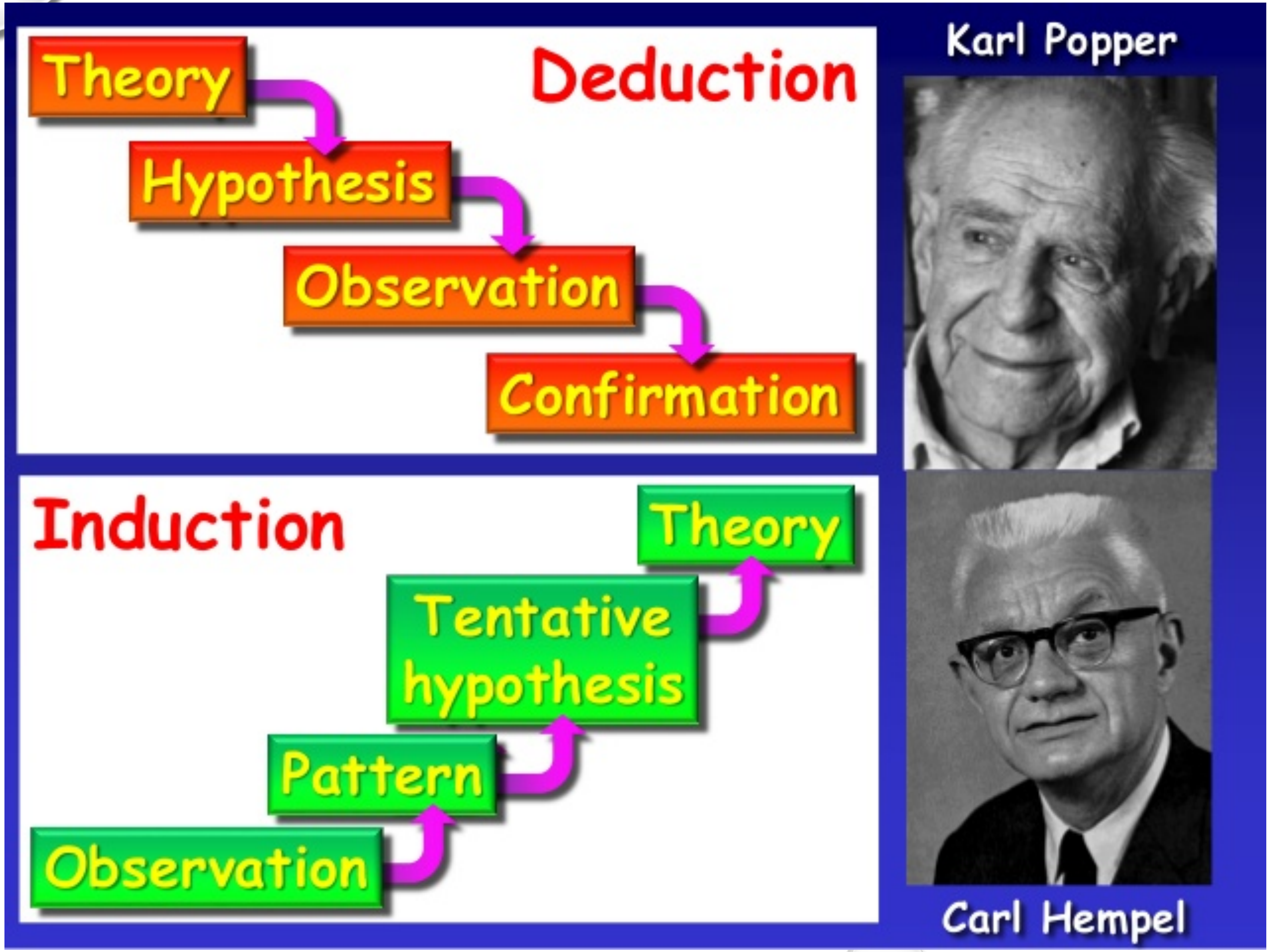
http://upfrontanalytics.com/market-research-system-1-vs-system-2-decision-making/

Seeing patterns in nature

http://www.ecosystema.ru/08nature/world/75abh/18.jpg



http://www.vcbio.science.ru.nl/images/landscape/landscape-vertical_zonation_eng.jpg



http://image.slidesharecdn.com/evidenceandimpact-160425150415/95/evidence-and-impact-3-638.jpg?cb=1461596771

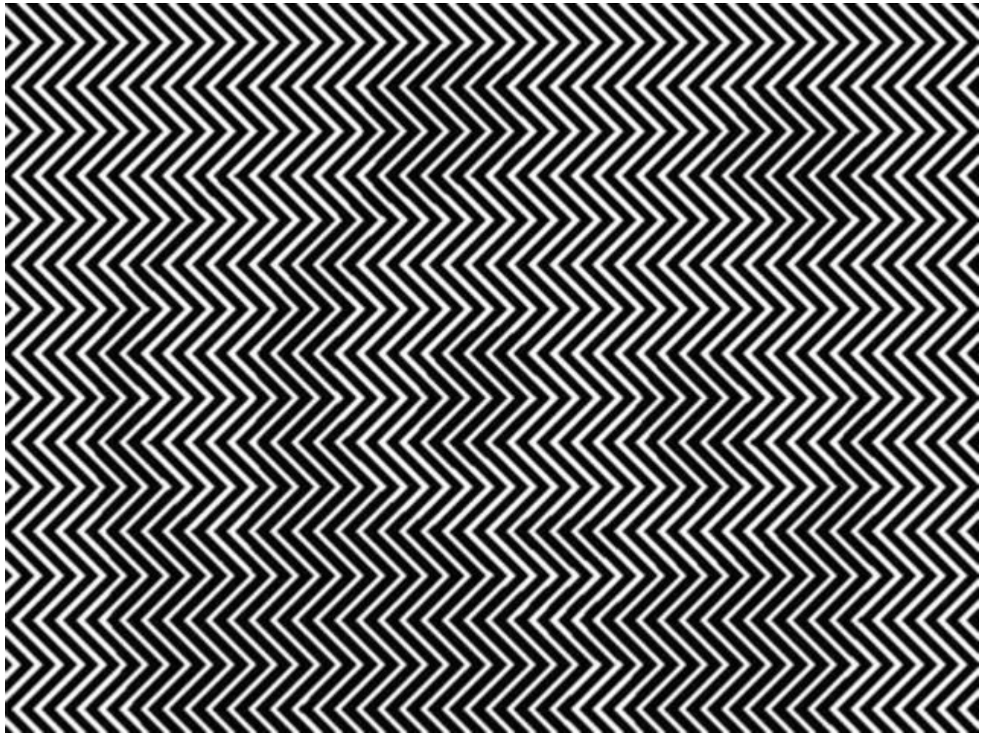
CLIMATE CHANGE

- PATTERNS IN NATURE ARE CHANGING, SOMETIMES QUICKLY
- WE WANT TO KNOW HOW MUCH TO ATTRIBUTE TO CLIMATE CHANGE, AND WHAT TO DO ABOUT IT
- WE MUST BASE FUTURE PREDICTIONS OF CLIMATE CHANGE IMPACTS ON WHAT WE OBSERVE TODAY AND IN THE PAST

ECOLOGICAL IMPACTS OF CLIMATE CHANGE: HOW DO WE TEST OUR ABILITY TO PREDICT THE FUTURE?

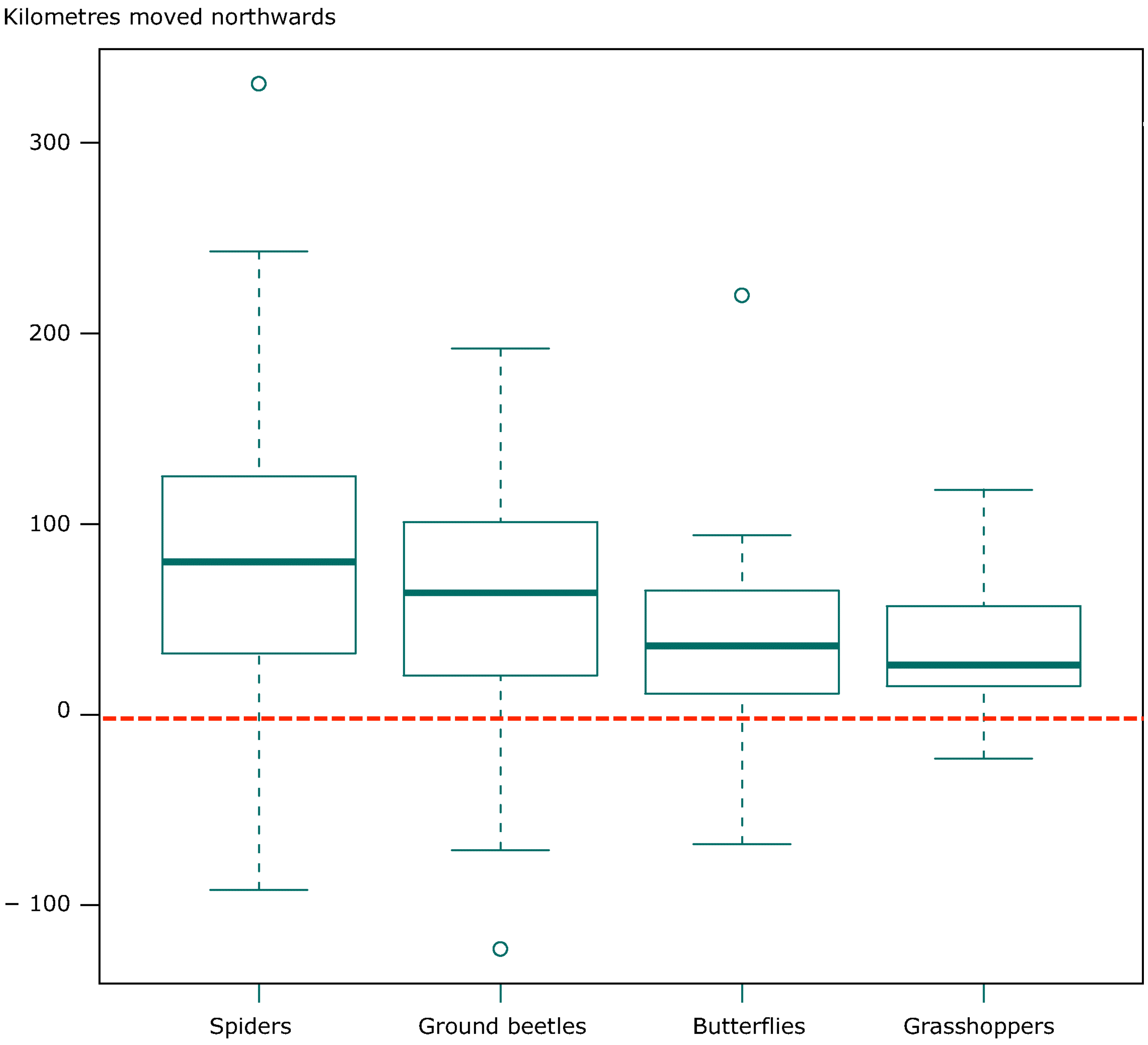
- WE ARE USING MODELS “TRAINED” WITH CURRENT CONDITIONS TO PREDICT RESPONSES UNDER NOVEL CONDITIONS
- HOW DO WE “KNOW WHAT WE DON’T KNOW”? AND HOW DO WE INCREASE OUR ABILITY TO PREDICT (AND PREVENT) NASTY “SURPRISES” SUCH AS TIPPING POINTS?
- ARE WE MEASURING THE RIGHT THINGS AT THE RIGHT SCALES?

Are we looking so hard for pattern that we miss important mechanisms?

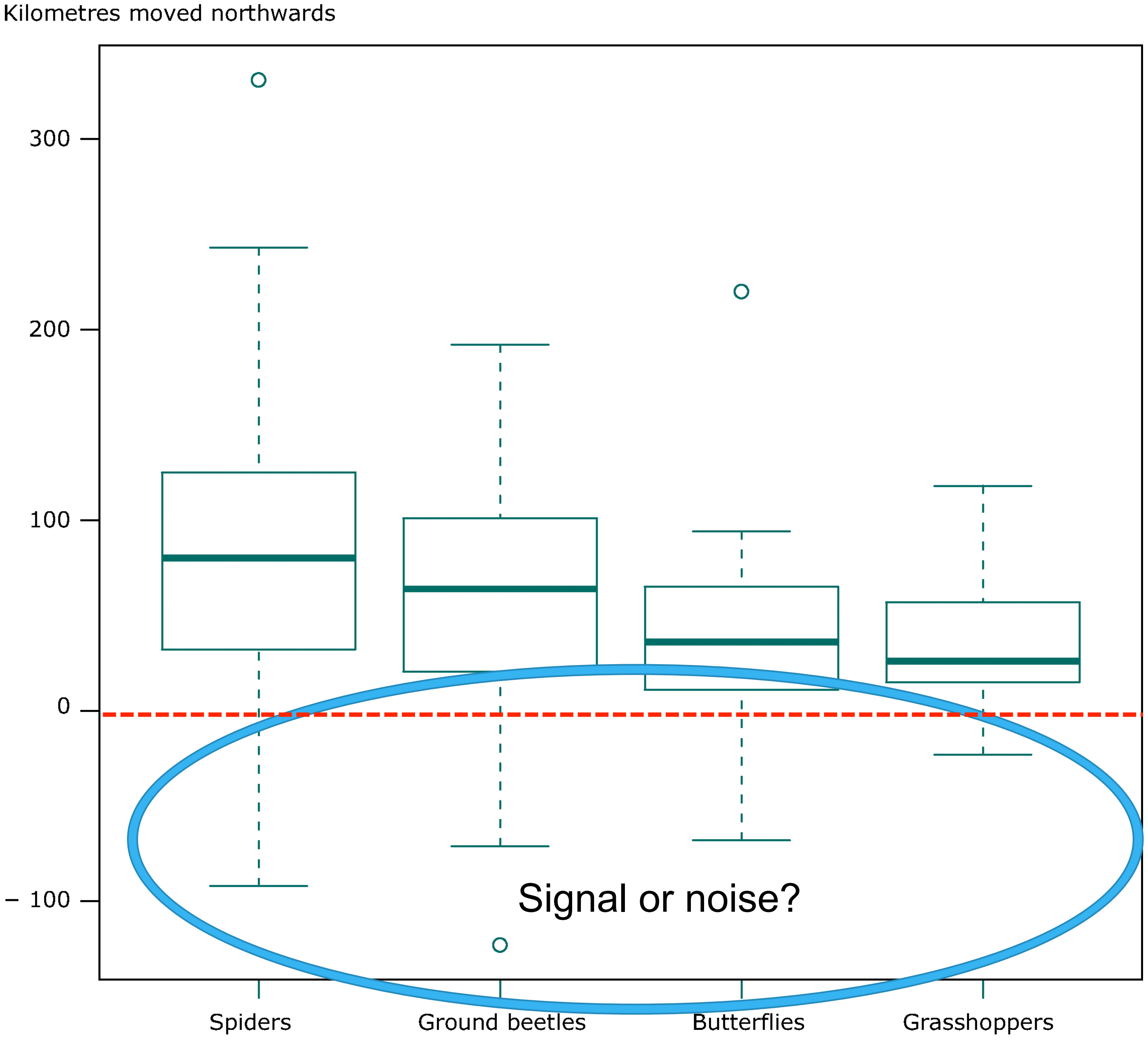


http://www.telegraph.co.uk/news/2017/02/02/levitation-optical-illusion-confuses-internet/

Source: cns-alumni.bu.edu



http://www.eea.europa.eu/data-and-maps/figures/observed-latitudinal-shifts-of-the



http://www.eea.europa.eu/data-and-maps/figures/observed-latitudinal-shifts-of-the

Changes in Climatic Water Balance Drive Downhill Shifts in Plant Species' Optimum Elevations
Shawn M. Crimmins, *et al.*
Science **331**, 324 (2011);
DOI: 10.1126/science.1199040

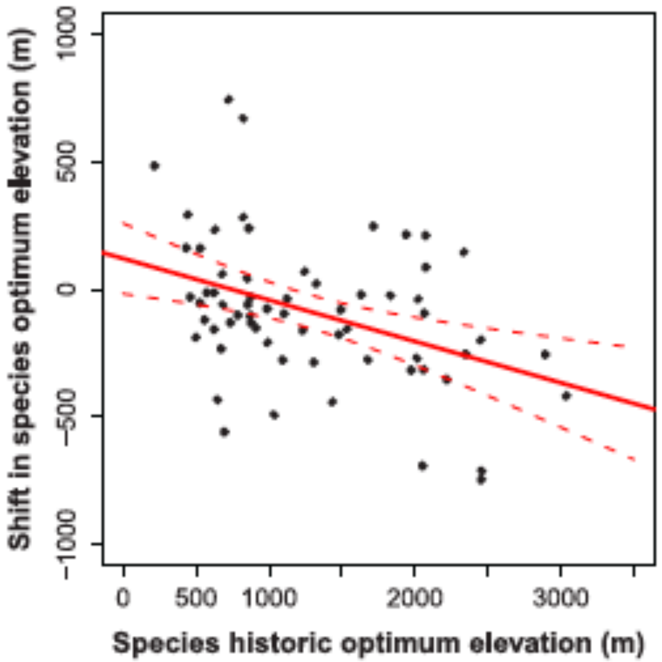
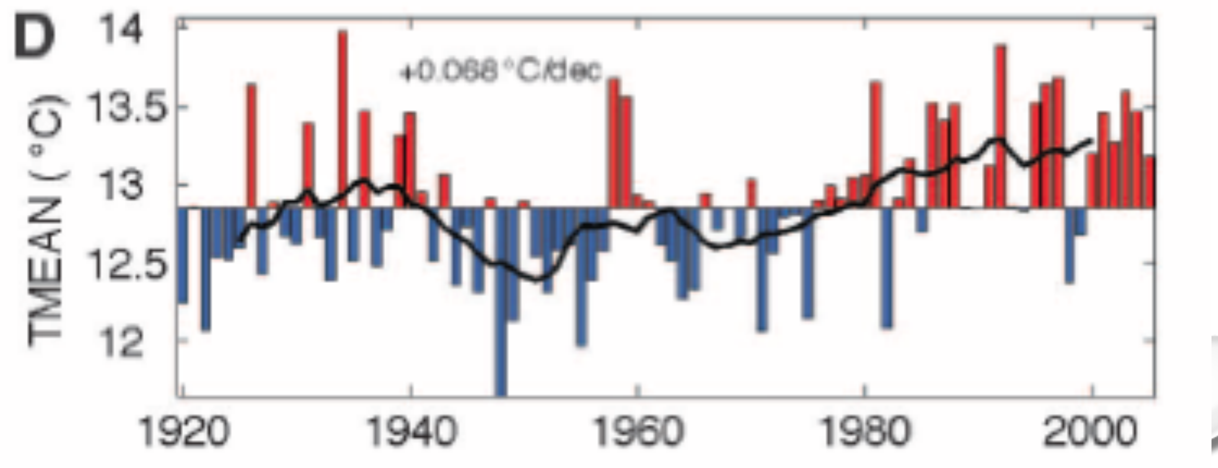
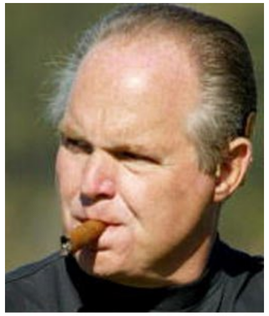


Fig. 4. Scatterplot of shift in optimum elevation (m) versus historical (circa 1935) altitudinal position (m) for plant species in California. Solid line represents linear regression model with 95% CI bands (as dashed lines).

Sixty four species of plants shifted downslope over last 75 years, despite increasing temperatures



Watts Up With That?



Getty

Home | About | Climate FAIL Files | Climategate | Reference Pages | Resources | Submit Story | Test | Tips & Notes | Widget | WUWT Stuff

← Surface temperature uncertainty, quantified

WMO: 2010 warmest, but no statistically significant difference between global temperatures in 2010, 2005 and 1998 →

Another IPCC claim contradicted with new science

Posted on January 20, 2011 by Anthony Watts

Remember this story bandied all over the press from 2008?

Climate Change msnbc.com

Study: Global warming chases plants uphill

Plants are found to be moving into higher, cooler elevations

Associated Press

WASHINGTON — Faced with global warming, plants are

Search

"...the world's most viewed climate website"

- Fred Pearce *The Climate Files: The Battle for the Truth about Global Warming*

Blog Stats

- 85,668,176 views

VOTED BEST SCIENCE BLOG

ELEVENTH ANNUAL weblog awards

THE 2011 BLOGGIES

Science AAAS

Changes in Climatic Water Balance Drive Downhill Shifts in Plant Species' Optimum Elevations
Shawn M. Crimmins, *et al.*
Science **331**, 324 (2011);
DOI: 10.1126/science.1199040

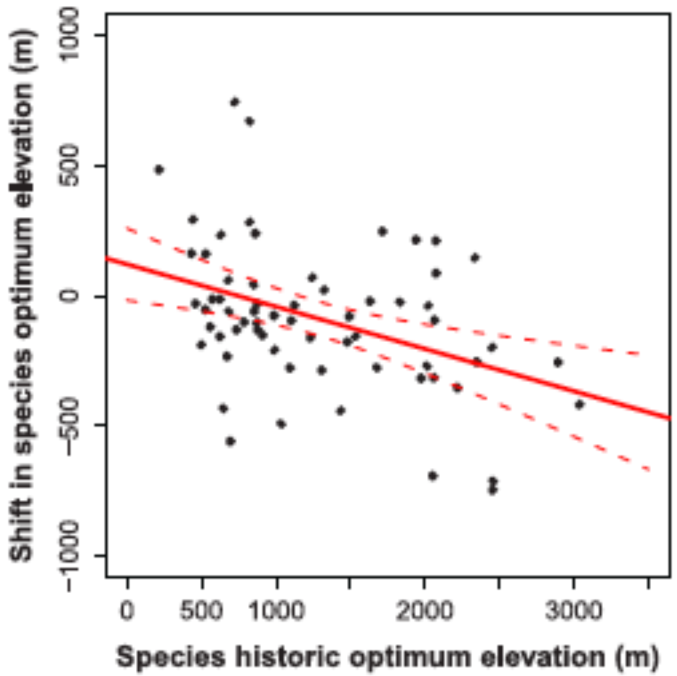
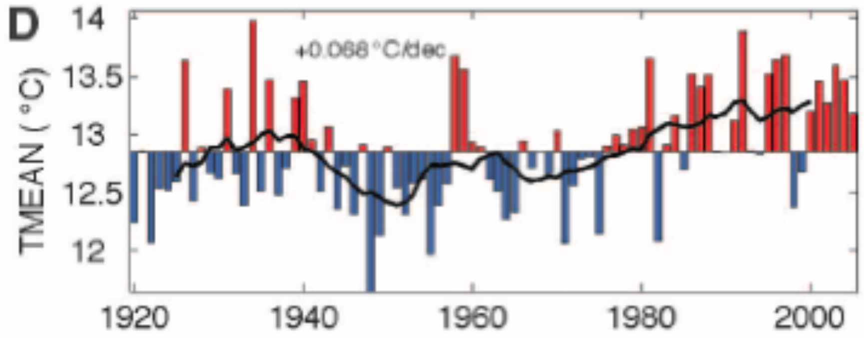
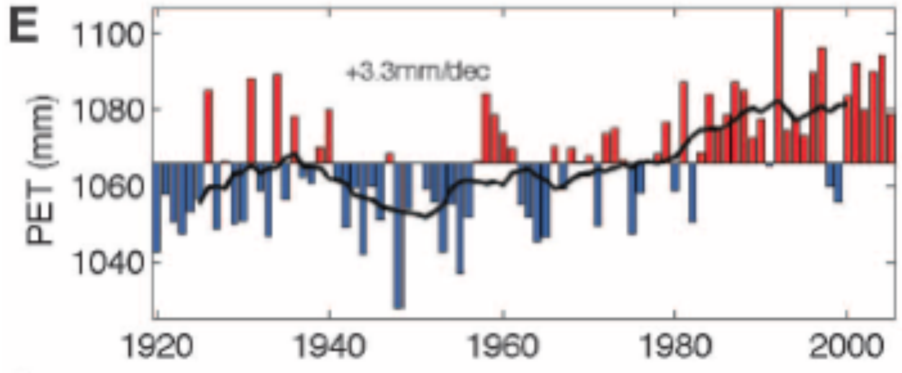


Fig. 4. Scatterplot of shift in optimum elevation (m) versus historical (circa 1935) altitudinal position (m) for plant species in California. Solid line represents linear regression model with 95% CI bands (as dashed lines).

Sixty four species of plants shifted downslope over last 75 years, despite increasing temperatures



Why? Precipitation also increased



GIBSON-REINEMER AND RAHEL 2015. *INCONSISTENT RANGE SHIFTS WITHIN SPECIES HIGHLIGHT IDIOSYNCRATIC RESPONSES TO CLIMATE WARMING* PLOS ONE

- ANALYZED PUBLISHED STUDIES THAT DOCUMENTED RANGE SHIFTS OF 273 SPECIES OF PLANTS, BIRDS, MAMMALS AND MARINE INVERTEBRATES. 42-50% SHOW "INCONSISTENCY IN THE DIRECTION OF THEIR RANGE SHIFTS, DESPITE EXPERIENCING SIMILAR WARMING TRENDS."

PRZESLAWSKI ET AL. 2012. *USING RIGOROUS SELECTION CRITERIA TO INVESTIGATE MARINE RANGE SHIFTS* ESTUARINE COASTAL AND SHELF SCIENCE

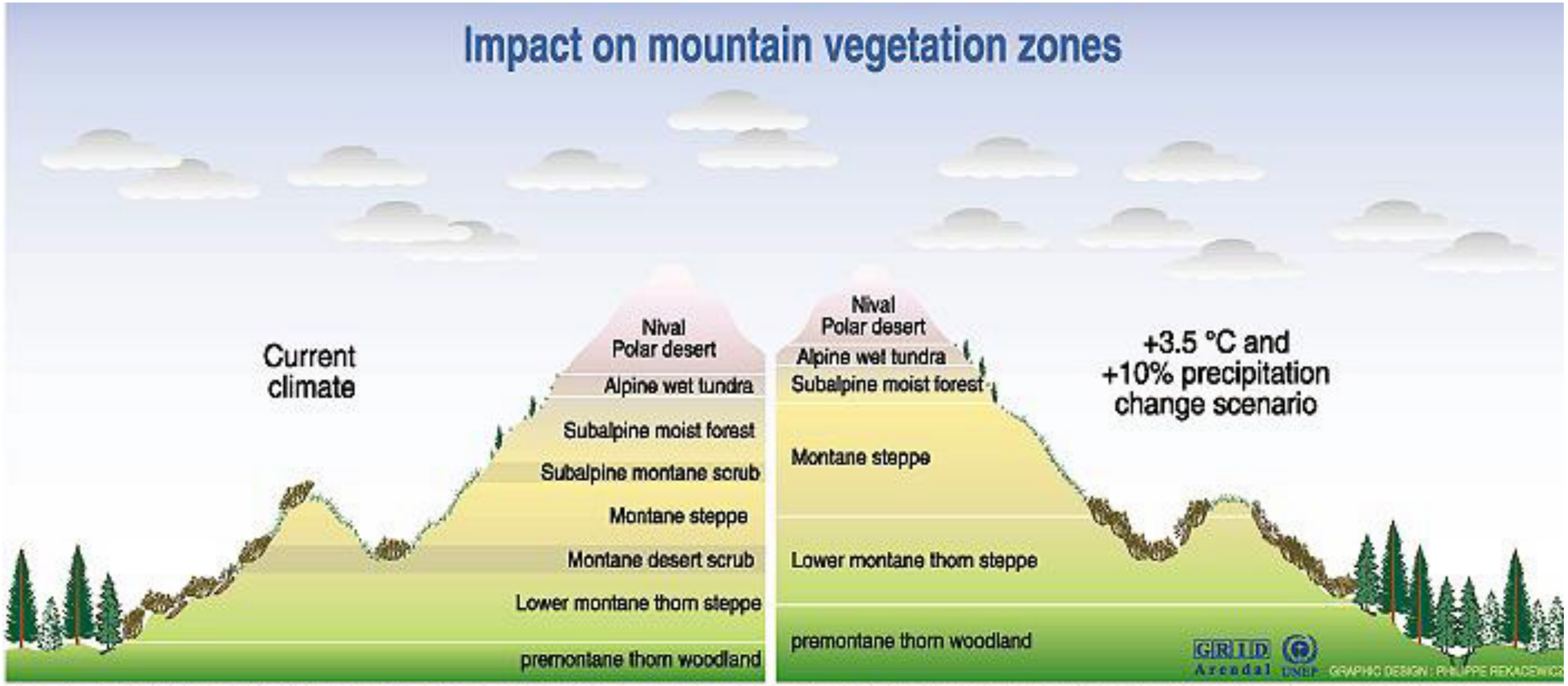
LOOKED AT 311 SPECIES FROM 13 STUDIES AND APPLIED RIGOROUS STANDARDS TO DETERMINE IF POLEWARD SHIFTS HAD OCCURRED-> SUGGESTED THAT AVERAGE RANGE SHIFT IS ORDER OF MAGNITUDE SLOWER THAN PREDICTED USING META-ANALYSIS

ARE EQUATORIAL SHIFTS (OR STASIS) IN RANGE BOUNDARIES, INCREASES IN PRODUCTIVITY OR IN BIODIVERSITY REALLY *INCONSISTENT* WITH WARMING?

..OR SHOULD WE BE MORE SOPHISTICATED IN HOW WE FRAME OUR HYPOTHESES AND COMMUNICATE EXPECTATIONS?

GENERALIZATIONS AREN'T VERY USEFUL WHEN PREPARING FOR CLIMATE CHANGE IMPACTS…. OR FOR FRAMING HYPOTHESES ABOUT CLIMATE CHANGE

- E.G., POLEWARD AND ALTITUDINAL RANGE SHIFTS



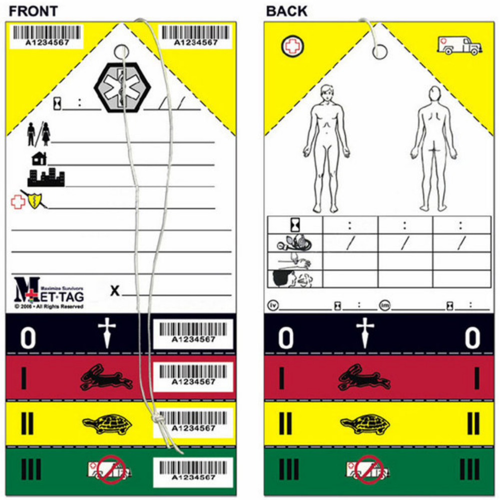
Sources: Martin Benitson, Mountain environments in changing climates, Routledge, London, 1994; Climate change 1995, Impacts, adaptations and migration of climate change, contribution of working group 2 to the second assessment report of the intergovernmental panel on climate change (IPCC), UNEP and WMO, Cambridge press university, 1996.

ECOLOGICAL FORECASTING
SCIENCE IN SERVICE OF SOCIETY

- Ecological forecasting informs

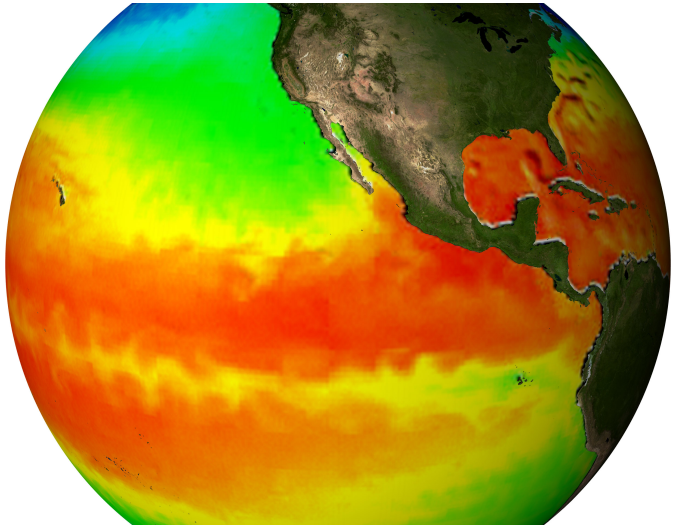
  and is a form of triage:

  how do we decide where to focus our efforts?

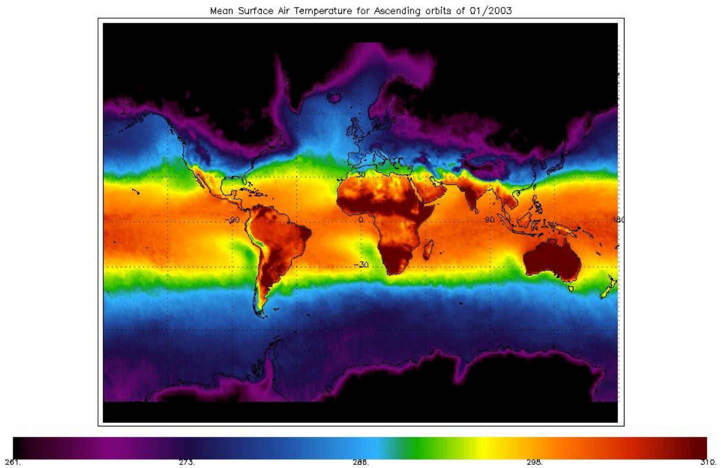


https://www.lifeaid.com.au/

ECOLOGICAL FORECASTING

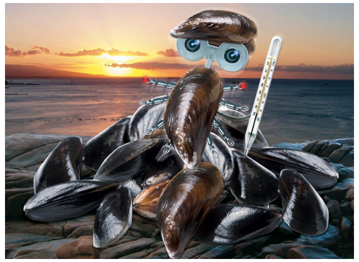


Weather Data and Forecasts



Risk maps and “what if” scenarios

Downscale to organisms, ecosystems and ecosystem services



Models and sensors

Scale up to ecological and societal impacts

WHAT CAN DEB THEORY TELL US ABOUT THE IMPORTANCE OF UNDERSTANDING "DETAILS" OF CLIMATE CHANGE IMPACTS AS PART OF ECOLOGICAL FORECASTING APPROACHES?

- SUBLETHAL RESPONSES TO ENVIRONMENTAL CHANGE THAT ULTIMATELY DRIVE ECOLOGICAL PROCESSES
- IDENTIFICATION OF HOTSPOTS, STEPPING STONES AND CLIMATE REFUGIA (MARINE SPATIAL PLANNING) AND THE POTENTIAL ROLE OF SMALL-SCALE PROCESSES

Kearney, M., S. J. Simpson, D. Raubenheimer, and B. Helmuth. 2010. Modelling the ecological niche from functional traits. Philosophical Transactions of the Royal Society B **365**:3469-3483.

Kearney, M. R., A. Matzelle, and B. Helmuth. 2012. Biomechanics meets the ecological niche: the importance of temporal data resolution. Journal of Experimental Biology **215**:922-933.

https://claremont.sd63.bc.ca/pluginfile.php/20148/mod_page/content/5/colored_puzzle_connection_400_wht_9893.png

Kearney, M., S. J. Simpson, D. Raubenheimer, and B. Helmuth. 2010. Modelling the ecological niche from functional traits. Philosophical Transactions of the Royal Society B **365**:3469-3483.

Kearney, M. R., A. Matzelle, and B. Helmuth. 2012. Biomechanics meets the ecological niche: the importance of temporal data resolution. Journal of Experimental Biology **215**:922-933.

Montalto, V., B. Helmuth, P. M. Ruti, A. Dell'Aquila, A. Rinaldi, and G. **Sàra**. 2016. A mechanistic approach reveals non linear effects of climate warming on mussels throughout the Mediterranean sea. Climatic Change **139**:293-306.

Montalto, V., G. **Sará**, P. Ruti, A. Dell'Aquila, and B. Helmuth. 2014. Testing the effects of temporal data resolution on predictions of bivalve growth and reproduction in the context of global warming. Ecological Modelling **278**:1-8.

Sarà, G., M. Kearney, and B. Helmuth. 2011. Combining heat-transfer and energy budget models to predict thermal stress in Mediterranean intertidal mussels. Chemistry and Ecology **27**:135-145.

Kearney, M., S. J. Simpson, D. Raubenheimer, and B. Helmuth. 2010. Modelling the ecological niche from functional traits. Philosophical Transactions of the Royal Society B **365**:3469-3483.

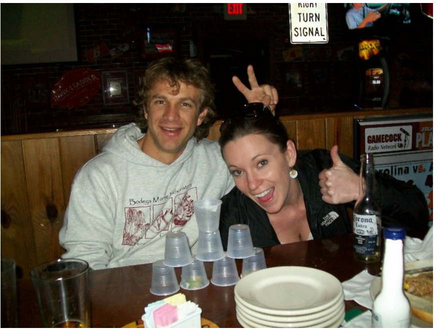
Kearney, M. R., A. Matzelle, and B. Helmuth. 2012. Biomechanics meets the ecological niche: the importance of temporal data resolution. Journal of Experimental Biology **215**:922-933.

Montalto, V., B. Helmuth, P. M. Ruti, A. Dell'Aquila, A. Rinaldi, and G. **Sàra**. 2016. A mechanistic approach reveals non linear effects of climate warming on mussels throughout the Mediterranean sea. Climatic Change **139**:293-306.

Montalto, V., G. **Sará**, P. Ruti, A. Dell’Aquila, and B. Helmuth. 2014. Testing the effects of temporal data resolution on predictions of bivalve growth and reproduction in the context of global warming. Ecological Modelling **278**:1-8.

Sarà, G., M. Kearney, and B. Helmuth. 2011. Combining heat-transfer and energy budget models to predict thermal stress in Mediterranean intertidal mussels. Chemistry and Ecology **27**:135-145.

Matzelle, A., V. Montalto, G. Sará, M. L. Zippay, and B. Helmuth. 2014. Dynamic energy budget model parameter estimation for the bivalve *Mytilus californianus*: Application of the covariation method. Journal of Sea Research **S1**:105-110.



Matzelle, A. J., G. Sarà, V. Montalto, M. Zippay, G. C. Trussell, and B. Helmuth. 2015. A bioenergetics framework for integrating the effects of multiple stressors: Opening a ‘black box’ in climate change research. American Malacological Bulletin **33**:150-160.

Monaco, C. J., D. S. Wethey, and B. Helmuth. 2014. A Dynamic Energy Budget (DEB) model for the keystone predator *Pisaster ochraceus*. PLoS ONE **9**:e104658.

WHAT DEB THEORY CAN TELL US ABOUT CLIMATE CHANGE IMPACTS

- **THE ROLE OF SUBLETHAL PROCESSES, AND CAUTIONS AGAINST USING AVERAGED ENVIRONMENTAL DATA**

MODEL SKILL AND STATIONARITY

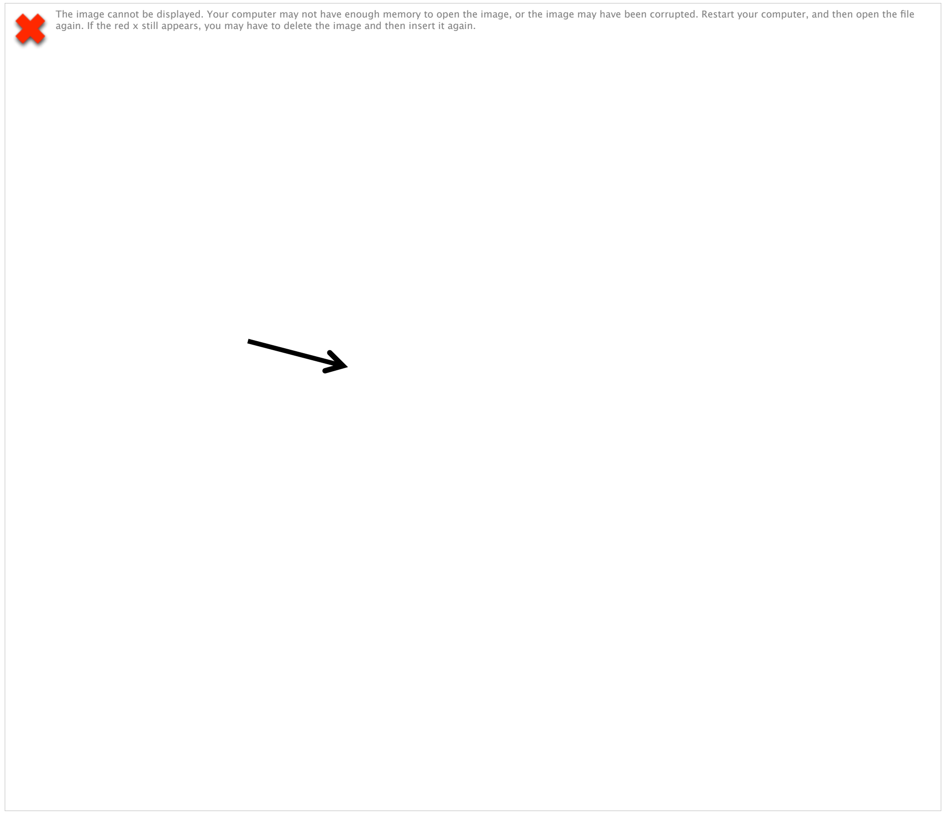
- *MODEL SKILL* = DEGREE OF CORRESPONDENCE BETWEEN MODEL PREDICTIONS AND FIELD OBSERVATIONS
- *MODEL STATIONARITY*= ABILITY OF A MODEL GENERATED FROM DATA COLLECTED AT ONE PLACE/TIME TO PREDICT PROCESSES AT ANOTHER PLACE/TIME

MODEL SKILL AND STATIONARITY

- *MODEL SKILL* = DEGREE OF CORRESPONDENCE BETWEEN MODEL PREDICTIONS AND FIELD OBSERVATIONS
- *MODEL STATIONARITY*= ABILITY OF A MODEL GENERATED FROM DATA COLLECTED AT ONE PLACE/TIME TO PREDICT PROCESSES AT ANOTHER PLACE/TIME

- **CLIMATE CHANGE MODELS- ESPECIALLY CORRELATIVE MODELS- ASSUME STATIONARITY IN TIME (SPACE FOR TIME SUBSTITUTION)**

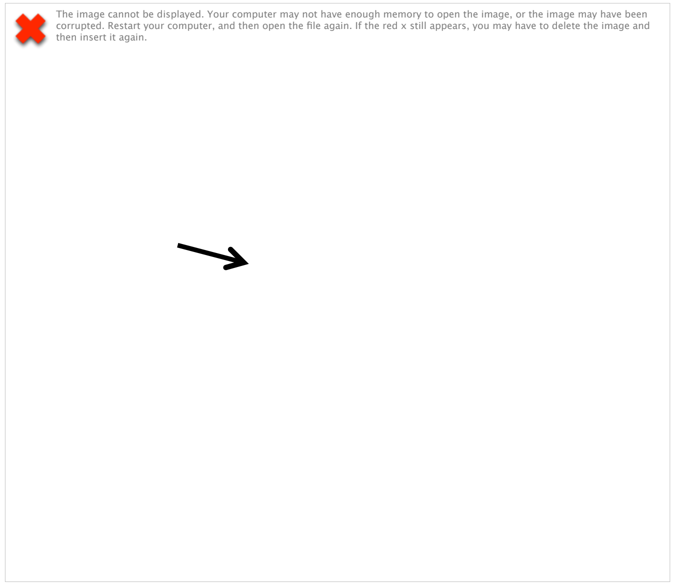
Testing model stationarity with and without physiological mechanism

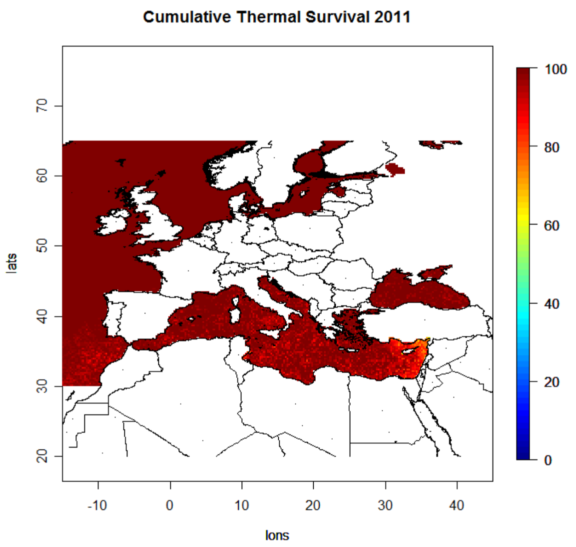


Model of mussel (*M. edulis*) distribution based on lethal temperatures

Jones et al. 2010 J. Biogeography

Model that works for the US fails in Europe



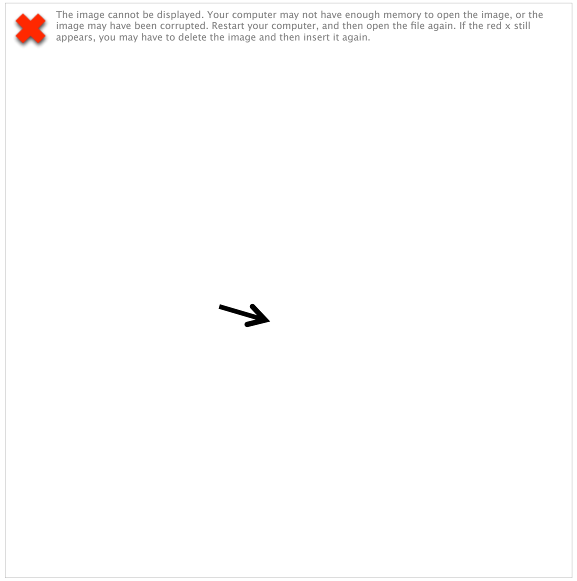


Model of mussel (*M. edulis*) distribution based on lethal temperatures

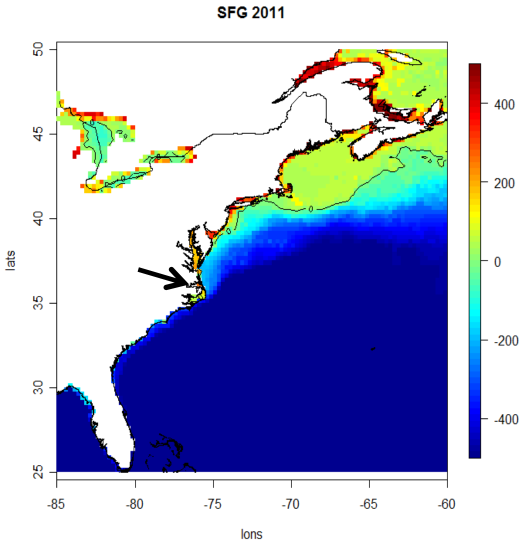
Jones et al. 2010 J. Biogeography

Testing model stationarity with and without mechanism

Lethal temperatures



Energetics

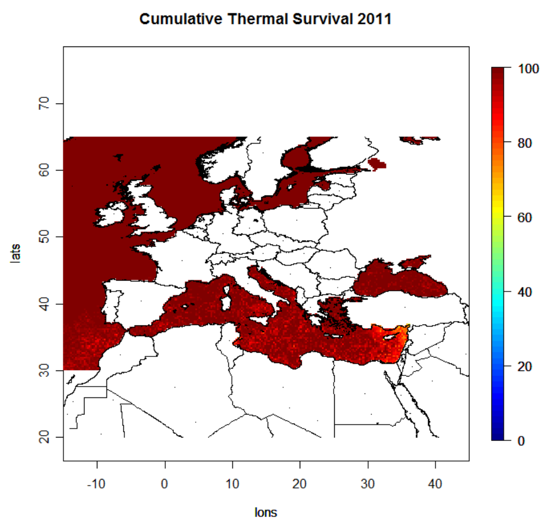


Two models of mussel (*M. edulis*) distribution-
one with details and one without give similar results

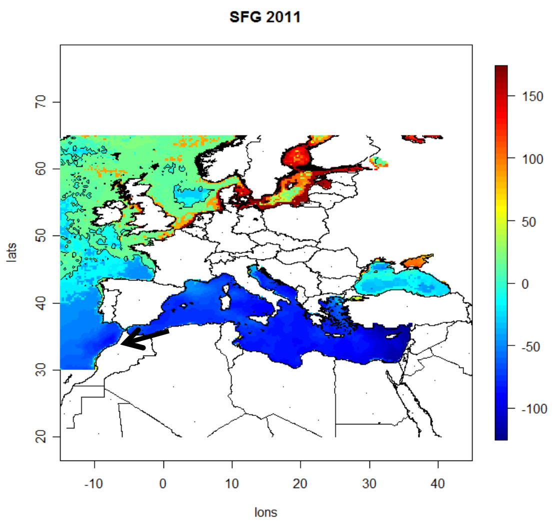
(Woodin, Hilbish, Helmuth, Jones and Wethey 2013)

Testing model stationarity with and without mechanism

Lethal temperatures



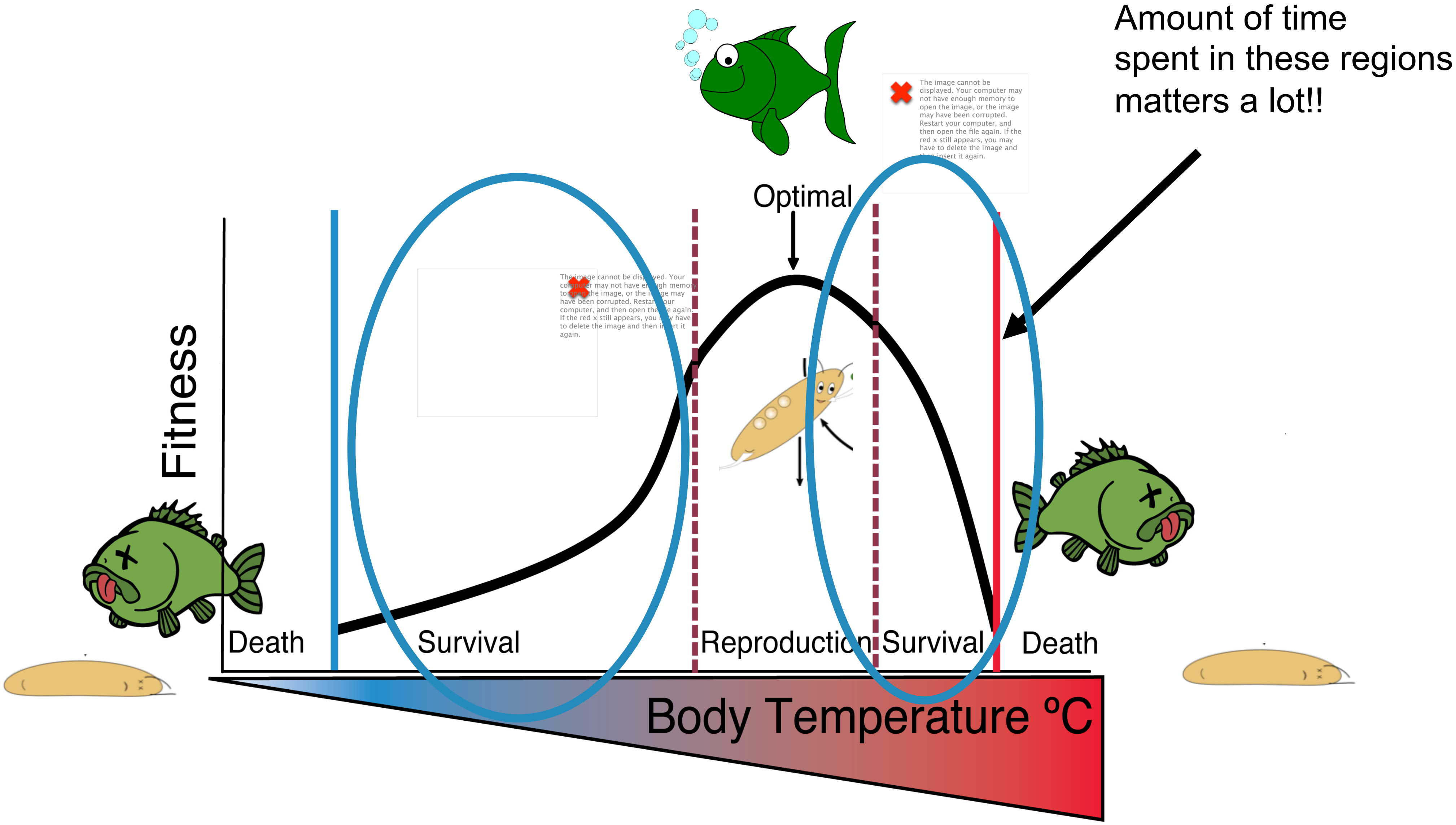
Energetics



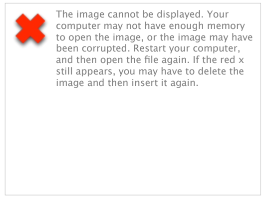
Lethal model fails miserably when applied to Europe; Energetics model does well

(Woodin, Hilbish, Helmuth, Jones and Wethey 2013)

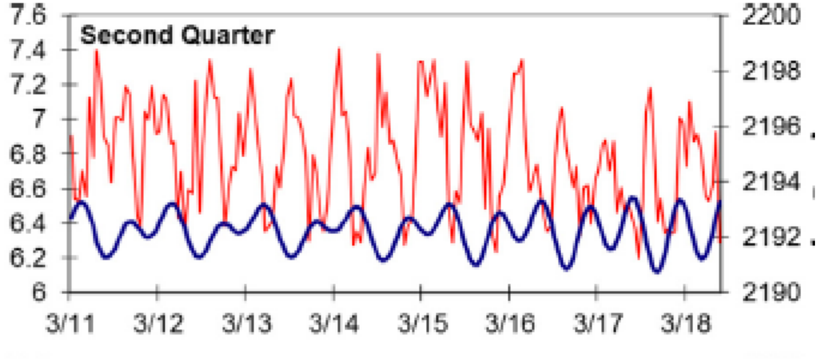
PHYSIOLOGICAL PERFORMANCE CURVES

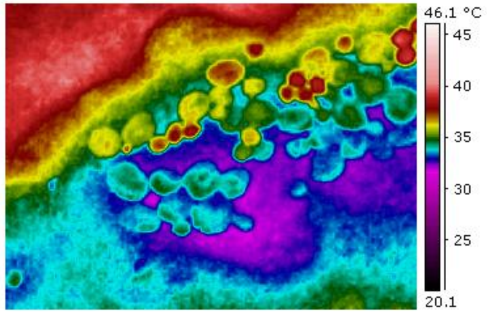


THE REAL WORLD IS FREQUENTLY MESSY WITH HIGH SPATIAL AND TEMPORAL VARIABILITY

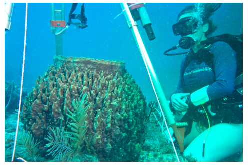


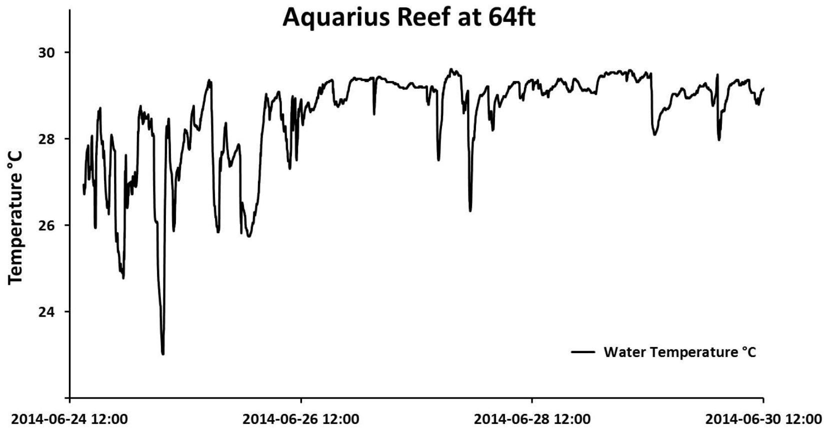
Lee et al. 2015: Hydrothermal Vents



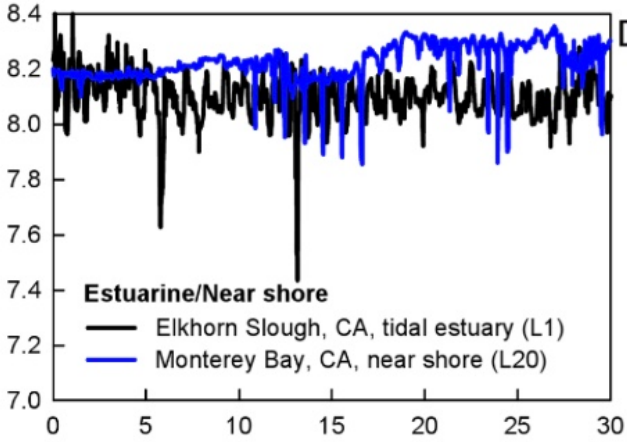


Terrestrial and intertidal (and even shallow subtidal) body temperature driven primarily by solar radiation (Helmuth 2002)





Internal waves, wind and upwelling lead to large and rapid changes in temperature and pCO_2 on reefs and shallow coastal regions



Large changes in nearshore pH over scales of hours (Hofmann et al. 2011)

THE MYTH OF A STABLE OCEAN

- TECHNOLOGICAL LIMITATIONS TO OUR ABILITY TO MEASURE THE ENVIRONMENT AT COARSE TEMPORAL AND SPATIAL RESOLUTION HAS BEEN CONFLATED WITH THE ASSUMPTION THAT THESE ARE THE ONLY SCALES THAT MATTER TO SPECIES DISTRIBUTIONS

COMMENT

CONSERVATION How cold-adapted species respond to climate change p.302

ANATOMY Unpacking Renaissance artist Vesalius's drawings of the body p.304

RESEARCH PRIZE Controversy over all-male list of awardees p.307

OBITUARY Paul Delos Boyer, chemist who discovered tiny molecular motor p.308

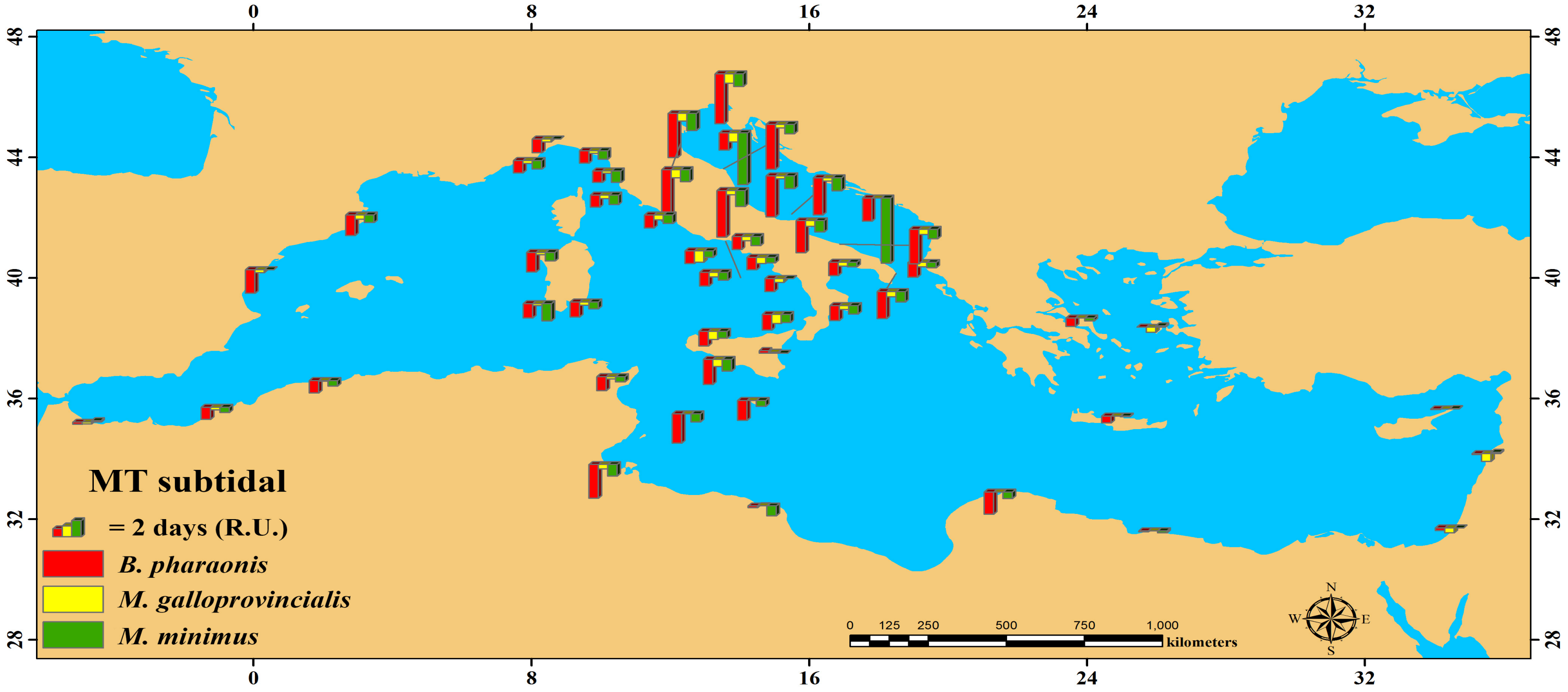
Fish and other marine life are affected by ocean weather: drastic variations in temperature, pH, oxygen and salinity that are in turn influenced by climate change.

Biologists ignore ocean weather at their peril

Bates et al. 2018 *Nature* Vol. 560

Valeria Montalto

FORECASTS OF MATURATION TIME USING DEB MODEL FOR THREE SPECIES OF MUSSELS IN THE MED.

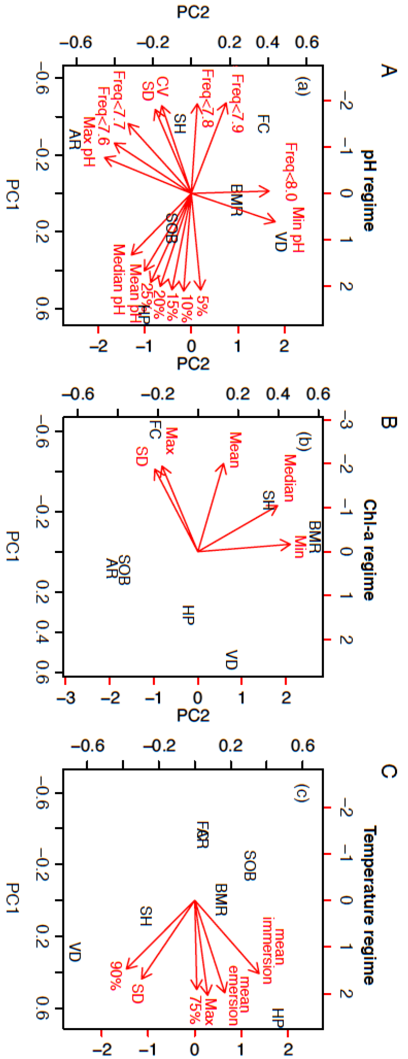


Montalto et al. 2016. Climatic Change

SPATIO-TEMPORAL COINCIDENCE OF MULTIPLE DRIVERS

Patterns of mussel growth best explained by coincidence of low food, low pH and high intertidal temperatures

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.



Kroeker et al., 2016 *Ecology Letters*

DYNAMIC ENERGY BUDGET THEORY

- CAN PROVIDE QUANTITATIVE MEANS OF LOOKING AT CUMULATIVE ROLE OF FLUCTUATING ENVIRONMENT, AND ESPECIALLY THE INTERACTION OF FOOD AND STRESS
- BUT *ONLY* WHEN WE USE ENVIRONMENTAL DATA AT THE RIGHT SPATIAL AND TEMPORAL SCALES
- *CANNOT* USE ANNUAL MEANS OR CLIMATE AVERAGES TO FORECAST ANY KIND OF MEANINGFUL ECOLOGICAL EFFECTS UNLESS THE ENVIRONMENT TRULY IS STATIC IN TIME AND UNIFORM IN SPACE

WHAT DEB CAN TELL US ABOUT CLIMATE CHANGE IMPACTS

- MARINE SPATIAL PLANNING: IDENTIFYING HOT SPOTS, REFUGIA AND STEPPING STONES, AND THE POTENTIAL ROLE OF SMALL-SCALE SPATIAL HETEROGENEITY

WE NEED TO BE VERY CAREFUL OF WHICH “ENVIRONMENTAL SIGNALS” WE PAY ATTENTION TO OVER GEOGRAPHIC SCALES

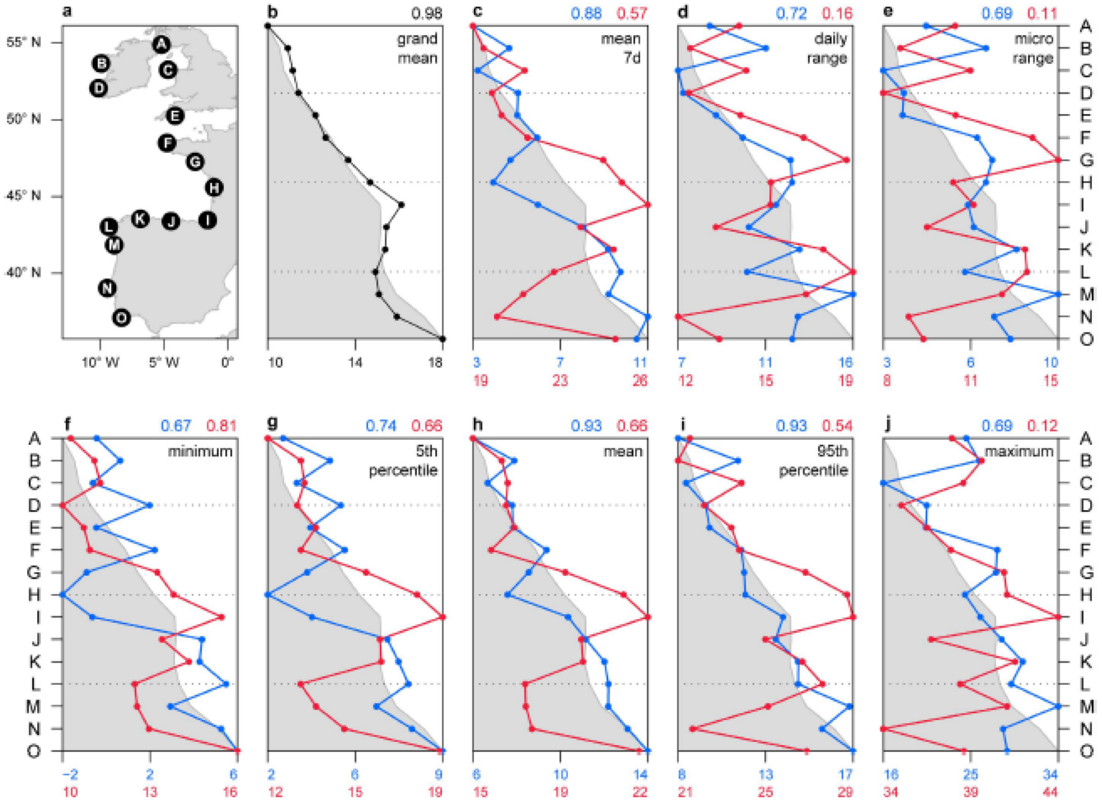
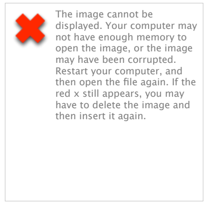


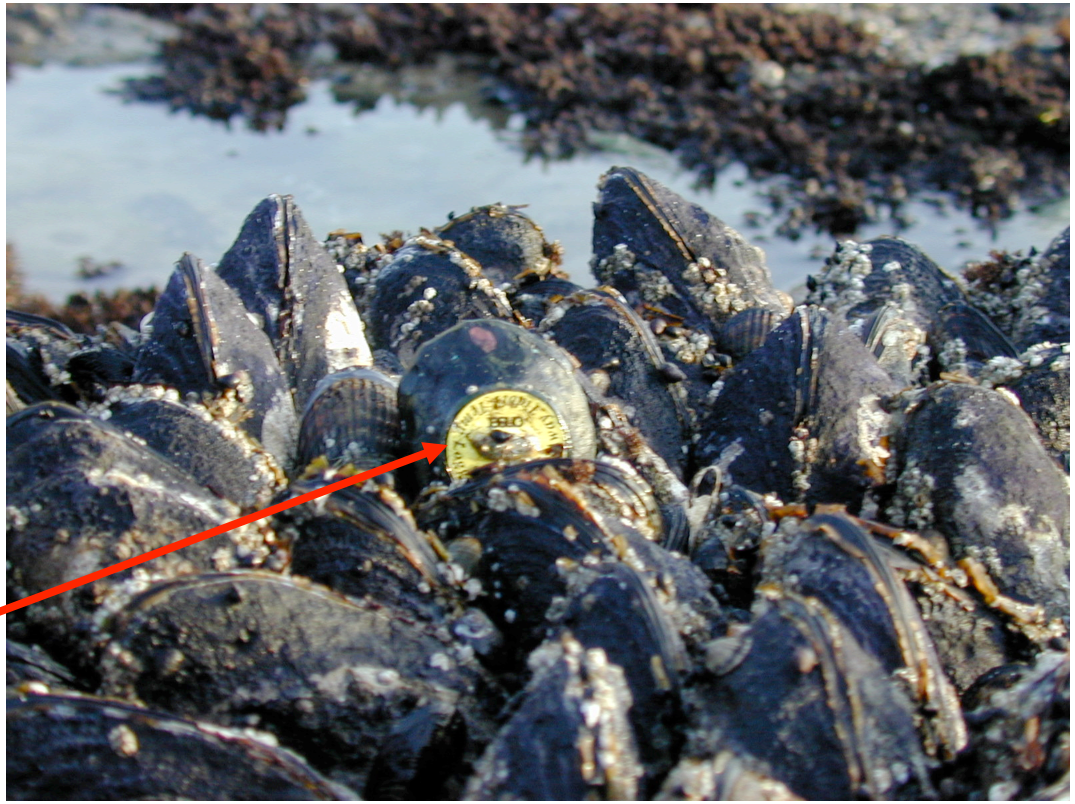
Figure 1. Patterns of temperature metrics across the European Atlantic intertidal ecosystem. (a) Locations surveyed. Geographic pattern of metrics: **(b)** grand mean, **(c)** 7 day mean, **(d)** daily range, **(e)** microhabitat range, **(f)** minimum, **(g)** 5th percentile, **(h)** mean, **(i)** 95th percentile, **(j)** maximum. Black line **(b)** is grand mean, calculated using all data from each shore. Red and blue lines **(c–j)** calculated using the warmest and coldest 30 days of each year (7 days for **(c)**), per shore. The shaded area is the pattern expected if each metric was perfectly correlated with latitude. Points in shaded area are “cooler than expected given latitude”, and points outside shaded area are “hotter than expected”. Correlation coefficients between each

Seabra et al. 2015 *Scientific Reports*

MEASURING THE ENVIRONMENT AT SCALES RELEVANT TO ORGANISMS WITH BIOMIMETIC SENSORS

"Robomussel"





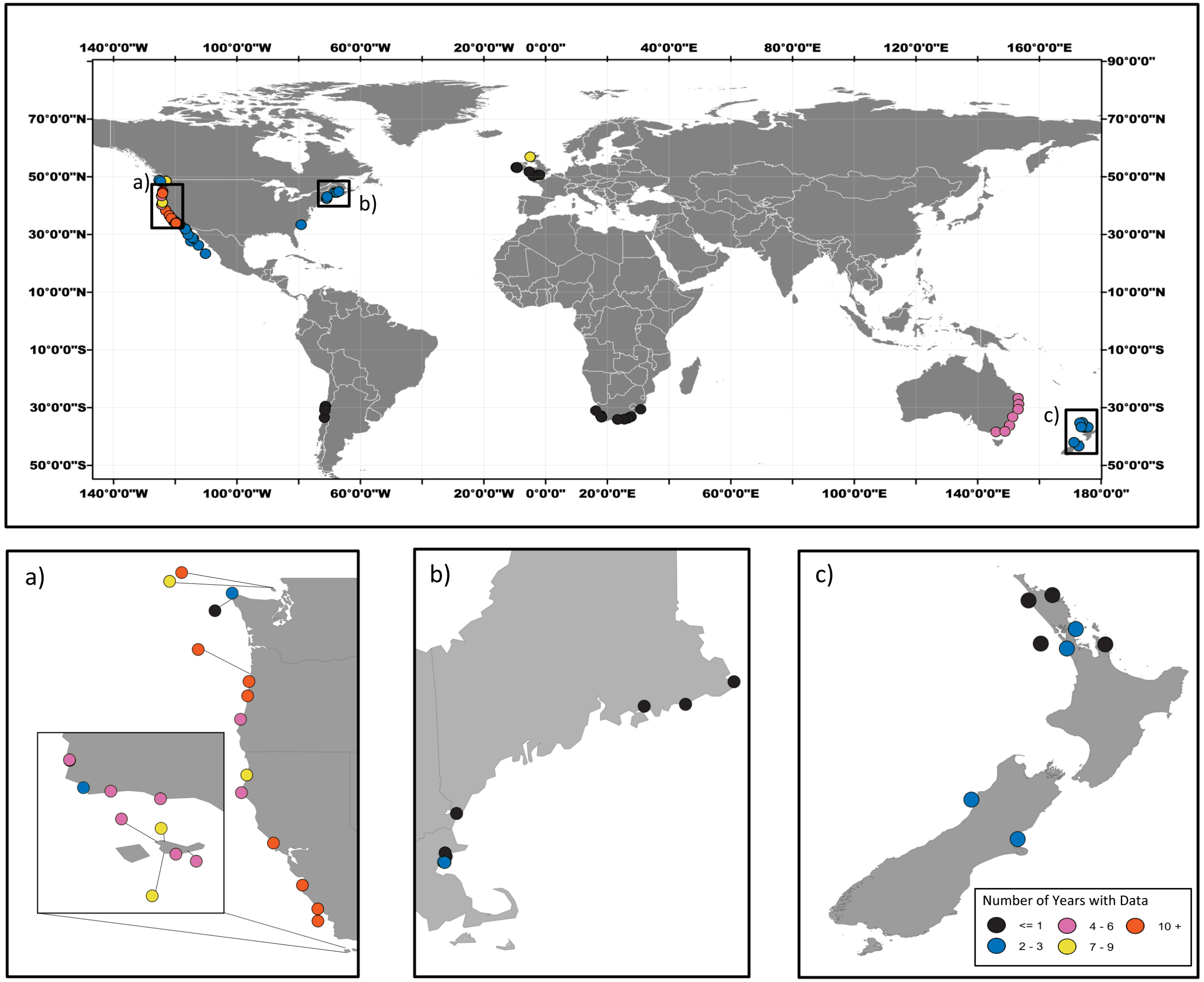
California mussel, *Mytilus californianus*

Unmatched loggers regularly create errors of >14°C;

Thermally matched loggers incur errors of ~2°C

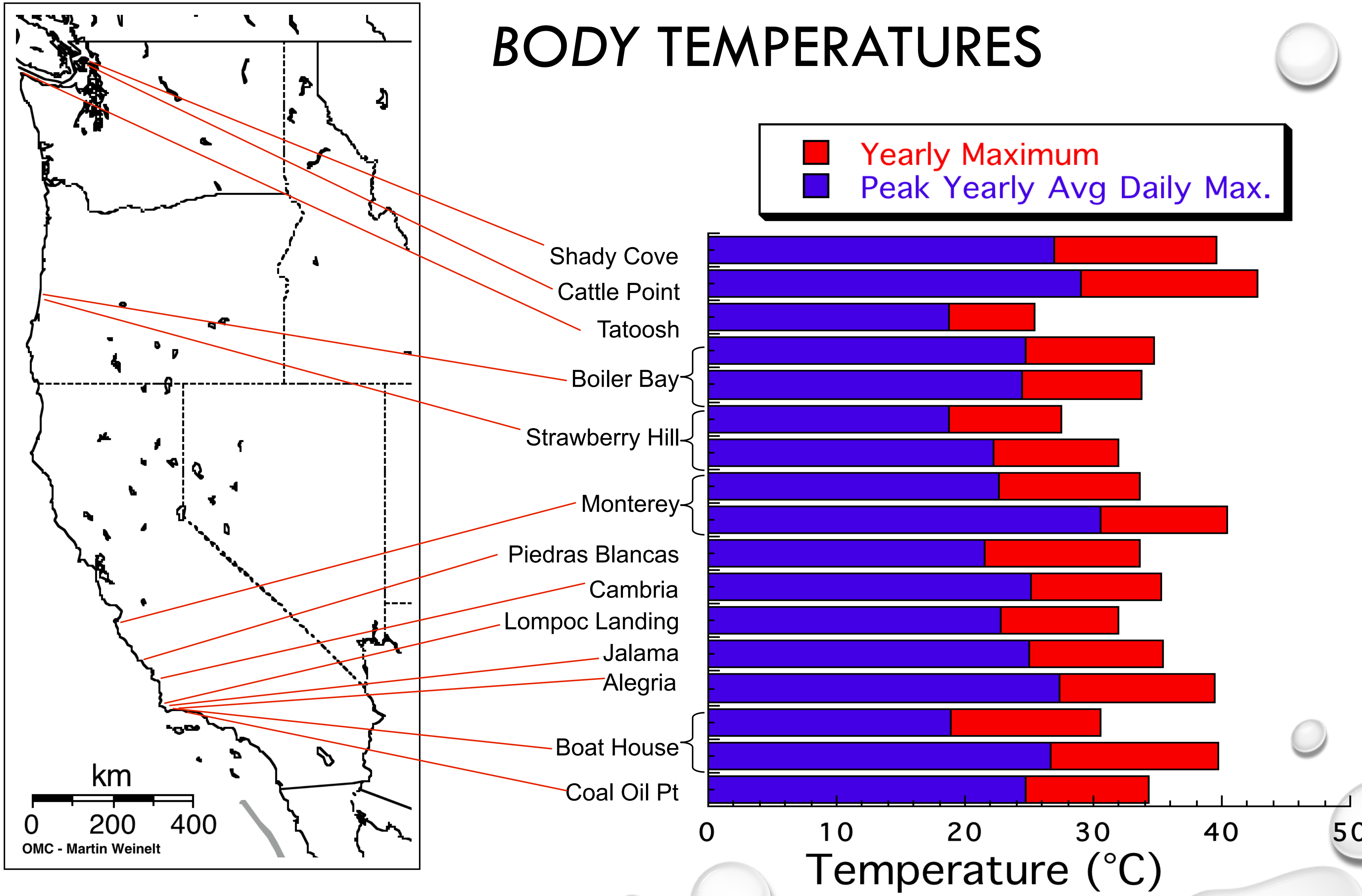
Fitzhenry et al. 2004 *Marine Biology* 145: 339-349.

71 INTERTIDAL SITES WORLDWIDE, RECORDING CONTINUOUSLY



Helmuth et al. 2016 *Nature Scientific Data*

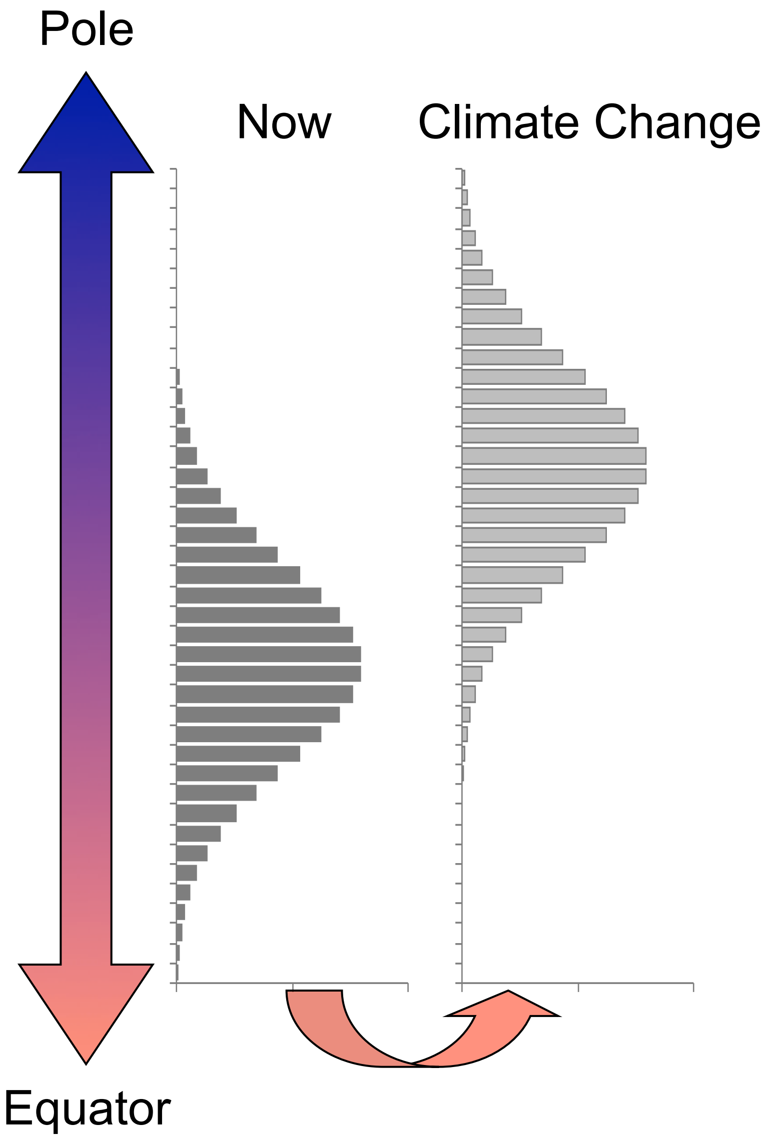
THERMAL MOSAIC IN MUSSEL *BODY* TEMPERATURES

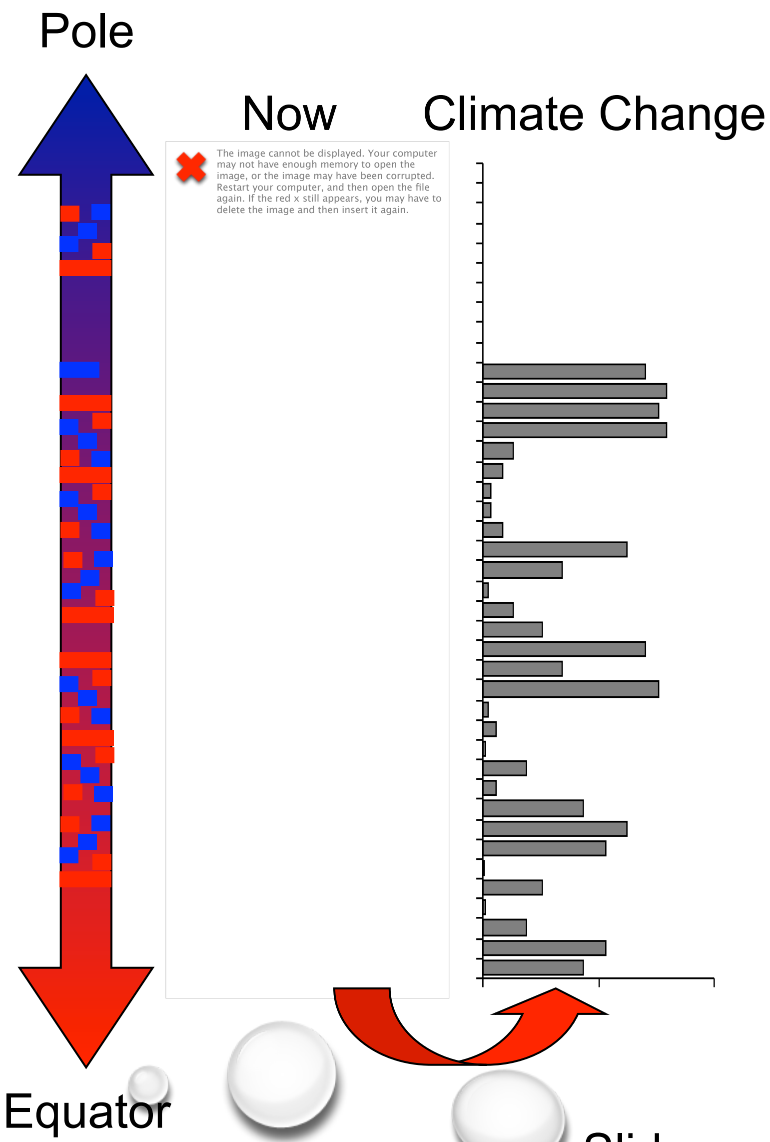


Helmuth et al. 2002 *Science*

CONCEPT OF A "THERMAL MOSAIC"

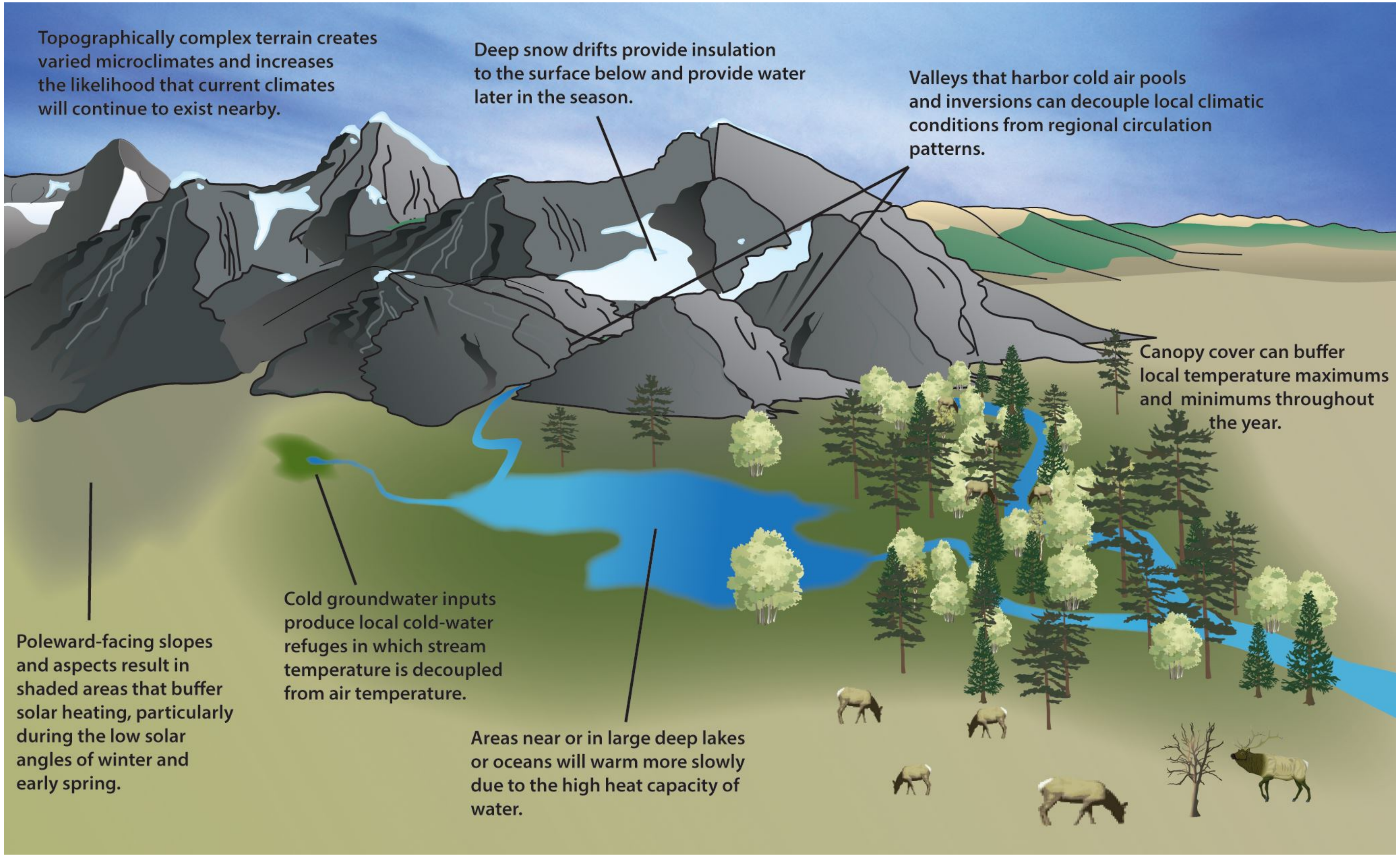
- Helmuth et al 2002, Gilman 2006, Finke et al. 2007, Torossian et al. 2016





Slide courtesy Sarah Gilman

CLIMATE REFUGIA



Morelli et al. 2016 “Managing climate refugia for climate adaptation” PLOS ONE 12: e0169725

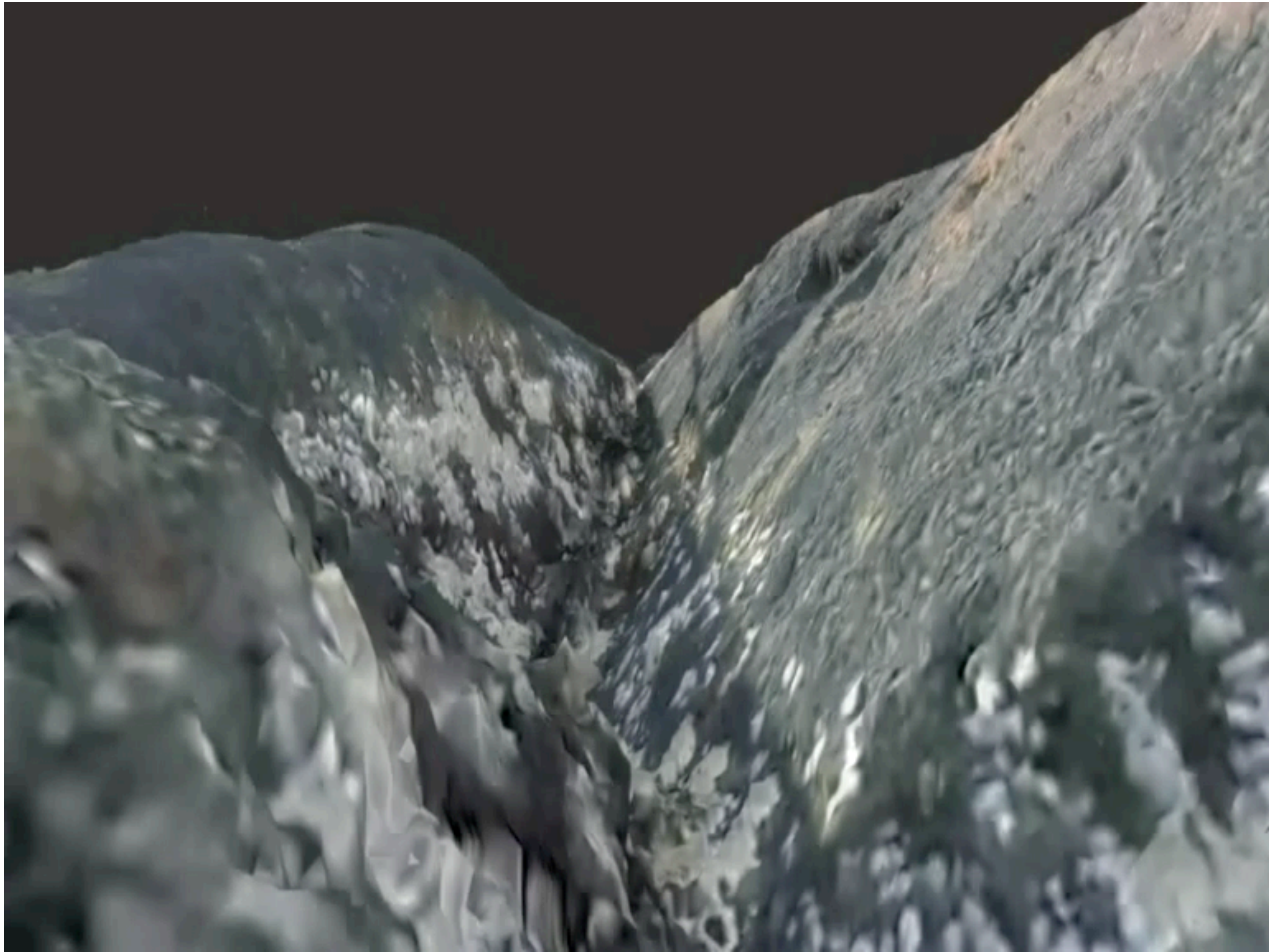
CLIMATE REFUGIA IN CLIMATE ADAPTATION

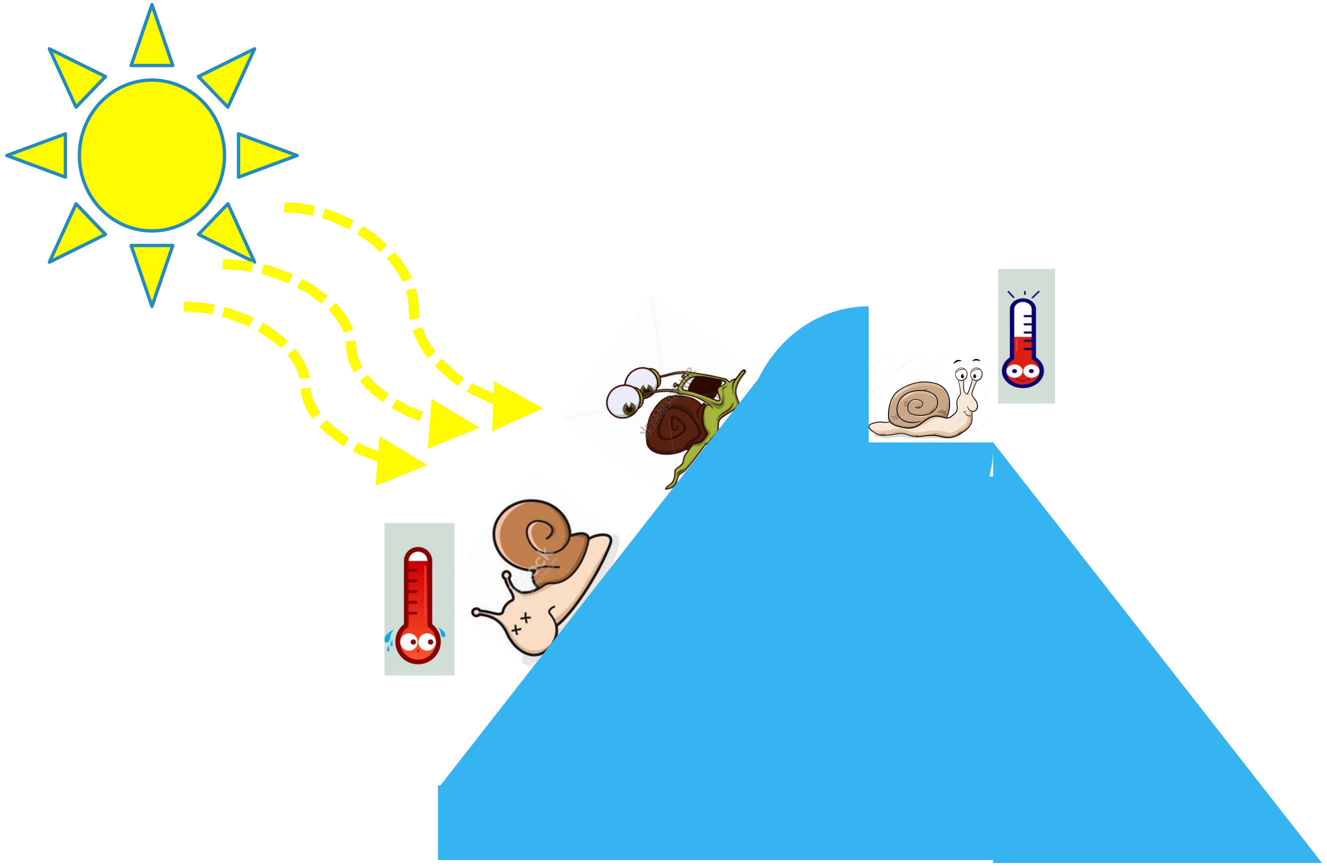
- HABITATS THAT PERMIT SURVIVAL DURING EXTREME EVENTS, AND SUBSEQUENT RECOVERY
- ARE BEING DISCOVERED IN MULTIPLE ECOSYSTEMS
- MAY SERVE AS A MEANS OF ENHANCING RESILIENCE

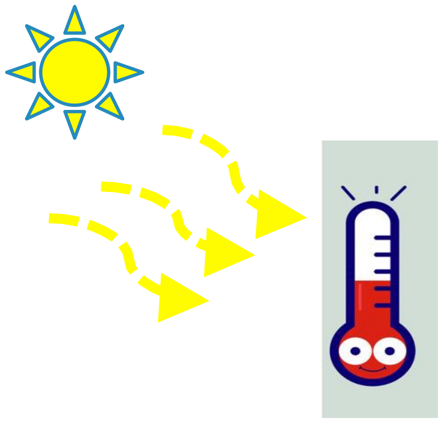
DOES THE SCALE OF "RESCUE EFFECTS" CHANGE WITH BODY SIZE AND BEHAVIOR?

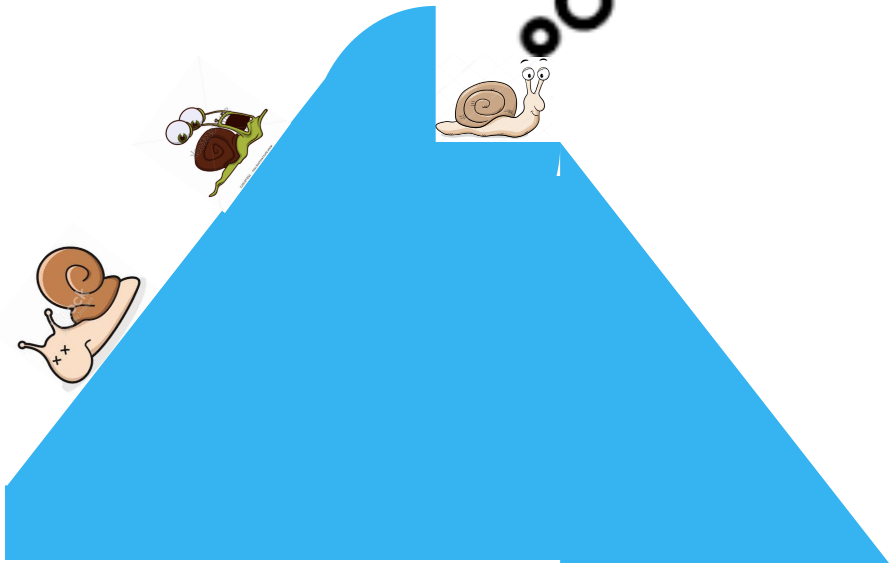
http://bpic.588ku.com/back_pic/00/00/69/40/18cbd649961b9b92762ec31fac5c34e6.jpg!/fh/300/quality/90/unsharp/true/compress/true
https://www.worldwildlife.org/species/whale

A snail's eye view of the world

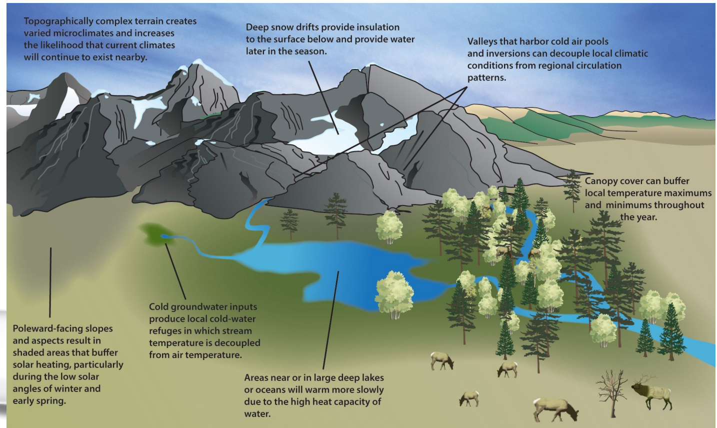






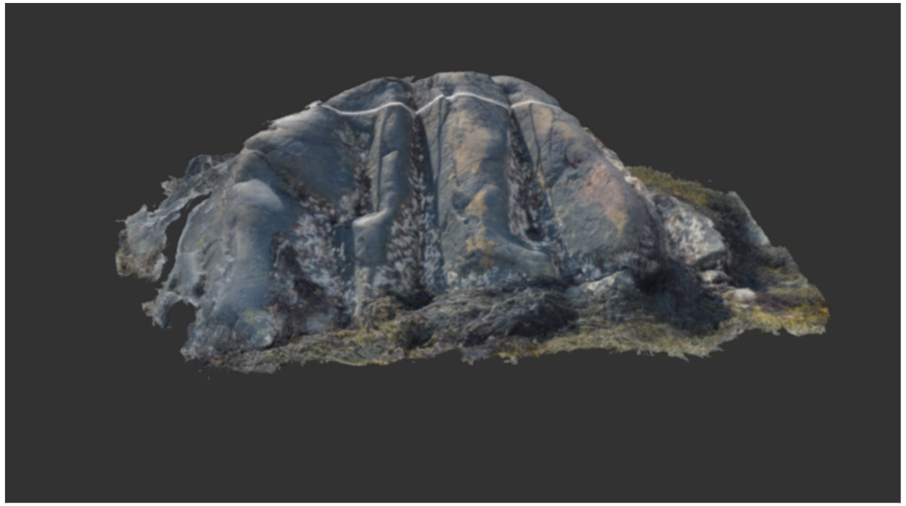



It's all just a matter of scale

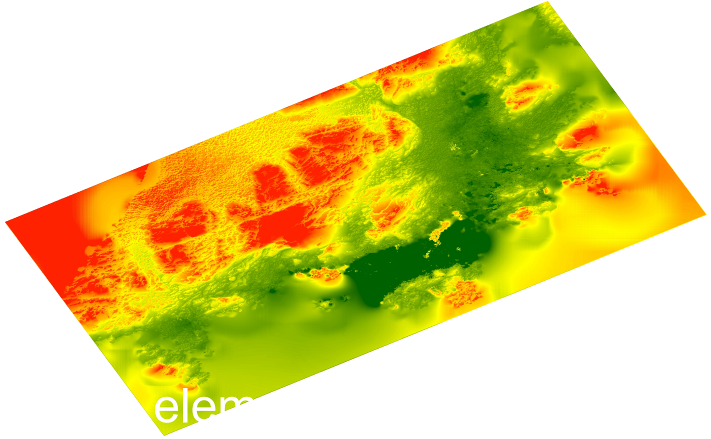

Topographically complex terrain creates varied microclimates and increases the likelihood that current climates will continue to exist nearby.
Deep snow drifts provide insulation to the surface below and provide water later in the season.
Valleys that harbor cold air pools and inversions can decouple local climatic conditions from regional circulation patterns.
Canopy cover can buffer local temperature maximums and minimums throughout the year.
Poleward-facing slopes and aspects result in shaded areas that buffer solar heating, particularly during the low solar angles of winter and early spring.
Cold groundwater inputs produce local cold-water refuges in which stream temperature is decoupled from air temperature.
Areas near or in large deep lakes or oceans will warm more slowly due to the high heat capacity of water.

MAPPING SMALL-SCALE THERMAL ENVIRONMENTS

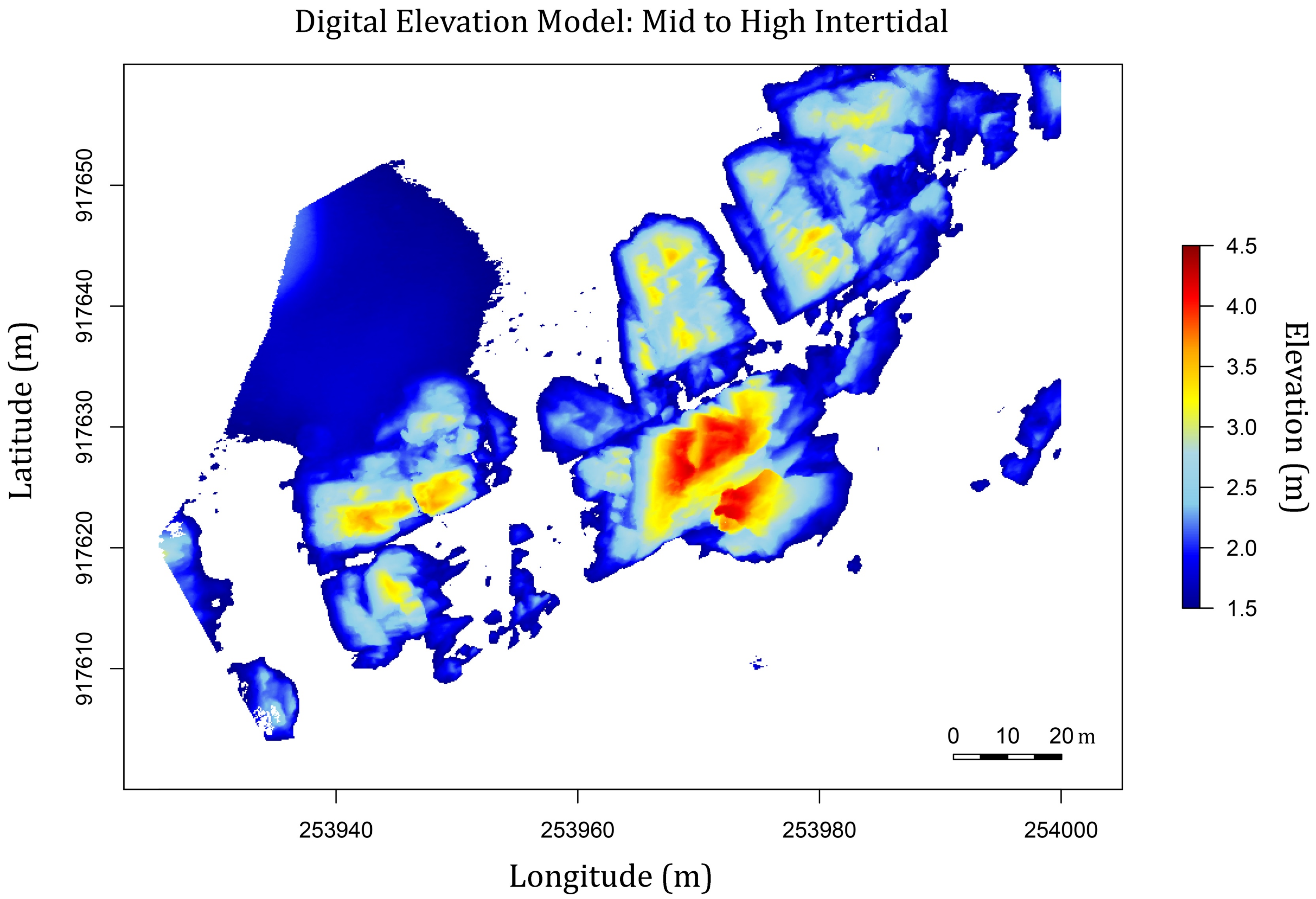
Drone imagery



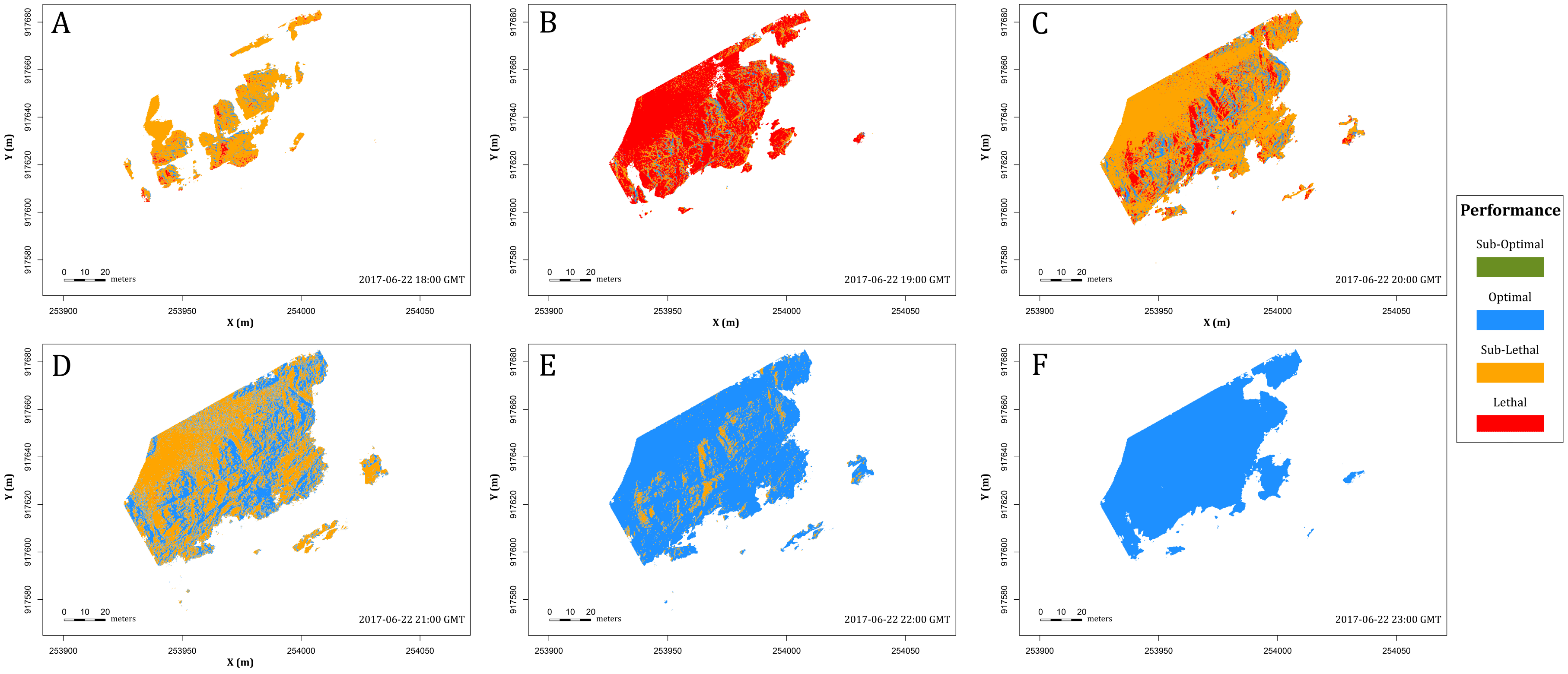
3D modeling

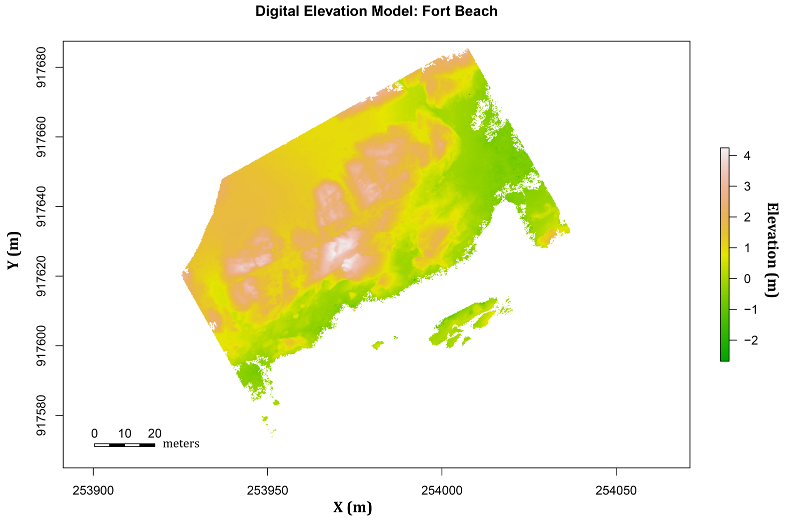


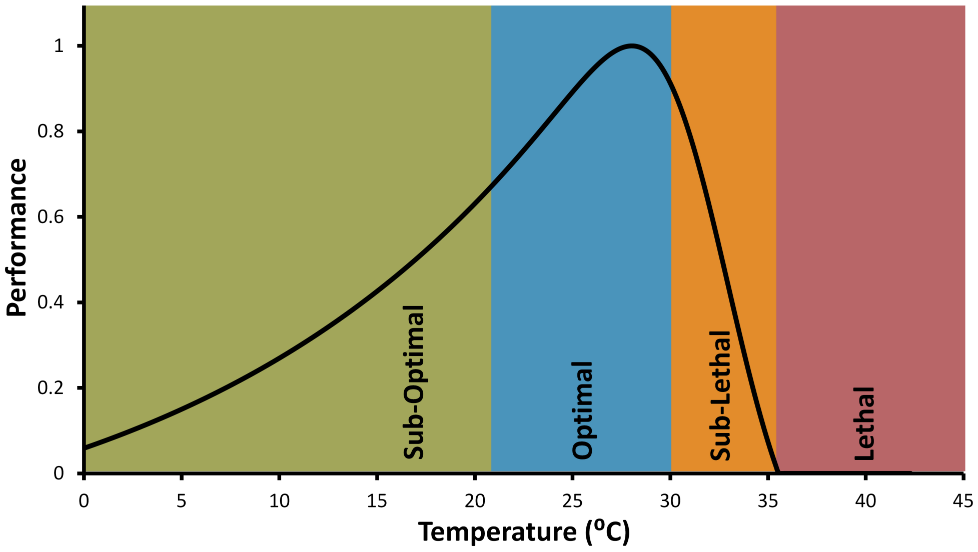
Heat budget models



3 Million pixels for a ~100x 25m site


A
B
C
D
E
F
Y (m)
X (m)
0 10 20 meters
2017-06-22 18:00 GMT
2017-06-22 19:00 GMT
2017-06-22 20:00 GMT
2017-06-22 21:00 GMT
2017-06-22 22:00 GMT
2017-06-22 23:00 GMT
Performance
Sub-Optimal
Optimal
Sub-Lethal
Lethal


Digital Elevation Model: Fort Beach
Y (m)
X (m)
0 10 20 meters
Elevation (m)


Performance
Temperature (°C)
Sub-Optimal
Optimal
Sub-Lethal
Lethal

PATTERNS OF WEIGHT GAIN IN MUSSELS

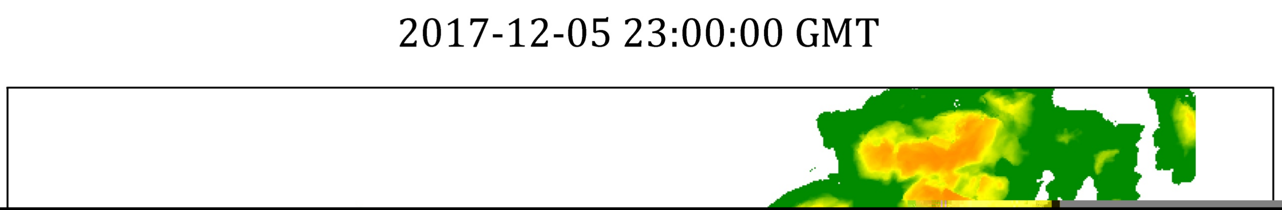
DEB parameters for *M edulis* from AMP:

Saraiva and Kooijman. 2017. AmP [redacted]
Mytilus edulis, version 2017/11/1[redacted]

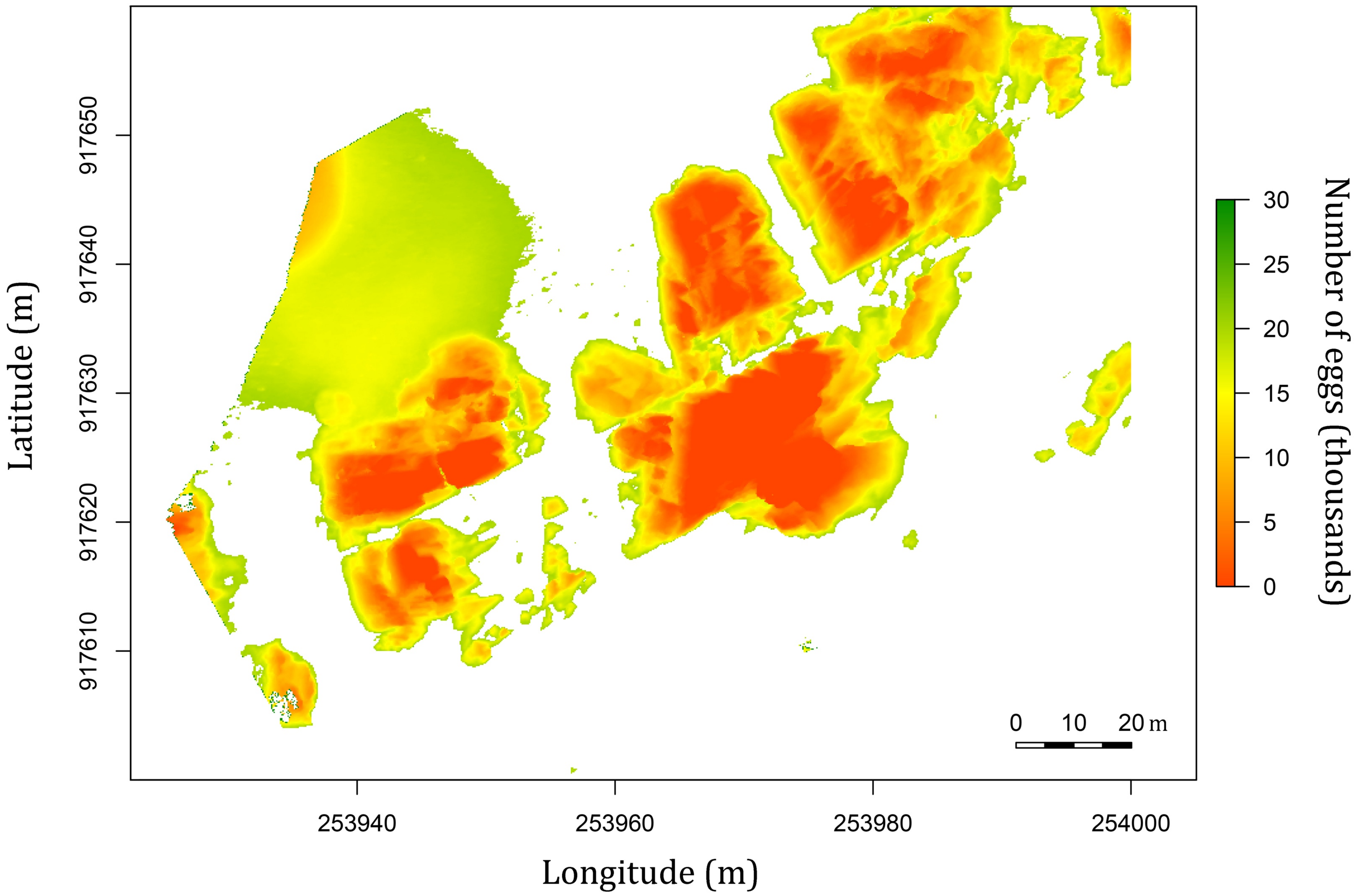
Model code by C. Monaco

Constant food assumed (2 µg/l)[redacted]

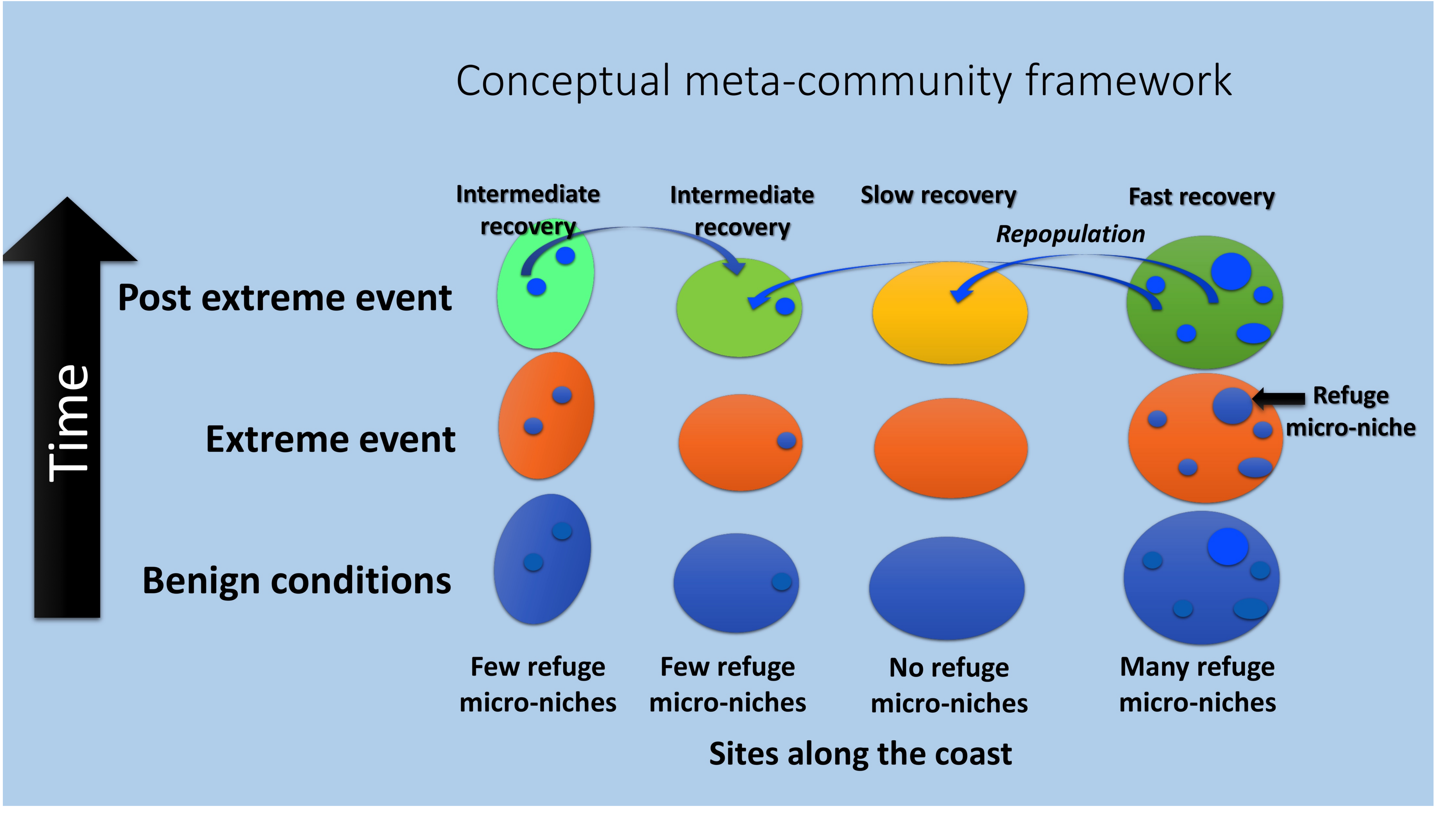
Run time: ~5 days for one year [redacted]
hourly data for each of 3
million pixels



[redacted]



917650
917640
917630
917620
917610
Latitude (m)
253940
253960
253980
254000
Longitude (m)
0 10 20 m
30
25
20
15
10
5
0
Number of eggs (thousands)


Conceptual meta-community framework
Time
Post extreme event
Extreme event
Benign conditions
Intermediate recovery
Intermediate recovery
Slow recovery
Fast recovery
Repopulation
Refuge micro-niche
Few refuge micro-niches
Few refuge micro-niches
No refuge micro-niches
Many refuge micro-niches
Sites along the coast

LARGE-SCALE PATTERN DRIVEN BY SMALL-SCALE PROCESSES?

- *SMALL-SCALE PROCESSES AT LEVEL OF MICROHABITATS MAY HAVE EMERGENT PROPERTIES AT GEOGRAPHIC SCALES, BY PROVIDING STEPPING STONES AND REFUGIA DURING EXTREME EVENTS*

WHERE DOES THIS LEAVE US?

- IMPACTS MAY BE OCCURRING IN UNEXPECTED LOCATIONS, AND IF WE ONLY LOOK AT RANGE EDGES WE ARE LIKELY MISSING A LOT!

WHERE DOES THIS LEAVE US?

- IMPACTS MAY BE OCCURRING IN UNEXPECTED LOCATIONS, AND IF WE ONLY LOOK AT RANGE EDGES WE ARE LIKELY MISSING A LOT!
- THE DETAILS OF MECHANISM MATTER AND PATTERNS OF VULNERABILITY MAY REFLECT EMERGENT PROPERTIES OF PROCESSES AT VERY SMALL AND TEMPORAL SCALES

WHERE DOES THIS LEAVE US?

- IMPACTS MAY BE OCCURRING IN UNEXPECTED LOCATIONS, AND IF WE ONLY LOOK AT RANGE EDGES WE ARE LIKELY MISSING A LOT!
- THE DETAILS OF MECHANISM MATTER AND PATTERNS OF VULNERABILITY MAY REFLECT EMERGENT PROPERTIES OF PROCESSES AT VERY SMALL AND TEMPORAL SCALES
- DEB CAN PROVIDE A CRITICAL WAY OF EXPLORING THESE PROCESSES, BUT CAREFUL DEB/ PHYSIOLOGICAL INFORMATION MUST BE MATCHED WITH EQUALLY CAREFUL ENVIRONMENTAL DATA (BE CAREFUL WITH AVERAGING!!)

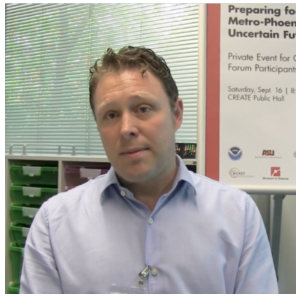
Thank you

For more information please visit northeastern.edu/helmuthlab

Francis Choi

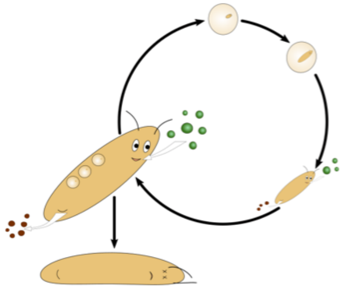
Ashley Cryan

Aubrey Foulk



David Sittenfeld

Jess Torossian



b.helmuth@northeastern.edu

@aquanaut1967

Northeastern University

Urban Coastal Sustainability Initiative

northeastern.edu/ucsi