Multi-Decadal Examination of Thermal Habitat Conditions for the Endangered Delta Smelt in the San Francisco Estuary using the Landsat Satellite Imagery Record

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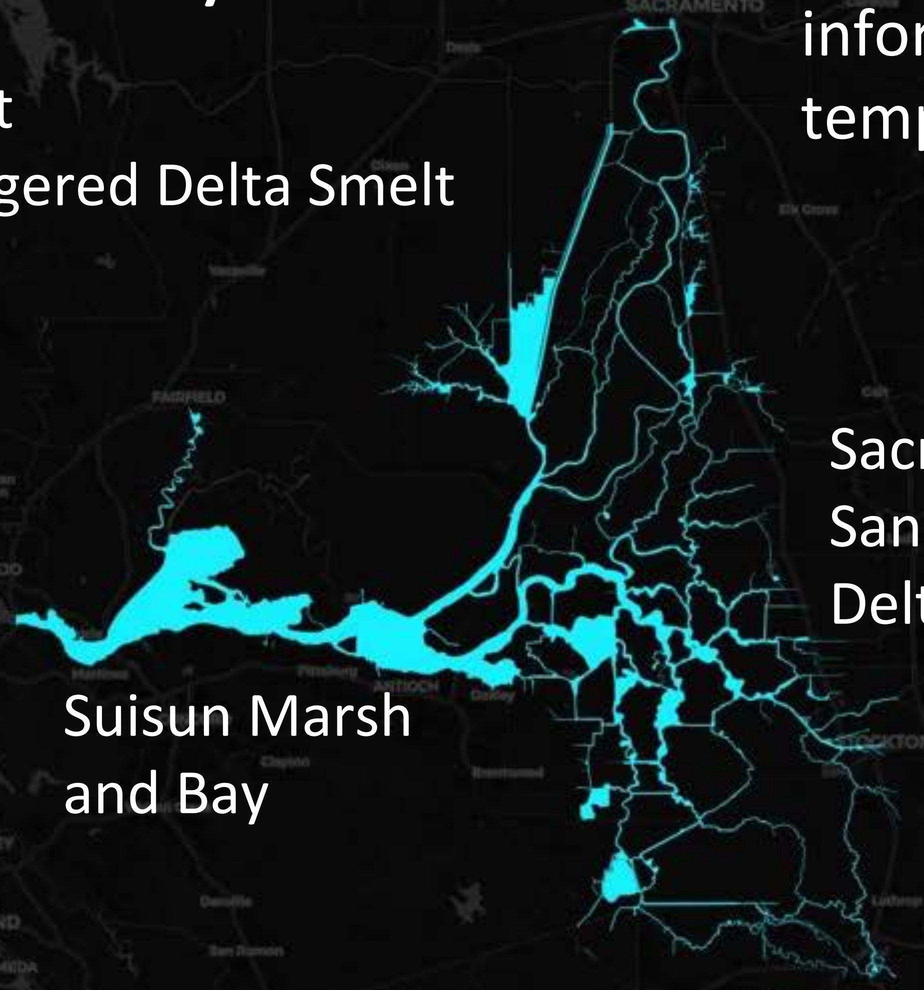
California Institute of Technology

San Francisco Estuary

- biodiversity hotspot
- home of the endangered Delta Smelt

Water management decisions affecting smelt habitat here can be informed by salinity, turbidity, and temperature.

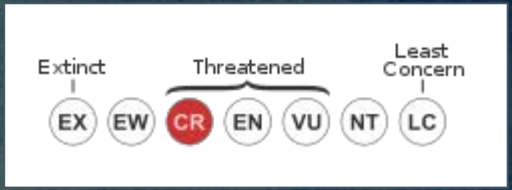


Water temperature is a driving factor of habitat suitability for fish, and we want to put forward remotely sensed surface temperature as an indicator of habitat suitability.

The delta smelt are endemic to the SFE and critically endangered.

CTmax: 28.6°C

Davis et al. 2019



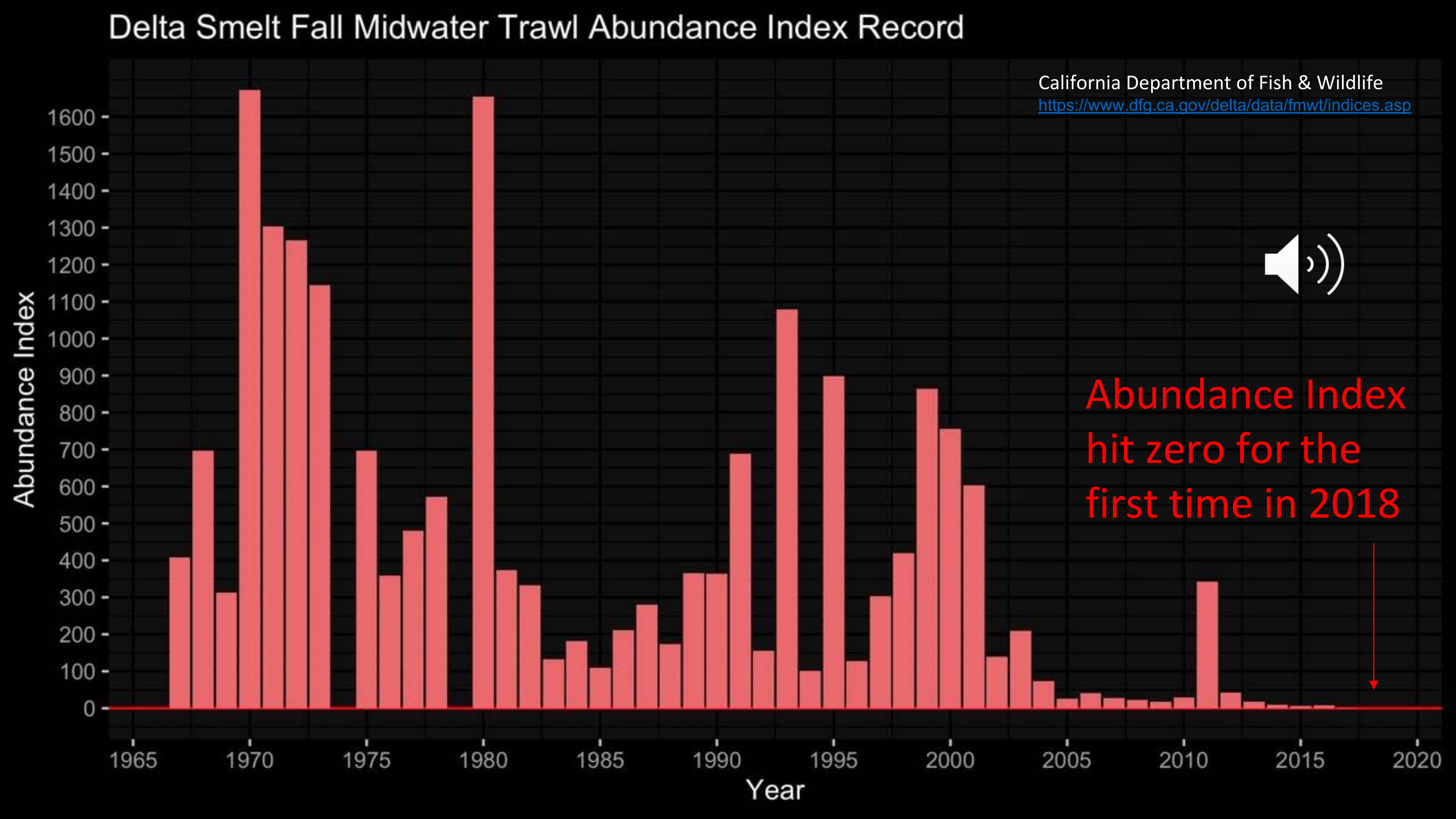
Delta Smelt

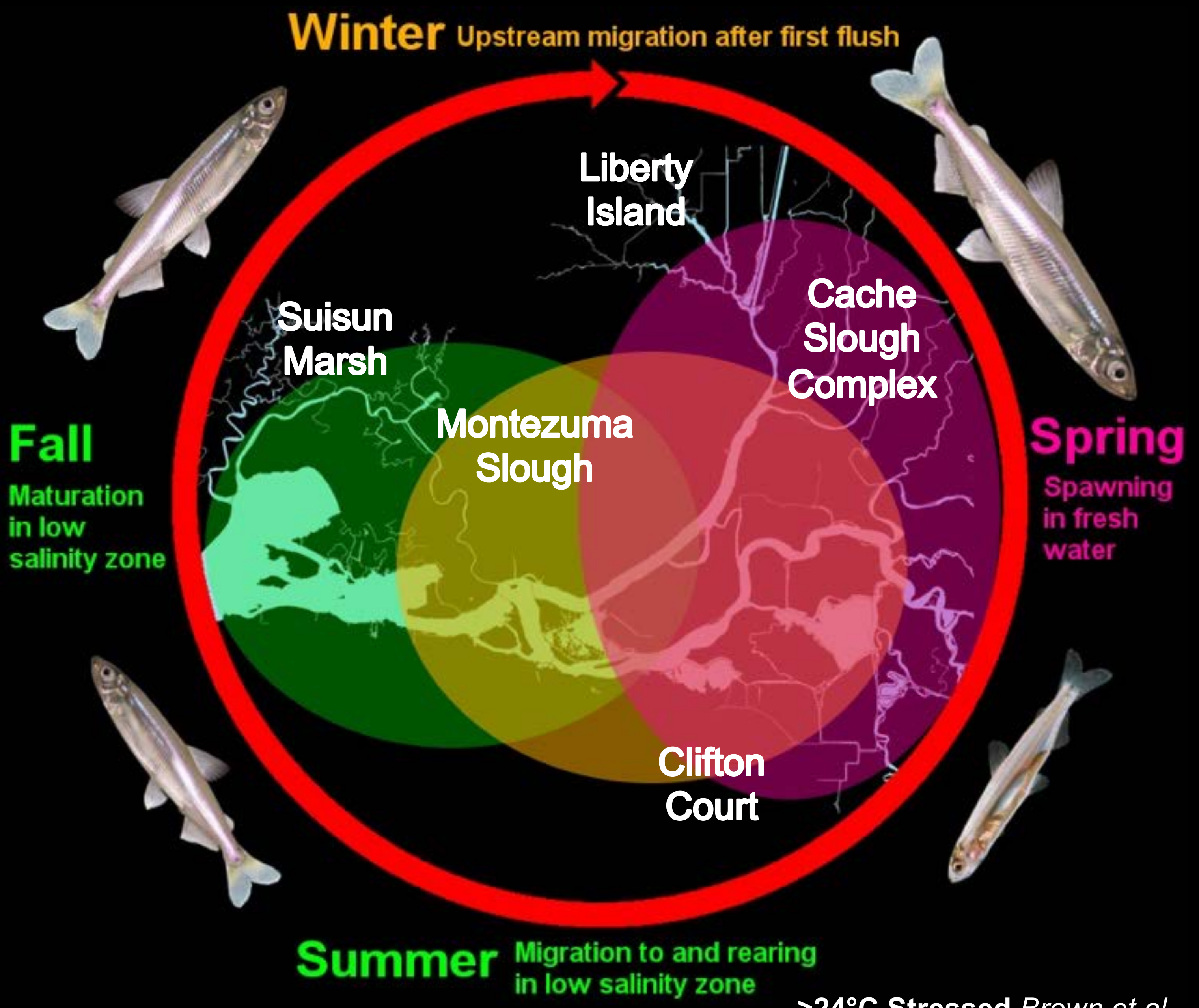
Hypomesus transpacificus

In decline due to reduced outflow, entrainment in pumps, and competition with invasive species.

Moyle et al. 2016

U.S. Fish and Wildlife Service
https://en.wikipedia.org/wiki/Delta_smelt#/media/File:Hypomesus_transpacificus.jpg

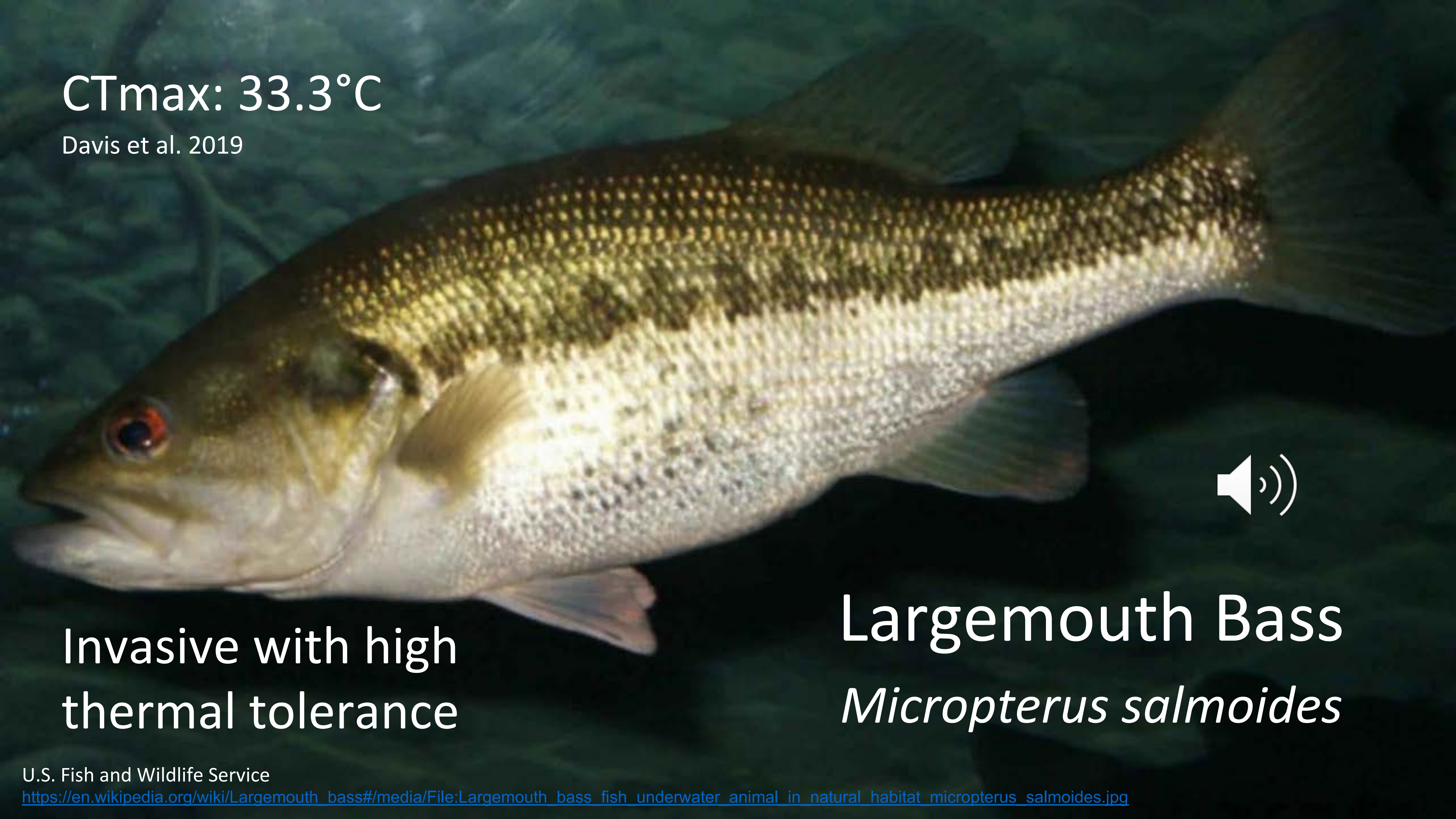

Delta Smelt Fall Midwater Trawl Abundance Index Record
California Department of Fish & Wildlife
https://www.dfg.ca.gov/delta/data/fmwt/indices.asp
Abundance Index
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Year
Abundance Index hit zero for the first time in 2018



15°C~20°C
Optimum for Spawning
Feb-May
Brown et al.
Nally et al.

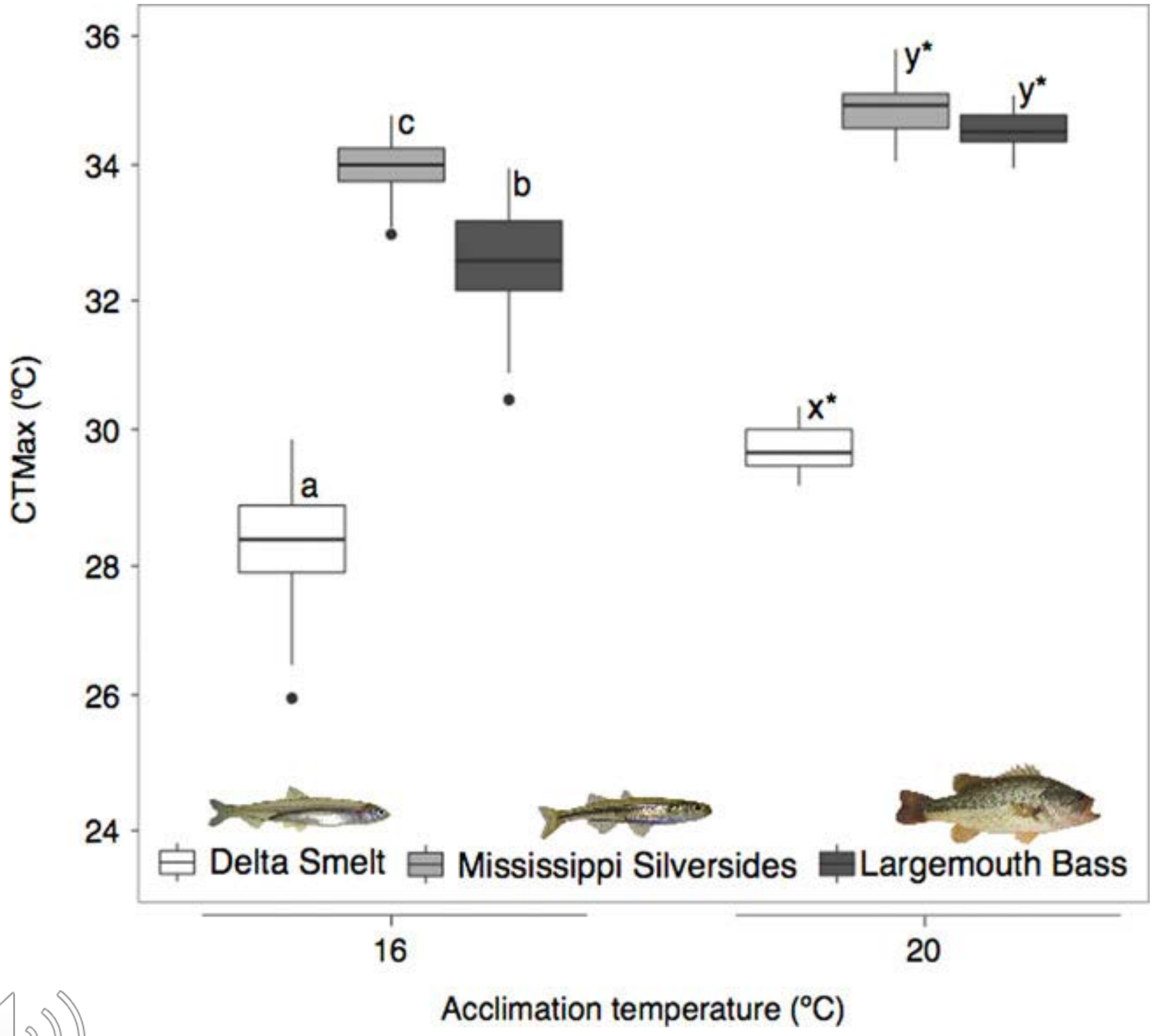
>24°C Stressed *Brown et al.*
>28.6°C Lethal *Davis et al.*

California Department of Fish & Wildlife
https://www.wildlife.ca.gov/Portals/0/Images/InlandFisheries/DeltaSmelt/DeltaSmeltLifeStages_JW.jpg


CTmax: 33.3°C
Davis et al. 2019
Invasive with high thermal tolerance
Largemouth Bass
Micropterus salmoides
U.S. Fish and Wildlife Service
https://en.wikipedia.org/wiki/Largemouth_bass#/media/File:Largemouth_bass_fish_underwater_animal_in_natural_habitat_micropterus_salmoides.jpg


CTmax: 34.1°C
Davis et al. 2019
Mississippi Silverside
Menidia beryllina
Invasive with high thermal tolerance
Photo Credit: Dave (Gio) Giordano

The invasive species considered here have higher thermal tolerances than the smelt.



Davis et al. 2019

This Presentation's Inquiry

How has thermal habitat suitability for endemic and invasive fish species changed over time?

- Laboratory-based studies of thermal tolerance for SFE fish: Delta Smelt, Largemouth Bass, Mississippi Silverside
- Long-term Landsat 5, 7, 8 record for water surface temperature

On-Going Considerations

How can we use this information to inform water management and ecosystem restoration?

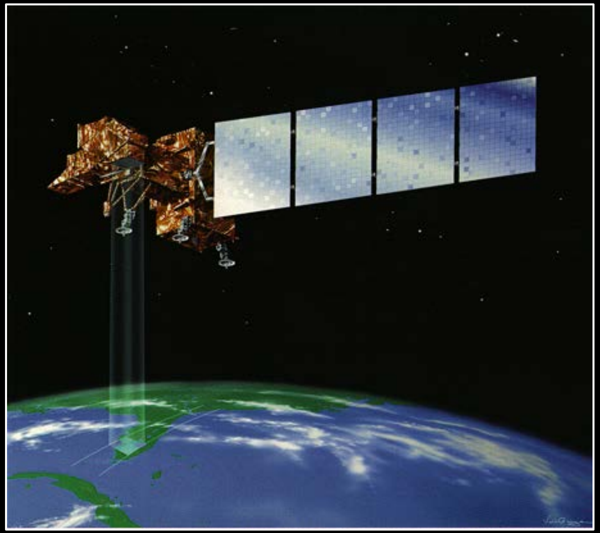
We would like to introduce the Landsat series of satellites as a remote sensing source of water temperature data for the SFE. Landsat 5, 7, and 8 provide a continuous record of surface temperature from 1984 to the present.

Landsat 5

60m, 1984-2011

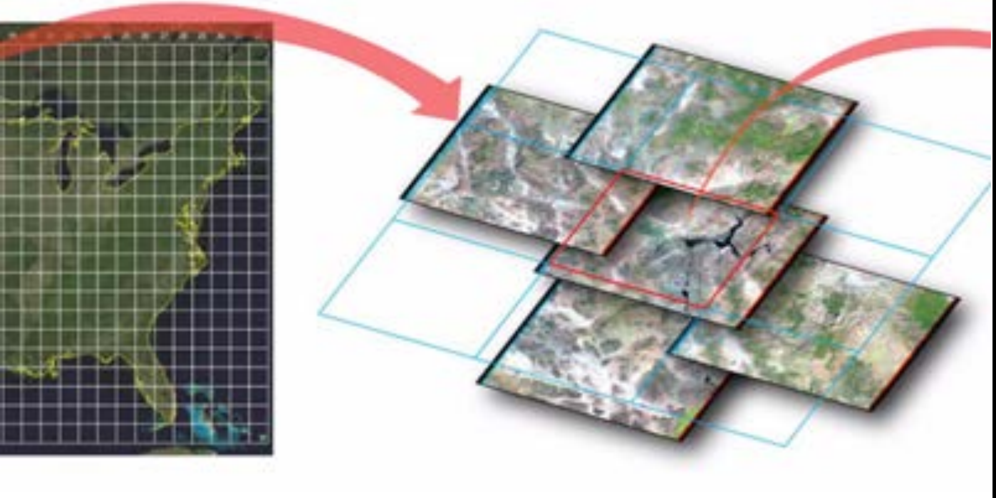
Landsat 7

60m, 1999-



Landsat 8

100m, 2013-



We processed Landsat level 1 thermal radiance into water surface temperature using the methods described in Malakar et al., 2018 and deployed in the Landsat Analysis Ready Dataset (ARD).

The first collection of the ARD had some issues over water surface, so we processed temperature in-house.

Validation

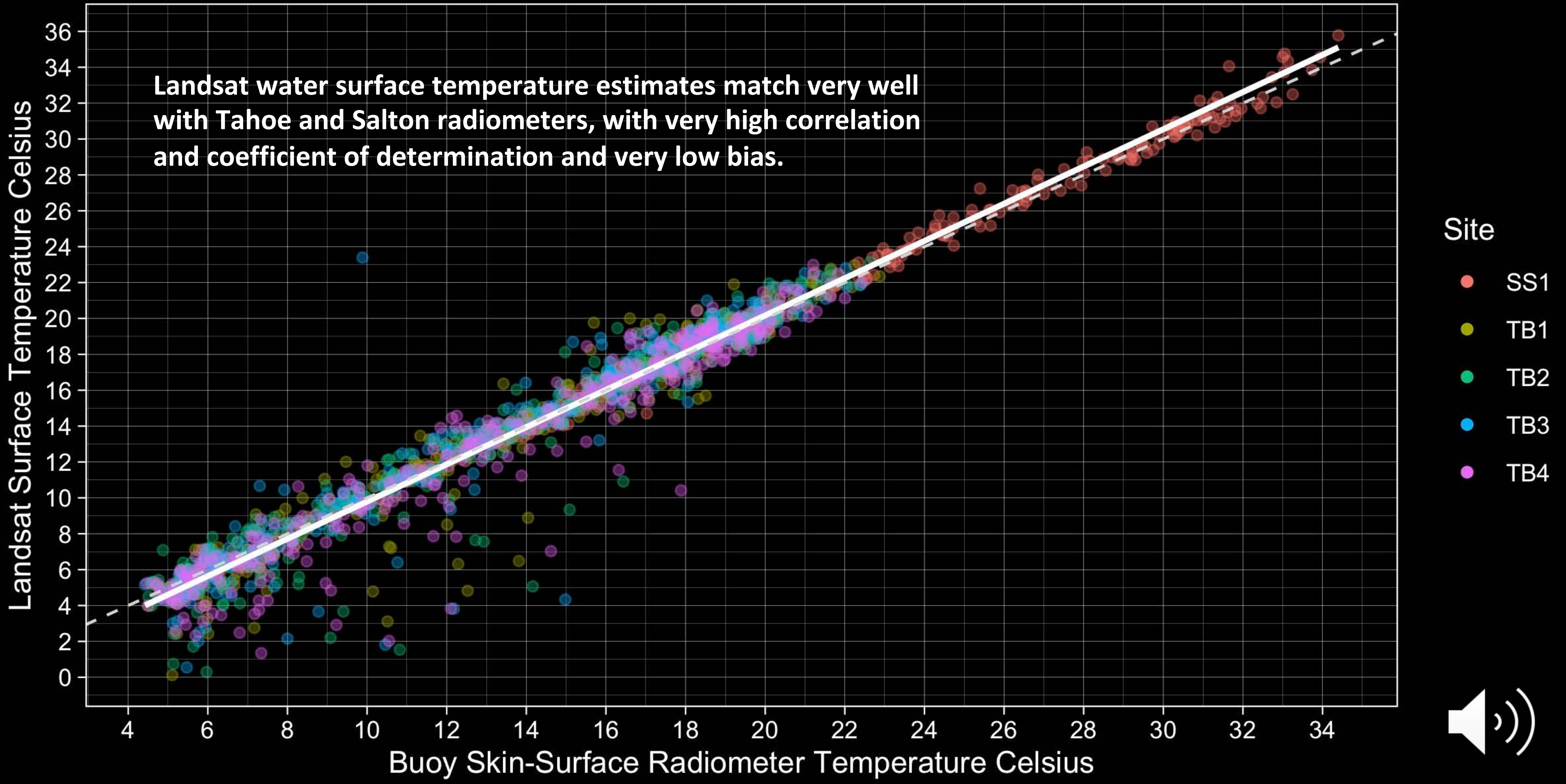
We validated our Landsat surface temperature output using water-surface radiometer sites at Lake Tahoe and the Salton Sea.

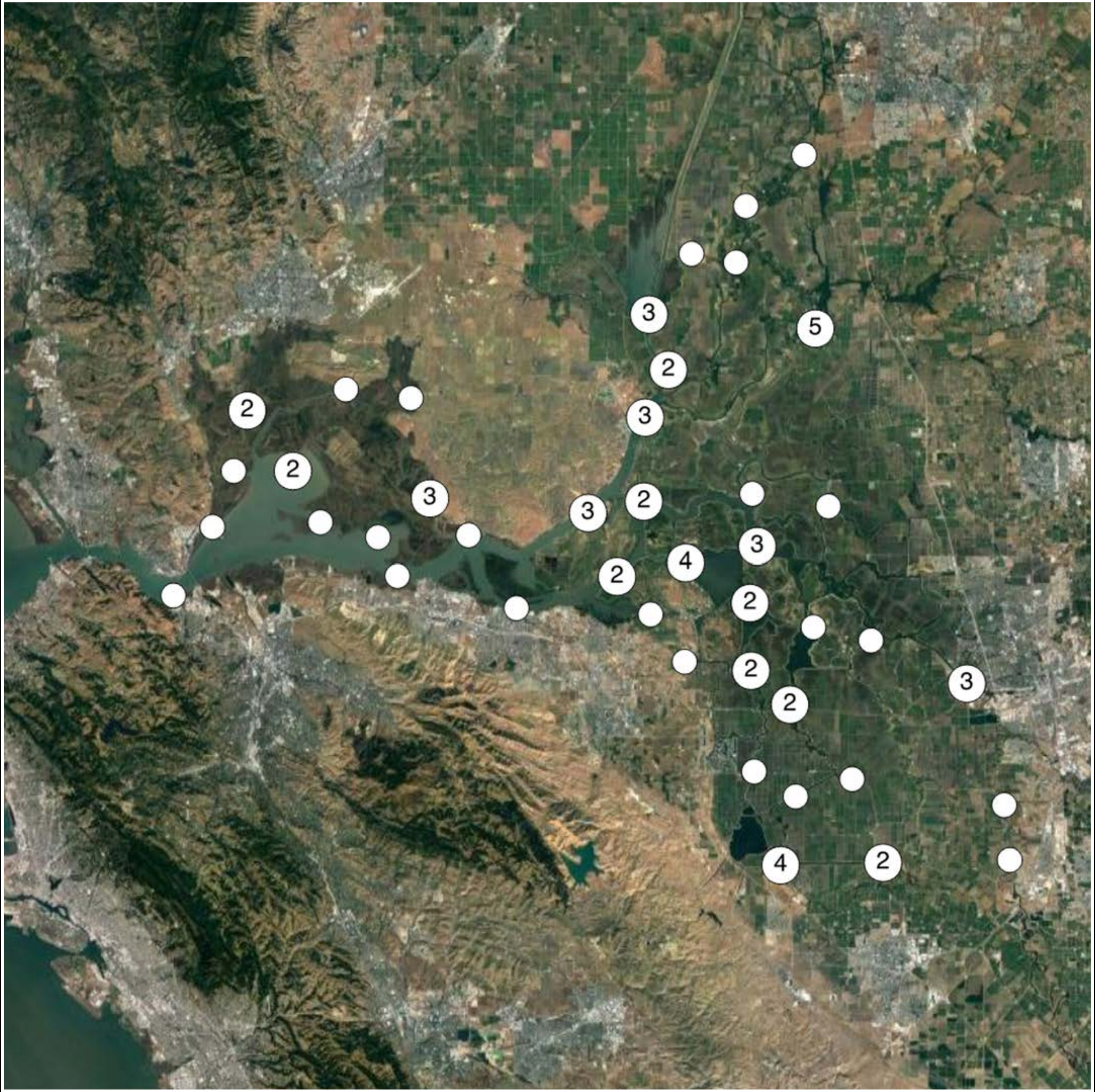
Skin-Surface Radiometers at Tahoe and Salton

Lake Tahoe

Salton Sea

Landsat WST & Tahoe/Salton Validation Sites
(Pearson r = 0.98, Linear R^2 = 0.96, β = -0.03)



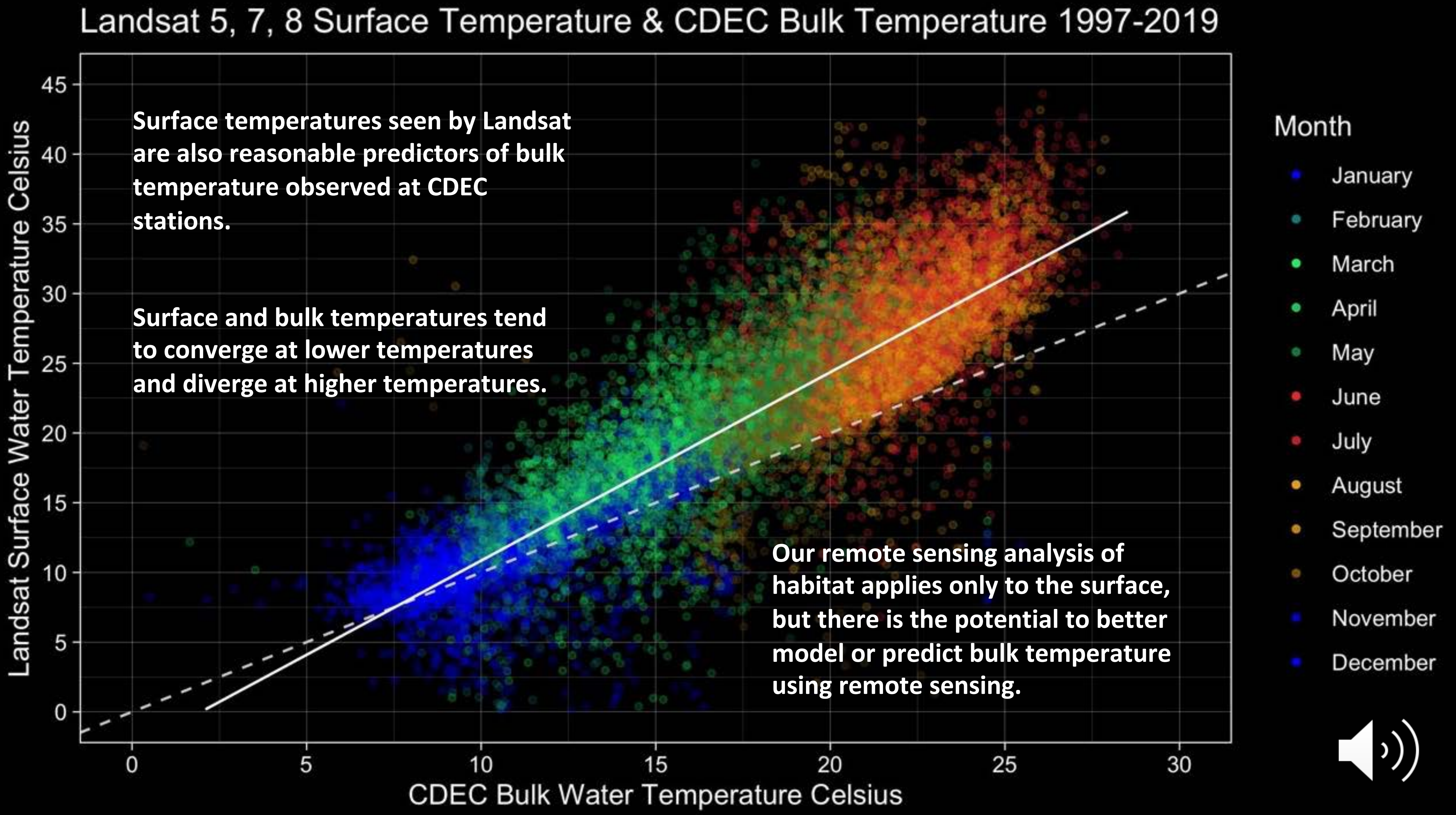


California Data Exchange Center

Ground observations of bulk water temperature are available at 80 sites across the San Francisco Estuary from the California Data Exchange Center (CDEC).

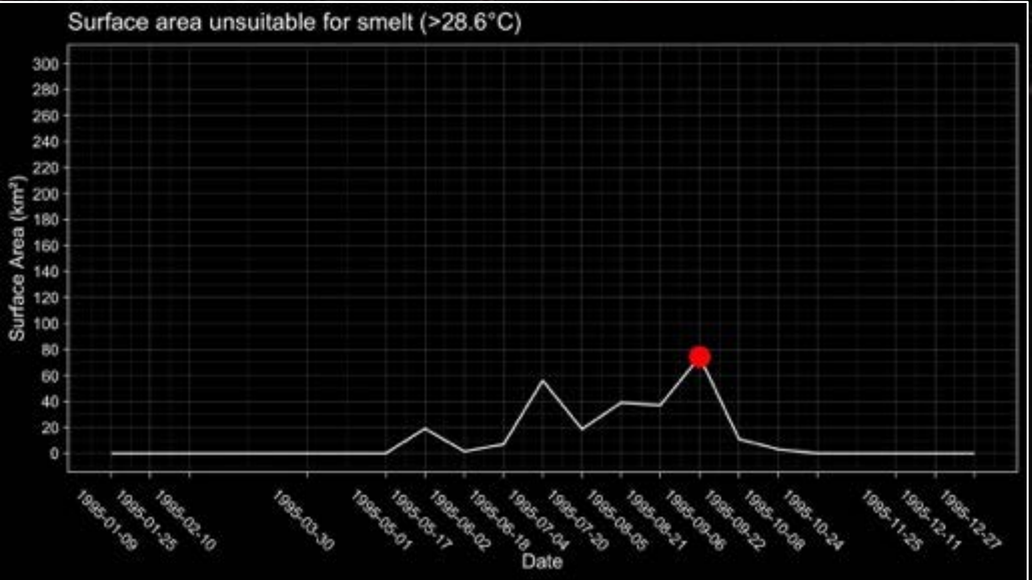
- good indicator of temperature in aquatic environment
- spatially sparse, making it difficult to track habitat

Department of Water Resources
https://info.water.ca.gov/index.html


Landsat 5, 7, 8 Surface Temperature & CDEC Bulk Temperature 1997-2019
Surface temperatures seen by Landsat are also reasonable predictors of bulk temperature observed at CDEC stations.
Surface and bulk temperatures tend to converge at lower temperatures and diverge at higher temperatures.
Our remote sensing analysis of habitat applies only to the surface, but there is the potential to better model or predict bulk temperature using remote sensing.
Landsat Surface Water Temperature Celsius
CDEC Bulk Water Temperature Celsius
0
5
10
15
20
25
30
35
40
45
Month
January
February
March
April
May
June
July
August
September
October
November
December

We quantified unsuitable surface area by counting the number of 30 m by 30 m pixels in each Landsat image with a surface temperature greater than CTmax. We selected the image with the largest surface area to represent each year.

Unsuitable Surface Area

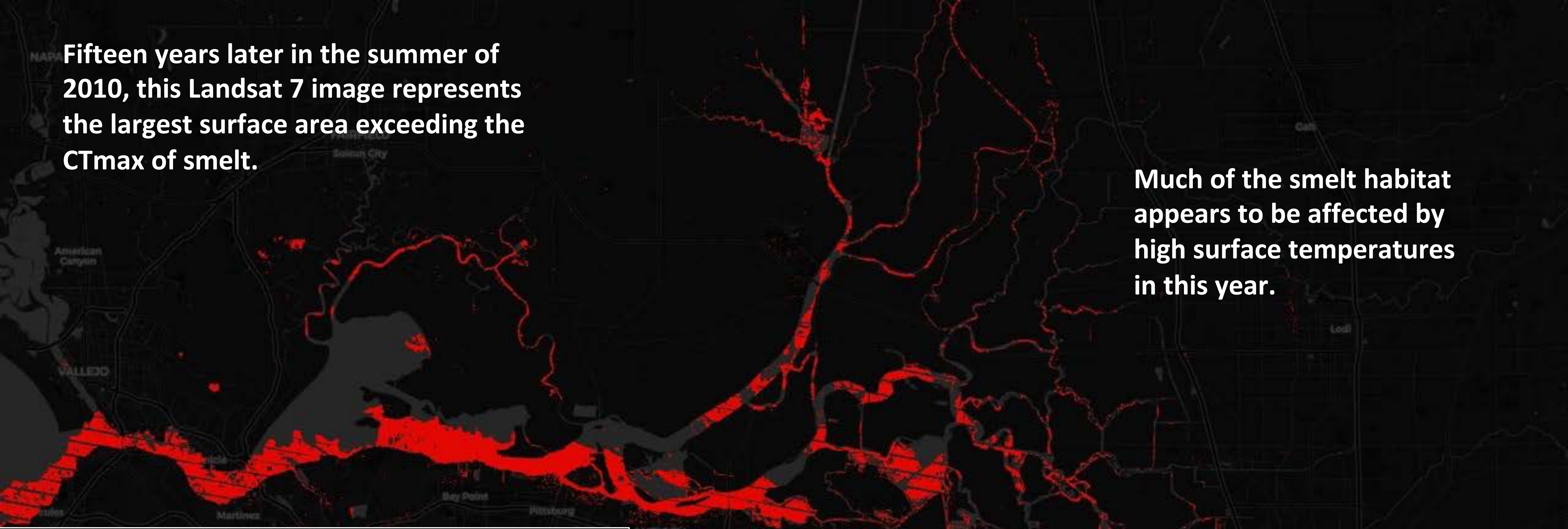


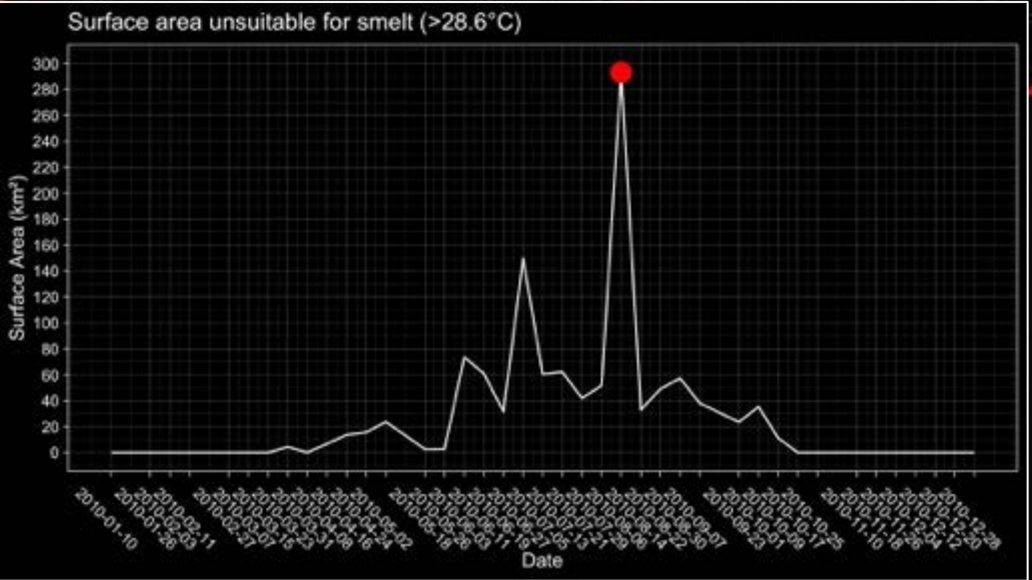
This Landsat 5 image from summer 1995 is the inter-annual low point of annual maximum thermally unsuitable surface area for smelt.

Summer 1995

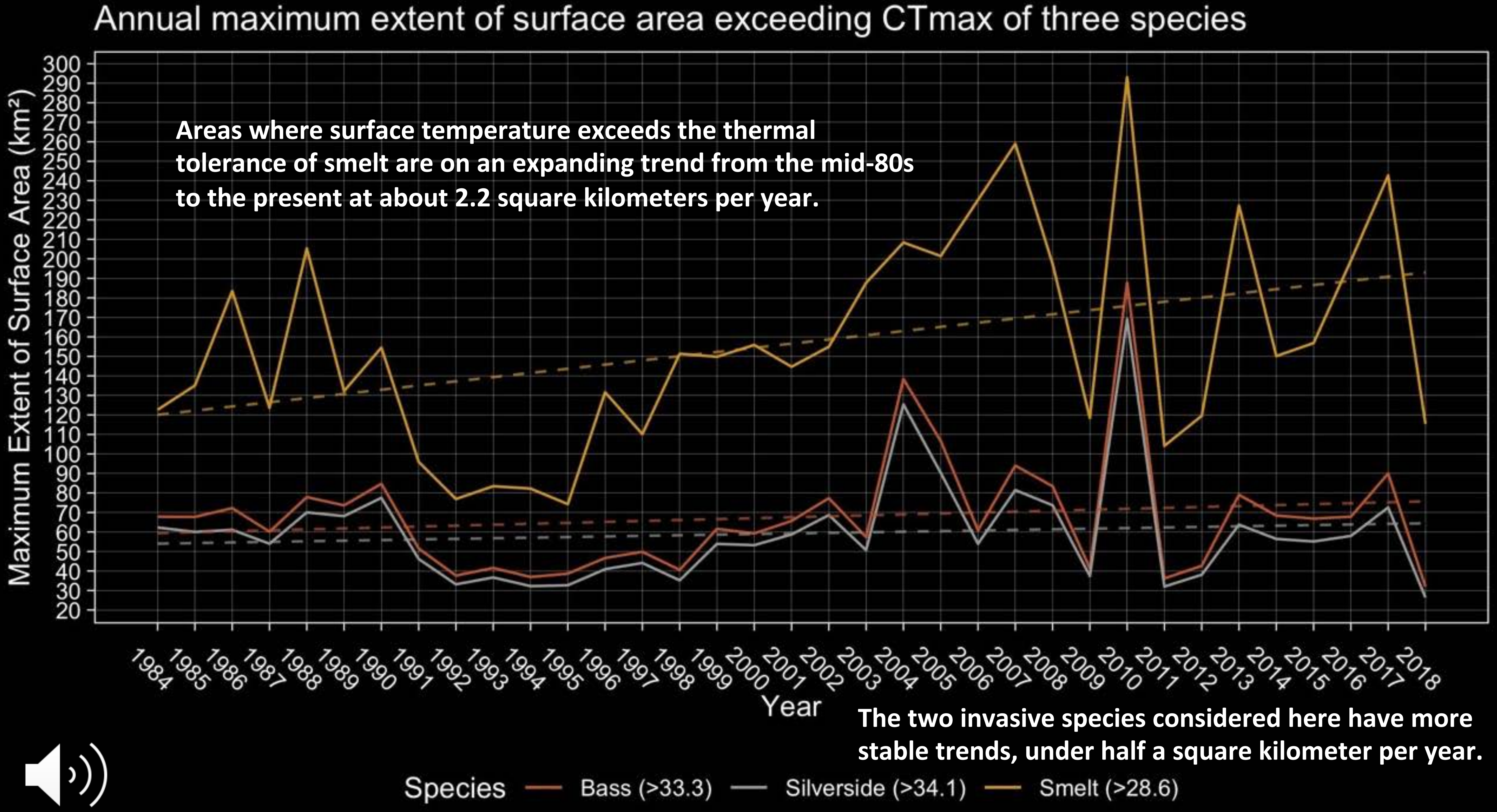
Fifteen years later in the summer of 2010, this Landsat 7 image represents the largest surface area exceeding the CTmax of smelt.

Much of the smelt habitat appears to be affected by high surface temperatures in this year.



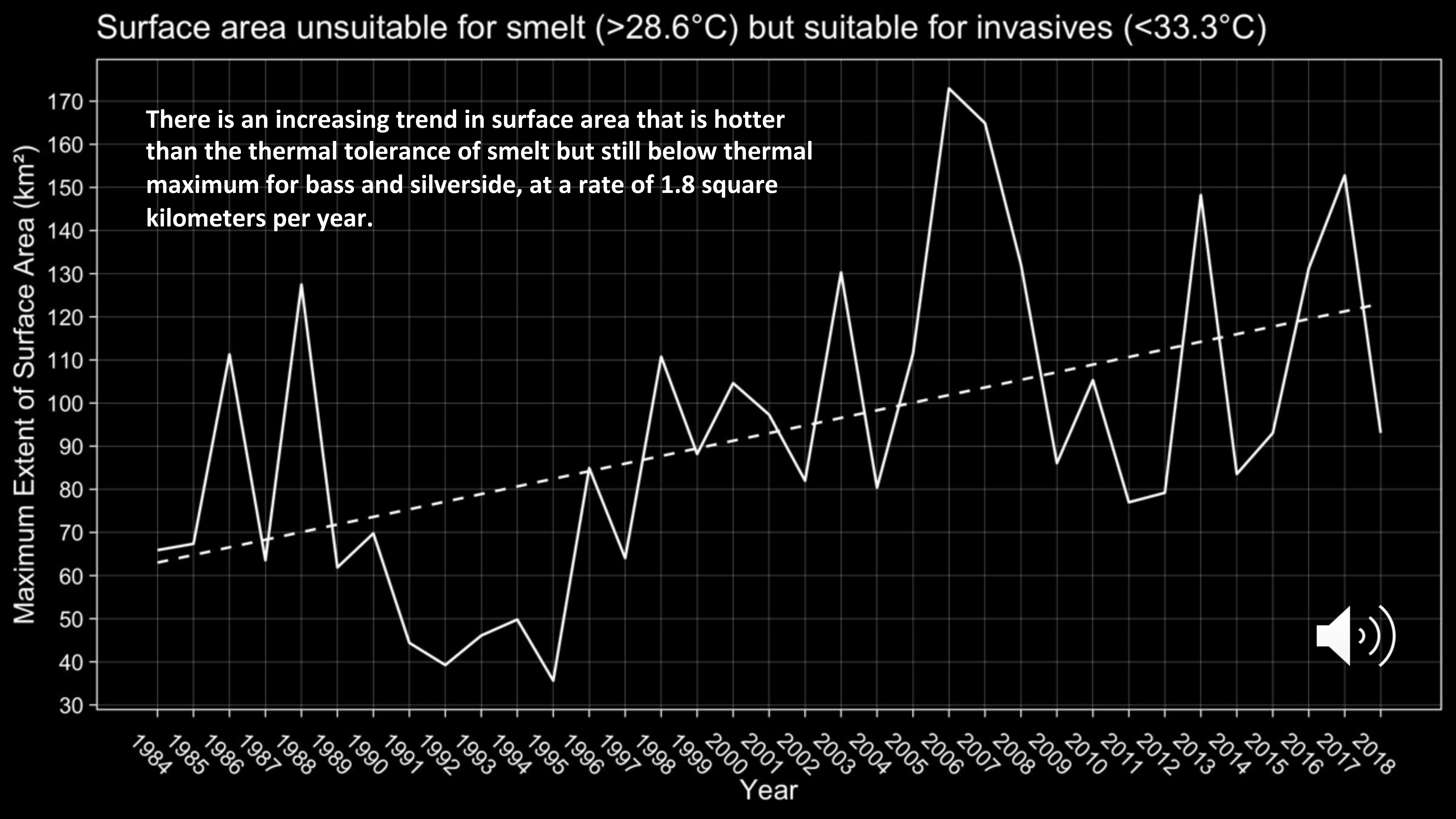


Summer 2010

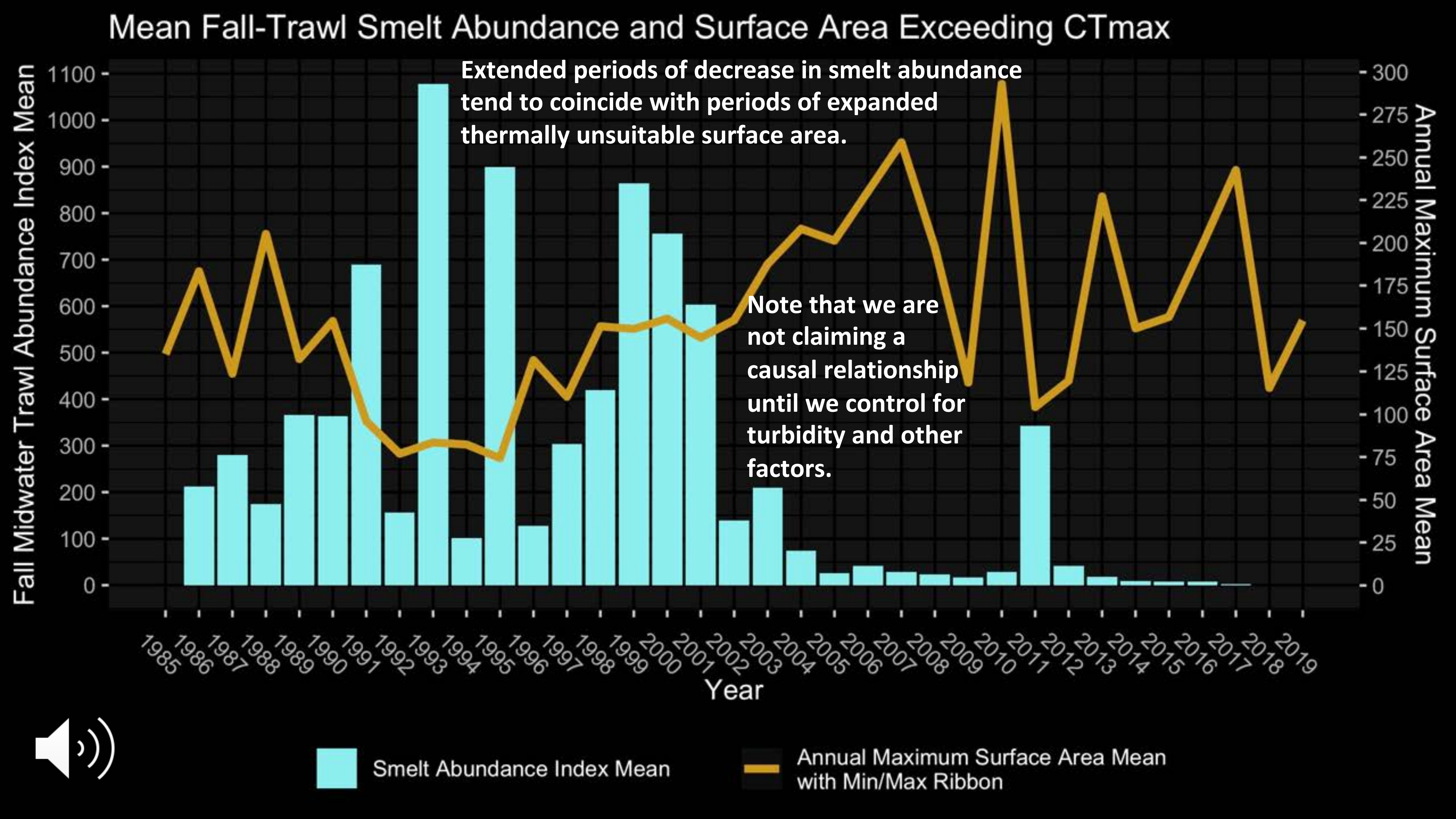


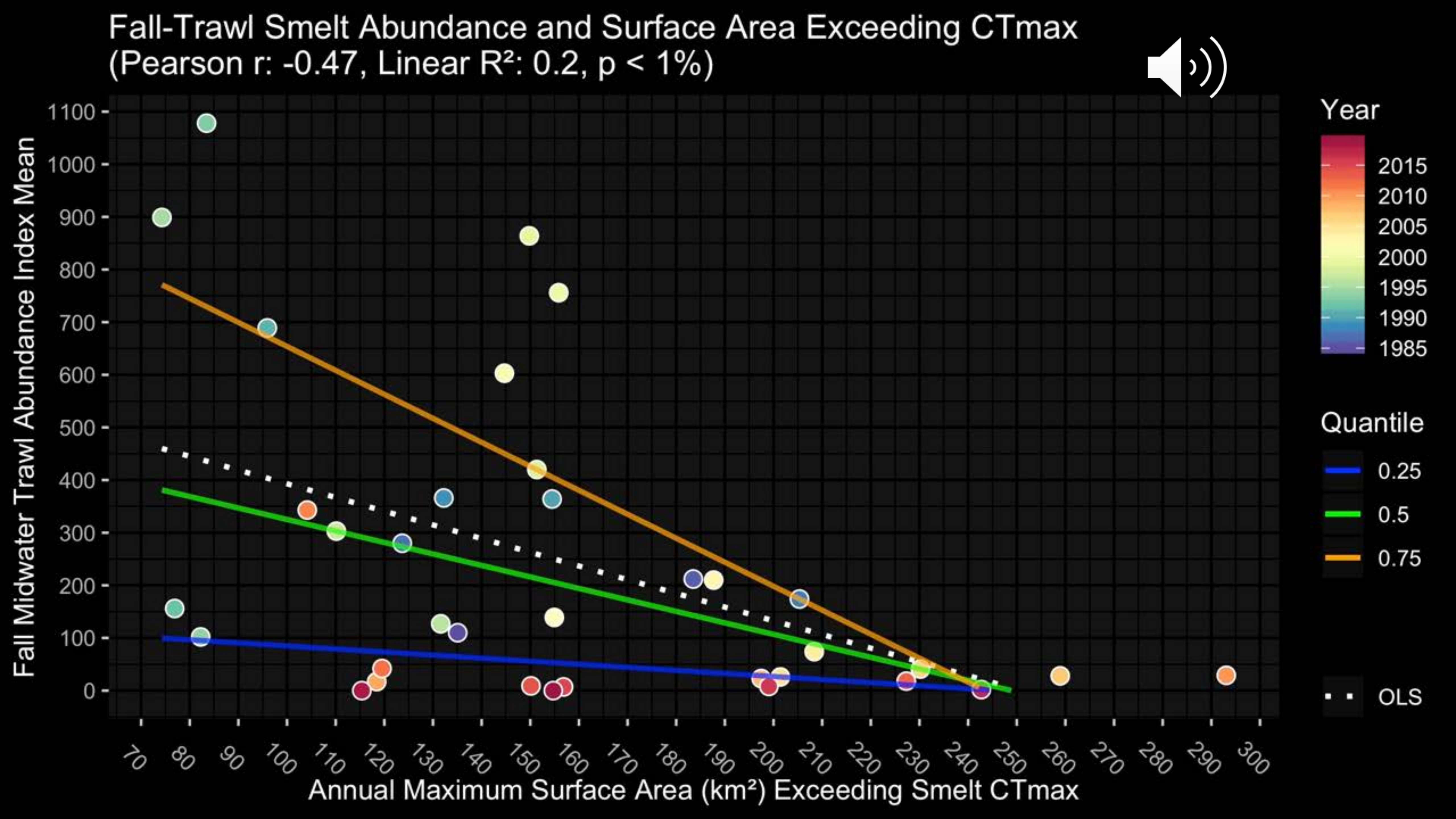
Areas where surface temperature exceeds the thermal tolerance of smelt are on an expanding trend from the mid-80s to the present at about 2.2 square kilometers per year.

The two invasive species considered here have more stable trends, under half a square kilometer per year.

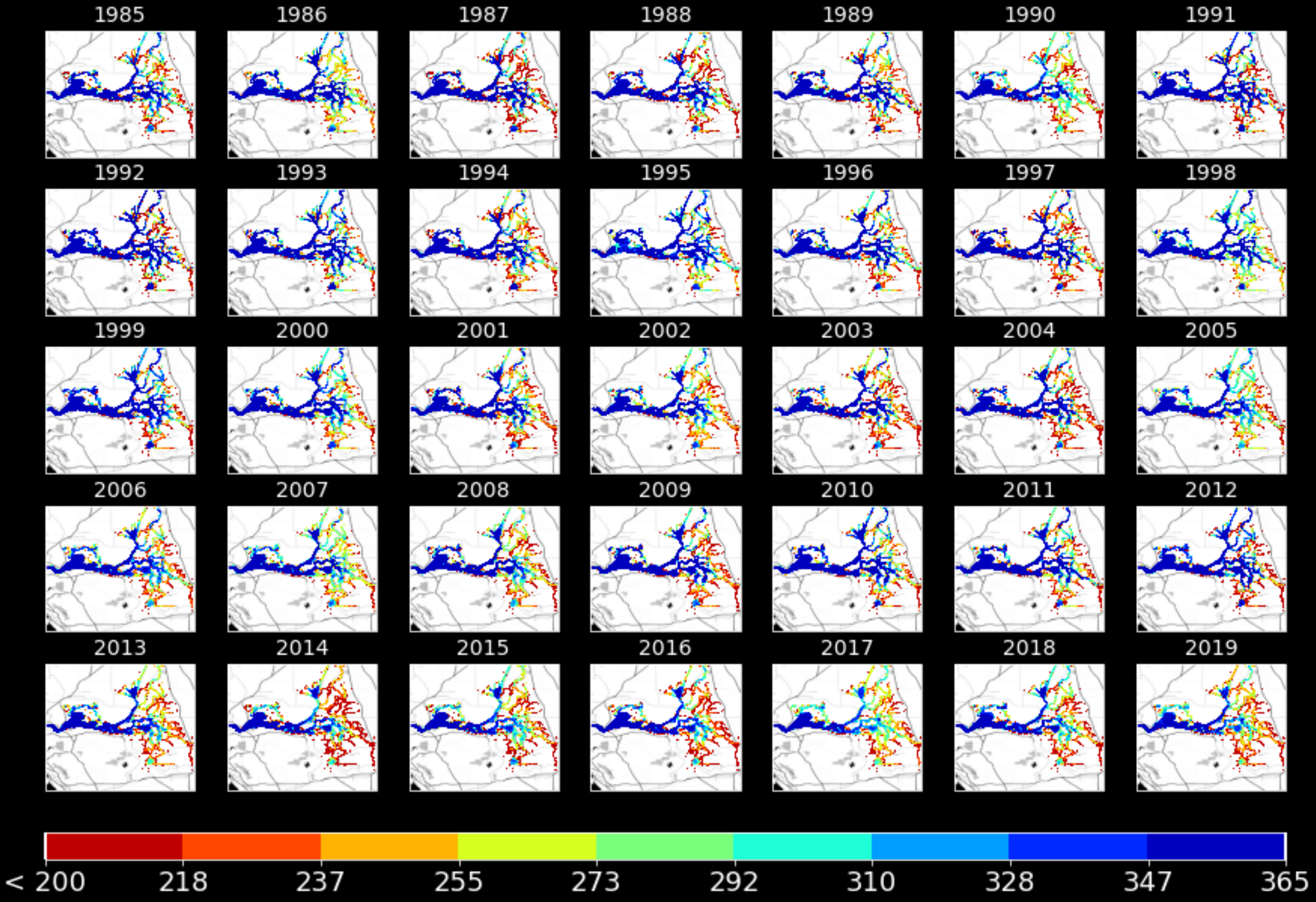


Surface area unsuitable for smelt (>28.6°C) but suitable for invasives (<33.3°C)
There is an increasing trend in surface area that is hotter than the thermal tolerance of smelt but still below thermal maximum for bass and silverside, at a rate of 1.8 square kilometers per year.
Maximum Extent of Surface Area (km²)
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Year


Mean Fall-Trawl Smelt Abundance and Surface Area Exceeding CTmax
Extended periods of decrease in smelt abundance tend to coincide with periods of expanded thermally unsuitable surface area.
Note that we are not claiming a causal relationship until we control for turbidity and other factors.
Fall Midwater Trawl Abundance Index Mean
Annual Maximum Surface Area Mean
Year
Smelt Abundance Index Mean
Annual Maximum Surface Area Mean with Min/Max Ribbon

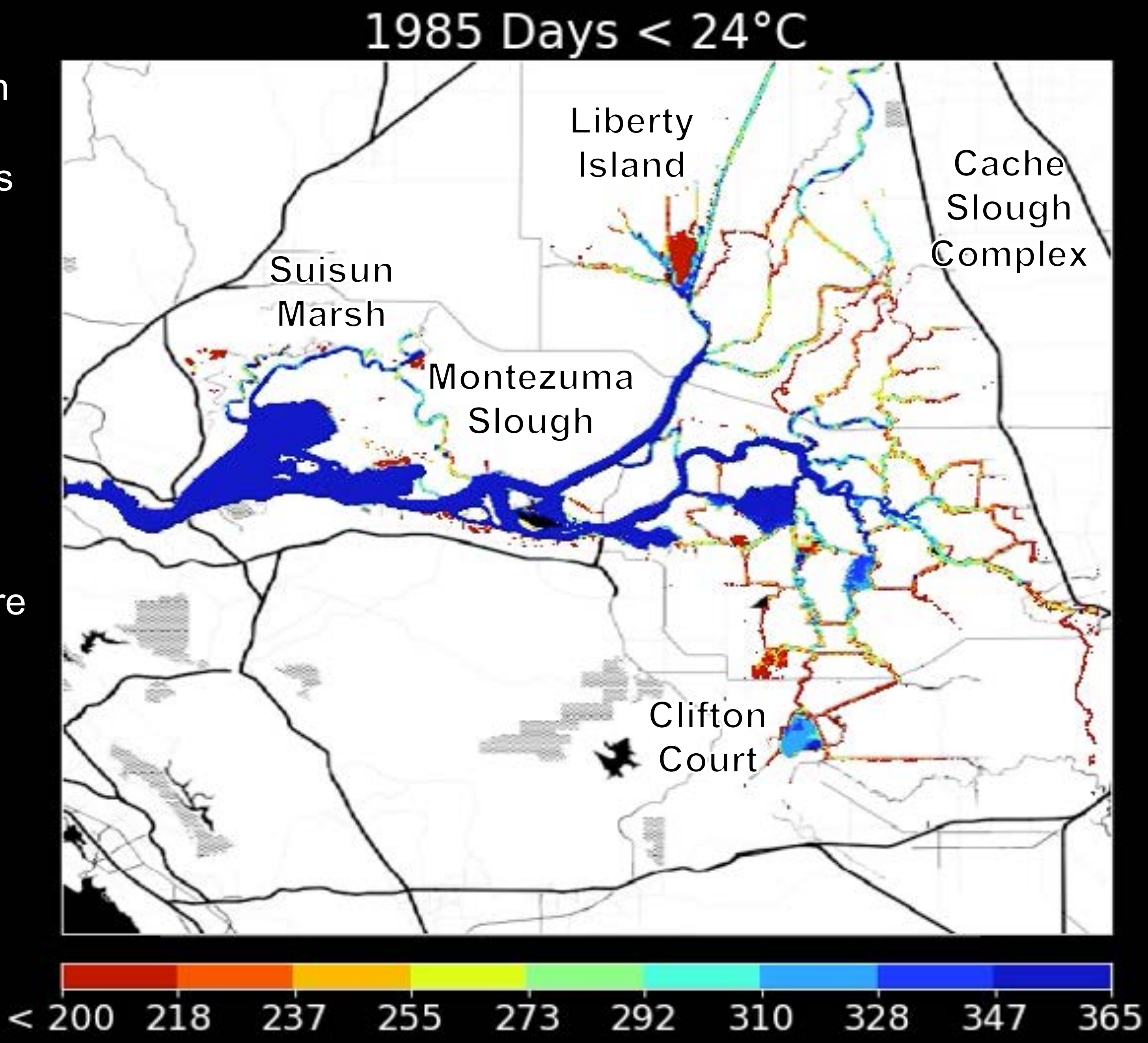

Fall-Trawl Smelt Abundance and Surface Area Exceeding CTmax
(Pearson r: -0.47, Linear R²: 0.2, p < 1%)
Fall Midwater Trawl Abundance Index Mean
1100
1000
900
800
700
600
500
400
300
200
100
0
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
Annual Maximum Surface Area (km²) Exceeding Smelt CTmax
Year
2015
2010
2005
2000
1995
1990
1985
Quantile
0.25
0.5
0.75
OLS

To assess changes in thermally available habitat for Delta Smelt across space, we quantified thermal availability across time in each year of the record. For each habitat pixel in each year, we took the time-series of Landsat ARD temperatures available for the year, including the last two of the previous year and first two of the following year, and linearly interpolated to a sequence of daily rasters. We counted the number of interpolated days at each pixel in each year in which the water surface temperature was less than the stress threshold of 24°C established in Brown et al.



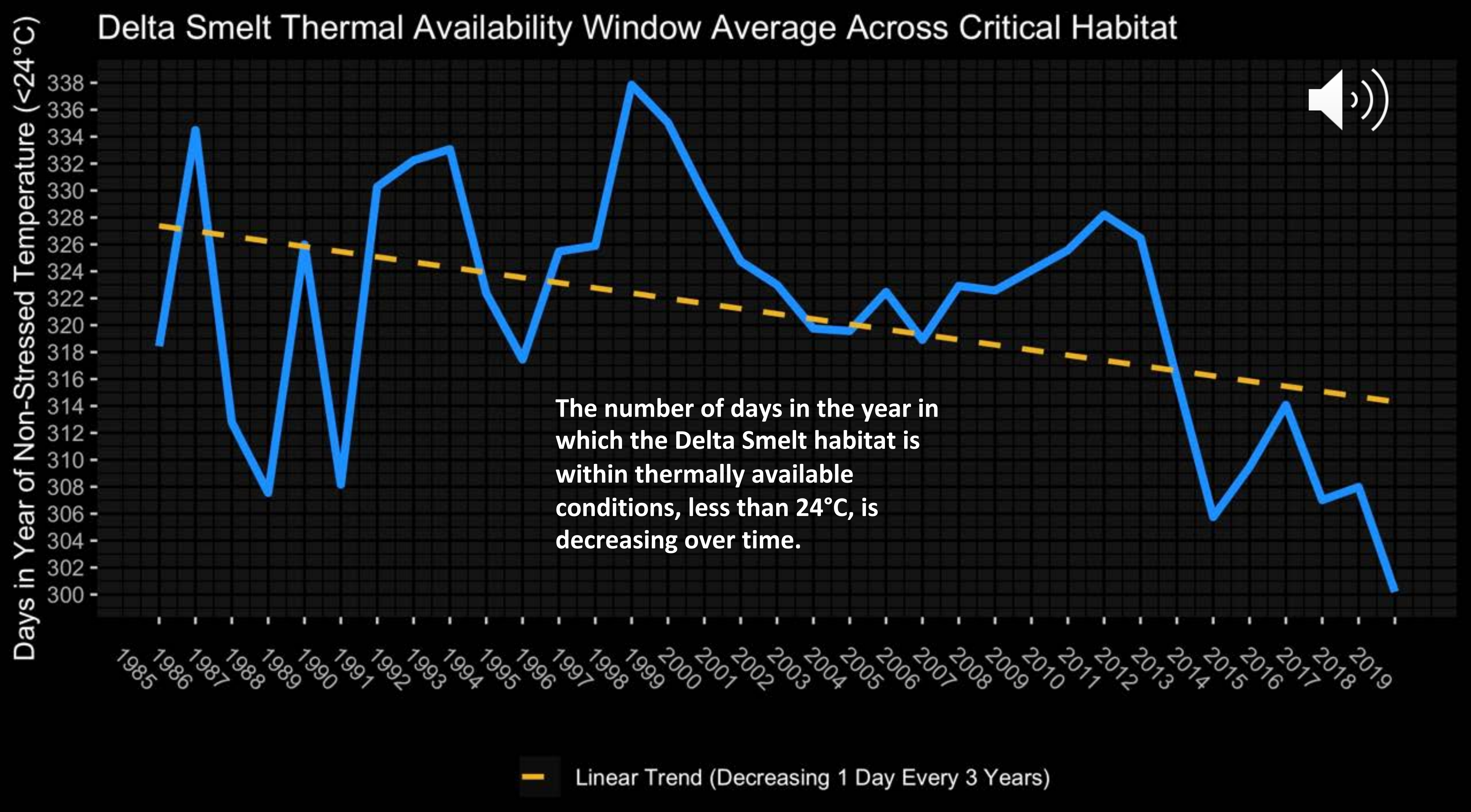
The period of days in the year with water surface temperatures less than the stress threshold of 24°C appears to be declining across the Delta Smelt habitat.

Montezuma Slough and Suisun Marsh are also decreasing in thermally available habitat.

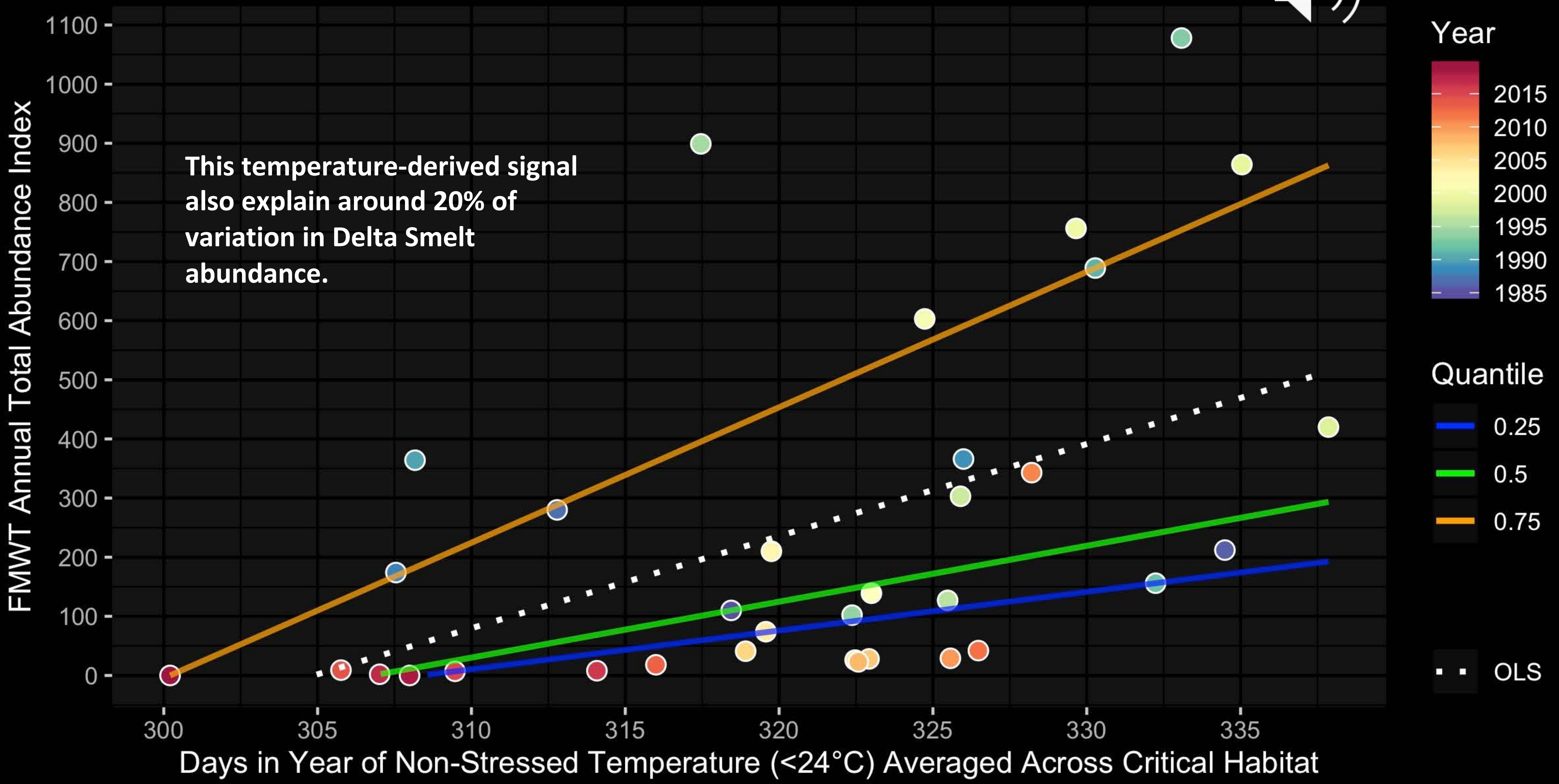


The open waters of Liberty Island appear to be improving, but the Cache Slough Complex surrounding it appears to be in decline.

The South Delta around Clifton Court appears to be declining in available habitat.

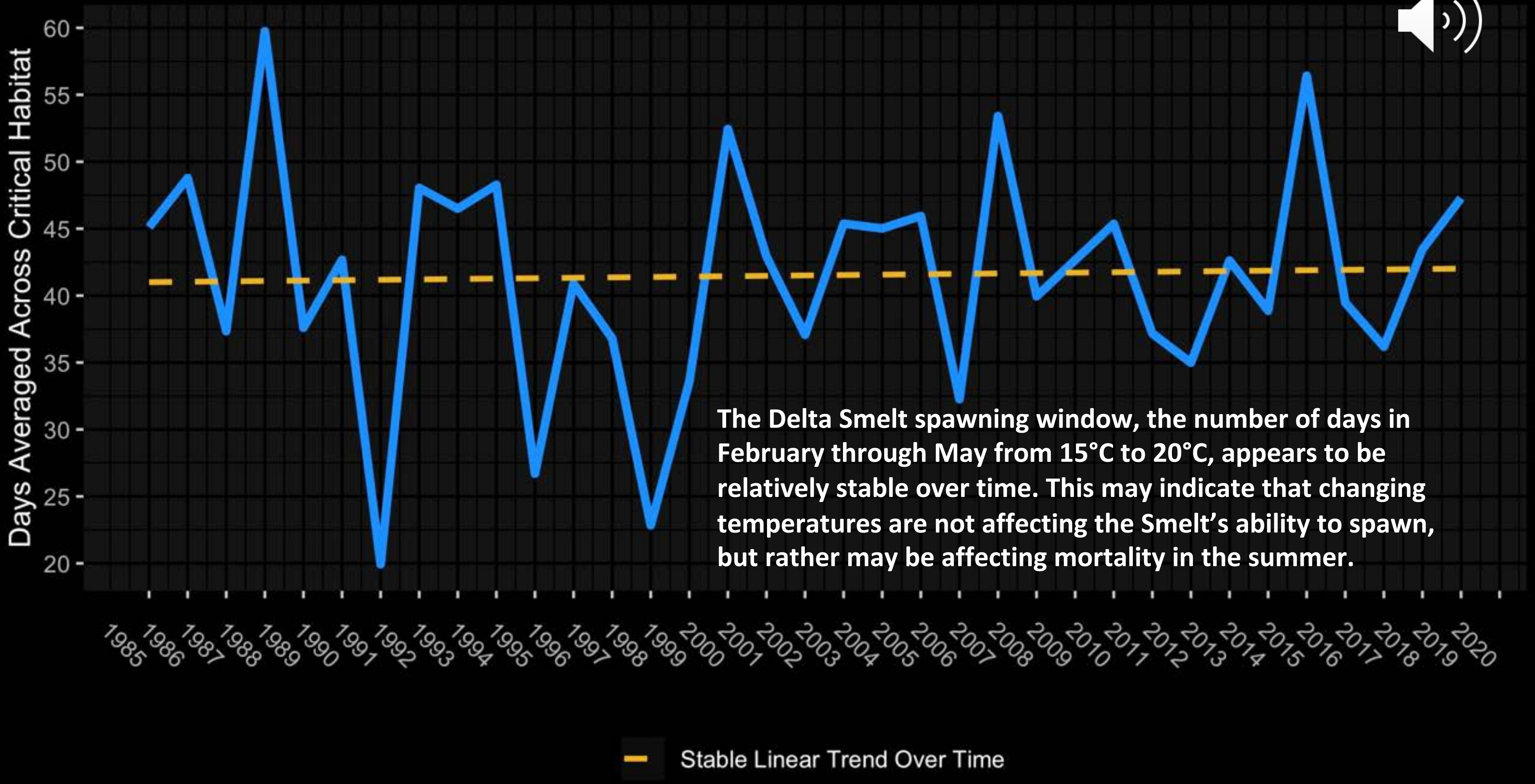

Delta Smelt Thermal Availability Window Average Across Critical Habitat
Days in Year of Non-Stressed Temperature (<24°C)
338
336
334
332
330
328
326
324
322
320
318
316
314
312
310
308
306
304
302
300
1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
The number of days in the year in which the Delta Smelt habitat is within thermally available conditions, less than 24°C, is decreasing over time.
Linear Trend (Decreasing 1 Day Every 3 Years)

Delta Smelt Thermal Availability Window and Abundance
(Pearson r: 0.49, Linear R^2: 0.22, $p < 1\%$)



This temperature-derived signal also explain around 20% of variation in Delta Smelt abundance.

Average Days of February-May Smelt Spawning Window (15°C-20°C)



The Delta Smelt spawning window, the number of days in February through May from 15°C to 20°C, appears to be relatively stable over time. This may indicate that changing temperatures are not affecting the Smelt's ability to spawn, but rather may be affecting mortality in the summer.

Findings

There is an increasing trend in thermally unsuitable habitat and decreasing trend in thermally available habitat for Delta Smelt from 1984 to the present. This is based on the skin-surface temperature, not accounting for refugia that may be under the surface.

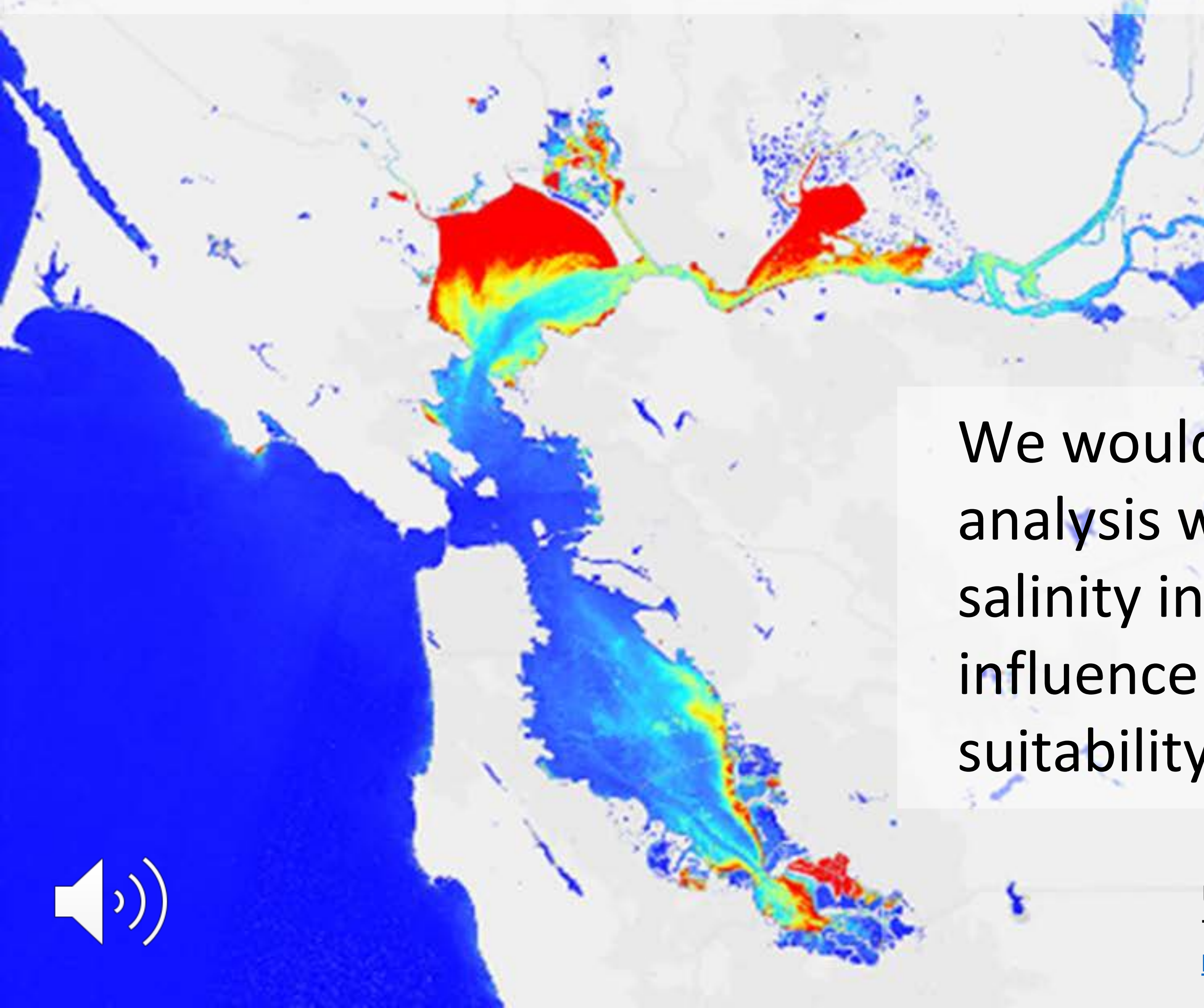
There is an increasing trend in surface area not tolerable to smelt but potentially tolerable to invasive competitors over the same time period.

Periods of increase in extent of water surface thermally unsuitable to delta smelt correspond to low abundance. Temperature may be a factor along with salinity and turbidity.

Changes in surface temperature explain about 20% of the historical variation in Delta Smelt abundance.

The Delta Smelt spawning window does not appear to be affected by changing temperature. Temperature may be affecting the Delta Smelt population through spatial and temporal increases of temperatures that place stress on Delta Smelt mortality.

Future Work with Turbidity



We would like to consider a multi-variate analysis with turbidity and possibly salinity in order to determine the influence of temperature on habitat suitability.

Utilizing NASA and ESA Earth Observations to Monitor Turbidity Conditions in the San Francisco-Bay Delta
https://develop.larc.nasa.gov/2017/summer/SanFranciscoBayDeltaWater.html

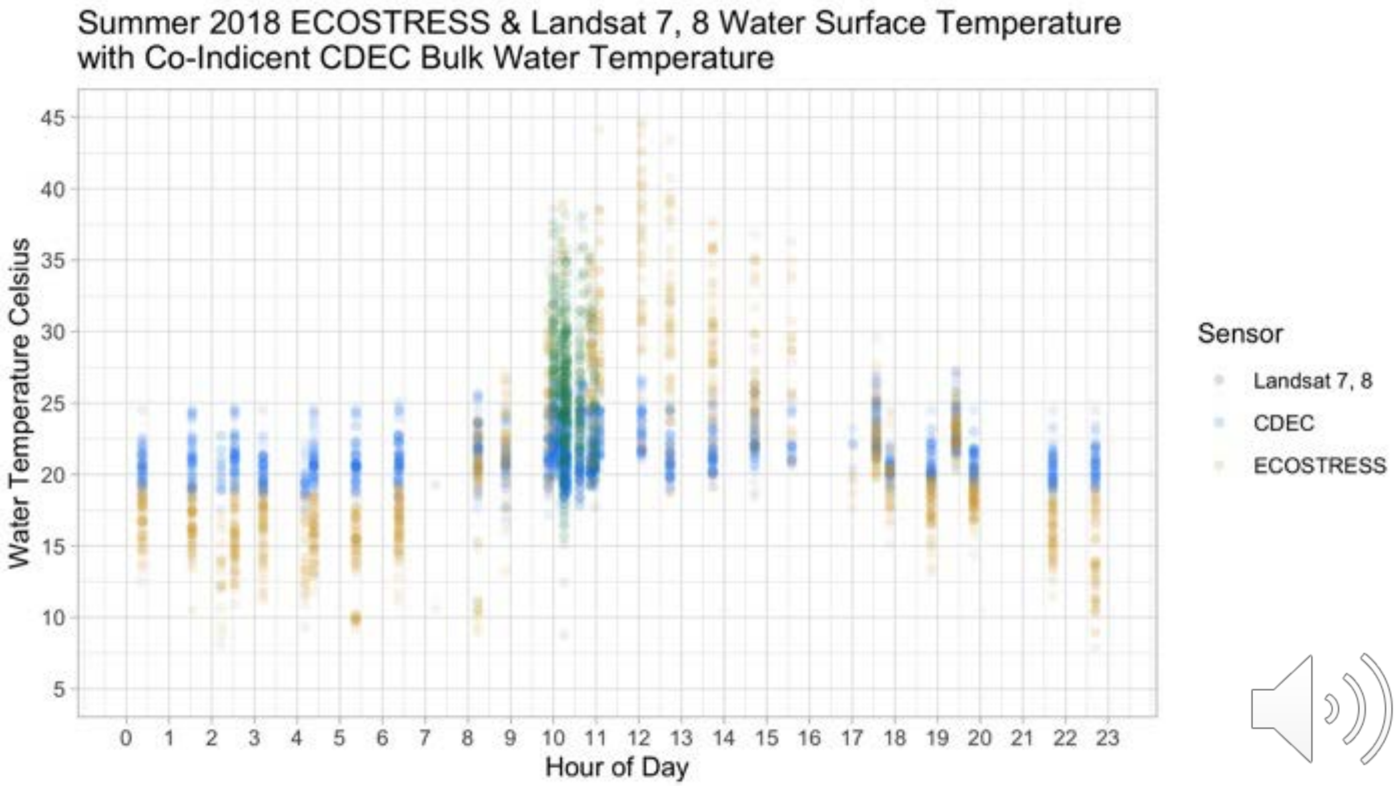
BAY - DELTA - LIVE

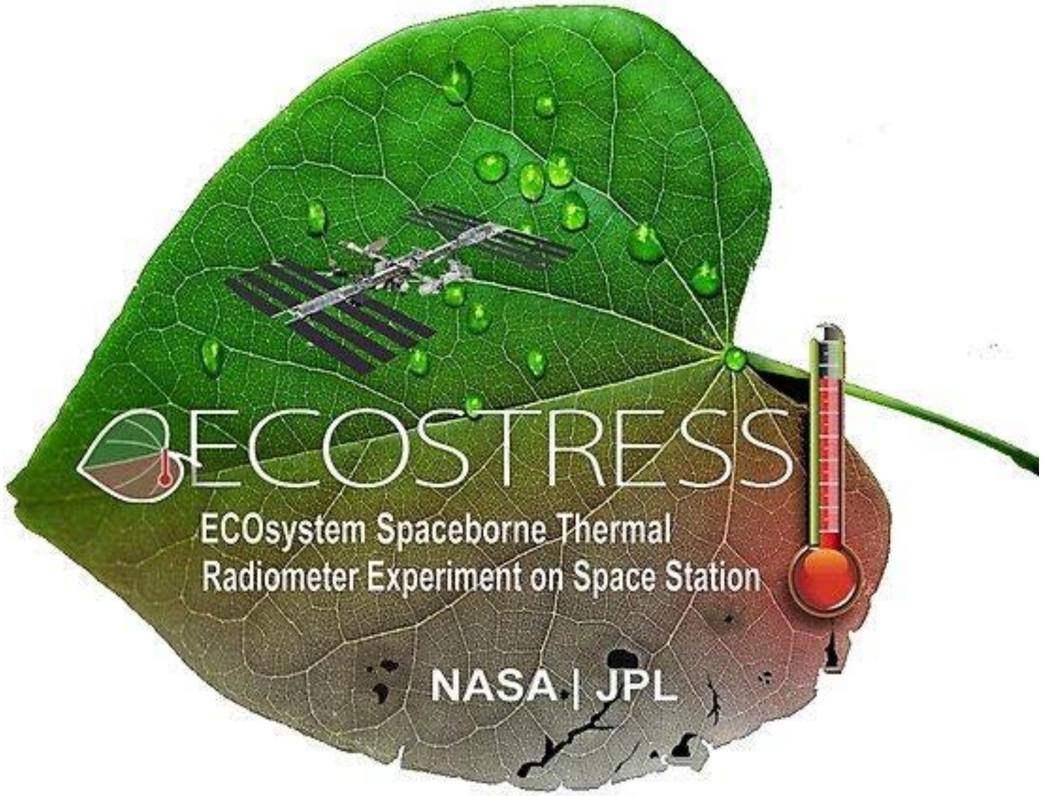
We're working with 34 North and the Bay Delta Live collaboration to make a decision support dashboard using temperature, turbidity, and chlorophyll.

Future Work with ECOSTRESS

- Using ECOSTRESS surface temperature is to observe the skin effect compared to CDEC bulk temperature
- Look into ways to model bulk temperature from remotely sensed surface temperature

70m, 2018-Present





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Algorithm

- Glynn Hulley

Validation

- Kerry Cawse-Nicholson
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Science Discussion

- Erin Hestir
- Shawn Acuña
- Brian Bergamaschi
- Nick Tuffilaro

Applications

- Brenden Palmieri
- Amye Osti

References

Brown, L. R.; Komoroske, L. M.; Wayne Wagner, R.; Morgan-King, T.; May, J. T.;288Connon, R. E.; Fangue, N. A. Coupled downscaled climate models and ecophysiological289metrics forecast habitat compression for an endangered estuarine fish. PLoS ONE, 2016

Brittany E Davis, Dennis E Cocherell, Ted Sommer, Randall D Baxter, Tien-Chieh Hung, Anne E Todgham, and Nann A Fangue. Sensitivities of an endemic, endangered California smelt and two non-native fishes to serial increases in temperature and salinity: implications for shifting community structure with climate change. Conservation Physiology, 2019.

Peter B. Moyle, Bruce Herbold, Donald E. Stevens, and Lee W. Miller. Life history and status of delta smelt in the sacramento-san joaquin estuary, california. Transactions of the American Fisheries Society, 1991.

Nabin K. Malakar, Glynn C. Hulley, Simon J. Hook, Kelly Laraby, Monica Cook, and John R. Schott. An Operational Land Surface Temperature Product for Landsat Thermal Data: Methodology and Validation. IEEE Transactions on Geoscience and Remote Sensing, 2018.

Mac Nally, R.; Thomson, J. R.; Kimmerer, W. J.; Feyrer, F.; Newman, K. B.; Sih, A.;291Bennett, W. A.; Brown, L.; Fleishman, E.; Culberson, S. D.; Castillo, G. Analysis of292pelagic species decline in the upper San Francisco Estuary using multivariate autore-293gressive modeling (MAR).Ecological Applications2010

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