Climate-Aquatics Blog #57:
Identifying & protecting climate refuge lakes for coldwater fishes

Hi Everyone,
The climate is changing and fish populations are changing in response (blogs 32, 34, 35, 42). Managing and conserving efficiently this century means having a good sense of where it's all headed and committing limited conservation resources accordingly. Committing to the wrong places risks being run over by the climate change train or squandering resources on populations that would have been fine regardless of what the climate does (blog #52). The sweet spot lies between the two extremes and figuring out where our investments will tip the balance toward more desirable outcomes later this century. So as alluded in the previous blog (#56), this time we're highlighting a set of related studies that constitute the current global gold standard in terms of developing the science, information, and management policies for making those commitments for one species in one landscape.

The work comes from a somewhat unexpected source—coldwater lakes in Minnesota and the research that Peter Jacobson and his many competent colleagues have done the past decade or two. Having grown up near Minnesota, the only climate related thing we ever thought of about that state was that it was freaking cold. I don't know how many weather reports I remember as a kid wherein International Falls, Minnesota was reported as having the nation's coldest temperatures that day. One of the other things one thinks about Minnesota is that it's the land of 100,000 lakes, as proudly proclaimed on the state's license places. Those lakes were sculpted out of the plains by the last great continental ice-sheet thousands of years ago. The combination of the two—a cold climate and lots of lakes—provides the raw ingredients for supporting numerous coldwater lake fish communities. One member of those communities, the cisco, is particularly important component in terms of providing a forage base for popular recreational fisheries, but Minnesota is at the very southern extent of the species range and the coldwater conditions it needs to persist (graphic 1). Because of this fish's importance, Minnesota DNR has long monitored its abundance—going on 60+ years—which began to reveal a declining trend starting in the 1970's when a warming trend started across the state (graphic 2; study hyperlinked here: http://www.schweizerbart.de/papers/adv_limnology/detail/63/77923/%23).

That's a worrisome correlation no doubt, but the next question was what was causing it? Without a clear understanding of the mechanism, a remediative prescription would be impossible. So Jacobson and colleagues then did research to describe the oxythermal niche for cisco in lakes across the state (graphic 3; study attached). Fish need oxygen to breath and it turns out they need quite a bit more when the temperatures are warmer. If oxygen availability and temperatures combine in such a way that a critical threshold is exceeded, fish simply die from broken hearts as described earlier (blog 46). From there, it's not much of a leap to realize that as climate change causes air and lake temperatures to warm, the coldwater habitats ciscos depend are shrinking; and during extreme heat waves, may disappear entirely to cause fish kills in some lakes.

With a biological mechanism nailed down, it was time for physics and the physical science guys to do their part and build good lake climate models to predict which of Minnesota's many lakes would/would not exceed that oxythermal threshold in the future. The lakes that were least likely to exceed that threshold then might serve as climate refugia for ciscos this century (graphic 4).

It's a big deal to have gotten that far, but Jacobson and colleagues were only getting warmed up. Paralleling the previous work, they were also studying the linkages between watershed land use, nutrient yield into lakes, and the effects those had on primary productivity and biological oxygen demand associated with various air temperature regimes. Understanding those relationships was key, as it provided a logical rationale for attempting to manage watershed activities in some areas. Moreover, with accurate lake climate models, those management activities could be directed precisely at lakes and watersheds where committing conservation resources was most likely to yield the greatest benefits (graphic 5, study hyperlinked here: http://www.sciencedirect.com/science/article/pii/S0304380012000907#). To complete this climate change adaptation grand slam, all that knowledge and means of prioritizing have been linked to various funding initiatives so that the means actually exist to do things on the ground to secure the future of ciscos in Minnesota (graphic 6; study hyperlinked here: http://www.schweizerbart.de/papers/adv_limnology/detail/64/81391).

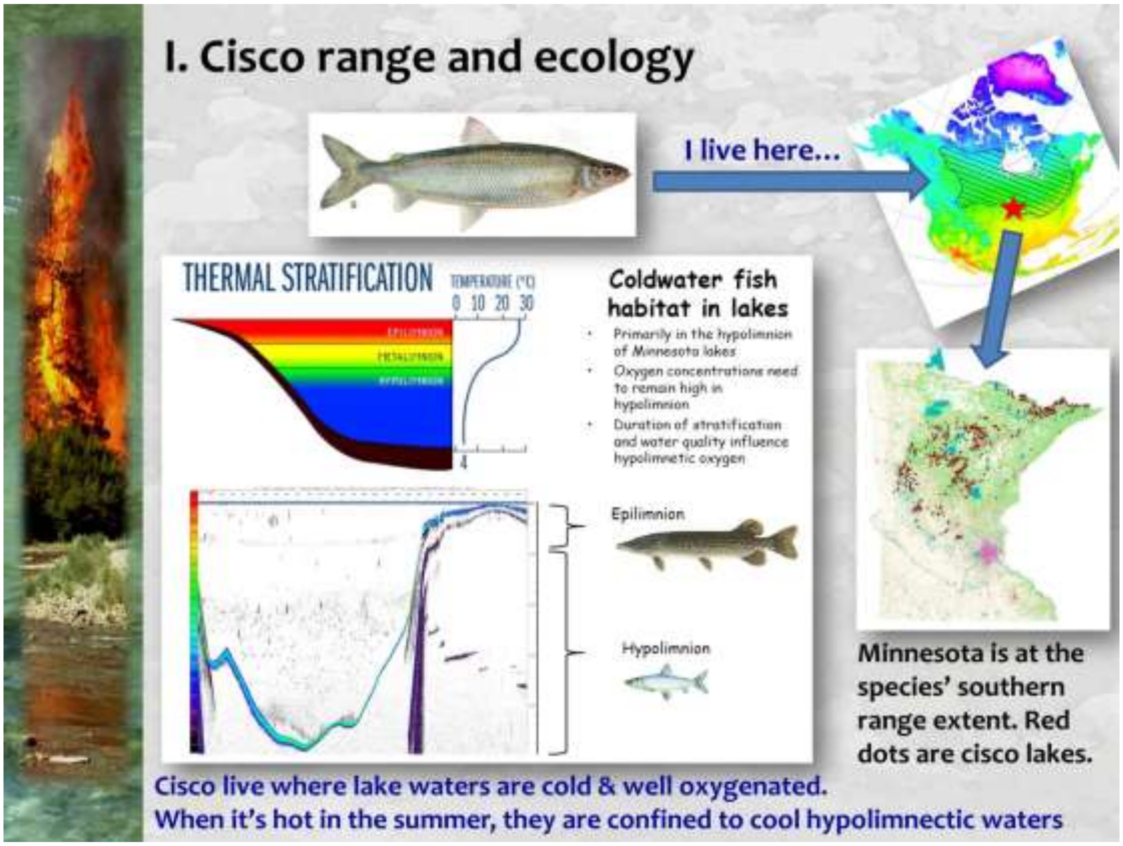
For that comprehensive body of work, I'd say Pete is truly a Climate-Aquatics Master. He and his colleagues have figured it all out and done something really special that can serve as inspiration to us all. We just have to replicate the process elsewhere and ferret out the details for the critters we care about in our local landscapes. It will take years, if not decades, of work but big things are possible by committed people.

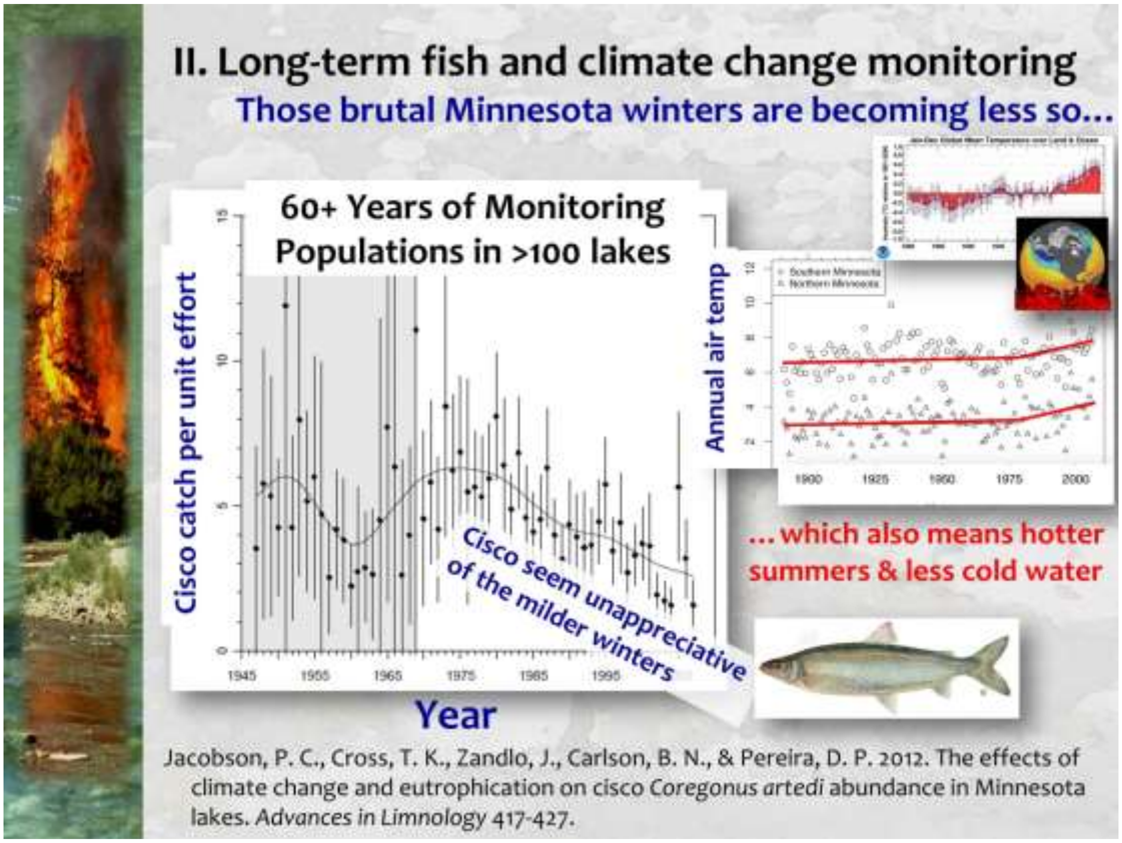
Before closing, then, I also wanted to acknowledge the significant body of work that one of Pete's key collaborators, Heinz Stefan, has done over the last 20 years to understand climate change effects on lake environments (graphics 7 – 9). The extensive research he's led, or mentored students through, means he's yet another Climate-Aquatics Master from the state of Minnesota. There must be something in the water from the land of those 100,000 lakes…now if only the state were as good at producing Super Bowl winning football teams…Go Vikes.

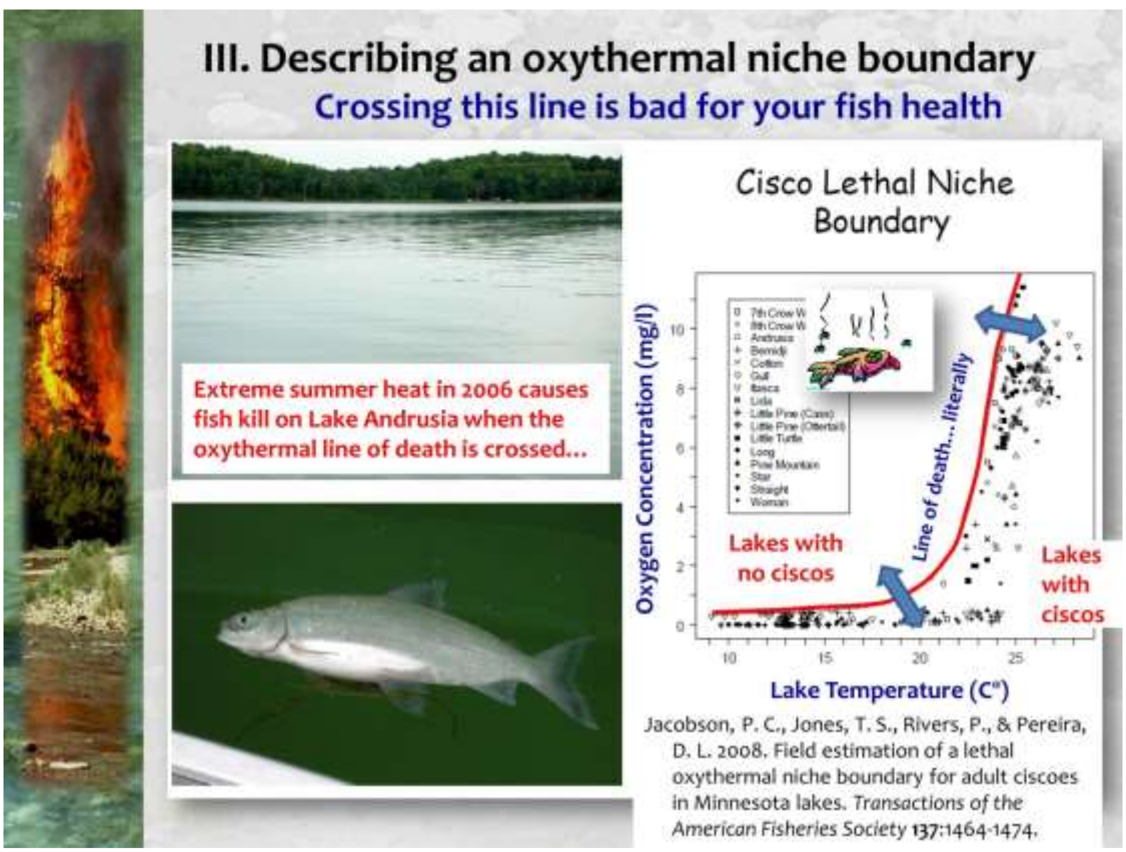
Until next time, best regards.
Dan

p.s., another good recent lake-climate effects study is one by Alofs and colleagues that documents fish distribution shifts in Ontario lakes (study attached).

Now Tweeting at [Dan Isaak@DanIsaak]

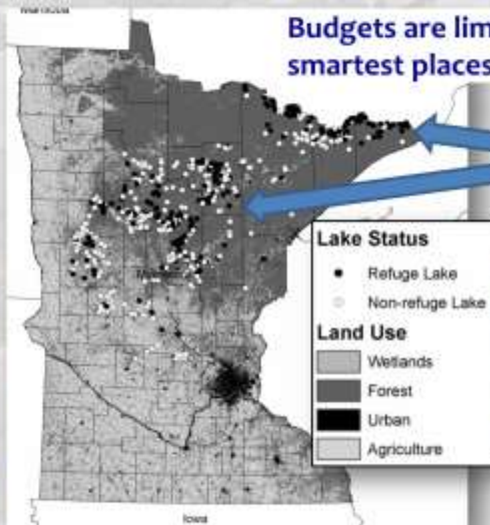



II. Long-term fish and climate change monitoring
Those brutal Minnesota winters are becoming less so…
60+ Years of Monitoring
Populations in >100 lakes
Cisco catch per unit effort
Year
Cisco seem unappreciative of the milder winters
Annual air temp
Southern Minnesota
Northern Minnesota
… which also means hotter summers & less cold water
Jacobson, P. C., Cross, T. K., Zandlo, J., Carlson, B. N., & Pereira, D. P. 2012. The effects of climate change and eutrophication on cisco Coregonus artedi abundance in Minnesota lakes. Advances in Limnology 417-427.


III. Describing an oxythermal niche boundary
Crossing this line is bad for your fish health
Extreme summer heat in 2006 causes fish kill on Lake Andrusia when the oxythermal line of death is crossed…
Cisco Lethal Niche Boundary
Oxygen Concentration (mg/l)
Line of death… literally
Lakes with no ciscos
Lakes with ciscos
Lake Temperature (C°)
Jacobson, P. C., Jones, T. S., Rivers, P., & Pereira, D. L. 2008. Field estimation of a lethal oxythermal niche boundary for adult ciscoes in Minnesota lakes. Transactions of the American Fisheries Society 137:1464-1474.

IV. Identifying & mapping climate refuge lakes for cisco this century

Budgets are limited, we must choose the smartest places to invest…



Accurate Lake Climate Models Identify 176 Lakes Most Likely to Serve as Refugia

Good investment

Poor investment

Fang, X., Jiang, L., Jacobson, P. C., Stefan, H. G., Alam, S. R., & Pereira, D. L. 2012. Identifying cisco refuge lakes in Minnesota under future climate scenarios. *Transactions of the American Fisheries Society* **141**:1608-1621.

Jiang, L., Fang, X., Stefan, H. G., Jacobson, P. C., & Pereira, D. L. 2012. Oxythermal habitat parameters and identifying cisco refuge lakes in Minnesota under future climate scenarios using variable benchmark periods. *Ecological Modelling* **232**:14-27.

V. Watershed linkages to oxythermal lake habitat

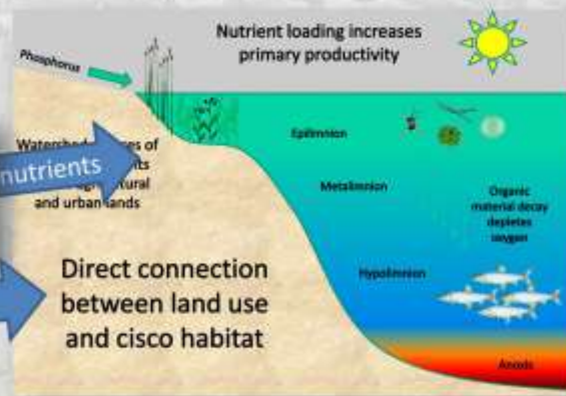
Land use affects lake nutrient loading, primary productivity, and oxygen availability

agriculture

subdivisions

nutrients

nutrients



Direct connection between land use and cisco habitat

Good habitat

Some lakes have better natural conditions for cisco and/or are more/less sensitive to land use

Poor habitat

Jacobson, P. C., Stefan, H. G., & Pereira, D. L. 2010. Coldwater fish oxythermal habitat in Minnesota lakes: influence of total phosphorus, July air temperature, and relative depth. *Canadian Journal of Fisheries and Aquatic Sciences* **67**:2002-2013.

VI. Protecting cisco climate refuge lakes through funding and watershed management

Land protected by public ownership or conservation easement (2008 GAP Ownership)

Once it's known where to invest & protect... the last step is just doing it!

Clean Water Legacy
Forest Stewardship Project-Tullibee Lake Watersheds

Private Forest Conservation Easements

Minnesota Forests for the Future

Pete Jacobson—a climate-aquatics master

Jacobson, P. C., Fang, X., Stefan, H. G., & Pereira, D. L. 2013. Protecting cisco oxythermal habitat from climate change: building resilience in deep lakes using a landscape approach. *Advances in Limnology* 323-332.

Another Minnesota Climate-Aquatics Master

Heinz Stefan & His Many Works...

Erickson, T. R., & Stefan, H. G. (2000). Linear air/water temperature correlations for streams during open water periods. Journal of Hydrologic Engineering, 5(3), 317-321.

Fang, X., & Stefan, H. G. (1996). Long-term lake water temperature and ice cover simulations/measurements. Cold Regions Science and Technology, 24(3), 289-304.

Fang, X., Stefan, H. G., Eaton, J. G., McCormick, J. H., & Alam, S. R. (2004). Simulation of thermal/dissolved oxygen habitat for fishes in lakes under different climate scenarios: Part 1. Cool-water fish in the contiguous US. Ecological Modelling, 172(1), 13-37.

Fang, X., Stefan, H. G., Eaton, J. G., McCormick, J. H., & Alam, S. R. (2004). Simulation of thermal/dissolved oxygen habitat for fishes in lakes under different climate scenarios: Part 2. Cold-water fish in the contiguous US. Ecological Modelling, 172(1), 39-54.

Fang, X., & Stefan, H. G. (2000). Projected climate change effects on winterkill in shallow lakes in the northern United States. Environmental Management, 25(3), 291-304.

Fang, X., & Stefan, H. G. (2012). Impacts of Climatic Changes on Water Quality and Fish Habitat in Aquatic Systems. In Handbook of Climate Change Mitigation (pp. 531-569). Springer US.

Fang, X., Stefan, H. G., & Alam, S. R. (1999). Simulation and validation of fish thermal DO habitat in north-central US lakes under different climate scenarios. Ecological Modelling, 118(2), 167-191.

Fang, X., & Stefan, H. G. (1998). Potential climate warming effects on ice covers of small lakes in the contiguous US. Cold Regions Science and Technology, 27(2), 119-140.

Fang, X., & Stefan, H. G. (2009). Simulations of climate effects on water temperature, dissolved oxygen, and ice and snow covers in lakes of the contiguous United States under past and future climate scenarios. Limnology and Oceanography, 54, 2359-2370.

Fang, X., & Stefan, H. G. (1999). Projections of climate change effects on water temperature characteristics of small lakes in the contiguous US. Climatic Change, 42(2), 377-412.

Fang, X., & Stefan, H. G. (1997). Simulated climate change effects on dissolved oxygen characteristics in ice-covered lakes. Ecological Modelling, 103(2), 209-229.

Gao, S., & Stefan, H. G. (1999). Multiple linear regression for lake ice and lake temperature characteristics. Journal of cold regions engineering, 13(2), 59-77.

Gao, S., & Stefan, H. G. (2004). Potential climate change effects on ice covers of five freshwater lakes. Journal of Hydrologic Engineering, 9(3), 226-234.

Another Minnesota Climate-Aquatics Master
Heinz Stefan... continued

Gu, R., & Stefan, H. G. (1990). Year-round temperature simulation of cold climate lakes. Cold Regions Science and Technology, 18(2), 147-160.

Hondzo, M., & Stefan, H. G. (1993). Regional water temperature characteristics of lakes subjected to climate change. Climatic Change, 24(3), 187-211.

Hondzo, M., & Stefan, H. G. (1996). Dependence of water quality and fish habitat on lake morphometry and meteorology. Journal of Water Resources Planning and Management, 122(5), 364-373.

Hondzo, M., & Stefan, H. G. (1991). Three case studies of lake temperature and stratification response to warmer climate. Water Resources Research, 27(8), 1837-1846.

Johnson, S. L., & Stefan, H. G. (2006). Indicators of climate warming in Minnesota: Lake ice covers and snowmelt runoff. Climatic Change, 75(4), 421-453.

Mohseni, O., & Stefan, H. G. (1999). Stream temperature/air temperature relationship: a physical interpretation. Journal of Hydrology, 218(3), 128-141.

Mohseni, O., Erickson, T. R., & Stefan, H. G. (2002). Upper bounds for stream temperatures in the contiguous United States. Journal of Environmental Engineering, 128(1), 4-11.

Mohseni, O., Stefan, H. G., & Erickson, T. R. (1998). A nonlinear regression model for weekly stream temperatures. Water Resources Research, 34(10), 2685-2692.

Mohseni, O., Erickson, T. R., & Stefan, H. G. (1999). Sensitivity of stream temperatures in the United States to air temperatures projected under a global warming scenario. Water Resources Research, 35(12), 3723-3733.

Mohseni, O., Stefan, H. G., & Eaton, J. G. (2003). Global warming and potential changes in fish habitat in US streams. Climatic change, 59(3), 389-409.

Novotny, E. V., & Stefan, H. G. (2007). Stream flow in Minnesota: Indicator of climate change. Journal of Hydrology, 334(3), 319-333.

Pilgrim, J. M., Fang, X., & Stefan, H. G. (1998). Stream temperature correlations with air temperatures in Minnesota: Implications for climate warming. Journal of the American Water Resources Association, 34(5), 1109-1121.

Sinokrot, B. A., & Stefan, H. G. (1993). Stream temperature dynamics: measurements and modeling. Water Resources Research, 29(7), 2299-2312.

Sinokrot, B. A., Stefan, H. G., McCormick, J. H., & Eaton, J. G. (1995). Modeling of climate change effects on stream temperatures and fish habitats below dams and near groundwater inputs. Climatic Change, 30(2), 181-200.

Another Minnesota Climate-Aquatics Master
Heinz Stefan... continued again

Stefan, H. G., & Fang, X. (1997). Simulated climate change effects on ice and snow covers on lakes in a temperate region. Cold Regions Science and Technology, 25(2), 137-152.

Stefan, H. G., Hondzo, M., & Fang, X. (1993). Lake water quality modeling for projected future climate scenarios. Journal of Environmental Quality, 22(3), 417-431.

Stefan, H. G., Hondzo, M., Fang, X., Eaton, J. G., & McCormick, J. H. (1996). Simulated long-term temperature and dissolved oxygen characteristics of lakes in the north-central United States and associated fish habitat limits. Limnology and Oceanography, 41, 1124-1135.

Stefan, H. G., Hondzo, M., Eaton, J. G., & McCormick, J. H. (1995). Predicted effects of global climate change on fishes in Minnesota lakes. Canadian Special Publication of Fisheries and Aquatic Sciences, 57-72.

Stefan, H. G., Fang, X., & Hondzo, M. (1998). Simulated climate change effects on year-round water temperatures in temperate zone lakes. Climatic Change, 40(3-4), 547-576.

Stefan, H. G., & Sinokrot, B. A. (1993). Projected global climate change impact on water temperatures in five north central US streams. Climatic Change, 24(4), 353-381.

Stefan, H. G., Fang, X., & Eaton, J. G. (2001). Simulated fish habitat changes in North American lakes in response to projected climate warming. Transactions of the American Fisheries Society, 130(3), 459-477.

Stefan, H. G., & Preud'Homme, E. B. (1993). Stream Temperature Estimation From Air Temperature. Journal of the American Water Resources Association, 29, 27-45.

Taylor, C. A., & Stefan, H. G. (2009). Shallow groundwater temperature response to climate change and urbanization. Journal of hydrology, 375(3), 601-612.

Williams, S. G., & Stefan, H. G. (2006). Modeling of lake ice characteristics in North America using climate, geography, and lake bathymetry. Journal of Cold Regions Engineering, 20(4), 140-167.

Williams, G., Layman, K. L., & Stefan, H. G. (2004). Dependence of lake ice covers on climatic, geographic and bathymetric variables. Cold Regions Science and Technology, 40(3), 145-164.

Skol

Welcome to the Climate-Aquatics Blog. For those new to the blog, previous posts with embedded graphics can be seen by clicking on the hyperlinks at the bottom or by navigating to the blog archive webpage here: (http://www.fs.fed.us/rm/boise/AWAE/projects/stream_temp/stream_temperature_climate_aquatics_blog.html). The intent of the Climate-Aquatics Blog is to provide a means for the 8,014 (& growing) field biologists, hydrologists, anglers, students, managers, and researchers currently on this mailing list across North America, South America, Europe, and Asia to more broadly and rapidly discuss topical issues associated with aquatic ecosystems and climate change. Messages periodically posted to the blog highlight new peer-reviewed research and science tools that may be useful in addressing this global phenomenon. Admittedly, many of the ideas for postings have their roots in studies my colleagues & I have been conducting in the Rocky Mountain region, but attempts will be made to present topics & tools in ways that highlight their broader, global relevance. I acknowledge that the studies, tools, and techniques highlighted in these missives are by no means the only, or perhaps even the best, science products in existence on particular topics, so the hope is that this discussion group engages others doing, or interested in, similar work and that healthy debates & information exchanges occur to facilitate the rapid dissemination of knowledge among those concerned about climate change and its effects on aquatic ecosystems.

If you know others interested in climate change and aquatic ecosystems, please forward this message to them. If you do not want to be contacted again in the future, please reply to that effect and you will be de-blogged.

Previous Blogs…

Climate-Aquatics Overviews
Blog #1: Climate-aquatics workshop science presentations available online
Blog #2: A new climate-aquatics synthesis report

Climate-Aquatics Thermal Module
Blog #3: Underwater epoxy technique for full-year stream temperature monitoring
Blog #4: A GoogleMap tool for interagency coordination of regional stream temperature monitoring
Blog #5: Massive air & stream sensor networks for ecologically relevant climate downscaling
Blog #6: Thoughts on monitoring air temperatures in complex, forested terrain
Blog #7: Downscaling of climate change effects on river network temperatures using inter-agency temperature databases with new spatial statistical stream network models
Blog #8: Thoughts on monitoring designs for temperature sensor networks across river and stream basins
Blog #9: Assessing climate sensitivity of aquatic habitats by direct measurement of stream & air temperatures
Blog #10: Long-term monitoring shows climate change effects on river & stream temperatures
Blog #11: Long-term monitoring shows climate change effects on lake temperatures
Blog #12: Climate trends & climate cycles & weather weirdness
Blog #13: Tools for visualizing local historical climate trends
Blog #14: Leveraging short-term stream temperature records to describe long-term trends

Blog #15: Wildfire & riparian vegetation change as the wildcards in climate warming of streams
Blog #23: New studies describe historic & future rates of warming in Northwest US streams
Blog #24: NoRRTN: An inexpensive regional river temperature monitoring network
Blog #25: NorWeST: A massive regional stream temperature database
Blog #26: Mapping thermal heterogeneity & climate in riverine environments
Blog #40: Crowd-sourcing a BIG DATA regional stream temperature model

Climate-Aquatics Hydrology Module
Blog #16: Shrinking snowpacks across the western US associated with climate change
Blog #17: Advances in stream flow runoff and changing flood risks across the western US
Blog #18: Climate change & observed trends toward lower summer flows in the northwest US
Blog #19: Groundwater mediation of stream flow responses to climate change
Blog #20: GIS tools for mapping flow responses of western U.S. streams to climate change
Blog #21: More discharge data to address more hydroclimate questions
Blog #22: Climate change effects on sediment delivery to stream channels

Climate-Aquatics Cool Stuff Module
Blog #27: Part 1, Spatial statistical models for stream networks: context & conceptual foundations
Blog #28: Part 2, Spatial statistical models for stream networks: applications and inference
Blog #29: Part 3, Spatial statistical models for stream networks: freeware tools for model implementation

Climate-Aquatics Biology Module
Blog #30: Recording and mapping Earth's stream biodiversity from genetic samples of critters
Blog #31: Global trends in species shifts caused by climate change
Blog #32: Empirical evidence of fish phenology shifts related to climate change
Blog #33: Part 1, Fish distribution shifts from climate change: Predicted patterns
Blog #34: Part 2, Fish distribution shifts from climate change: Empirical evidence for range contractions
Blog #35: Part 3, Fish distribution shifts from climate change: Empirical evidence for range expansions
Blog #36: The "velocity" of climate change in rivers & streams
Blog #37: Part 1, Monitoring to detect climate effects on fish distributions: Sampling design and length of time
Blog #38: Part 2, Monitoring to detect climate effects on fish distributions: Resurveys of historical stream transects
Blog #39: Part 3, Monitoring to detect climate effects on fish distributions: BIG DATA regional resurveys
Blog #41: Part 1, Mechanisms of change in fish populations: Patterns in common trend monitoring data
Blog #42: BREAKING ALERT! New study confirms broad-scale fish distribution shifts associated with climate change
Blog #43: Part 2, Mechanisms of change in fish populations: Floods and streambed scour during incubation & emergence

Blog #44: Part 3, Mechanisms of change in fish populations: Lower summer flows & drought effects on growth & survival
Blog #45: Part 4, Mechanisms of change in fish populations: Temperature effects on growth & survival
Blog #46: Part 5, Mechanisms of change in fish populations: Exceedance of thermal thresholds
Blog #47: Part 6, Mechanisms of change in fish populations: Interacting effects of flow and temperature
Blog #48: Part 7, Mechanisms of change in fish populations: Changing food resources
Blog #49: Part 8, Mechanisms of change in fish populations: Non-native species invasions
Blog #50: Part 9, Mechanisms of change in fish populations: Evolutionary responses
Blog #51: Part 10, Mechanisms of change in fish populations: Extinction
Blog #52: Review & Key Knowable Unknowns
Blog #53: DNA Barcoding & Fish Biodiversity Mapping
Blog #56: New studies provide additional evidence for climate-induced fish distribution shifts

Climate-Aquatics Management Module
Blog #54: Part 1, Managing with climate change: Goal setting & decision support tools for climate-smart prioritization
Blog #55: Part 2, Managing with climate change: Streams in channels & fish in streams

Future topics…
Climate-Aquatics End Game