

Use of BasinTemp to Model Summer Stream Temperatures in the South Fork of Ten Mile River, CA

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Abstract

We used *BasinTemp* to predict summer stream temperatures in South Fork Ten Mile River (SFTMR), Mendocino County. *BasinTemp* is a temperature model that attempts to quantify the basin-wide effects of high summer stream temperatures in basins where the data inputs are scarce. It assumes that direct solar radiation is the chief mechanism behind stream summer heating in mid latitudes. We applied it in the SFTMR basin to understand the dynamics of summer stream temperatures, the influence of timber management and the effects of climate change on water temperatures, and its implications for coho salmon habitat. Three vegetation scenarios (current vegetation conditions, reference vegetation conditions and topography only conditions) and their effects on the Maximum Weekly Average Temperatures (MWATs) throughout the basin were analyzed for 3 different years. We predicted a significant increase in water temperature related to the decrease in shade as vegetation conditions shift from reference to current and to topographic conditions under timber management. We also found that current vegetation conditions account for significant amounts of shade that reduce solar radiation and stream temperatures and that discharge has a growing effect in water temperatures as the basin approaches topographic conditions.

Key words: BasinTemp, riparian shade, stream temperature, model, watershed management

Introduction

The effect of high water temperatures on fish populations is well documented and substantial (Berman 1998). Potential effects of water temperatures may become more pronounced if summer temperatures continue rising as climate change models predict (Kiparsky and Gleick 2003). There is considerable interest in understanding and quantifying the interactions between summer stream heating dynamics, aquatic habitat quality and quantity, and the influence of land management activities on water temperature and its effects on fish populations. Theory supported by considerable empirical research indicates that in mid-latitude regions, direct solar radiation is the most important mechanism driving summer stream heating (Bartholow 2000, Beschta et al. 1987, Brown 1969, Ice 2001), comprising more than 80 percent of the heat budget (Monteith and Unsworth 1990). In these locations riparian shade and topography are the most important controls on the amount of direct solar radiation reaching the water surface (Ice 2001).

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Shading supplied by topography and riparian vegetation during the summer months is considered to be essential for moderating high stream temperatures (Bartholow 2000, Beschta et al. 1987, Brown 1969, Ice 2001, Johnson and Jones 2000, Rutherford et al. 1997); particularly in small, low-order streams that are highly sensitive to changes in the thermal environment due to the relatively low heat carrying capacity of these streams.

BasinTemp, developed by Allen and Baker in 1999, addressed the need to find a simple way to predict high summer stream temperatures at a watershed scale. Since BasinTemp model was presented at the 2004 Redwood Region forest science symposium and its methods were discussed in a paper by Allen et al. 2007 in the symposium's proceedings, we will only refer to them briefly here. BasinTemp is a mechanistically based model which assumes that direct shortwave radiation drives stream summertime temperatures, emphasizing the role of the riparian vegetation in the control of insolation and water temperatures. It is composed of several modules including (1) a GIS Pre-processor that assembles a channel network, elevations and vegetation heights; (2) a radiation model that generates daily-averaged, spatially explicit shortwave radiation predictions ($\text{W/m}^2/\text{day}$) from the above data; (3) a simple hydrology model that assumes that groundwater accretion is a linear function of drainage area and estimates low wetted widths from empirical values; (4) a simple 1D heat balance model which uses solar radiation, discharge, groundwater accretion and hydraulic geometry values to predict MWAT values for the whole basin; (5) an optimization routine which improves model predictions using field measured temperature data derived from a number of thermistors deployed in the watershed.

BasinTemp was applied to the South Fork Ten Mile River (SFTMR) Basin to confirm the effectiveness of BasinTemp in a current vegetation conditions scenario, to assess and quantify spatially explicit summer stream temperatures in the basin and more explicitly to study the influence of topography, vegetation patterns, climate change and the effect of land management on these and on stream temperatures. The study attempts to answer the following questions: (1) What is the role of shading by riparian vegetation in controlling summer stream temperatures? (2) How does the importance of riparian shade vary across the basin, and if so? (3) How do different riparian vegetation conditions affect stream temperatures locally and downstream? (4) How might changes in regional climate patterns affect stream temperatures in the South Fork Ten Mile River Basin?

Study Area

The SFTMR is a small sub-watershed (100 km^2) in the Ten Mile River Basin, 13 km north of Fort Bragg, CA (*fig. 1*), with elevations that range between 6 m and 950 m. It has four main tributaries, three of them coming in from the right (Smith, Campbell and Redwood creeks) and one from the left (Churchman Creek). The climate in the SFTMR basin is characterized by two distinct seasons: a hot, dry summer and a cool, wet winter. This is modified by the effect of the coastal fog which towards the ocean, moderates summer temperatures (Albin and Law 2006). Temperatures range between 12°C at the coast to 30°C inland.

We subdivided the watershed into three main zones depending on the reach and influence of the fog layer: (1) a coastal or fog zone, extending approximately 4 km inland, where August average maximum daily air temperatures are below 20°C ; (2) a

transition zone, extending from 4 km to 9 to 10 km from the coast, where temperatures increase from 20 to 26°C; (3) an inland zone, extending farther than 9 to 10 km from the coast, where temperatures are predominantly over 26°C. Results from the fog zone were discarded in the optimization and in the validation of this study because the model is inappropriate for conditions where incoming shortwave radiation is no longer the dominant heat energy flux (Allen 2007).

The geology is comprised of homogeneous Franciscan Coastal Belt composed of greywacke sandstone, shales, siltstones and conglomerates and has relatively small influence in the model output due to its homogeneity. Redwood (*Sequoia sempervirens*) in the coast and Douglas-fir (*Pseudotsuga menziesii*) inland are the dominant tree species in the basin.

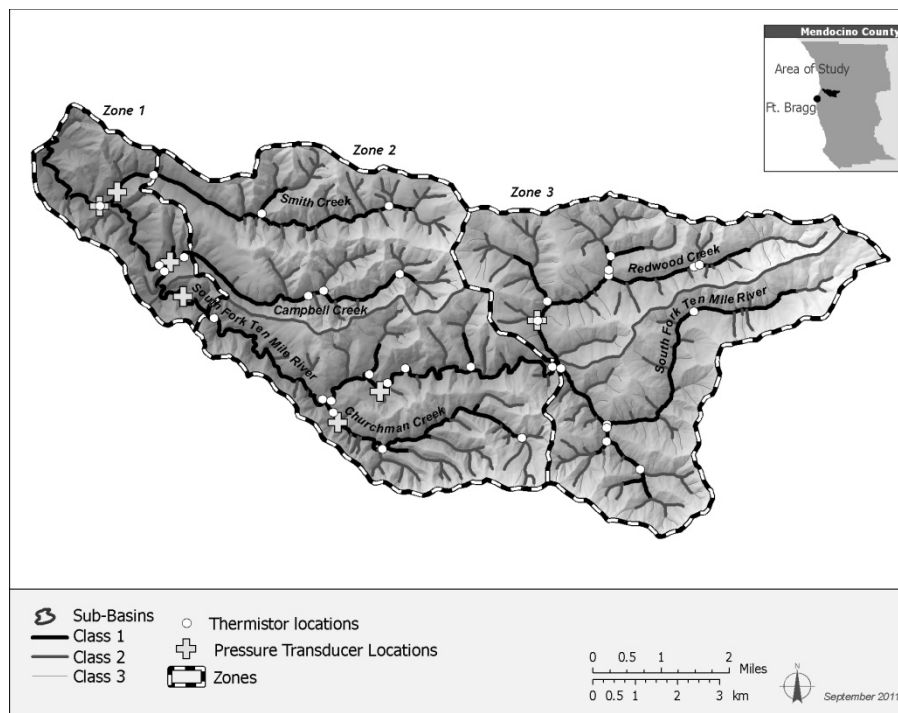


Figure 1—Study area.

Currently all of the SFTMR basin is privately owned. Over 90 percent is owned by Campbell Timber Management. The watershed was heavily logged between 1910 and 1940 and has been recovering by natural means since 1930, although in 1945 a wildfire burnt most of the inland part of the watershed to the south of Smith Ridge to the north and to the west of Sherwood Ridge delaying its recovery substantially (Ambrose et al. 1995). This can be seen today as late seral stages dominate the western half of the basin while early seral stage stages dominate the eastern half. Native fish species include Chinook salmon (*Oncorhynchus tshawytscha*), steelhead (*O. mykiss*), coho salmon (*O. kisutch*), and sculpin species (*Cottus spp.*). This study focuses on the effects on the temperature sensitive juvenile life-stage of coho salmon, which are listed as endangered by both the federal government and the State of California. The input data used in the study are shown in *table 1*. The basic stream channel network was provided by Campbell Timberland Management (CTM). It was expanded to include headwater swales and split into 30 m segments which constitute

the minimum unit for which MWATs, solar radiation, discharge and wetted widths are modeled.

Three scenarios were tested: (1) topographic conditions, representing the worst case scenario assuming no vegetation anywhere and topography derived shade only; (2) current vegetation conditions representing shade derived from topography plus vegetation heights as of 2006; and (3) reference vegetation conditions representing shade from undisturbed riparian conditions and assigning late seral tree heights to the riparian vegetation.

Table 1—*Data types used for BasinTemp in the SFTMR basin.*

Data type	Data used for SFTMR
Stream network	Modified USGS 1:24,000 DLG hydrography
Topography	USGS 10m DEM
Tree heights	Landsat TM imagery classified according to the California Wildlife Habitat Relations (CWHR) system (Fox et al. 1997)
Channel geometry	Power-law relationship between drainage area and field measured low-flow widths throughout the SFTMR basin
Low flow discharge	7-day mean daily discharge data from pressure transducers set throughout the basin by CTM and from the Noyo River USGS gage near Fort Bragg
Observed stream temperature data	2006, 2007 and 2010 thermograph data compiled by CTM

Absolute tree heights are obtained from combined topographic data and estimated tree heights derived from vegetation information (Allen 2007). Topographic elevations were extracted from a USGS 10 m DEM and were used with no modification in the topographic conditions scenario. Estimated vegetation tree heights were added to the 10 m DEM elevations for the current and reference vegetation condition scenarios.

For current vegetation conditions tree heights were generated using vegetation data from 1994 Landsat Thematic Mapper (TM) imagery classified according to a modified California Wildlife Habitat Relationships (CWHR) classification scheme (Fox et al. 1997) where DBH-height relationships were established for current and reference condition vegetation as shown in *table 2*. These height were validated by 2005 CTM stand data summarized into average tree heights and if within 90 m of any streams, updated with 2005 1 m National Agricultural Imagery Program (NAIP) color orthophotography resampled in several steps to 30 m.

Water temperature data was provided by CTM for 2006, 2007, and 2010. Thermostats were evenly distributed throughout the basin and located upstream and downstream of major confluences. Of these 3 years, 2007 was the most typical of hot and dry conditions while 2006 was an abnormally hot, useful for estimating temperature increases that might result from climate change. The year 2010 was the most representative of average temperature and discharge conditions (*fig. 2*). As mentioned above, to calibrate the model, sites in the fog zone (Zone 1, *fig. 1*) were removed from the analysis. Hobo™ data loggers were used to measure actual stream temperatures throughout the basin for 3 years. Thirty two sites were studied in 2010,

twenty two in 2007 and twenty in 2006. They recorded temperatures at 15 minute intervals which were combined into daily averages. These were calculated into 7 day moving averages or average weekly average temperatures (AWATs). The maximum AWAT in the year (MWAT) was extracted for each station and the most common MWAT value for each station was defined for every year: July 27th for 2006 and 2007 and July 21st for 2010. Wetted widths were measured in August of 2006 and 2007 and extrapolated to 2010 due to the lack of measurement. July monthly average maximum air temperatures, 21°C for 2006 and 2007 and 15.8°C for 2010, were derived from 4 km Oregon State University PRISM grids. A single basin-wide average was used as an input parameter in the heat transfer model.

Table 2—Diameter at breast height (DBH) to tree height relationships for CWHR vegetation assemblages.

DBH range (inches)	Tree height (m)						
	Mixed Hardwood	Mixed Pine	Mixed Fir	Mixed Conifer and Hardwood	Mixed Oak Woodland	Mixed Hardwood and Conifer	Mixed Conifer
6-Jan	10	7	7.5	7.5	5	10	10
11-Jun	15	10	15	15	10	15	15
24-Nov	20	17.5	20	22.5	15	20	25
> 24	25	25	30	30	20	27.5	35
> 36 ^a	-	-	-	-	-	-	45

^a Only applies to the Mixed Conifer class.

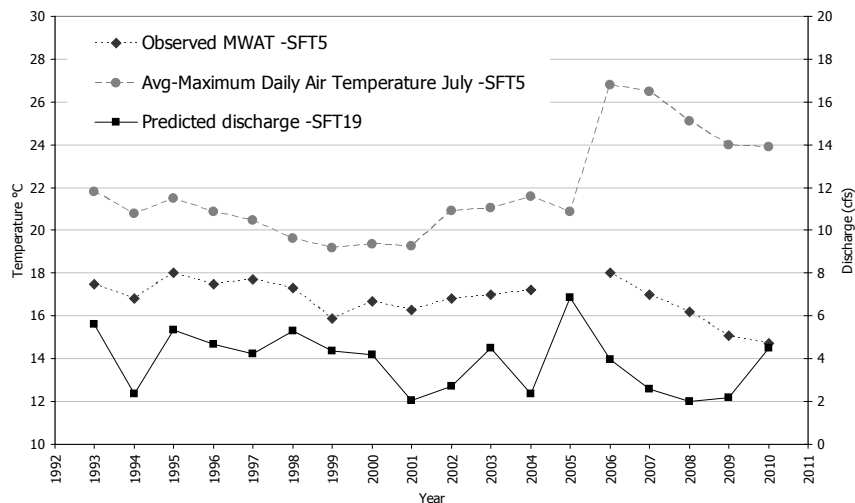


Figure 2—Long-term water temperature (MWAT), air temperature (average maximum daily air temperature from PRISM) at SFT5, and estimated discharge for site SFT19 in the South Fork Ten Mile basin, 1993 to 2010.

In 2006 and 2007 discharge values at SFT19, the lowest station in the watershed, were 3.7 m³/s and 2.7 m³/s respectively, some of the lowest values since 1993 (*fig. 2*). The calculated 2006 and 2007 accretion rates were 0.000414 and 0.00030571 m³/km respectively. With no 2010 discharge data in the SFTMR basin, we estimated the

discharge at SFT19 based on values from the USGS gage in the Noyo River near Forth Bragg and in their high correlation with SFT19 discharge in other years. Discharge for 2010 at SFT19 was estimated to be $4.5 \text{ m}^3/\text{s}$ and the accretion rate $0.000504 \text{ m}^3/\text{km}$.

Results

A high correlation between observed and modeled results was observed in 2010 (average water year) with a root mean square error (RMSE) = 0.3°C and a $R^2 = 0.89$. 2007 (dry water year) had a RMSE of 0.59°C and an R^2 of 0.67. Model parameters derived from these best-fit relationships were later applied for subsequent temperature prediction scenarios (reference vegetation conditions, and topographic shade-only). We assume the higher correlation and lower RMSE in the 2010 data to be a result of a lower temperature range in the observed temperatures in 2010 (2.9°C) than in 2007 (3.1°C). The better placement of the thermistors after several years of field surveys is possibly another reason for the better fit.

The spatial distribution of predicted MWATs closely tracks the observed MWAT temperatures. Warmest predicted MWATs relative to drainage area are generally observed in the eastern portion of the basin in upper Redwood Creek and the Upper South Fork Ten Mile River near the confluence with North Fork Redwood Creek (*fig. 3*). Downstream of that confluence, temperatures warm up to 17°C , over the preferred range for coho salmon, during the dry water year and remain at 17°C until the river reaches the fog zone. Temperatures for the average water year (2010) warm up in the mainstems of Redwood Creek and South Fork Ten Mile River in the inland zone but at 15°C stay within the preferred range for coho and remain at close to 15°C until the waters reach the fog zone where the water cools down. This warming is apparently due to the combined influence of warm July air temperatures and reduced shading provided by early seral-stage vegetation. A net water loss of the reach (personal observation) may be another cause of the warmer temperatures in the reach. Overall, less than 1 km of stream length has temperatures higher than the preferred range for coho salmon in the dry water year, while all predicted temperatures are below 15.5°C in the average water year.

Upstream of Churchman Creek (drainage area 10.3 km^2 (*fig. 3*), tributaries draining into the mainstem South Fork Ten Mile below its confluence with Redwood Creek are all small and hence have relatively small thermal dilution effects. Water temperatures cool downstream of the Churchman Creek confluence, where temperatures less than 13 or 15°C (for average or dry water year types, respectively) empty into the mainstem South Fork Ten Mile River.

MWAT temperature predictions for shade provided by topography only were generated for average and dry water year data. Under current vegetation conditions, the average water temperatures are 0.9°C and 1.3°C (average and dry water years, respectively) cooler than under topographic-shade-only conditions. Water temperatures in the headwaters start out cool at less than 13°C due to cold groundwater temperatures, but due to the lack of vegetative shading heat loading is high, resulting in temperatures predicted to exceed 18°C in the mainstem South Fork Ten Mile River for all of Zone 2 and much of Zone 3 in 2007. In 2010 there is less heating in the mainstem. Temperatures reach 17°C below the confluence of South

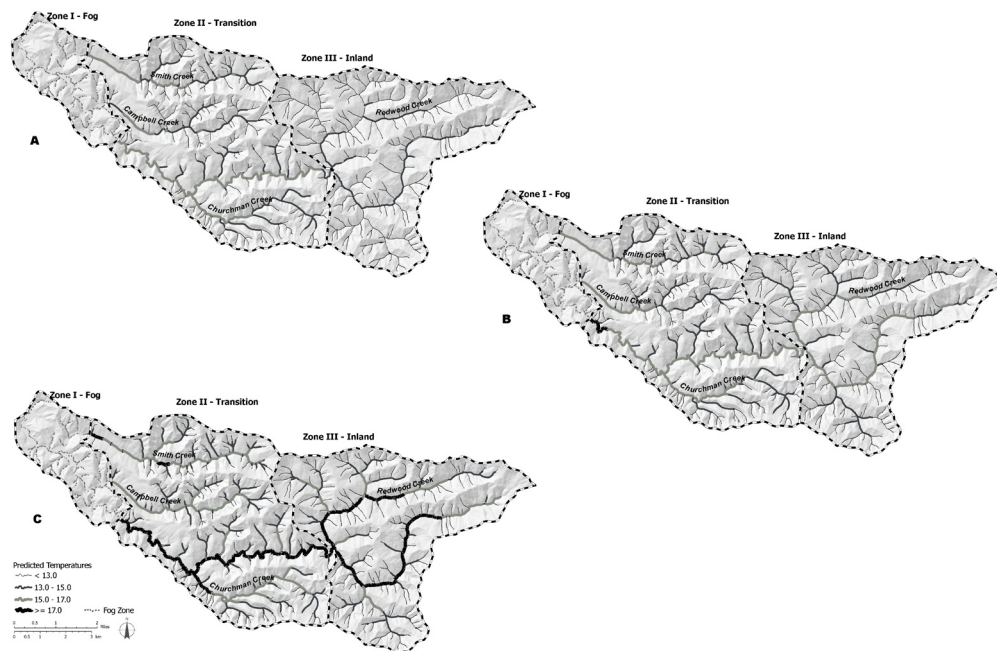


Figure 3—2010 MWAT predictions for SFTMR for (A) reference vegetation, (B) current vegetation and (C) topographic conditions.

Fork Ten Mile and Redwood Creeks, increasing until 18°C below the confluence with Churchman Creek to cool down when we enter the fog zone. Although the difference with temperatures observed under current conditions is smaller than in the dry water year, observed temperatures are still higher.

The year 2006 was considered to be a climate change scenario. Current climate change models for northern California (Cayan et al. 2006) predict a trend of increasing summer air temperatures. Total annual precipitation is predicted to remain similar to current conditions, with most rainfall continuing to occur during a relatively short winter season. Summer air temperature predictions range from increases of about 2 to 5°C over the next 50 to 100 years depending on the scenario. To predict water temperatures based on climate change models, we modeled shade under current and reference conditions based on data collected during a record-breaking heat wave event that was experienced between July 16 – 26, 2006. The water temperature dynamics during summer 2006 were very similar to what is predicted for northern California climate change. This scenario predicted that over 27 km of stream channel would have temperatures greater than 17°C under current vegetation conditions, and over 7 km under reference vegetation conditions. Based on our results, if these climate models are accurate, we predict a trend of increasing MWATs in the South Fork Ten Mile River, regardless of land management actions. Under these conditions, more of the mainstem South Fork Ten Mile River will become too warm for coho salmon, and cooler tributaries, such as Churchman and Smith creeks, and areas located downstream within the cooler coastal fog zone, will likely play a heightened role in overall salmon productivity. Precisely how exceptional this period was and how it affected water temperatures in the South Fork Ten Mile Basin can be seen by comparing MWATs recorded in 2006 compared with

average MWATs recorded at the same gages between 1993 to 2004 (*fig. 2*). Observed MWATs for 2006 gages were all warmer than MWATs in previous years, some significantly so.

Discussion

The study shows an expected rise in average basin wide MWATs with an increase in air temperatures (See *table 3* and *fig. 2* to compare the 3 year's average air temperatures). Predicted MWATs also increases regardless of the scenario, 2.3 °C under current and reference vegetation conditions and 2.0 °C under topographic conditions. We found that MWATs increased 0.4°C from reference to current conditions in 2006 and 2010 and 0.8°C in 2007 and 0.6°C, 0.9°C and 1.3°C between current vegetation conditions and topographic conditions in 2006, 2010 and 2007 respectively. Even though 2006 was an extremely hot year (*fig. 2*), the difference in predicted MWAT values is smaller than in 2007, a cooler year but with higher discharge.

Table 3 shows the percentage of the stream network outside the fog zone with MWATs under 15°C. Over 90 percent of the stream channel network is within the preferred range of coho salmon (15°C MWAT) for reference vegetation conditions in 2007 and 2010, and 74 percent in 2006. The decrease in the percentage of channel network under 15°C as we depart from the reference conditions is 16 percent in 2006 (the climate change scenario) and 8 percent in 2010 (the average water year). MWATs under current vegetation conditions are closer to MWATs under reference vegetation conditions (best case scenario) than to topographic conditions (worst case scenario), indicating the positive effects of current land management conditions in maintaining low stream temperatures.

Table 3—Average predicted MWATs (°C), percentage of total stream length and percentage of Class I stream length with MWATs under 15°C in zones 2 and 3 for topographic, current and reference vegetation conditions in years 2010, 2007 and 2006.

Year	Topographic Conditions	Current Vegetation Conditions	Reference Vegetation Conditions
2010	14.2°C / 92% / 68%	13.3°C / 100% / 99%	12.9°C / 100% / 100%
2007	15.7°C / 73% / 5%	14.4°C / 83% / 35%	13.6°C / 90% / 62%
2006	16.2°C / 58% / 1%	15.6°C / 68% / 20%	15.2°C / 74% / 23%

Table 3 also shows the percentage of the stream network outside the fog zone with MWATs under 15°C, but this time constrained to the mainstem SFTMR and main tributaries as defined by STREAM CLASS = 1 (*fig. 1*). This query extracts the main channels from the boundary of the fog zone to the upper extent of the fish bearing streams allowing us to see the impact of tree shade on the channel network's aquatic reaches. The reduction of channel length under 15°C is concentrated in the main channels rather than in the headwater channels and it is more pronounced as the air temperature increases. We find that 68 percent of the main channels outside of the fog zone have MWATs less than 15°C in an average water year (2010) even in topographic conditions while only 1 percent have in the climate change scenario reinforcing the importance of vegetation shade in the climate change scenario.

The effects of vegetation shading on the main channels are reduced substantially with higher air temperatures. In the climate change scenario (2006) only 1 percent of the channels are under the 15°C threshold in the climate change scenario under topographic conditions and 23 percent under reference conditions. But a small decrease in air temperature or increase in discharge (2007) results in a significant increase in the length of main channel under the 15°C MWAT to 35 percent in current conditions and 62 percent in reference conditions. As the air temperature increases the importance of the role of the vegetation in the reduction of the temperatures also increases. It is interesting to observe how current land management practices maintain main channel MWATs closer to reference conditions than topography conditions.

BasinTemp has been used as a tool in this study to predict basin-wide temperatures in the SFTMR with a few, simple parameters and with a limited field effort. We consider the model to be a valid tool to get a good first estimate of a basin's temperature and complementary to reach-based temperature models. RMSE's for the 3 years studied ranged between 0.3 and 0.6°C.

We found land management in the SFTMR basin to keep the riparian vegetation in conditions that are closer to reference heights than bare ground conditions thus helping current MWATs to stay below 15°C in an average water year (2010) and in most reaches in a dry water year (2006). In the 3 years shown here, current temperatures are closer to reference than to topographic conditions.

With regard to the main four questions stated in the introduction we found that: (1) Riparian shading in the SFTMR reduced summer stream temperatures in all 3 years studied. This reduction of predicted MWATs in the whole basin was greatest in 2007 and 2006 and we found that riparian shading effects were reduced in 2010 due to higher discharge and lower air temperatures (*table 3* and *fig. 2*); (2) Riparian shade is important throughout the basin. Shaded lower order streams feed colder water to higher order tributaries reducing water temperatures in these reaches. Riparian shade has greater effect in reducing MWATs in Class I streams as it lowers stream temperatures and their propagation downstream (*table 3, fig. 3*); (3) Reference vegetation conditions help keep stream temperatures low in upper stream reaches feeding colder into larger tributaries and reducing the propagation of high temperatures downstream in Class I streams reducing temperature impact on salmonids. Current land management practices help maintain riparian shade effects closer to reference vegetation conditions than topographic conditions keeping most of the channels under 17°C; and (4) Predicted climate change scenarios leading to higher air temperatures and reduced flows are expected to reduce the influence of vegetation shade in the control of stream temperatures increasing stream temperatures.

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