Restoring the water temperature of small streams with riparian revegetation

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Abstract:

The water temperature regime of freshwater ecosystems is a critical habitat element, influencing the distribution of biota and rates of important ecosystem processes. We investigate the success of a 3.5 year stream revegetation project in restoring water temperature regimes in a 1-5m wide tributary of the South Maroochy River in southeast Queensland. The temperature regime change of the revegetated stream was measured by comparing 4 summers (1 pre rehabilitation and 3 post rehabilitation) of ½ hourly water temperature recordings at a treatment stream and adjacent unforested control and forested reference streams of similar size. We found that small un-vegetated streams were up to 12 ^{0}C warmer than fully vegetated streams, with a 10 ^{0}C greater diel temperature range. Following revegetation of the treatment stream, there was an increase in maximum stream temperature for one summer, corresponding to a reduction in shading by weed removal on stream banks prior to replanting. This was followed by a consistent reduction in water temperatures, approaching that of the forested reference stream 3 years after revegetation. To provide guidance for catchment scale revegetation planning we measured the downstream change in water temperature for the upper 50 km of the Mary River. By analysing the relationship between downstream temperature change and riparian shade we found that the maximum positive benefit of revegetation on water temperature was likely to be for small streams with a bankfull width less than 20 m.

Key Words:

Temperature, Stream Rehabilitation, restoration, revegetation, riparian, shade

Introduction:

The water temperature regime of freshwater ecosystems is a critical habitat element. Temperature controls the solubility of gases, viscosity and density of water, and patterns of physical stratification. It also influences the distribution of some biota and rates of important biotic processes, including nutrient cycling and decomposition (Islam et al. 1986). For fish, the temperature regime can influence migration cues, egg maturation, spawning, incubation success, growth, and general stress which relates to intra-specific competition and susceptibility to parasites and diseases (Armour 1991). The body metabolism of fish and other ectothermic organisms, such macroinvertebrates, is controlled by the temperature of the surrounding environment. Changes in temperature regime can make otherwise suitable habitats uninhabitable for such organisms. For example, low-level cold water release from Lake Eildon has resulted in a drop in the January median water temperature in the Goulburn River (Victoria, Australia) from 19.5^{0}C to 12.5^{0}C (Gippel et al. 1993). The reduction in water temperature has removed Australian native warm-water fish from the reach downstream of the dam because their spawning temperature cues are likely to range from 16-23^{0}C through the summer months (Gippel et al. 1993).

In small streams, shading by riparian vegetation and stream banks is a major factor controlling water temperature regimes (Bunn et al. 1999). One of the consequences of having poor riparian vegetation cover is direct solar heating of the water surface. Poorly vegetated streams with high summer maximum water temperatures may become unsuitable for temperature sensitive biota, including many PET taxa (Plecoptera, Ephemeroptera and Trichoptera), which are important components of stream ecosystems. Large diel ranges in temperature can also have a similar effect of making poorly vegetated streams uninhabitable for taxa with narrow thermal tolerances (stenotherms).

Much of the research on the effects of riparian vegetation on stream thermal regimes has been undertaken in temperate biomes (e.g. Hopkins 1971; Armour 1991; Davies-Colley et al. 1998; Johnson et al. 2000). The potential influence of riparian shading is likely to be quite different in tropical systems, where solar intensity is much higher and the orientation of the sun may diminish the effectiveness of riparian and bank shading.

To date, the potential difference in stream temperatures for vegetated and un-vegetated streams has not been presented for subtropical or tropical streams.

Replanting of riparian vegetation is a common stream rehabilitation activity largely because of the relatively low cost, limited expertise required and large range of potential benefits. The latter include reducing channel erosion (Anderson 1985; Henderson 1986; Gurnell 1995; Shields et al. 1995; Beeson et al. 1996; Stott 1997), moderated stream temperatures (Rutherford et al. 1999; Johnson et al. 2000; Poole et al. 2000), increasing carbon supplies (Bilby et al. 1980) and enhancing nutrient cycling. This project focuses on the quantification of temperature "recovery" following riparian revegetation. The purpose of this paper is to firstly quantify the difference in daily maximum temperatures and daily temperature ranges between vegetated and unvegetated streams, and secondly to estimate the time required for stream temperature restoration following a riparian rehabilitation project.

Methods:

Water temperature was simultaneously monitored at three tributaries of the South Maroochy River in south east Queensland. The streams had similar elevations (200-300m above sea level), catchment areas (1.5 km^2) and geological characteristics. The treatment stream (Echidna Creek) was revegetated in February to April 2001 by clearing scrubby weeds and planting tube stock of endemic species at 2 m centres. The second stream was a nearby control stream (Dulong Creek) where the riparian zone is vegetated with pasture grass (mostly exotic Kikuyu grass, *Pennisetum clandestinum* Hochst. ex Chiov). The third stream was a reference stream (Piccabeen Creek) with a fully forested catchment located in nearby Mapleton State Forest. The water temperature of all three streams was measured at half hourly intervals from December 2000 until March 2004. To examine the effect of riparian vegetation on days where high stream temperatures may pose a threat to stream biota, we only considered maximum daily temperatures and daily temperature ranges within summer months. To further distinguish between "hot clear" days and "cool overcast or rainy" days we excluded days where discharge in any two of the three streams exceeded a baseflow threshold (see (Marsh et al. 2004). There is generally less direct solar radiation during periods of cloud cover and rainfall, and reductions in stream temperature may occur during floods due to the increased thermal mass (i.e. the greater volume of water is not as easily heated).

The three streams considered were small (1-5 m wide) and shallow (<0.3 m) and dominated by extended periods of low flow. These elements combine to provide shallow, low velocity water that has a high residence time in open sections of the channel, providing a large potential for heating due to direct solar radiation, and consequently a large temperature response to shading by revegetation (Rutherford et al. in press). For larger streams, the effect of riparian vegetation of water temperature is likely to be much less because of riparian vegetation would not completely shade the channel. To investigate the relative effectiveness of revegetation on channels of increasing size, we measured the downstream trend in water temperature from 17 February to 24 April 2002 at 7 sites in the upper 50 km of the Mary River in southeast Queensland. The sites sampled had a reasonably continuous stand of fringing riparian vegetation on the bank top (but poor floodplain vegetation). The vegetation height varied slightly according to the dominant riparian vegetation type, but was mostly around 10-15 m in height. We also measured gross channel dimensions to build a coarse model to illustrate for which stream size the water temperature would be most influenced by revegetation (Bunn et al. 1999).

Results and Discussion:

Temperature response to stream revegetation

In the 2000-2001 summer (before treatment) the mean daily maximum water temperature in the treatment stream (Echidna Creek) (25.0 ± 1.6) was midway between the control (29.2 ± 1.5) and reference (19.9 ± 0.6) streams (Table 1). For the first summer following revegetation in April 2001, maximum temperatures of Echidna Creek (28.1 ± 2.5) were markedly higher than in the forested reference (21.0 ± 0.8) and similar to the pasture control (28.6 ± 1.6). This was because of the removal of scrubby weeds along the Echidna Creek channel prior to replanting. During summer 2002-2003 maximum temperatures in Echidna Creek and the pasture control were again similar, and both were higher than the forested reference. Although Echidna Creek had been replanted, shrubs and trees were still too low to provide significant shade. The standard deviation of daily summer maximums was smaller for the forested reference site than for the treatment or control sites because the full canopy cover reduced the direct solar radiation component throughout the day.

The daily temperature range at the treatment site show a similar pattern to mean maximum temperature: an increase in the first 2 years after treatment because of the removal of shrubby vegetation, but a return to pre-treatment values in 2003-2004 (Table 2).

Table 1: Mean daily summer maximum temperatures (^{0}C) (± standard deviation (n)) for baseflow periods.

	2000-2001	2001-2002	2002-2003	2003-2004
Treatment (Echidna Creek)	25.0 ±1.6 (48)	28.1 ±2.5 (88)	25.7 ±1.8 (56)	25.7 ±1.7 (41)
Control (Dulong Creek)	29.2 ±1.5 (48)	28.6 ±1.6 (88)	26.4 ±1.2 (56)	30.9 ±2.1 (20)
Reference (Piccabeen Creek)	19.9 ±0.6 (48)	21.0 ±0.8 (88)	20.2 ±0.6 (56)	20.6 ±1.0 (41)
Air at Nambour DPI	28.6 ±2.2 (48)	29.4 ±4.8 (88)	28.3 ±2.7 (56)	28.4 ±3.5 (41)

Table 2: Mean daily summer temperature ranges (^{0}C) (± standard deviation (n)) for baseflow periods.

	2000-2001	2001-2002	2002-2003	2003-2004
Treatment (Echidna Creek)	3.9 ±1.1 (48)	6.4 ±2.5(88)	5.5 ±2.0 (56)	3.4 ±1.4 (41)
Control (Dulong Creek)	4.8 ±1.5 (48)	3.1 ±1.1(88)	2.3 ±0.9 (56)	5.3 ±2.2 (20)
Reference (Piccabeen Creek)	0.3 ±0.3 (48)	0.3 ±0.2 (88)	0.5 ±0.5 (56)	0.3 ±0.2 (41)
Air Temperature Range at Nambour DPI	9.8 ±2.3 (48)	9.8 ±3.4 (88)	10.7 ±3.3 (56)	10.1 ±2.5 (41)

To reduce the effects of climatic variation we calculated the mean (and SE) of the daily differences in maximum stream temperature between treatment, reference and control sites and also of the differences between maximum air temperature and water temperature at the treatment site (Figure 1). In 2000-2001 (pre-treatment) the pasture control was ~4^{o}C warmer, while the forested reference was ~5^{o}C cooler, than Echidna Creek as discussed earlier. In 2001-2002 temperatures were similar at the treatment and control sites because shrubby vegetation along Echidna Creek had been removed prior to re-planting. There was also a bigger temperature difference between treatment and reference sites, which is consistent with reduced shading in the treatment stream. In 2002-2003 temperatures were again similar at the treatment and control sites, but the difference between treatment and reference sites was similar to that pre-treatment.. In 2002-2003 the treatment was ~5^{o}C cooler than the pasture control, presumably because of shading by the re-planted riparian vegetation, which was comparable with the pre-treatment difference. The difference between treatment and forested reference sites was also similar to that pre-treatment. The difference in maximum temperatures between the treatment and control streams in the 2003-2004 summer was not significantly different to the temperature difference before treatment (2000-2001) (ANOVA, $P<0.05$, Tukey HSD). Thus, 3 years after re-planting the treatment stream still had a mean daily maximum temperature 5.1 ±1.6^{o}C higher than the forested reference. It may take several years before the full benefits of restoration are seen at the treatment site.

The difference in the summer mean of the daily maximum temperatures between the forested reference and unforested control sites varied from 6.2-10.9^{0}C over the four summers. This reflects variations of climate (notably radiation, air temperature, wind and humidity). However, the single hottest day each summer (or the day of maximum temperature range) may be of critical importance in determining whether or not a stream has a suitable thermal regime for biota. A single day of high temperatures could adversely affect biota not able to seek or locate temperature refugia. The single largest difference in daily maximum temperature between the forested reference and pasture control sites was 10-12^{0}C in each summer (Table 3, column 2). In the summer following revegetation (2001-2002) the single hottest day in the treatment site was 13^{0}C higher than the forested reference stream, but this decreased to 9^{o}C and 8^{o}C in the following 2 summers as shade increased.

There was a 5.7-10.7^{0}C difference between maximum temperature ranges for the control and reference sites (Table 3, column 3). The highest daily range at the treatment site (Echidna Creek) was 11.4^{0}C in the summer following treatment (2001-2002) but this declined for the next two summers following revegetation. Relative to the forested reference stream, the daily range in the treatment stream was 10.9^{0}C greater in the summer immediately following revegetation, but this difference had returned to 6.1^{0}C greater daily temperature range three summers after revegetation.

All of the above results demonstrate an increase in daily maximum water temperatures at the treatment site immediately following treatment associated with the removal of scrubby vegetation along the channel margins prior to replanting. Over the next 3 years daily maximum temperature decreased as a result of increasing shade and has now recovered to the pre-treatment state. The daily maximum water temperature is likely to continue to decrease at the treatment site as the riparian vegetation continues to grow and eventually forms a dense canopy over the stream.

Table 3: Difference in the maximum temperatures and maximum temperature ranges for each summer.

	Maximum difference in daily maximum summer temperatures between:		Maximum difference in daily range of water temperature between:	
	Reference and control streams	Reference and treatment streams	Reference and control streams	Reference and treatment streams
2000-2001	12.0	8.1	7.7	6.3
2001-2002	11.6	13.1	5.6	10.9
2002-2003	9.0	8.9	4.5	9.1
2003-2004	13.3	7.9	10.7	6.1

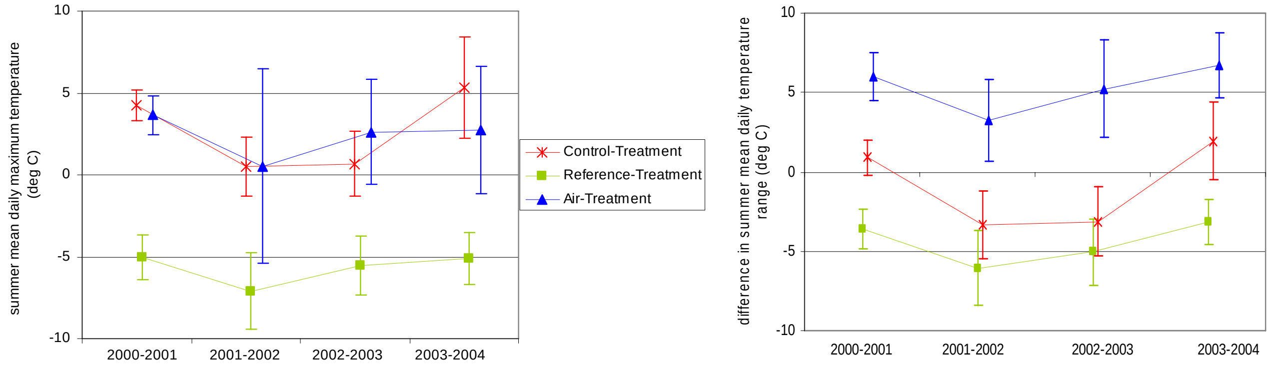

Figure 1: Mean and standard deviation of Control-Treatment for daily maximum summer temperatures (A), and mean and standard deviation for each summer of the daily differences in temperature range between the treatment and reference, treatment and control and treatment and air temperatures (B).

Downstream trends in water temperature in the Mary River

Shading the stream effectively reduces the number of hours each day that direct solar radiation reaches the water surface (Figure 2A). In small, forested streams with closed canopies, little direct sunlight will reach the water surface. However, as you move downstream, t he relative effect of revegetation is affected by channel size because trees have a limited maximum size. Hence for a small channel the relative decrease in direct solar radiation hours will be greater than for wide channels. This is a simple model for predicting where bank revegetation is likely to have the greatest effect on water temperature. A key assumption here is that stream orientation is north-south. For other variations of orientation reach length is of critical importance (i.e. the east-west dimension), especially in higher latitudes (Bunn et al. 1999).

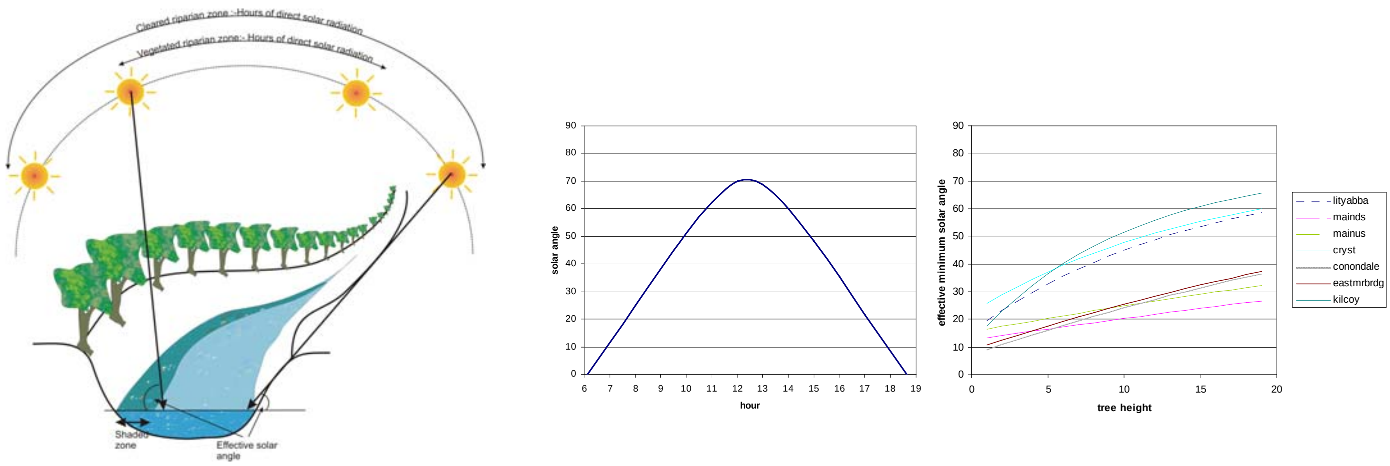

Figure 2: Shading reduces the number of hours of direct solar radiation (A). Solar angle for each hour of the day (1/3/2003) (B) compared to the minimum solar angle to hit the water surface for different tree heights (C).

We considered the measured channel geometry for each site and assumed that the low flow channel was centred within the bankfull channel. We determined the elevation angle of the banks from the stream centreline and assumed that, in the absence of trees, this was the minimum solar angle to hit the water surface (Figure 2B). We also determined the minimum solar angle to hit the water surface for alternate tree heights (Figure 2C). We then calculated the elevation angle of the sun every hour on 1st March 2003, compared this with the elevation angle of the banks or trees and calculated the proportion of the wetted channel under direct solar radiation for each hour of the day from 6am to 6pm. We assumed 10m high trees on all of the reaches. We summed these values to give an effective number of hours that the channel was under full solar radiation.

There was a strong, positive correlation between the observed daily maximum water temperature at the 7 sites on the Mary River and the calculated hours of solar radiation (Figure 3A). Given this relationship we calculated how the stream temperature would increase if all the riparian trees were removed. With the trees removed the minimum effective solar angle is reduced and the hours of full solar radiation is increased, and from Figure 3A we can predict the resulting temperature. We predicted that in the absence of trees the maximum daily temperature (in March) would be around 25^{0}C in all sites (25.1-25.2^{0}C). This represents a maximum temperature increase of 4^{0}C for the narrowest reach (bankfull width =12m) and no real change in maximum temperatures for reaches with bankfull widths greater than around 40m (Figure 3B).

The curve fitted to Figure 3B is only indicative because it is based on only 7 points. However, it indicates a large increase in the number of solar hours after vegetation removal for sites with a bankfull width less than ~20 m. The Mary River is an entrenched stream with a shallow low flow channel inset within a much deeper flood flow channel, Davies-Colley and Quinn (1998) found that in New Zealand streams the amount of incident light reaching the stream increased dramatically when the stream width exceeded 3.5 m. One reason for the difference is that in the Mary River, the banks (typically ~3 m high) provide considerable shade to the low flow channel, whereas bank height was low in the New Zealand study. Another reason is that shading is provided by tall trees (~10 m high) along the Mary River whereas vegetation height was highly variable in the New Zealand study. On the other hand, in the New Zealand study wetted width ~90% bankfull width (Figure 5, (Davies-Colley et al. 1998)) whereas at the 7 sites studied in the Mary River, wetted width ~35%bankfull width (R^2=0.94, least squares linear model). This means the wetted channel in the Mary is often some distance away from the banks, which decreases their effectiveness in providing shade. Overall, our calculations indicate that tall trees (~10 m high), especially when growing along the top of high banks (~3 m high), shade channels up to ~20 m in width.

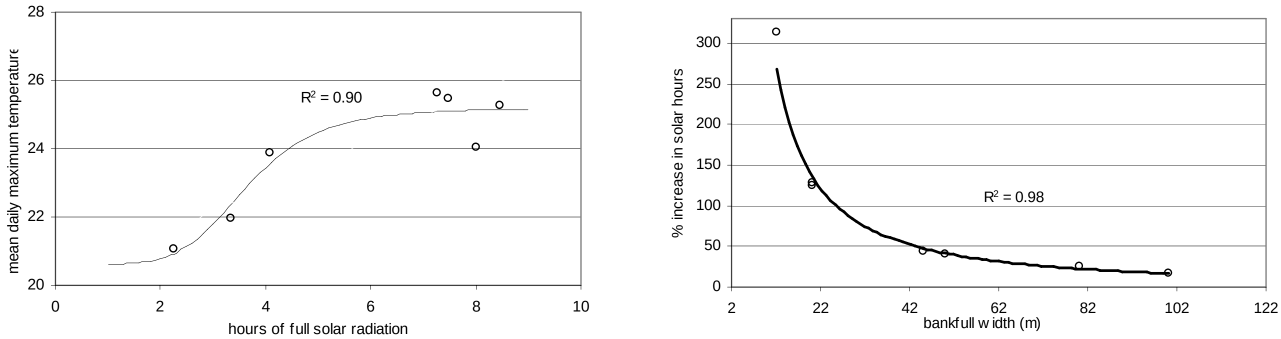

Figure 3: Computed hours of full solar radiation versus measured mean of daily maximum water temperatures (A). Increase in solar hours (hours of full sun for the full low flow wetted width) with increasing channel size if trees are removed (B).

Conclusion:

The revegetation of Echidna Creek resulted in an initial increase in stream temperature in the summer following the treatment. This increase in stream temperature was due to the removal of scrubby vegetation that was providing some shade to the stream. Three summers after revegetation the water temperature had fallen below the pre-treatment water temperature, but was not fully restored to reference stream levels. Based on the current rate of temperature restoration we would expect temperature restoration to take a minimum of 8 years from the commencement of planting. This restoration timeframe would vary across Australia, where vegetation is slower growing or the stream channel is larger than Echidna Creek.

The effectiveness of vegetation in controlling stream temperature regimes is heavily influenced by channel width. For Southeast Queensland rivers (like the Mary) where the banks are typically ~3 m high and riparian forest trees are typically ~10 m high, riparian forest has the most dramatic effect on water temperature where the bankfull width is less than ~20 m. Where the bankfull width significantly exceeds 20 m, even tall riparian forest will not shade the low flow channel (or pools) when these occur midway between the banks. The channel (or pools) often occur close to steep banks at the outside of sharp bends, where they may be shaded by the banks and riparian forest. Nevertheless, in large rivers like the Mary main stem there are long lengths of channel that are poorly shaded. This does not mean that we cannot provide temperature refugia in such large main channels. Small tributaries immediately upstream from their confluence with the main channel could be the focus for revegetation. Cool water from small, shaded tributaries could provide localised temperature refugia in the main river just below the tributary confluences. These temperature refugia may only be important for a few hours each day during extremely hot years, but the lack of a suitable refuge from high temperatures could limit the suitability of a whole reach for temperature sensitive biota.

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