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Restoring pasture streams in New Zealand: can computer models help?

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SUMMARY: Nuisance blooms of attached filamentous algae occur occasionally in eutrophic pasture streams during summer low flow. An important management issue is whether restoring stream shade will reduce water temperatures, maintain grazing insects and prevent algal blooms. A combination of experimental studies and computer modelling shows that temperature sensitive insect grazers (notably the mayfly *Deleatidium*) can prevent algal blooms provided temperatures remain below 20°C and flows remain stable. However, it is predicted that algal blooms may occur following spates, because spates reduce grazer biomass. Snails (notably *Potamopyrgus*) are more tolerant of high temperature and can prevent algal blooms below c. 30°C but appear to have a lower re-colonisation rate following spates than mayflies. Thus streams with a high incidence of spates are susceptible to prolonged algal blooms when water temperatures exceed 20°C. Computer modelling predicts that 70% shade restoration (c.f., 95-98% shade in forest streams) may be sufficient to maintain water temperatures below 20°C in temperate climates. This level of shade will help prevent algal blooms during steady flows but will not eliminate post-spate blooms.

MAIN POINTS

- restoration of 70% shade is predicted to maintain temperatures below the upper limit for sensitive grazing insects.
- 70% shade will help prevent algal blooms in eutrophic pasture streams during steady flows.
- algal blooms may still occur after spates which reduce grazer biomass.
- dense shade (c. 98%) is needed to prevent blooms following spates.

1. INTRODUCTION

Unshaded streams occasionally exhibit nuisance blooms of attached (filamentous) algae during summer low flows. Aquatic insects (e.g., mayflies and snails) exert strong grazing pressure on algae and can prevent nuisance blooms during low flows (Welch *et al.* 1992). However, many important insect grazers (notably mayflies) have low thermal tolerances and their reported absence from unshaded pasture streams in New Zealand is probably the result of high water temperature (Quinn and Hickey 1990). High stream temperatures may release algae from grazer control, thereby enabling nuisance blooms to occur. An important management issue is whether restoring stream shade will reduce water temperatures, maintain grazing insects and prevent algal blooms. This paper describes two complementary approaches to this issue and uses findings from a multi-disciplinary study of small pasture streams near Hamilton. First, the thermal tolerance of sensitive grazers is measured in the laboratory and a computer model (STREAMLINE) is used to predict the level of riparian shade required to maintain stream temperatures below this limit. Second, an ecosystem model (SAL) is used to predict the combined effects of stream temperature, riparian shade and floods on periphyton and grazer biomass, and to investigate the potential for riparian shade to prevent algal blooms.

2. THERMAL TOLERANCE OF INSECTS

In a laboratory study Quinn *et al.* (1994) exposed mayflies (*Deleatidium* spp.) to constant temperature and found that 50% died after 96 hours exposure to 23°C. Mayflies were the most sensitive grazers tested. We postulate that if stream temperatures are low enough to support a wide range of grazers then there will be high grazing pressure on algae and less likelihood of algal blooms.

The question arises how temperature limits derived from constant temperature laboratory experiments should be applied in streams which exhibit a diurnally-varying temperature profile. To ensure 50% survival is it necessary for the daily mean or the daily maximum to be less than 23°C? We exposed mayflies to constant and diurnally varying temperatures (± 5°C) in the laboratory. Whereas 50% survived at a constant temperature of 25°C (c.f., Quinn's 23 °C) only 10% survived 25 ± 5°C, but 85% survived 20 ± 5°C (Figure 1). From the constant temperature results we might postulate a limit of 25°C to ensure 50% survival for 96 hours. If this limit is applied to the daily mean temperature in a stream where temperature varies diurnally, it is likely to provide rather poor protection. On the other hand, if the same limit is applied to the daily maximum temperature, it is likely to be conservative. The limit needs to be applied to a temperature intermediate between the mean and

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maximum. We are currently testing a computer model which will enable an appropriate limit to be set for any specified diurnally varying temperature regime based on mortality rate measurements made at a range of constant temperatures.

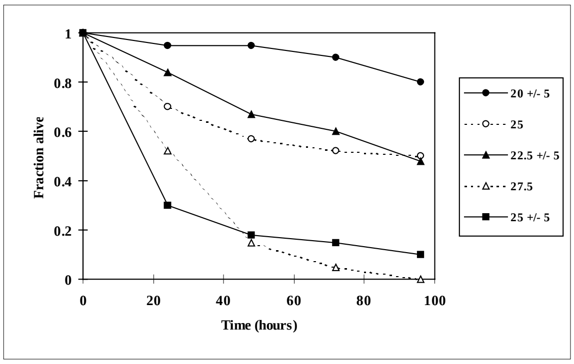

Figure 1: Mayfly mortality measured in the laboratory over 96 hours at constant (dashed) and diurnally varying (solid) temperature.

3. TEMPERATURE MODELLING

In small pasture streams, banks and hillsides contribute significantly to shading. None of the currently available models (e.g., Theurer *et al.* 1984) is suitable for modelling temperature in small streams and so we developed our own model (STREAMLINE) which assumes steady flow but predicts diurnal and day-to-day temperature variations. The model quantifies shading by riparian vegetation, hillsides and streambanks. It has been tested in a small pasture stream, using field measurements which include water and bed temperatures, shade levels (measured directly using a pair of canopy analyzers, Davies-Colley and Payne 1997) plus short and long-wave radiation fluxes into and out of the channel. Observed and predicted temperatures match closely (RMS errors 0.3-0.4^{o}C [calibration] and 0.3-0.5^{o}C [testing]). There is also a close match between observed and predicted long-wave radiation fluxes at night but an unexplained discrepancy in short-wave fluxes during the day. Details of the model and experimental data are published elsewhere (Rutherford *et al.* 1997).

4. SHADE TARGETS FOR INSECTS

Figure 2 shows daily maximum and minimum summer temperatures predicted by the STREAMLINE model in 1st, 2nd and 3rd-order streams flowing from heavily shaded native bush into pasture. Maximum temperature increases with distance because of increased solar radiation but the rate of heating decreases with increasing stream size because, for a given surface heat flux, the rate of change of water temperature is inversely proportional to mean depth. Eventually temperature reaches a dynamic equilibrium when heat gains balance heat losses, and thereafter daily maximum temperature does not change with distance. The maximum equilibrium temperature varies inversely with stream order. Daily minimum water temperature hardly changes with distance downstream and is independent of stream size.

One possible limit on temperature to protect sensitive organisms is 20^{o}C. Figure 2 indicates that in streams flowing out of dense shade into pasture where shade is 50%, daily maximum temperature is likely to reach 20^{o}C within 250 m (1st-order), 500 m (2nd-order) and 1.5 km (3rd-order). For 70% shade these distances increase to 500 m (1st-order), 1.5 km (2nd-order) and 5 km (3rd-order). In the Whatawhata study area 1st, 2nd, and 3rd-order streams are typically 1 km, 2 km and 5 km long. Thus 50% shade is probably sufficient to maintain daily maximum temperatures below 25^{o}C but not below 20^{o}C, whereas 70% shade seems likely to maintain temperatures below 20^{o}C in 2nd and 3rd-order streams, but not in 1st-order streams. Shade levels to total radiation under plantation pines and native forest are typically 90-96% (authors' unpublished data) but our predictions suggest that it may not be necessary to restore shade to these high levels in order to reduce water temperatures.

In small pasture streams (channel width c. 2 m) trees planted in the riparian zone are likely to achieve complete canopy closure even if they are set back from the edge of the channel (a sensible precaution in case of channel meandering or bank instability). Measurements in managed plantation stands indicate that shade levels of 70% occur where trees are planted 7-10 m apart (authors' unpublished data). Additional shading may be provided by the stream banks so that trees may be planted 10 m apart or more. This is a desirable spacing which allows light to reach the banks and maintain groundcover (e.g., ferns, grasses etc) which helps stabilize the channel against erosion (Davies-Colley 1997).

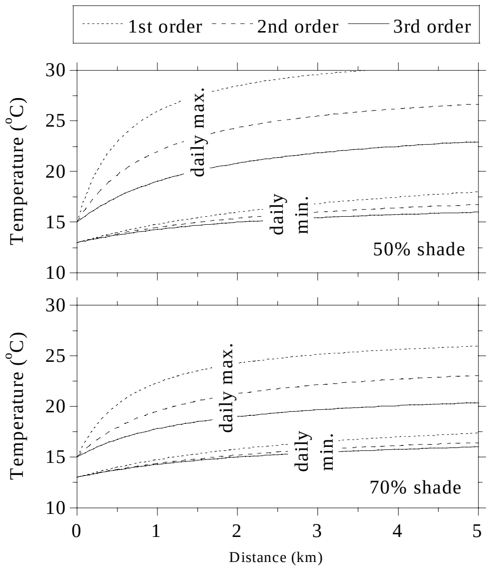

Figure 2: Changes of daily maximum and minimum water temperatures in 1st, 2nd and 3rd-order streams flowing out of native bush into pasture.

5. ALGAE-INSECT MODELLING

We are currently developing a computer model (SAL, Stream ALgorithm) which predicts the biomass of stream algae and grazing insects. The objective of this modelling is to better understand how variations of light, temperature and flow influence algal and grazer biomass. SAL is a refinement of the model of McIntire (1973) and has been calibrated using results from our laboratory experiments on grazer feeding rate and field measurements of biomass.

Figure 3 shows steady-state biomass predicted by the model for the simplified problem of a single idealised diatom population grazed by a single idealised mayfly population. In the model diatoms and mayflies have upper temperature limits of 28°C and 23°C respectively. Above 23°C the mayfly is predicted to die out and, in the absence of any other grazer, the diatom blooms. Simulations have also been made with snails (upper temperature limit 32°C) and filamentous green algae (optimum temperature c. 25°C). At steady-state snails are predicted to prevent diatom filamentous at all temperatures, but green algae can escape grazing control by snails above 32°C.

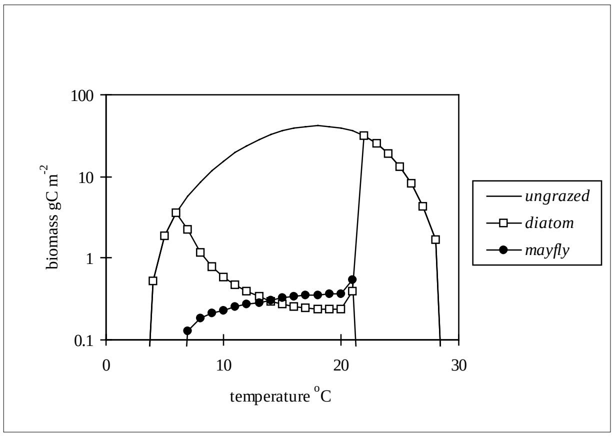

Figure 3: Steady-state model predictions of diatom and mayfly biomass as a function of temperature in an unshaded stream. The solid line (no symbols) denotes diatom biomass in the absence of grazers, open squares denote diatom biomass in the presence of grazers, and solid squares denote grazer biomass.

These simulations support the hypothesis that algal blooms can occur if high temperatures reduce mayfly numbers and snail numbers are low. They also suggest that below 20°C mayflies have the potential to prevent algal blooms. These conclusions are simplistic for at least two reasons. First, when flow and temperature are constant (as in spring-fed streams) the model predicts that algal and grazer biomass undergoes natural, periodic fluctuations ('boom-bust' cycles) with occasional algal blooms. The amplitude and frequency of these cycles depends on the stream temperature, whether or not there are 'refuges' where algae can escape from grazing (e.g., high current regions), and the rate of re-colonisation by drift. We are not yet able to quantify these processes precisely in our study streams but preliminary estimates suggest that cycles have a frequency of 6-12 months. Such natural 'boom-bust' cycles may be important in spring-fed streams where flows are stable but are probably not important in pasture streams, which experience regular spates.

Second, floods periodically 'reset' algal and grazer biomass. While floods might be perceived as beneficial in maintaining low algal biomass, the model predicts that after a flood there is often a period when algae proliferate. This occurs because floods reduce grazer numbers, which take time to build up again. When this occurs there is a short-lived 'post-spate' bloom, as illustrated in Figure 4. The flood resets algal and grazer biomass to 0.1 & 0.01 gC m^{-2} respectively. Immediately after the flood there is an algal bloom lasting c. 20 days before grazer numbers build up and control the bloom. The severity and duration of the 'post-spate' bloom varies depending on the grazer biomass surviving the flood and the rate of re-colonisation by drift from upstream. Streams which experience regular spates usually contain few snails whereas mayflies have the ability to re-colonise streams quickly after a spate. One implication of our modelling work is that if snails are prevented from reaching high biomass (by regular spates and low re-colonisation rates) then streams will be susceptible to algal blooms when water temperatures exceed 20°C and reduce mayfly grazer activity.

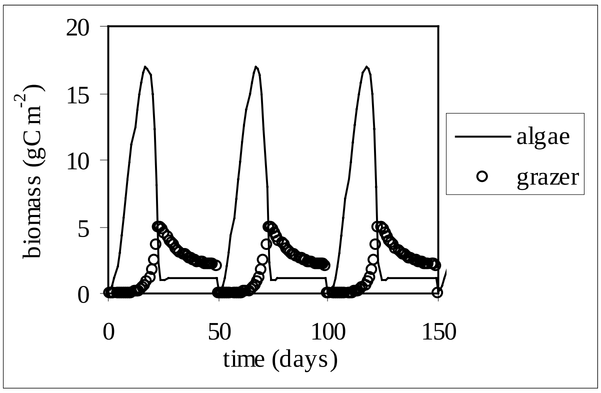

Figure 4: Variations of algal and grazer biomass predicted using the SAL model in an unshaded stream at 20°C with a flood every 50 days.

6. SHADE TARGETS FOR ALGAE

Shading reduces the light available to algae with consequent effects on growth rate and biomass. Figure 5 shows predicted algal and grazer biomass at three light levels. Light levels of 1000 W m^{-2} occur at unshaded sites and 25 W m^{-2} in dense forest (98% shade). In unshaded streams 'post spate' blooms reach 17 gC m^{-2}, at 95% shade blooms are still c. 10 gC m^{-2} and shade of 98% is required to ensure that maximum biomass remains below 5 gC m^{-2}. These simulations indicate that very high levels of riparian shade may be required to prevent 'post spate' algal blooms from occurring.

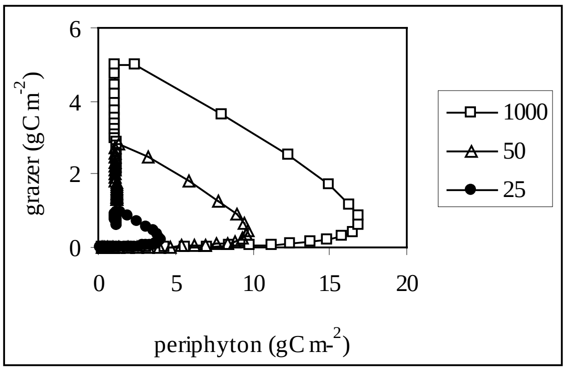

Figure 5: Predicted algal and grazer biomass for three different levels of shade with floods every 50 days. Incident light is 1000 W m^{-2} (unshaded), 50 W m^{-2} (95% shade) or 25 W m^{-2} (98% shade).

7. CONCLUSIONS

Laboratory studies indicate that sensitive insect grazers require stream temperatures below c. 20°C and recent work will help quantify temperature limits when there is a large diurnal variation in stream temperature. The STREAMLINE computer model predicts that for 2nd and 3rd-order streams in temperate climates, restoring shade to c. 70% may be sufficient to maintain temperatures below the 20°C limit and thereby safeguard sensitive grazers. Thus it may not be necessary to restore shade levels to those typical of native forest streams (95-98%) to maintain a diverse grazer fauna which may help prevent algal blooms. The ecosystem computer model SAL predicts that sensitive grazing insects (notably mayflies) have the potential to prevent algal blooms provided temperatures remain below 20°C and flow is steady. However, the model predicts that algal blooms may occur following spates which reduce grazer biomass and provide an opportunity for algae to escape from 'top-down' control. It is predicted that dense shade (c. 98%) is required to prevent such post-spate blooms.

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