MICROCLIMATIC EXTREMES UPSET AQUATIC MACROINVERTEBRATES IN TROPICAL, MONTANE LOW ORDER STREAMS

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ABSTRACT

Microclimates are vital to endemic aquatic ecosystems, especially in the extreme seasonality of wet and dry periods, so typical of the Tropics. Existing shading of low order, montane streams is of utmost importance to aquatic biota because for these temperature sensitive taxa, riparian vegetation offers a buffer from extreme climatic conditions. To investigate the likely future impacts on these aquatic communities, baseline knowledge on how microclimatic conditions are affecting existing aquatic taxa is crucial. To test this idea, twelve stream segments within three ecotone site types were selected for analysis: rainforest/stream edge, regrowth/stream edge and grazed/stream edge in two tropical headwaters of the Barron and North Johnstone River in the Wet Tropics of North Queensland, Australia. Within each 1-ha site microclimatic measures were captured simultaneously at paired midstream and orthogonal transects (water and air temperature, RH, solar radiation). Concurrently, aquatic macroinvertebrate kick net samples were taken in five pools and five riffles habitats along the included 100m stream section as including other physical ecotone data. Thermal environments along grazed stream edges were found to be significantly hotter than those existing in regrowth forests. In contrast, native tropical rainforest-stream edges were quite dynamic and often unpredictable. The dominant aquatic macroinvertebrate groups found, showed distinct sensitivity responses (changes in persistence, stability, community structure) to the thermal extremes in these trialed ecotones. These results indicate that closed forest-stream edges provide thermal protection to headwater streams and their thermal-sensitive aquatic fauna, reducing in-stream channel thermal conditions by up to 1.5 degrees compared to just 30m of exposure without substantial tree cover. Improvements in water quality, using macroinvertebrate communities as surrogate, are not only strongly linked to decreases in water temperature, but also to local climatic conditions created by lateral and longitudinal ecotone vegetation. Thus suggesting healthy stream biota are strongly linked to canopy closure with long riparian buffers and protection of headwaters. Expectations of riparian buffer zones, to uphold stream conditions and support their aquatic biota, under the increasing pressures of climate change in the Wet Tropics, need to be moderated by knowledge of (1) quality and dynamics of riparian vegetation, and (2) spatial arrangement of riparian networks within a catchment.

Introduction

In the wet tropics, stream temperature is affected by many more different factors than in the temperate zones. Rainforest covered catchments are the link to healthy river systems. That is what we could expect in the Wet Tropics (WT) World Heritage Area (WHA) in the north-eastern Queensland, Australia**.** Past climate change advanced the distribution of high-diversity rainforest and its unique biota, where dry phases restricted the rainforest to the highest mountain peaks (e.g. Mt Hypipamee, Bellender Ker, Bartle Frere) and uplands, including the Atherton Tablelands (Hopkins *et al*. 1993 in Krockenberg *et al.* 2003). Today we find a fragmented landscape with a matrix of landuse (agriculture and grazing) interspersed with intact remnants. Clearing in the recent past (80-100 years ago) divided the rare rainforest types across upland catchments and reduced them to small strips of riparian vegetation, abruptly changing their connectivity, width and length while generating hardened edges. The ecotones created are typically between the stream, the stream-side vegetation and the landuse, altering the thermal regime (reduced moisture, greater temperature extremes see Chen *et al*. 1999) of these montane, tropical streams.

Whether a stream runs hot or cold depends critically on the amount of solar radiation reaching the stream channel as modified by streamside shading. When investigating river temperature, the many dynamics can be classified into five key factors, in accordance with the tropical streams under investigation (see Fig.1):

(i) **Atmospheric conditions** are responsible for the heat exchange processes at the water surface, including changes in phase, rainfall and cloud interception, which at high altitude sites (>1000m) in the WT, is significant. Upper montane cloud forests (e.g. Mt Hypipamee) have a positive net water balance right through the year, yielding it an important source of dry season river flows and their remarkably large annual run off (~6500 mm year-1) is a key source of downstream water (McJannet *et al.* 2007).

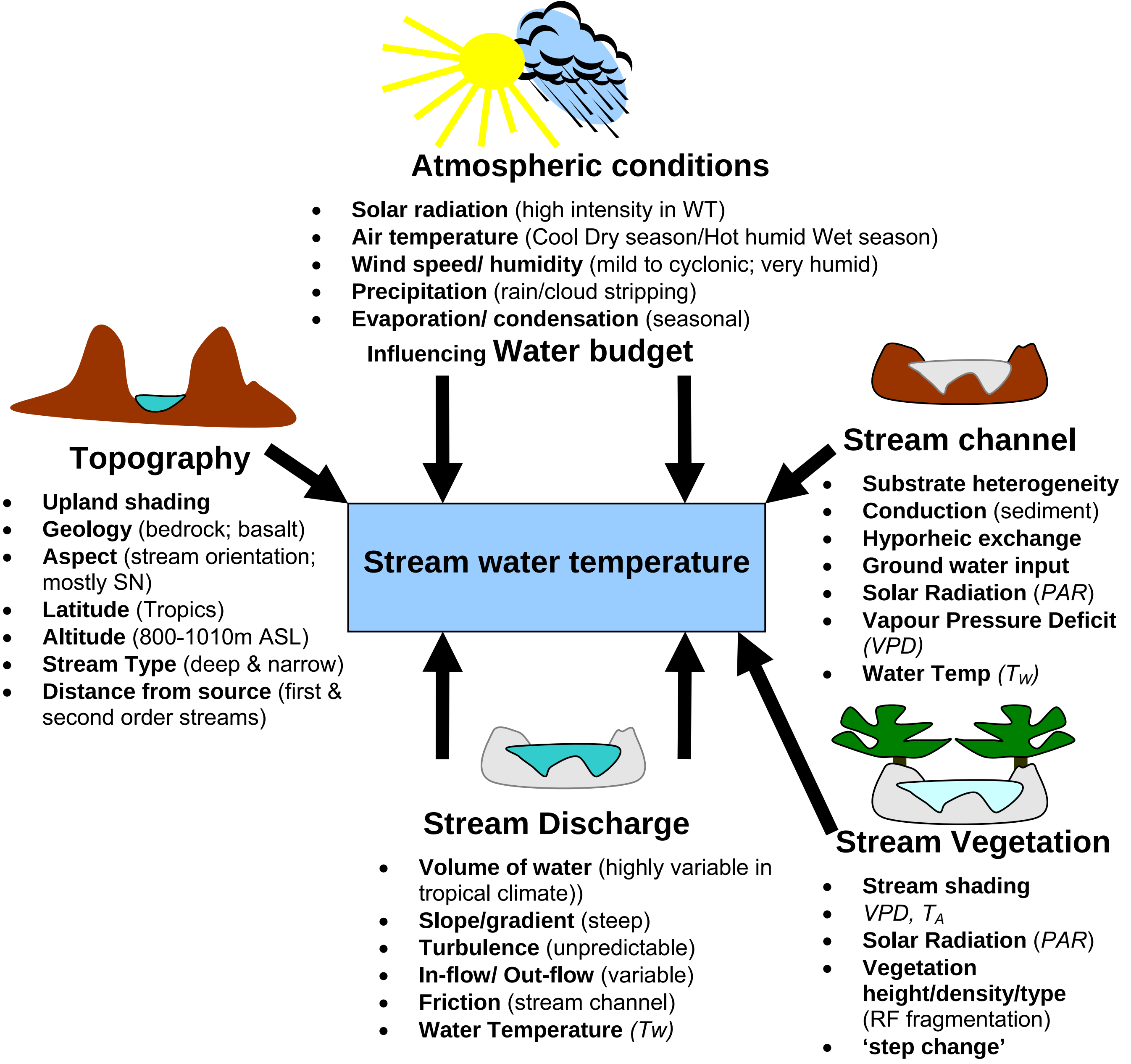
(ii) **Topography** or geographical setting (influences atmospheric conditions): in montane WT we find deep valleys surrounding Mt. Hypipamee with sharply descending slopes. In the tropics, where solar intensity and orientation are rather different to other parts of Australia, riparian shading can reduce the effectiveness of riparian and bank shading (Marsh *et al.* 2005).

(iii) **Stream-side vegetation** is impacted by the effects of rainforest fragmentation in the WT creating new, sealed edges; increasingly common in tropical river-scapes.This effect reduces moisture availability for the ecotone, and adds to greater temperature extremes (Chen *et al.* 1999). The interactions between vegetation condition and stream health are complex and often non-linear (e.g. Karr, 1999).

(iv) **Stream channel** defines the type of stream creating certain thermal conditions. For example here the deeply incised, narrow montane streams have the potential to be easily shaded by topography and streamside vegetation, even tall grasses (e.g. Quinn *et al.* 1997 in Rutherford *et al* 2004)

(v) **Stream discharge** is mostly a function of river hydraulics (e.g. in/outflow influences the heating capacity (volume of water) and/or cooling through mixing with e.g. cooler ground water). In small montane streams of the WT, these first to third order streams are influenced by cooler groundwater at the source.

Fig 1. ***Land- biosphere- atmospheric interactions:*** Factors influencing the thermal regime of rivers in the Wet Tropics (modified from Cassie 2006)



Atmospheric conditions

- **Solar radiation** (high intensity in WT)
- **Air temperature** (Cool Dry season/Hot humid Wet season)
- **Wind speed/ humidity** (mild to cyclonic; very humid)
- **Precipitation** (rain/cloud stripping)
- **Evaporation/ condensation** (seasonal)

Influencing Water budget

Stream water temperature

Topography

- **Upland shading**
- **Geology** (bedrock; basalt)
- **Aspect** (stream orientation; mostly SN)
- **Latitude** (Tropics)
- **Altitude** (800-1010m ASL)
- **Stream Type** (deep & narrow)
- **Distance from source** (first & second order streams)

Stream channel

- **Substrate heterogeneity**
- **Conduction** (sediment)
- **Hyporheic exchange**
- **Ground water input**
- **Solar Radiation** (*PAR*)
- **Vapour Pressure Deficit** *(VPD)*
- **Water Temp** (T_W)

Stream Discharge

- **Volume of water** (highly variable in tropical climate))
- **Slope/gradient** (steep)
- **Turbulence** (unpredictable)
- **In-flow/ Out-flow** (variable)
- **Friction** (stream channel)
- **Water Temperature** *(Tw)*

Stream Vegetation

- **Stream shading**
- *VPD*, T_A
- **Solar Radiation** (*PAR*)
- **Vegetation height/density/type** (RF fragmentation)
- **'step change'**

The five factors above show the overall interactions between the land, biosphere and atmosphere which cover principally spatial and temporal variability in stream microclimates. This Includes the landscape setting from a large (bioregion, catchment, subcatchment) to a small scale (e.g. reach, pools-riffles).

At a spatial scale**,** the overall thermal conditions for small tropical, montane streams need to include some other observations, like:

- the mean daily water temperature increases in downstream direction (longitudinally) as the stream order increases (Cassie 2006); the increase in water temperature (T_W) is not linear and the rate of increase is greater for small streams than for large rivers (e.g. Ward 1985; Rutherford *et al.* 2004).
- Connection within and between waterways (upstream-downstream effects, lateral flow influencing longitudinal flows) modify stream temperature potentially dissimilar in the tropics (e.g. Vannote & Sweeney 1980).
- these linear relationships are modified by '*step changes'*, where the stream moves abruptly from one state to another (e.g. flows through sharp boundaries of vegetated to un-vegetated parts of the catchment) (Rutherford *et al.* 2004; Marsh, Bunn & Rutherford 2005)

On a temporal scale, water temperature varies following both, diel and annual cycles. Daily changes reach a daily minimum in the early morning (at sunrise) and a maximum in late afternoon to early evening (at sunset). The solar azimuth in these WT zones is at 11.19 am when the sun reaches its highest point in the sky, with the highest intensity of solar input. The daily variations (daily minimum-maximum) are generally small for cold headwater streams and increase for larger streams (less dominated by groundwater, more meteorological input) (Cassie 2006). In montane headwater streams in the WT these diel and annual cycles have been only partially assessed to date (e.g. Pearson & Dawson 2001; McJannet *et al*. 2007).

Overall, a measured change in water temperature (T_W) will depend on ambient solar radiation (measured as photosynthetically active radiation or *PAR*), air temperature (T_A) and vapour pressure deficit (*VPD*) - a measure of healthy vegetation condition and living space for aquatic insects as a function of T_A and relative humidity (*RH*) (see Fig.1). These microclimatic settings regulating air and water temperature, and other important stream parameters (e.g. *DO, pH*) within the ecotones dictate where aquatic fauna can and will live (e.g. Connolly *et al*. 2004; Marsh *et al.* 2005).

Stream water temperature does link up with aquatic habitats intrinsically. The connection between microclimatic conditions and macroinvertebrates lies in their needs as Ectotherms. These insects are cold-blooded and need external heat sources to regulate their temperature balance and metabolic rate. Therefore, the surrounding environment envelopes a specific tolerance of thermal ranges for aquatic larvae (often with terrestrial adult lives) making them totally dependent on their aquatic-terrestrial ecotone (Marsh *et al.* 2005; Cassie 2006).

In tropical Australia, stream temperatures experience erratic fluctuations with unpredictable wet and dry seasons (e.g. cyclones, bushfires) exposing streams to meteorological impacts. Therefore, existing shading of low order, montane streams is of utmost importance to aquatic biota because for these temperature sensitive taxa, riparian vegetation offers a buffer from extreme climatic conditions (e.g. heat exchange, diurnal temperature ranges, solar radiation impacts). Sensitivity of responses by the local macroinvertebrate fauna can be assessed using measures of community structure (total abundance, richness (*H'*) and evenness (*J'*)), stability (defined by presence/absence of species) and persistence (changes in abundance) (e.g. Folke *et al.*2004; McKie *et al.*2004)

These microclimatic parameters, from spatial to temporal scale, are critical for stream health. The faster water temperature changes spatially (e.g. over reach length, through sub-catchments) and temporally (daily, seasonally), the poorer the stream health for its biota, and ultimately for us. Alarmingly, the recent IPCC (2007) report predicting the rise of novel climates by 2100 AD with add ional warming and high seasonality of temperature, primarily in tropical and subtropical regions.

With these thermal conditions as a reference for biotic responses, it is clear that overall climate change, impacting at regional and local scales, might have key consequence for already disturbed aquatic systems (e.g. landscape fragmentations in the WT). Variability in water temperature can occur naturally, or as a direct impact of anthropological disturbance (thermal pollution, deforestation, flow modification) or indirectly as climate change. In the 20th century, global mean surface temperature rose by about 0.3 to 0.6 ºC. This includes global and/or local experiences of modification in geographic seasonality, and in vertical atmospheric temperature (IPCC 2007; NASA GISS 2008). The prediction of a further change in our existing climate towards more extreme conditions is alarming. This includes a stepping up of extreme events (more frequent and intense heat waves, cold periods, wet and dry periods).

This paper focuses on a short investigation of the thermal conditions of montane, low order streams in the WT by using mostly one example: Gwynne Creek, Upper Barron Catchment in relation to the other field sites; this might provide some possible insights into the thermal conditions and potential implication on aquatic habitat with impending climate change scenarios in the WT.

Methods

Two upper montane rivers from the Wet Tropics bioregion in north-eastern Australia, on the Atherton Table subregion (see Fig 3), were assessed by using maps created in ARCVIEW to eliminate confounding variables. These maps consisted of data layers on climatic conditions, regional ecosystems, landuse, land cover types, vegetation types and extent, topography, cadastre and catchment hydrology based on Landsat (ETM+) imagery, aerial photography and GIS derived data (CSIRO Atherton),

The overall study design included the adjacent upper catchments of the Barron and North Johnstone River which are comparable in: total areas (2180km^2 / 2330 km^2), stream lengths (165km/145km) and altitudes (880 -1008 m ASL). Originating at the crater of Mt Hypipamee National Park (1050m ASL), these low order streams also share the volcanic geology and undulating topography of the basalt-derived Malaan soils (Nix 1991) and similar hydrology (see Fig 4). Originally, these upper catchments were covered by intact complex notophyll vine forest, type 5a, classified by Tracey (1982). All investigated streams are subject to a summer-high flow, winter-low flow seasonality. The prevailing landuse is grazing in this upper catchment matrix of remnant rainforest and regrowth.

The climate of the region is tropical and seasonal with 70% of the annual rainfall (annual mean ~ 1650 mm) falling during the warm, humid wet season (December-March). Stream discharge during this period is highly variable, whereas during the cool, misty dry season it is low and constant or steadily diminishing. Stream temperatures usually range from ~11ºC to 23ºC,

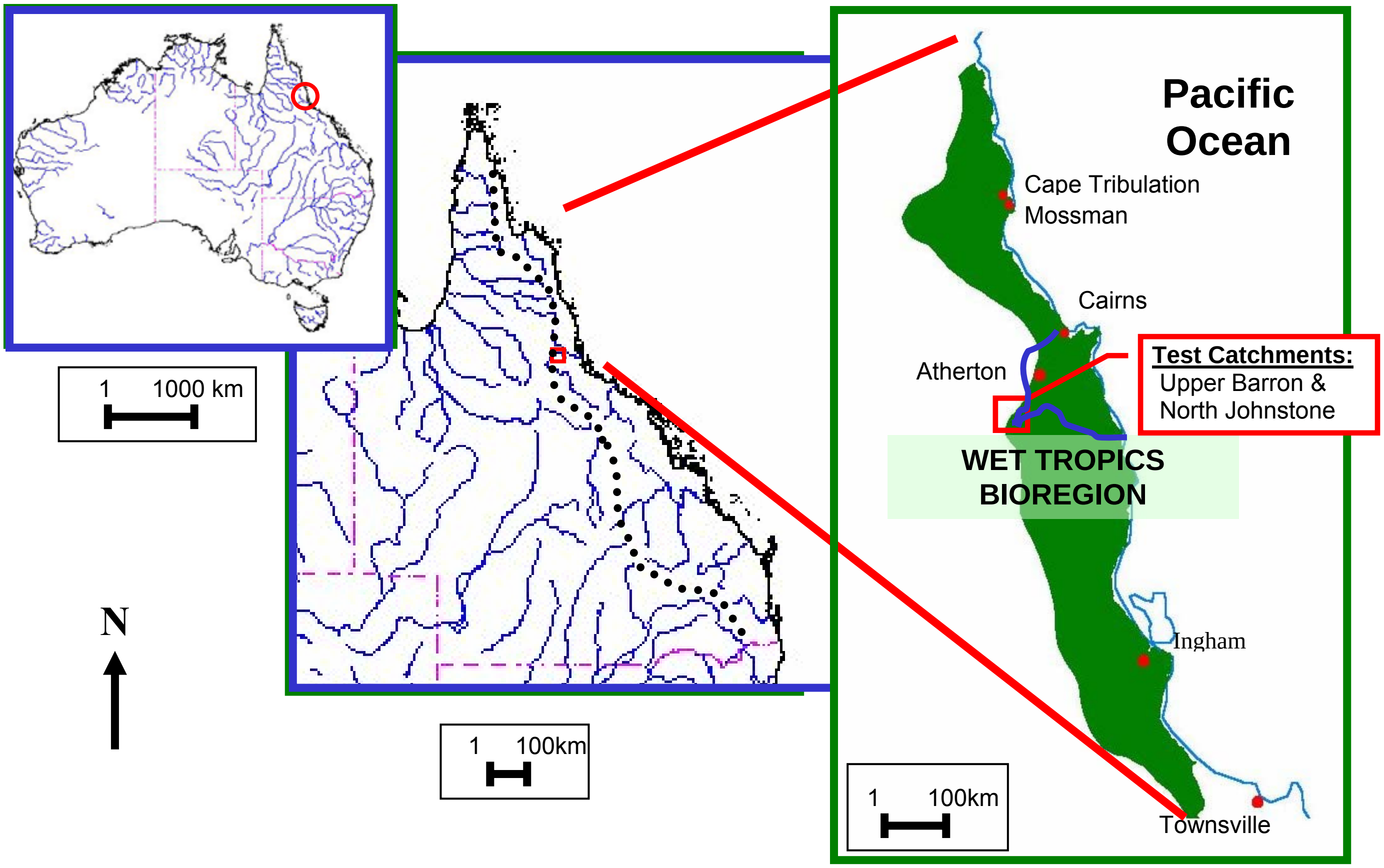


Fig.3 Drainage Maps of Australia, North Queensland and extent of the Wet Tropics World Heritage Area (WT WHA) with the two test catchment areas (Barron and North Johnstone River).

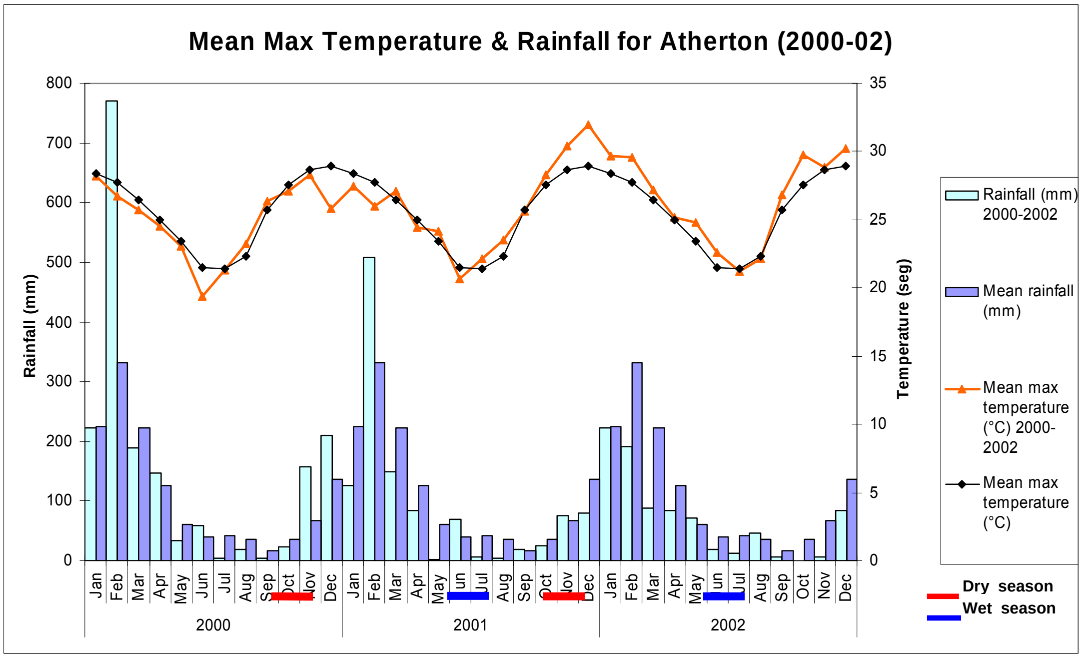


Fig.4 Mean monthly maximum temperature and rainfall over the sampling seasons (2000 -2002) from the meteorological station at Atherton, 782 m ASL (derived from data by BoM & NRW 2008). Bars represent late dry season (June/July) and late wet season (October/November) sampling months.

Samples were taken using a hierarchical sampling design incorporating four successive nested spatial scales (subcatchment, 1ha plot including a 100m reach, pools/riffles and sample). I chose four 1ha plots in the pre-selected upper catchments, including a 100m reach for each of three ecotone types:

- forested (at least 60 years of regrowth with intact canopy)
- riparian (at least 50m strips of remnants and grazing)
- cleared (with improved pasture and grazing)

These twelve sites were compared with a quite rare ‘control site’, or most ‘natural’ site, covered by intact endemic rainforest throughout its subcatchment (see Fig. 5 and Table 1 for details). Convergence from this reference (benchmark) can be assessed either directly or indirectly depending on the response variable of interest.

All thirteen sites included 100m stream sections of alternating pools and riffles originally (pre-fragmentation) with basaltic substrates of cobbles, gravel and sand. In each 100m reach, a sequence of five pools-riffles were checked for various physical and water quality parameters, and in each pool or riffle, I took one kick net sample (250 µm net) in an area of 1 m^2 for two minutes. This sample size was chosen because it allowed taking a higher number of samples for a given effort, to reduce the encountering of ‘zero values’ (Norris *et al.* 1992).

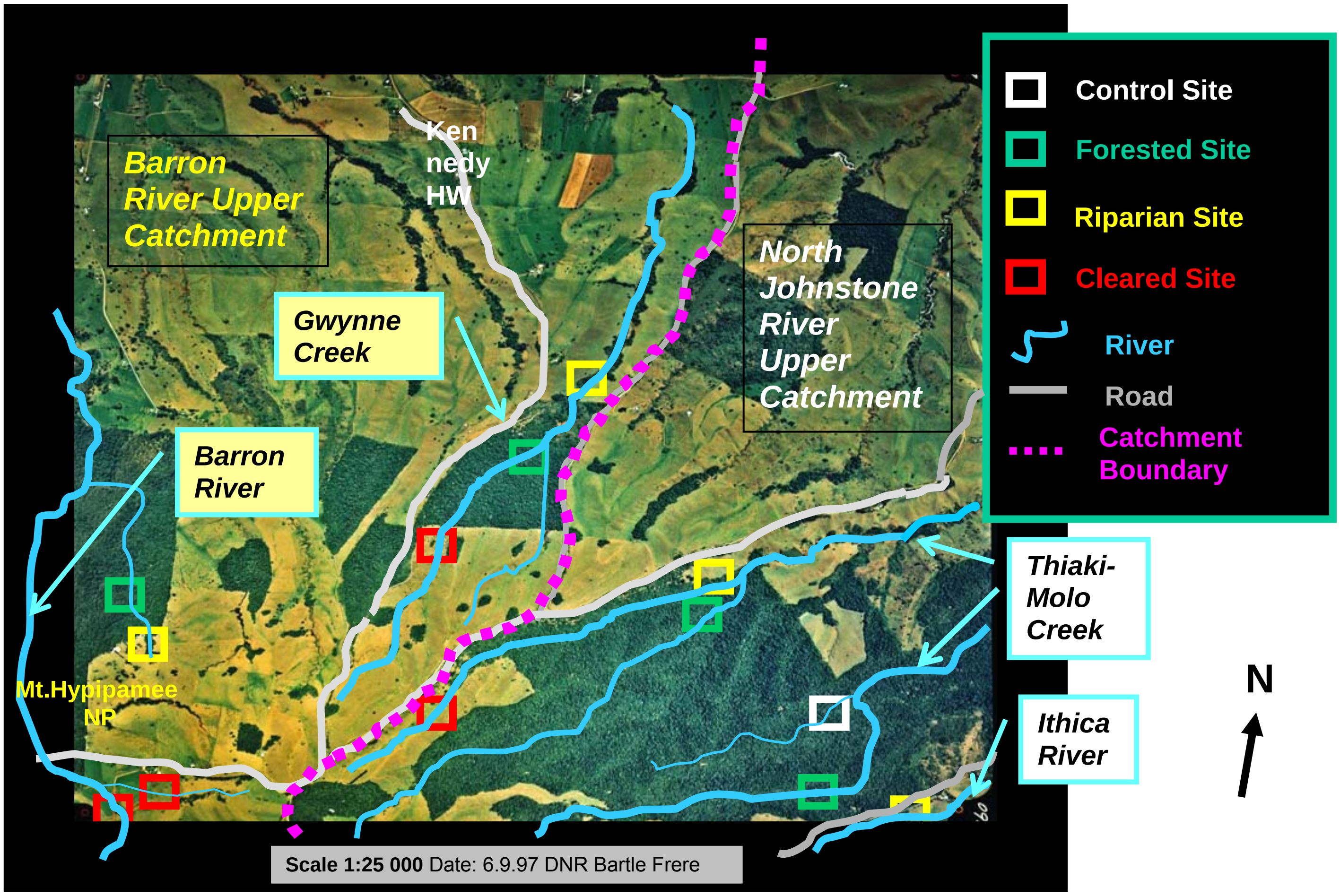


Fig.5 Aerial Map of sample sites in the upper catchment areas of the Barron and North Johnstone River system (Scale 1:25000, DNR (now NRW) 6.9.1997 Bartle Frere). This old map was used because of new fragmentation that occurred post 2002.

The study periods (see Fig.4) were chosen to fall in the late dry season (October-November) of 2000/2001 and late wet season (June-July) 2001/2002 due to distinct seasonal changes affecting the aquatic biota (Pearson 2005).

Table 1 Locations and summary of sampling sites (note **Gwynne Creek**)

Site Name	Upper Rivers	Creek	Lat (-S)*	Long (E)*	ASL* (m)	Orientation*
Forested						
F1	**Barron**	Unnamed	17° 26’ 22.2”	145°29' 58.8”	996	SN
F2	**Nth Johnstone**	Myola /Thiaki	17° 25’ 29.6”	145° 31' 58.1”	865	WE
F3: REF	**Nth Johnstone**	unnamed	17° 25’ 56.8”	145° 32' 34.2”	848	WE
F4	**Nth Johnstone**	Molo	17° 26’ 13”	145° 32' 19.7”	867	SSW-NNE
F5	**Barron**	**Gwynne**	17° 24’ 42.1”	145° 31'22.8”	885	SW-NE
Riparian						
R1A	**Nth Johnstone**	Thiaki	17° 25’ 20.6”	145°31' 50”	869	SWW-NEE
R1B	**Barron**	Unnamed	17°26’ 29.5”	145° 29’ 58.9”	1005	SN
R2A	**Nth Johnst**	Ithica	17° 26’ 19.6”	145°32' 27.2”	846	WE
R2B	**Barron**	**Gwynne**	17° 24’ 26.3”	145°31' 37.7”	837	SW-NE
Cleared						
C1	**Barron**	Raspberry	17° 26’ 39.4”	145°29' 55.1”	981	EW
C2	**Barron**	unnamed	17° 26’ 22.4”	145°30' 13.9”	995	SN
C3	**Nth Johnst**	Thiaki Ck	17° 25’ 43.5”	145°32' 58.1”	945	SWW-NEE
C4	**Barron**	**Gwynne**	17° 25’ 10.2”	145°30' 58.3”	986	SW-NE

* Stream orientation from source

Within each 1-ha site, ecotone microclimatic measures were captured simultaneously at paired midstream and orthogonal transects (see details in Fig.6 and Fig. 7).

Ecotone microclimatic parameters and structural variables assessed at site scale (1ha plots) are:

- **Microclimate in transects**
    - T_A, relative humidity (*RH), PAR; VPD* calculated from T_A and *RH*
- **Riparian vegetation**
    - vegetation structure - tree density/height, *DBH*
    - vegetation condition - % weeds,
    - vegetation cover - % canopy cover

In-stream microclimatic parameters assessed in the100m stream section are:

- **Stream morphology** (channel material)
- **Stream channel**
    - longitudinal morphology - pool-riffle ration, slope/gradient, flow rate
    - cross sections – width:depth ratio, channel bank slopes
- **Water Quality** (pH, DO, turbidity, conductivity, water temperature)
- **Macroinvertebrates**
    - aquatic larvae in kick net samples (for community structure: abundance (in this case the same as density), taxon richness, diversity, evenness; for resilience: stability and persistence metrics)

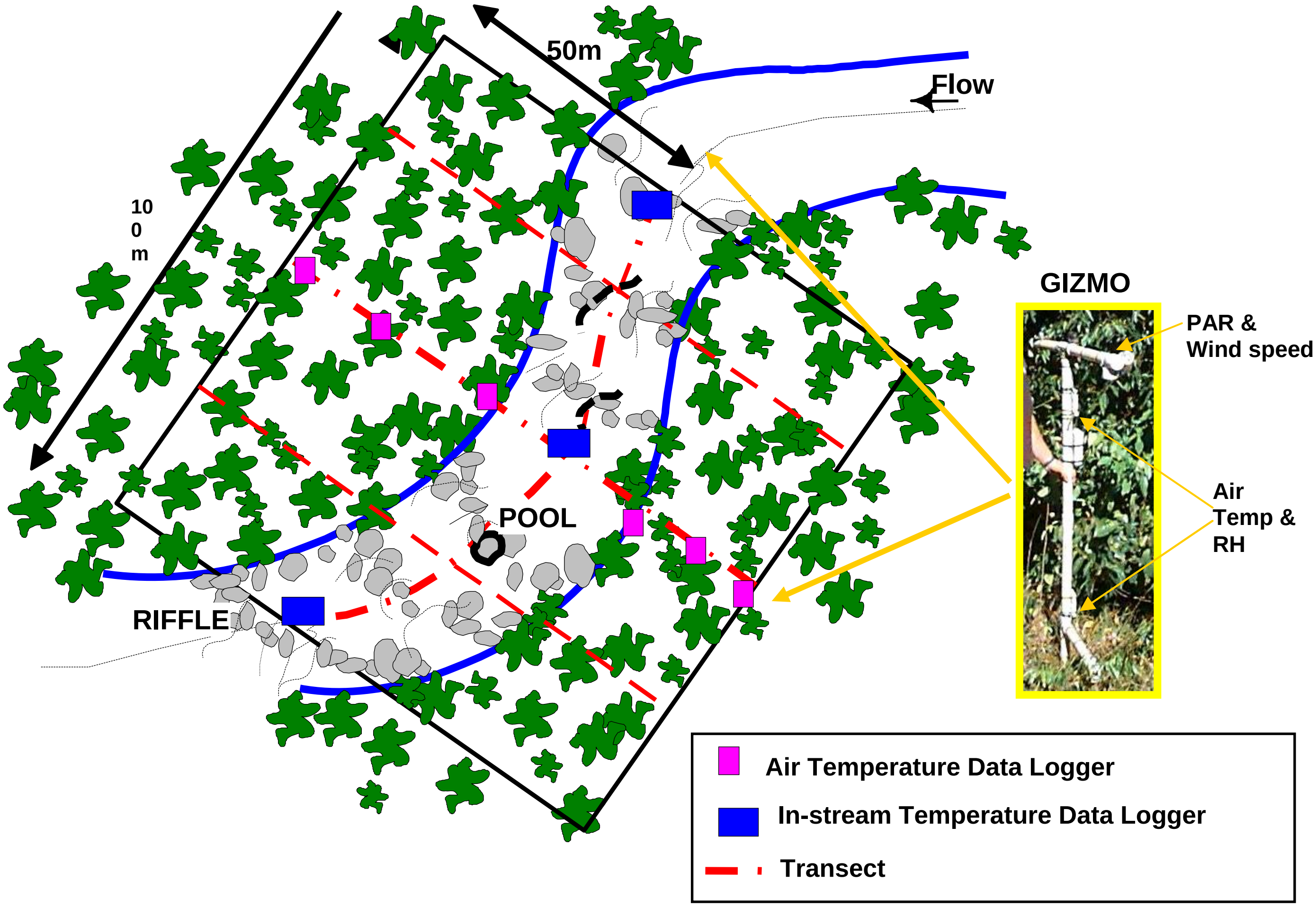


Fig.6 **<u>At 1-ha & point scale</u>**: sampling of various microclimatic, stream channel & riparian data including water quality measures in pools and riffles at all types of sampling sites.

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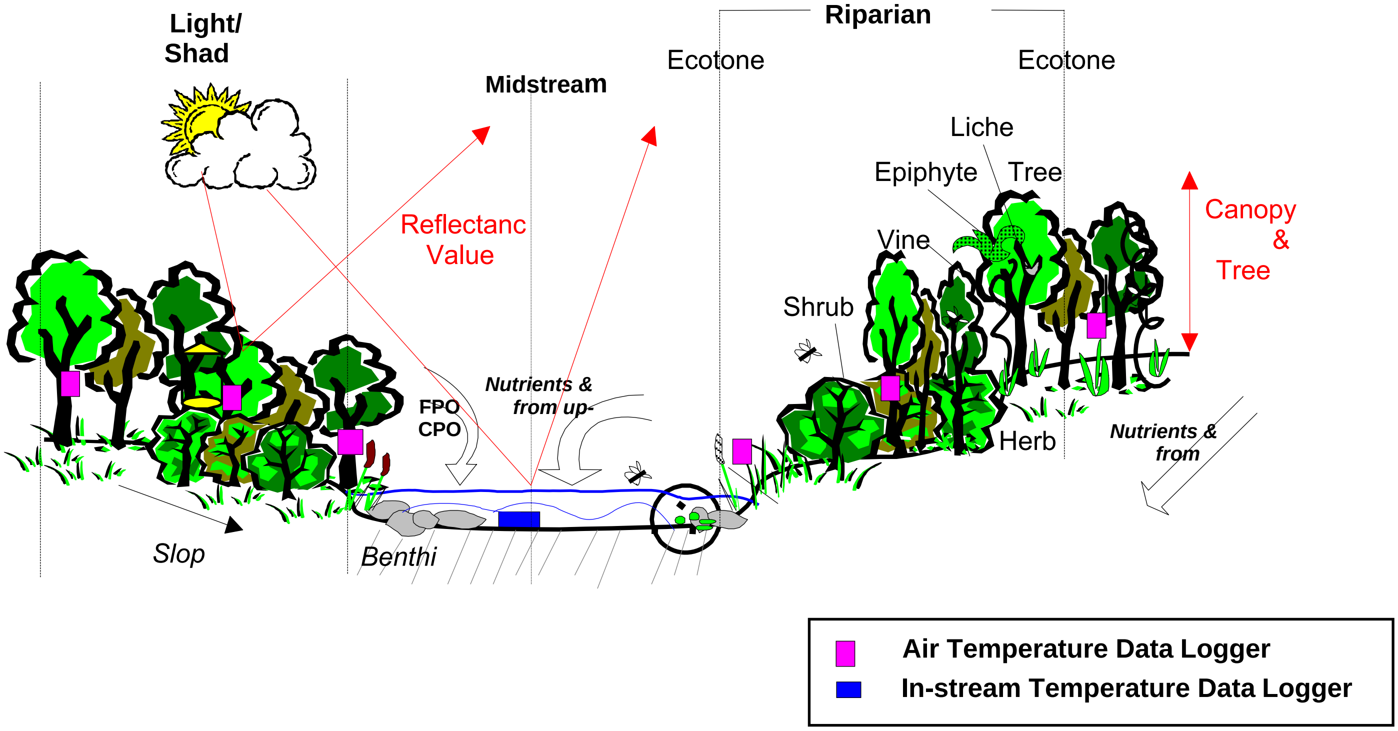

Fig.7 **<u>At 1-ha & point scale</u>** Vertical view of the orthogonal transects at 50m across the stream,

Concurrently, aquatic macroinvertebrate kicknet samples were taken in five pools and five riffle habitats along the 100m stream section while including other physical ecotone data (see above). The aquatic macroinvertebrate samples were immediately preserved in undiluted methanol and kept for the laboratory. Later they were sorted under the dissecting microscope, identifying all insects to family or genus (where possible to species or morpho-species) and counting the number of individuals per taxon in each sample investigated. Because of time restraints only one pool and one riffle sample (at midpoint of the100m stream reach) were chosen for identification to species or morpho-species level where possible.

For the purpose of this study, I focused on aquatic taxa from six dominant families (☚ 10 genera each) of macroinvertebrates found right across all field side types, seasons and years of sampling:, Hemiptera, Coleoptera, Diptera and PETs (Plecoptera, Ephemoptera, Tricoptera). PET indexes indicate river health according to AUSRiVas (NRW 2001).Two other orders, Decapoda and Gastropoda, while also common at all sites were not included in the dominant group because or their low numbers (≤ 3 genera each).

The dataset contained occurrence patterns (presence-absence) of 20 other taxa (class/orders) like Ostracoda , Decapoda, Megaloptera, Collembola, Cladocera, Copepoda, Neuroptera, Lepidoptera, Conostraca, Odonata, Hirunidea, Oligochaeta, Nematoda, Hydracarina, Arachnea, Platyhelma, Bivalva, Amphipoda, Hydroidea and Gastropoda) mostly from lower phyla and only occurring at low taxa numbers (≤ 3 genera each).

Various metrics were calculated for the identified taxa, including assemblage structure and density, as well as stability and persistence of taxa.

Aquatic macroinvertebrate assemblage structure (from dominant 26 taxa) was described using:

- **total abundance/density** (total number of individuals per sample equal to density since sample area of $1m^2$ was constant)
- **taxon richness** (number of taxa per sample)
- **evenness** (*J'=H' ln S*, *H'* is the Shannon's diversity index, *S* the taxon richness (see Magurran 1988).

Overall parameters for ecosystem resilience (Folke *et al.*2004) included measures across spatial and temporal scales for

- **Stability** - change in abundance (log transformed); larger changes indicate less stability
- **Persistence** - defined by presence and absence of taxa; higher persistence indicates a increased possibility of resilience in the system.

For the purpose of this paper these wide-ranging analyses of the aquatic taxa are restricted to some telling examples.

For the overall analysis, the data for the 13 sites were organised into three groups:
(i) Structural variables of types of riparian vegetation (ecotones) and in-stream samples
(ii) Microclimatic variables for ecotone and in-stream conditions (VPD, T_A, $T_{W,}$, PAR)
(iii) Aquatic macroinvertebrate assemblage measures (structure, density, stability, persistence)

Repeated within-site measurements collected and summarised for structural variables of riparian vegetation (%weeds, tree height (m)/density (trees/ha), shade or canopy density) and in-stream (, riffle-pool ratio, substrate, width:depth ratio; bank and stream channel slope) were averaged to create a mean value for each site within each treatment (forested, riparian, cleared and reference).

To further assess the pattern of bio-physical conditions among the 13 sites, I analysed the eight structural variables of riparian and in-stream ecotones using non-metric multidimensional scaling ordination (NM-MDS) in the multivariate PRIMER (2002) software package, Version 5. Analysis of similarity (ANOSIM) within PRIMER (a type of non-metric, multivariable ANOVA), was used to test the statistical significance of variation in bio-physical conditions amongst ecotone types. The data were standardised prior to and permutated (with 9999 iterations) to allow analysis by a Bray-Curtis Euclidian distance measure.

By using the same NM-MDS ordination approach for

- microclimatic conditions in the ecotone and in-stream sections and
- for macroinvertebrate community data (distinct riffle data)

a similar assessment approach was taken for selected thermal variables (*VPD, PAR*, T_A, T_W) and aquatic fauna metrics (community structure and resilience) prior to using the ordination. Additionally, the aquatic data prior to ordination was square root transformed to weigh down the influence of dominant species. Further, some variables were dismissed because of poor performance in the ordination.

In all analyses, the representations of two and three-dimensional NM-MDS solutions were compared using the stress value function with the ordination yielding the lowest value being preferred (Stress values of ~ 0.10 or less for a good ordination, less 0.05 is excellent, but rare). The higher the dimensional space, the more easily are results misinterpretation (PRIMER user manual 1994). The significance of separation of so-called site grouping on MDS plots were tested using ANOSIM (analysis of similarity) routine in Primer V.5, with alpha set at 0.05, Additional overlays of the ordination with environmental, microclimatic and macroinvertebrates variables (biplots) were presented as arrows in the plot after a randomized Monte-Carlo test and ANOSIM to determine their significance.

Results & Discussion

While a wide range of ecotone and aquatic microclimatic parameters were recorded over the total study, in this paper, I am focussed on selected overall results showing the effects of microclimatic extremes impacting on dominant aquatic biota (at family level). For this purpose, I am concentrating on the most prominent, general effects of microclimate on all study sites using Gwynne Creek sub-catchment of the Upper Barron River as a special case (Fig.5 & Fig.14;Table1).

In view of the sets used in the statistical analyses, the results are grouped into:
(i) **Structural parameters** for ecotone and in-stream conditions (NM-MDS ordination plot)
(ii) **Microclimatic derived variables** of aquatic-terrestrial ecotones for late dry season samples (NM-MDS ordination plot); and a special, spatial sub-set investigation at Gwynne Creek.

(iii) **Aquatic macroinvertebrate assemblage metrics** (structure including density, stability) for riffles only (NM-MDS ordination plot); while persistence was only explored in a descriptive way.

Thermal environments at the aquatic–terrestrial ecotone

Overall, the thermal environments along grazed stream edges (cleared sites) were found to be significantly hotter (higher level of radiant energy with more light reaching the stream channel for a larger part of the day) than those streams in regrowth forests with intact canopies. In contrast, native tropical rainforest-stream edges were found to be quite dynamic and often unpredictable. Possible reasons are that this rainforest has an old, inhomogeneous, often open vegetation structure (only up to 80% stream shading) with tall emergent trees, and tree falls at stream edges along steep stream channels. In contrast, the equal-aged regrowth forest shows a closed homogenised canopy cover, shading streams more deeply (up to 90%). Riparian sides are of a complex nature (with two ecotones – one with the stream, the other with landuse) and have not been further investigated here at site scale. These general results at landscape scale for cleared, riparian, forested and rainforest sites including wet/dry seasons over two years, are the back drop of the following NM-MDS ordination plots (n=52) at all seasons with an overlay (biplot) of bio-physical and thermal parameters. For ecotone and macroinvertebrate parameters, the data used for the ordination (n=26) was a combination of dry season (2000 & 2001) and wet season (2001 & 2002).

Ecotone and in-stream environment*: Structural Parameters*

To show the significant similarity of all field sites, a two dimensional NM-MDS ordination plot (Fig 8) depicts all ecotone sites as grouped by distinct site characteristics; it singles out the cleared sites as distinctly different to all others. The arrows represent the environmental variables (ANOSIM tested), to determine which structural variables describe best any of the ecotone types. The presence of **weeds** (% weeds) is a great indicator for **vegetation condition** (representing intact (< 5%), riparian (30-50%), cleared (<95%) and rainforest (<5%)). Additionally, to weeds, silt (up to 20 cm deep in some stream channels) clearly describes cleared sites. The result of highly significant (p<0.01**) descriptors of intact regrowth forest and rainforest are **vegetation condition and structure** (tree height and density) as well as **canopy cover** or **shade.** This corresponds well with the data where **tree height** for intact sites is 18-25m, while at the reference site tree heights range from 30 to 35m, with some emergent trees (up to 45m) and often with tree falls around the stream edge, thus opening up the above stream canopy. The **tree densities** for forested sites is at around 620 trees/ha and highly dense in the rainforest (950 trees/ha). Both vegetation variables (structure and condition) indicate the validity of shade (p<0.01**) as a factor for sites with regrowth forest (80-90%) and rainforest (70-80%).

The riffle-pool ratio, which was moderate (0.12) for cleared sites, indicates shallow, wide channels with slow flows and no great distinction between pool and riffle sites. This sets the contrast to the rainforest sites (0.14); but this variable is only mildly significant (p<0.05*) .Riffle-pool ratios were strongest at the rainforest sites (0.04) with their deep, narrow channels and fast flows. The channel material points to the importance of substrata type's ability to alter flow, velocity of streams and increase heat retention. Vegetation structure (tree height and density), vegetation cover and shading again emphasize the extremes between cleared pasture sites and the rainforest control site. Interestingly, in the late wet season exotic para grass (*Bracharia mutica*) is prominent at the cleared stream channels, and can grow up to 2 m high, shading the stream quite distinctly. Only DO, seen as a strong indicator of stream health, was not specifically significant to any of the sample sites. The stress of 0.11 for this ordination is acceptable when taking into account that the plot is in two-dimensional space making it easier to interprete the findings.

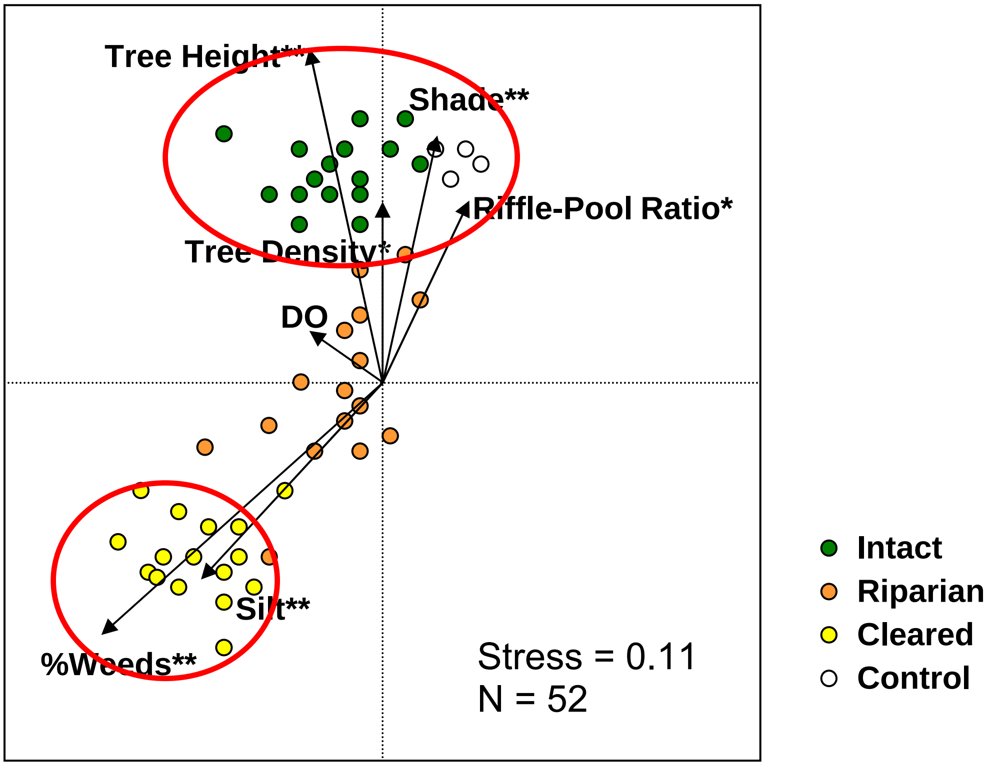

Fig 8 Ecotone and in-stream environment: *Structural Parameters*
2D Non-metric multidimensional scaling ordination (n=52, stress =0.11) of 13 ecotone sites (four of each Intact, riparian, cleared sites and one control site) over late dry/wet season from 2000-2002, in the WT area around Mt.Hypipamee NP, Atherton Tablelands in north-eastern Queensland, Australia. Arrows represent the significant biophysical, structural variables (ANOSIM $p<0.05$*; $p<0.01$**). The circles indicate a strong relationship between sites and variables.

Vegetation structure (especially %weeds) and condition, together with shading, varied significantly between densely forested ecotone sites (regrowth and riparian site), and was often inconclusive for riparian sites but distinctly different in cleared ecotones. Variation among sites and their ecotone nature indicate that riparian management and monitoring should be site type and reach specific.

Ecotone and in-stream environment*: Microclimatic Parameters*

After investigating spatially the bio-physical stream setting, I will now explore the spatio-temporal changes at the 1ha plot scale using seasonal and diel (day and night temperature) changes. Concentrating on all site data from the late dry (October-November) and late wet (June-July) season, the effects on thermal parameters of terrestrial microclimates and at the in-stream environments were tested, using ordination plots as previously described.

The overlaid variables used with all field sites, were: **seasonal microclimate effects in ecotone transects** (expressed as changes in ambient T_A, *VPD*, *PAR*) and **in-stream parameters over 100m sections** (using changes in T_W and mid-stream *PAR*) depicted as arrows with significance factors in the biplot below (Fig.9).

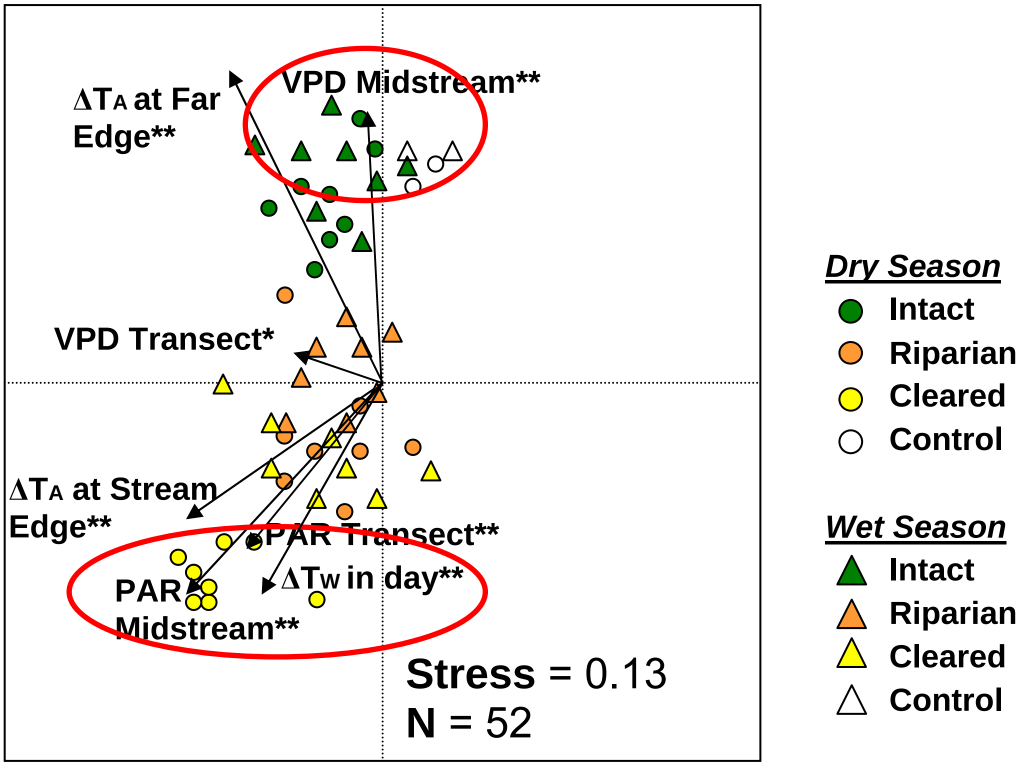

Fig 9 Ecotone and in-stream environment*: Microclimatic Parameters*
2D Non-metric multidimensional scaling ordination (n=52, stress=0.13) of 13 ecotone sites (Intact, riparian, cleared sites and one control site) divided into seasonal scale of two late dry (Oct-Nov) and two late wet (Jun-Jul) season from 2000-2002, in the WT area around Mt.Hypipamee NP, Atherton Tablelands in north-eastern Queensland, Australia. Arrows represent the significant microclimatic parameters measured in-stream and in orthogonal riparian transects (ANOSIM $p<0.05$*; $p<0.01$**). The circles indicate a strong relationship between sites and variables.

VPD (as a function of T_A and *RH*) is an important measure of healthy vegetation, and especially important for rainforests needing warm, and moist growing conditions. *VPD* is also an important factor for ectothermic, aquatic-terrestrial insects. The midstream *VPD* for forested sites and somewhat for the reference site is important in moderating stream temperature in the dry or wet season. This has also indications for the aquatic fauna, finding a less extreme thermal environment.

Also, the plot shows that there are clear differences between the seasons. Especially the dry season data has a definite grouping effect on the cleared sites (in *PAR* at transect/in-stream together with changes in diel temperatures). This points out the open-channel nature of these cleared sites right across the 1-ha plot, where they are exposed to higher solar radiation/intensity (at day time) with a fast cooling effect at night (no oasis effect see below).

A special case: *Gwynne Creek*

In a more detail investigation on diel temperatures at Gwynne Creek (not presented here), the midstream *VDP* was always higher compared to the ecotone transects, but more pronounced in the late dry. One explanation of this result could be the '*oasis effect'*, where riparian vegetation (especially with hardened edges) buffers the stream from abrupt temperature changes at the adjacent ecotone e.g. low cover pasture. While the air temperature cools in grassed sites, *RH* is high, in midstream the T_A stays warmer and consequently, *RH* rises. This keeps the stream 'warmed' by vegetation.

Additionally, I found in this case that the *VPD* between the late dry and the late wet season does change from year to year. This is not the case for *PAR*, which is more dependent on sun angle, topography and aspect. Gwynne Creek links all sample sites types (cleared – forested – riparian), and therefore all stream segments are sharing the same aspect (SW-NE), topography and solar angle (see Fig. 5 and Table 1), which results in very low differences for *PAR*.

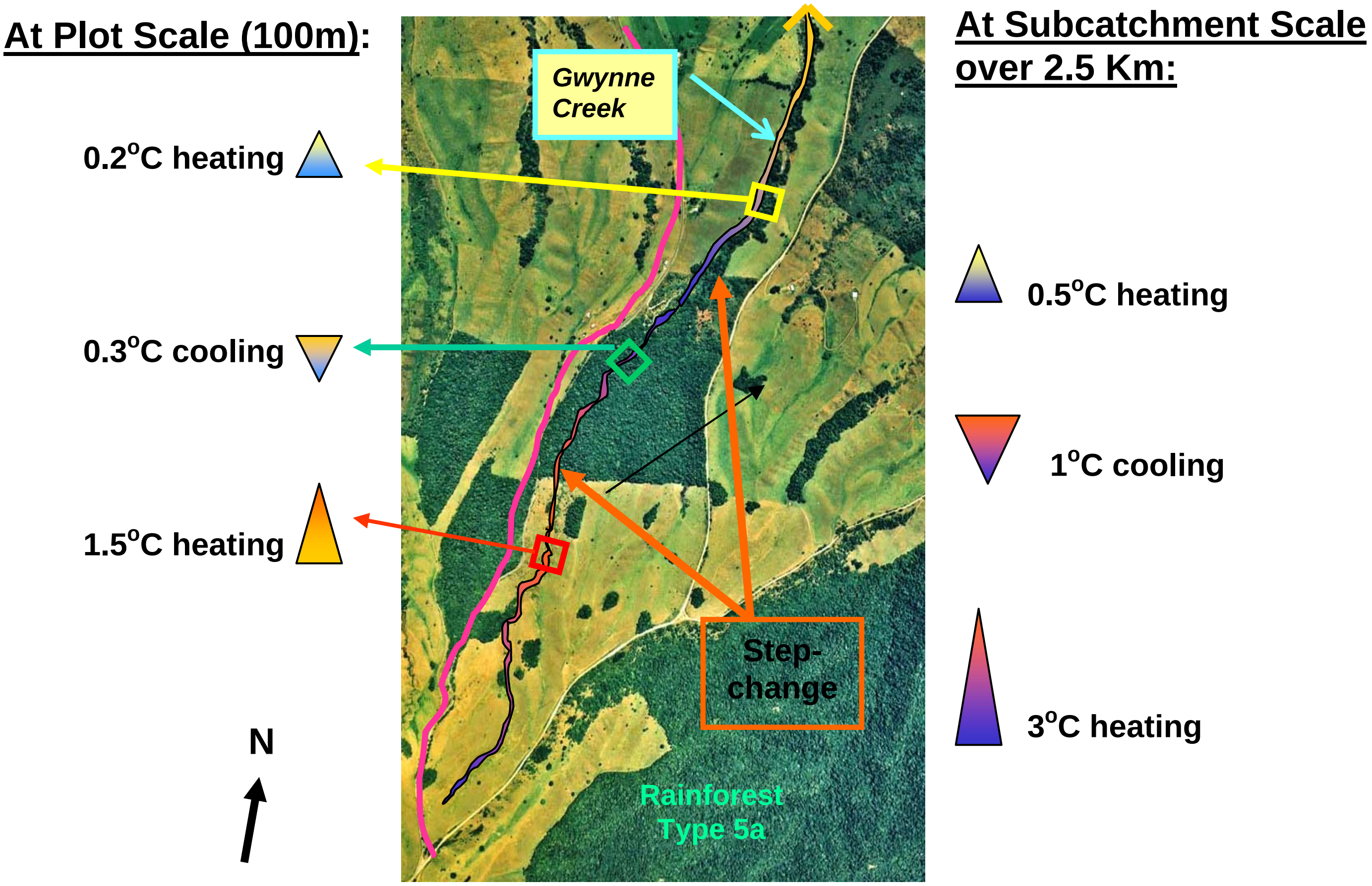

Fig 10 Gwynne Creek (Upper Barron Catchment): Stream heating/cooling at Plot scale and at Subcatchment scale with step-change.

At Gwynne Creek (Fig.10) an overall picture emerges. Comparing the results of stream temperature changes (ΔT_w) independently, plot-by-plot (100m) in a longitudinal way, heating (by 1.5°C) seemed most extreme at the cleared site, with modest cooling at the forested site (by 0.3°C) and little heating in the riparian site (by 0.2°C). When we shift our perspective from the plot scale to the subcatchment scale, these results look quite different. If we take the total length of stream into account, from the source through the step-changes, the ΔT_w results are quite different. The most extreme event is at the source site where the T_W increased by 3ºC over 1200m flowing through open pasture while in the forested area (over 750m) there was an actual cooling by 1ºC. At this scale, we know that the stream was previously heated before entering the forest, and then gradually cooled off again. After flowing through the riparian ecotone the stream, after previous cooling in the forest, had been heating up again (over 750m) by 0.5ºC.

Summary – for microclimates

- Microclimate influence of riparian forest on stream temperature differs with different spatial & temporal scales
- Rainforest Forests as benchmarks are complex (width is not everything)
- Non-shaded riparian verges show significantly hotter and more extreme conditions than shaded ones (except rainforest sites possibly)
- Topography and tree cover/shading are the main variables influencing stream temperature in the tropical uplands of the Atherton Tablelands

At sub-catchment scale we find an interdependent view of the stream's journey. For Gwynne Creek the heating/cooling events over a distance of 2.5km moved through distinct 'step change' that were not detectable at a 100m plot analysis. Sudden cooling or heating of a low-order, montane stream by ~ 1ºC.across a distance of 100m can potentially affect water quality. In turn this type of extreme can impact on in-stream biota (e.g. Williams *et al*. 2003; Rutherford *et al.* 2004).

Montane stream taxa in the Wet Tropics

Various metrics were calculated separately based on one riffle and one pool kicknet sample from each of the 13 field sites and are shown in Table 5 below. The six dominant aquatic macroinvertebrate groups (Coleoptera, Hemiptera, Plecoptera, Ephemoptera, Trichoptera and Diptera) found were investigated for distinct sensitivity of responses to any thermal extremes in the trial ecotones. But first we need to investigate the aquatic taxa regarding its community structure, stability and persistence at different ecotone sites to find any possible correspondence.

The **community structure** revealed that riffles are predominantly richer in abundance/density, as well as in species diversity across all types of ecotones, in all seasons and over all years sampled. The Shannon-Wiener biodiversity index (*H'*) condenses assemblage information into a single number expressing both richness (number of species) and evenness (the spread of individuals among species). Thus diversity increases with more species and with more evenness among species (see Table 5).

The reference site maintained the highest diversity in all seasons and years, followed by the forested sites. As expected, the cleared site had the lowest diversity, while riparian sites where somewhat in the middle ranges. No distinction between dry and wet seasons were found for the forested sites, The rainforest site aquatic larvae favoured the late dry seasons, while in the cleared sites they seem to prefer wet conditions. The increased shading by high paragrass along the stream channel in the wet could explain this behaviour for the pasture sites.

Table 5 Four ecotone sampling sites with summary data for macroinvertebrate samples (wet/dry and overall years), including mean number of taxa (± SE) or richness, abundance/density (± SE), % of dominant orders in the sample, spread of dominant orders in riffles, Diversity Index (H’) and Evenness (J’).

Site Name	Sample Season	Mean No. of taxa per sample S ± SE	Mean Abundance per sample (= Density) ± SE	% of Dominant Orders*	Riffles	Div Index H’ **log$_{10}$	Even J’
REF: F3	**DRY**	**33.5 ± 2.9**	**100.3 ± 3.2**	93.1	98.5	0.69	0.88
	WET	**28.5 ± 2.1**	**138.5 ± 1.5**	88.5	93.7	0.58	0.75
All Fs seasons	**DRY**	**30.6 ± 3.5**	**198.9± 10.7**	81.9	92.0	0.62	0.80
	WET	**26.1± 3.5**	**149.9± 8.6**	72.6	85.3	0.62	0.80
All Rs seasons	**DRY**	**43.6 ± 5.2**	**151.1± 9.1**	81.6	93.0	0.51	0.64
	WET	**208.6± 2.3**	**182.6 ± 11.9**	78.8	88.9	0.60	0.78
All Cs seasons	**DRY**	**44.0 ± 2.7**	**192.8 ± 7.5**	78.3	85.4	0.37	0.47
	WET	**32.7 ± 3.6**	**297.3 ± 19.5**	75.5	85.5	0.46	0.59
REF: F3		**31.0 ± 2.5**	**119.4 ± 4.8**	90.8	96.1	0.63	0.81
All Fs		**28.4 ± 3.2**	**174.4 ± 9.8**	**77.2**	64.3	0.62	0.80
All Rs		**36.1 ± 4.5**	**182.6 ± 11.9**	80.2	67.4	0.56	0.71
All Cs		**37.4 ± 4.4**	**297.3 ± 19.5**	76.9	64.0	0.41	0.53

Results from the **stability and persistence** calculations will not be presented here. The persistence, expressed as changes in absence/presence data of dominant taxa versus lower phyla, will only be described. The percent of **dominant species** does include PETs (Plecoptera-Ephemoptera-Tricoptera), which can be used as generally good water-quality indicative organisms relative to the rest of the fauna. This metric works best in the extreme conditions of streams (cleared versus forested stream ecotones). Streams close to original conditions (e.g. forested sites with mixed gravel, sand and cobble substrata) do best. While cleared streams with deep silt in the late dry season have low flow and warm temperatures with more tolerant taxa namely dipteran larvae of Chironomids (in high abundance) and a high diversity of lower phyla (e.g. worms, ostracods, amphipods). Plecopterans are generally missing from cleared sites (need tolerant taxa), but some more tolerant Ephemoptera are present. Most PET taxa prefer coarse substrates and running water.

Stability (log transformed) and community structure data are most easily visualised by plotting these data values (as vectors) on the ordination (NM-MDS) plot for all ecotone sites for the late dry/wet samples (see Fig. 11). Aquatic taxa diversity is highest (most significant) in samples with rainforest/forest ecotones (see circle) and lowest in cleared sites. The abundance/density of macroinvertebrates was highest in cleared ecotones (circle), especially in the wet season. Stability (or changes in abundance) differed greatly between ecotones and resulted in the pattern being strongest in forested stream sites.

Ecotones, Seasons & Macroinvertebrate Assemblages

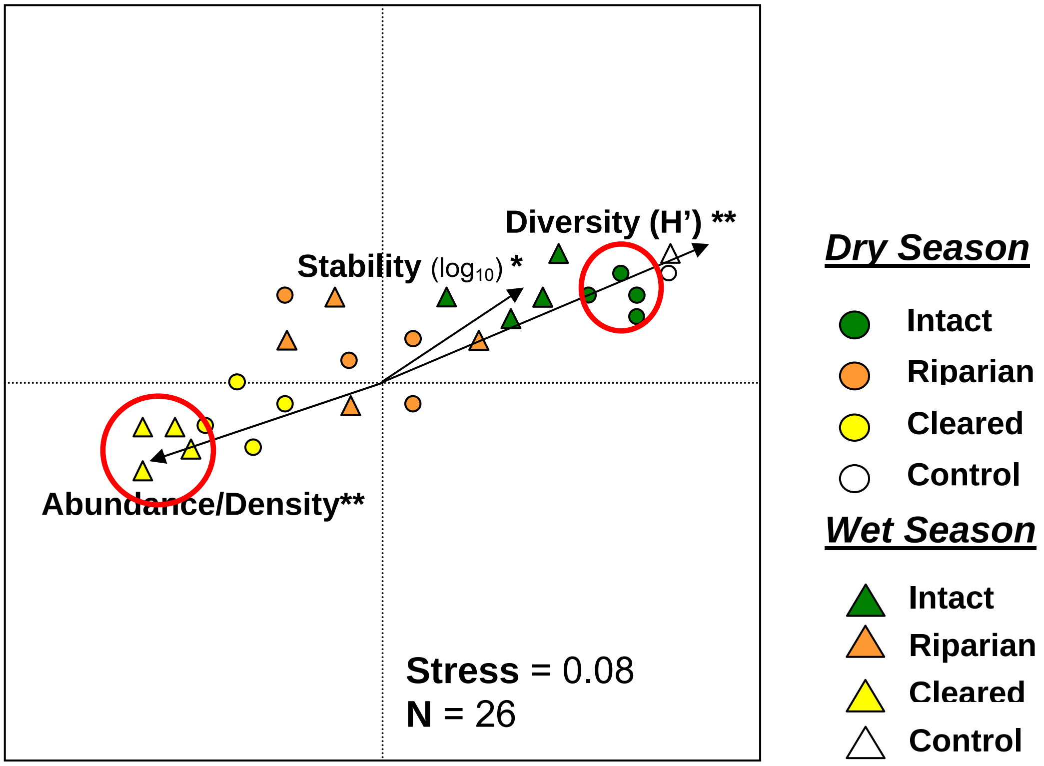

Fig 11 Ecotone data & macroinvertebrate assemblages
3D Non-metric multidimensional scaling ordination (n=26, stress=0.08) of 13 ecotone sites (Intact, riparian, cleared sites and one control site) over combined late dry (2000/2001) and wet (2001/2002), in the WT area around Mt.Hypipamee NP, Atherton Tablelands in north-eastern Queensland, Australia. Arrows represent the significant community structure and stability variables (ANOSIM $p<0.05$*; $p<0.01$**). The circles indicate a strong relationship between sites and variables.

Macroinvertebrates in montane streams of the Wet Tropics

The effect of **microclimatic extremes** on the structure of stream macroinvertebrate assemblages (total abundance/density, taxon richness, and evenness), including the resistance and stability of these aquatic tropical ecosystems, is not obvious. To assess these impacts in montane low order streams of the Wet Tropics is difficult since we do not have long-term data on local conditions as a benchmark. There are different signals in the results between ecotonal microclimatic conditions and macroinvertebrate assemblage structures. Especially, I found quite unlikely results in the 'natural' reference site and totally mixed signals in the riparian sites. The clear distinctions between the forested and cleared sites show that benchmarks at the extreme ends of a spectrum are easier to establish. The regrowth of the rainforest sites (for more than 60years after clear-cutting) show quite homogamous stands of trees of around the same age. But these sites are missing the old emergent rainforest giants and the quite dynamic systems creating patchiness in endemic forests (e.g. natural tree falls creating light gaps; no weeds). Therefore, the impact of microclimatic condition, in cleared and regrowth ecotones, are probably the best starting point to investigate impacts by microclimatic extremes on aquatic taxa in montane, low order streams in the Wet Tropics.

OUTCOMES

Overall, microclimatic conditions in the eco-tones and in-stream suggesting healthy stream biota are strongly linked to canopy closure with long riparian buffers and protection of headwaters. Expectations of riparian buffer zones, to uphold stream conditions and support their aquatic biota, under the increasing pressures of climate change in the Wet Tropics, need to be moderated by knowledge of the (1) quality and dynamics of the riparian vegetation and (2) spatial arrangement of riparian networks within a catchment.

FUTURE

The relationship between air and water temperature needs closer analysis, and the direct impact of microclimatic parameters on the tropical macroinvertebrate fauna needs further investigation.

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