CSIRO ECOSYSTEM SCIENCES
www.csiro.au

Using environmental variables to predict distribution and abundance of non-native fish in the Wet Tropics

MTSRF 2.6.2: Final report

Frederieke Kroon, John Russell, Paul Thuesen, Tina Lawson, Fiona Thomson
March 2011

Report for Marine and Tropical Sciences Research Facility
Commonwealth Environmental Research Facilities Program

Australian Government
Department of the Environment, Water, Heritage and the Arts

Queensland Government
Primary Industries and Fisheries

CSIRO Ecosystem Sciences

Citation

Kroon FJ, Russell J, Thuesen P, Lawson T, Thomson F (2011) Using environmental variables to predict distribution and abundance of non-native fish in the Wet Tropics. MTSRF 2.6.2: Final report. CSIRO, Atherton, Australia.

Copyright and disclaimer

Important disclaimer

Contents

Figures

Tables

Acknowledgments

The authors are grateful for the contributions and co-operation of staff at DEEDI (Northern Fisheries Centre, Cairns), Damien Burrows (TropWater, James Cook University, Townsville), and all workshop participants. This report was funded through the Marine and Tropical Science Research Facility, the CSIRO and Qld DEEDI. Proofreading by David Westcott improved the report.

Executive summary

The Wet Tropics World Heritage Area of Far North Queensland contains 78 (40%) of Australia's 190 freshwater fish species. These species, however, are threatened by the presence of at least six non-native (i.e. non-native) fish species, including two species of Cichlidae and four species of Poecilidae in the Wet Tropics region, and more than 13 non-native fish species from adjacent areas. Eradication of non-native populations has rarely been achieved within the Wet Tropics region and control options vary in their effectiveness. Understanding the distribution and abundance of non-native fish species in the Wet Tropics landscapes may enable the prediction of those landscape features that may drive invasion.

In this study, we examined whether environmental variables could be used to predict the presence and abundance of non-native fish at the stream, catchment and regional scale in the Wet Tropics region. First, we conducted a proof-of-concept using existing fish and environmental data from previous projects at the stream scale. To determine whether non-native fish abundance varied with environmental variables at the stream scale, we used correlation analysis to relate relative spotted tilapia (*Tilapia mariae*) abundance (Freshwater Creek) or guppy abundance (*Poecilia reticulata*) (Mossman River) with water quality, habitat, and catchment (guppy only) variables. Relative abundance of *T. mariae* increased significantly with maximum pool width, average pool width, and snags in pools. Relative abundance of *P. reticulata* decreased significantly with root masses, and proportion of grazing land use in the area upstream of the sampling location.

Second, we conducted a field study at a catchment scale to assess whether the correlations established at stream scale would hold up at larger scales. To determine whether non-native fish abundance varied with environmental variables at the catchment scale, we conducted backpack electrofishing surveys at 26 freshwater sites in the Mulgrave Catchment from December 2008 to March 2009. We found three non-native fish species (*T. mariae* 11 sites, *P. reticulata* 5 sites, and the southern platy *(Xiphophorus maculatus)* 3 sites). The relative abundance of *T. mariae* was not significantly related with any of the environmental variables examined. In contrast, the relative abundances of *P. reticulata* and *X. maculatus* were significantly related with 18 and 15 out of the 64 environmental variables examined. Results from non-metric multidimensional scaling indicate that species abundance assemblages from sites with non-native species were consistently more similar to each other than to those from sites without non-native species, and vice versa. In particular, native (*Tandanus tandanus*, *Hephaestus fuliginosus*, *Glossamia aprion*) and endemic (*Glossogobius bellendenensis*, *Cairnsichthys rhombosomoides*) fish species were more abundant at sites without non-native species.

Finally, we aimed to identify potential hot-spots for non-native fish at the catchment and regional scale, using predictor environmental variables identified at stream and catchment scale. To document locations of non-native fish, we (i) extracted presence records from the Fish Atlas of Northern Australia, and (ii) obtained presence and absence records from seventeen local and regional fish experts during a one-day workshop. A total of 1,106 records were identified comprising 347 presence and three uncertain records for a total of seven species, and 756 absence records, and submitted to the relevant Queensland Government agency through the North Qld Pest Fish Advisory Group for inclusion in State-wide pest fish maps. These records were intersected with nine spatial layers containing environmental information, and locations where combined environmental variables are suitable (presence) or non-suitable (absence) for non-native fish were identified in the Wet Tropics region.

Combined, this information will contribute to improved management of the fish fauna of the Wet Tropics region, including minimisation and reduction of spread of non-native fish species. Specifically, we conclude that restoration of native riparian vegetation is likely to provide a long-term control mechanism for non-native fish species in the Wet Tropics region.

1 Introduction

The Wet Tropics World Heritage Area of Far North Queensland contains 78 (40%) of Australia's 190 freshwater fish species (Pusey and Kennard 1996). The two most common families are the Melanotaenidae (rainbowfishes) and Pseudomugilidae (blue-eyes), while Gobiidae (gobies) and Eleotridae (gudgeons) are the two most speciose families recorded in the area (Russell and Hales, 1993; Pusey and Kennard, 1994; 1996; Russell *et al.*, 1996a; Russell *et al.*, 1996b; Russell and Hales, 1997; Russell *et al.*, 1998; Russell *et al.*, 2000). The area also contains at least eight endemic species (Pusey *et al.*, 2004), including *Cairnsichthys rhombosomoides* (Nichols & Raven, 1928), *Glossogobius bellendenensis* Hoese & Allen, 2009, *Guyu wujalwujalensis* Pusey & Kennard, 2001, *Hephaestus tulliensis* DeVis, 1884, *Melanotaenia eachamensis* Allen and Cross 1982, *Melanotaenia utcheensis* McGuigan, 2001, *Synclidopus hogani*, and *Schismatogobius* species.

The Wet Tropics region contains at least six non-native (i.e. non-native) fish species, , including two species of Cichlidae, namely *Tilapia mariae* Boulenger, 1899 (Spotted tilapia) (Bradford *et al.*, 2011) and *Oreochromis mossambicus* (Peters 1852) (Mozambique tilapia) (Russell *et al.*, 2012), and four species of Poecilidae, namely *Poecilia reticulata* Peters, 1859 (Guppy), *Gambusia holbrooki* (Girard, 1859) (Plague minnow), *Xiphophorus helleri* Heckel, 1848 (Swordtail), and *X. maculatus* (Günther, 1866) (Platy) (Allen *et al.*, 2003; Webb, 2007). Both species of tilapia (*O. mossambicus* and *T. mariae*) are a declared noxious pest under Queensland legislation; they have the potential to spread and establish self-sustaining populations on Cape York Peninsula and in rivers draining into the Gulf of Carpentaria. In addition to these introduced species, more than 13 non-native fish species have also been recorded from adjacent areas (Webb, 2007).

Eradication of non-native populations has rarely been achieved within the Wet Tropics region and control options vary in their effectiveness (but see (Thuesen *et al.*, 2011). Understanding the distribution and abundance of non-native fish species in the Wet Tropics landscapes may enable the prediction of those landscape features that may drive invasion. Specifically, the ability to spatially predict presence and abundance of non-native fish in Wet Tropics' landscapes relies on the use of (or combinations of) environmental variables that can (i) highlight the most probable locations for inspection and remediation, and (ii) provide recommendations for landscape rehabilitation and management to prevent and reduce spread.

In this study, we examined whether environmental variables could be used to predict the presence and abundance of non-native fish at the stream, catchment and regional scale in the Wet Tropics region. First, we conducted a proof-of-concept using existing fish and environmental data from previous projects at the stream scale. Second, we conducted a field study at a catchment scale to assess whether the correlations established at stream scale would hold up at larger scales. Finally, we aimed to examine whether we could identify potential hot-spots for non-native fish at the catchment and regional scale, using predictor environmental variables identified at stream and catchment scale. Combined, this information will contribute to improved management of the fish fauna of the Wet Tropics region, including minimisation and reduction of spread of non-native fish species.

2 Methods

2.1 Proof-of-concept at stream scale

2.1.1 *TILAPIA MARIAE* IN FRESHWATER CREEK

A detailed inventory of the habitat and fisheries resources of the Barron River catchment was conducted by (Russell *et al.*, 2000). From this holistic catchment scale study, a sub-set of data from Freshwater Creek was selected for proof-of-concept because (i) it is a large, higher order tributary of a major Wet Tropics catchment (Barron), and (ii) at the time of survey, Spotted tilapia (*Tilapia mariae*) had been collected from the system.

Seven sites were sampled in the Freshwater Creek catchment over the period of the study. Each site consisted of two meso-habitats, a pool/glide and riffle zone. Within these areas of the stream, key micro-habitats (Appendix 1), if present, were sampled using a pulsed direct current from a Smith-Root® Model LR24 backpack electrofisher. Electrofishing 'on time' was standardised for each micro-habitat at 100 seconds, with voltage, pulse width and frequency optimised for each site before sampling begun. Fish species and their estimated lengths and numbers and associated instream habitat were recorded. Specimens that were difficult to identify *in-situ* were retained and later frozen/preserved for more detailed inspection. Some specimens were sent to the Queensland Museum for positive identification. All sites were fished twice per year, once immediately after the wet season and again just prior to the wet season (between May 1997 and December 1998).

Fifty-two stream habitat parameters, including riparian vegetation structure, sedimentation, stream structure, instream cover, non-native grasses, disturbance rating, and six *in-situ* water quality (conductivity, dissolved oxygen (2x), pH, salinity and turbidity), were assessed at each site (Appendix 1). Instream habitat, apart from water quality parameters, was assessed using qualitative visual techniques similar to those used by (Russell and Hales, 1993; Russell *et al.*, 1996a; Russell *et al.*, 1996b; Russell and Hales, 1997; Russell *et al.*, 1998). In addition, the presence of migratory barriers to fish movement, man-made (culverts, weirs, causeways) or natural (waterfalls) were recorded if present at a site, with fish surveys and water quality parameters recorded above and below the barrier. To maintain consistency, the same personnel conducted assessments at the sites.

2.1.2 *POECILIA RETICULATA* IN MOSSMAN RIVER

A detailed description of the fish and environmental variables collected is given in Kroon and Bruce (in review); data collection occurred in 29 reaches in the Mossman River, Saltwater Creek and Daintree River in 2004. Data from 9 stream reaches in the Mossman River, containing *Poecilia reticulata*, were chosen for our proof-of-concept.

In short, fish were collected using multi-pass backpack electrofishing (Smith-Root LR-24 Backpack Electrofisher). Prior to collection, two block nets (15 m x 1.3 m x 8 mm stretch) were placed at either end of the sampling reach. Individual fish were identified to species level and the total number of individuals per species was recorded. Fish abundance was standardised to number of individuals captured per species per 30 minutes. Individuals that could not be identified in the field were taken to the laboratory and/or Queensland Museum for confirmation of species identification. After the third and last pass, both nets were removed and fish were returned to the location of capture.

At each individual reach, data on 10 water quality and 36 habitat variables were collected. Water quality variables included temperature, pH, conductivity, dissolved oxygen, phosphorus, orthophosphate, total nitrogen, nitrate, nitrite, and ammonia. Habitat variables included various reach dimensions, and cover estimates of aquatic macrophytes, algae, filamentous algae, emergent aquatic vegetation, overhanging terrestrial vegetation, submerged terrestrial vegetation, root masses, leaf litter (including fine woody material < 1 cm ∅), small woody debris (1-10 cm ∅), large woody debris (≥10 cm ∅), and undercut bank. Riparian condition was assessed using a modified version of Jansen *et al.*'s (2003) Rapid Appraisal of Riparian Condition (RARC) index method (Kroon and Bruce, in review). Finally, catchment-related parameters for each sampling reach, comprising total distance to river mouth (km), total distance to upstream forest (km), upstream catchment area (ha), and upstream land uses (ha, current to 1999) were derived within a GIS with reference to satellite derived data and published topographic maps.

2.1.3 RELATIONSHIPS BETWEEN NON-NATIVE FISH AND ENVIRONMENTAL VARIABLES AT STREAM SCALE

First, to determine whether non-native fish abundance varied with environmental variables, we used correlation analysis to relate relative spotted tilapia abundance (Freshwater Creek) or guppy abundance (Mossman River) with water quality, habitat, and catchment (guppy only) variables. Non-native fish abundance was corrected for effort to obtain an estimate of catch per unit effort (CPUE).

2.2 Validation at catchment scale

2.2.1 MULGRAVE CATCHMENT

Field data collection

A larger scale survey was undertaken in the Mulgrave Catchment by DEEDI from December 2008 to March 2009. This encompassed a total of 26 freshwater sites that included many of the same locations sampled in previous surveys by (Russell *et al.*, 1996b). For small shallow streams, the same methodology described above for the Freshwater catchment was employed to quantify the habitat and fisheries resources in the Mulgrave catchment. In addition, a boat-mounted 7.5KVA Smith-Root® Model electrofisher was employed for surveying deeper freshwater sites in the main river channel (sites 13, 14, 15, 37 and 1001). Fish abundance was corrected for effort to obtain an estimate of CPUE.

Catchment variables

Catchment-related parameters for each sampling site, comprising stream order, total distance to river mouth (km), and up- and downstream distances to nearest artificial physical barriers (Lawson *et al.*, 2010) were derived within a GIS with reference to satellite derived data and published topographic maps.

2.2.2 RELATIONSHIP BETWEEN NON-NATIVE FISH AND ENVIRONMENTAL VARIABLES AT CATCHMENT SCALE

Only data from sites that were sampled using backpack electrofishing were included in the following analyses.

First, to determine whether non-native fish abundance varied with environmental variables at the catchment scale, we used correlation analysis to relate relative abundance (CPUE) of guppy, spotted tilapia and platy with water quality, habitat, and catchment variables, respectively.

Second, we compared species assemblages at sites with and without non-native fish, using non-metric multivariate data analysis techniques (Primer 6 package, Plymouth Marine Laboratory, UK), following (Clarke and Gorley, 2006). First, to graphically illustrate and compare assemblages across sites with and without non-native species in the nMDS ordinations, we used Bray-Curtis dissimilarity matrices based on standardised and $\log_{(x+1)}$ transformed data. Goodness of fit between the configuration distances and the dissimilarity distances was measured by 'stress', where as a 'rule-of-thumb' a stress value of less than 0.10 indicates a 'good ordination with no real risk of drawing false inferences' (Clarke, 1993).

Third, to determine whether the composition of the species assemblages differed significantly between sites with and without non-native species, nested ANOSIM (analysis of similarity) tests were performed on similarity matrices. The ANOSIM procedure is based on the R statistic, which is a measure of similarity between sites; its statistical significance is assessed by permuting the grouping vector to obtain the empirical distribution of *R* under null-model. If the calculated value of R looks unlikely to have come from this distribution (depending on the level of significance, i.e. 5%), there is evidence to reject the null hypothesis (Clarke and Warwick, 2001).

Fourth, to determine which species contributed to the highest levels of dissimilarity between sites with and without non-native species, we used the SIMPER (similarity of percentages) procedure (Clarke and Warwick, 2001). Data were standardised and $\log_{(x+1)}$ transformed, and species were subsequently listed in decreasing order of their importance in discriminating between different groups of samples (Clarke and Gorley, 2001).

Finally, to examine which water, habitat and catchment components were associated with the observed patterns in species assemblages across the 21 sampling sites, we used the BIOENV procedure following (Clarke and Gorley, 2006). This procedure calculates a harmonic rank correlation coefficient between the reach similarity matrices on the biotic (species assemblages) and abiotic (water quality, habitat and catchment variables) data. All environmental data were $\log_{(x+1)}$ transformed and normalised, prior to entering simultaneously into the BIOENV procedure. The global BEST match permutation was used to test for statistical significance of the BIOENV procedure; for each test 999 permutations were run.

2.3 Application at Wet Tropics regional scale

2.3.1 NON-NATIVE FISH DATA FROM THE WET TROPICS FISH ATLAS

Presence data for non-native fish for the Wet Tropics was obtained from the Fish Atlas of Northern Australia (http://www.jcu.edu.au/vhosts/actfr/Projects/FishAtlas/Index.htm).

2.3.2 NON-NATIVE FISH DATA FROM EXPERT WORKSHOP

We organised a one day expert workshop on non-native fish species in the Wet Tropics region of Queensland which was held at CSIRO in Atherton. The aims of the workshop were to

- consolidate existing knowledge on the distribution, or likely distribution, of non-native fish in the Wet Tropics;
- identify environmental attributes that are conducive to the establishment, persistence and spread of non-native fish populations; and
- nominate catchments and sub-catchments that are at risk of invasion and prioritise areas of high conservation value for managers.

Workshop participants were asked to share their records of presence, absence, and location of six non-native fish species, namely *Gambusia holbrooki*, *Poecilia reticulata, Oreochromis mossambicus, Tilapia mariae*, *Xiphophorus helleri*, and *X. maculatus*.

Presence data from the Fish Atlas[1], and presence and absence data received from workshop participants were entered into an Excel spreadsheet with latitude and longitude. The Excel spreadsheet was saved as a .csv file and opened in ArcGIS, to display and convert X and Y co-ordinates into a shape file. The shape file was subsequently split into records showing the presence of non-native fish (as reported by workshop participants) and records showing the absence of non-native fish (workshop reported absence).

2.3.3 RELATING NON-NATIVE FISH PRESENCE/ABSENCE TO ENVIRONMENTAL VARIABLES

To determine whether the presence or absence of non-native fish species is attributable to certain environmental variables, we sourced the following spatial data layers for the Wet Tropics region:

- BVG: Broad vegetation groups,
- Geology: geology from the 1:250 000 vector geological Digital Map Series,
- Bc01: Bioclim layer of mean annual temperature,
- Bc12: Bioclim layer of mean annual rainfall,
- DCDB: Digital Cadastral Database, to find land tenure,
- Qlump: Queensland Land Use Mapping Program (Q-Lump),
- Residential distance:
- Roads: roads from the 1:50 000 vector topological Digital Map Series, and
- Barriers: Potential barriers to fish passage in the Wet Tropics region (Lawson *et al.* 2010).

We also assessed a riparian spatial layer recently developed by remote sensing staff at DERM (Andrew Clark, pers. comm.). This layer was not suitable for our purposes, as it is an outline of the riparian area and does not indicate the presence or absence of vegetation, or any riparian condition attributes.

In ArcGIS, we intersected the locations of all 'presence' records of all non-native fish from the Fish Atlas and workshop with each spatial layer separately. This showed the value of the environmental variable at each presence location, such as the mean annual temperature at that location for the Bc01 spatial layer, etc. Once all environmental variables at all 'presence' locations (within the boundaries of each spatial layer) were determined, we extracted the value where the majority of the "presence" records fell for each of the nine layers. These values were subsequently used to create nine new spatial layers, such as a spatial layer of suitable temperature, geology, rainfall, etc. The nine new layers were intersected to show those locations where values co-exist for the nine environmental variables, representing conditions suitable for non-native fish presence within the Wet Tropics region. Finally, this layer was intersected with the Wet Tropics World Heritage Area (WT WHA) layer to show areas within the WT WHA that are potentially at risk of exotic fish invasion.

We repeated the same process for our 'absence' records (available from the workshop only).

[1] http://www.jcu.edu.au/vhosts/actfr/Projects/NAFF/About.htm

3 Results

3.1 Proof-of-concept at stream scale

3.1.1 *TILAPIA MARIAE* IN FRESHWATER CREEK

Field data collection

A total of 5,387 fish from thirty six freshwater fish species including the exotic fish species *T. mariae*, *P. reticulata* and *X. helleri* were sampled in this catchment over the period of the study. *Tilapia mariae* was the most common non-native fish in this sub-catchment (present at 7 sites), making up about 3.4% of the total number of freshwater fish caught. *Tilapia mariae* were abundant in all lower sites of Freshwater Creek where the stream gradient and the pool to riffle ratio were low. *Tilapia mariae* appeared to prefer slow laminar stream flow, and in particular, backwater eddies.

Instream habitat and water quality data were collected from all seven sites in the Freshwater catchment; detailed analyses of these data are given in (Russell *et al.*, 2000).

Relationship between spotted tilapia and environmental variables

Relative abundance of spotted tilapia increased significantly with two out of the 19 physical components measured, namely maximum pool width ($r = 0.958$, $p = 0.001$) and average pool width ($r = 0.931$, $p = 0.002$) (Table 4.1). Of the 39 cover components measured, relative abundance of *T. mariae* increased significantly with only one component, namely snags in pools ($r = 0.792$, $p = 0.034$).

3.1.2 *POECILIA RETICULATA* IN MOSSMAN RIVER

Field data collection

Almost 29 hrs of backpack electrofishing was conducted in 29 reaches of the Mossman River, Saltwater Creek and Daintree River, yielding 19 fish species and 3,551 individuals. Of these, *Pseudomugul signifer* was the most common species, accounting for 23.7% of the individuals, followed by *Morgurnda* spp (19.1%) and the non-native *P. reticulata* (18.4%). *Poecilia reticulata* occurred in eight of the nine reaches sampled in the Mossman River, but not in any of the other rivers sampled. No other exotic fish species were recorded.

Relationship between guppy and environmental variables

Relative abundance of *P. reticulata* did not change significantly with any of the 17 physical components examined, or with riparian condition (Table 4.2). Of the 19 cover components, relative abundance of *P. reticulata* decreased significantly with root masses ($r_s = -0.725$, $p < 0.05$) and leaf litter ($r_s = -0.730$, $p < 0.05$). Of the nine catchment components examined, relative abundance of *P. reticulata* decreased significantly with proportion of grazing land use in the area upstream of the sampling location ($r_s = 0.708$, $p < 0.05$).

3.2 Validation at catchment scale

3.2.1 MULGRAVE CATCHMENT

Field data collection

A total of 3,172 fish representing 54 species were surveyed in the Mulgrave River catchment, including three exotic species, *T. mariae* (11 sites), *P. reticulata* (5 sites) and *X. maculatus* (3 sites). *Pseudomugil signifier* was the most common native fish, representing 18.9% of the total fish fauna, followed by *Hypseleotris compressa* (14.7%) and *Melanotaenia splendida splendida* (12.9%). *Tilapia mariae* was the most common non-native fish, representing 6.0% of the total fish fauna, while guppy and swordtail represented 1.9% and 0.3%, respectively.

Relationships between Poecilids and environmental variables

The relative abundances of *P. reticulata* and *X. maculatus* were significantly related with 18 and 15 of the 64 environmental variables examined, respectively (Table 4.3). Six of these were the same for both species, with relative abundances increasing with sedimentation, grasses in pool, and grasses in reaches, and decreasing with pH, O_2 (%), total length of reach, and average width of pool.

Relationships between *Tilapia mariae* and environmental variables

The relative abundance of *T. mariae* was not significantly related with any of the environmental variables (Table 4.3).

Relationships between species assemblages and environmental variables

The ordinations showed clear separations between sites with and without non-native species for the abundance assemblages (Fig. 4.1). The ordination was a reasonable representation of the data, with a stress level of 0.19. This suggests that samples from sites with non-native species were consistently more similar to each other than to those from sites without non-native species, and vice versa.

One-way ANOSIM revealed that samples collected in sites with non-native species were significantly different from those collected in sites without non-native species ($R = 0.245$, $p = 0.003$).

SIMPER revealed that the first ten species that contributed to the total average dissimilarities in assemblages between sites with and without non-native species, explained 57.3% of this dissimilarity in abundance assemblages. The ten most important species in contributing to this dissimilarity were (in order of contribution to dissimilarity) *Hypseleotris compressa* (7.4%), *Pseudomugil signifier* (6.4%), *Glossogobius bellendenensis* (6.2%), *Cairnsichthys rhombosomoides* (6.2%), *Tandanus tandanus* (5.8%), *Melanotaenia splendida splendida* (5.5%), *Hephaestus fuliginosus* (5.1%), *Tilapia mariae* (4.9%), *Poecilia reticulata* (4.7%), and *Glossamia aprion* (4.5%). Out of these ten species, *Glossogobius bellendenensis*, *Cairnsichthys rhombosomoides*, *Tandanus tandanus*, *Hephaestus fuliginosus*, and *Glossamia aprion* were more abundant at sites without non-native species.

The intended BIOENV analysis was not conducted, as only 32 out of the original 63 variables were available for all 21 sampling sites. These 32 variables excluded variables previously identified as being related to the relative abundance of Poecilids, such as pH, O_2, sedimentation, and grasses in reaches.

3.3 Application at Wet Tropics regional scale

3.3.1 NON-NATIVE FISH DATA FROM THE WET TROPICS FISH ATLAS

A total of 258 presence records from the Fish Atlas were extracted from the Fish Atlas (June 2009), comprising *G. holbrookii* (24 records), *O. mossambicus* (60 records), *P. reticulata* (78 records), *T. mariae* (32 records), *X. helleri* (7 records), *X. maculatus* (53 records), *Amphilophus labiatum* (1 record), *A. citrinellus* (1 record), and *Hemichromus bimaculatus* (2 records) (Appendix 2a-e).

3.3.2 NON-NATIVE FISH DATA FROM EXPERT WORKSHOP

Seventeen people from five organisations (CSIRO, DEEDI, JCU, Griffith University, Terrain NRM) and other businesses or private interest groups attended the workshop (Table 4.4). The workshop consolidated existing knowledge on the distribution, or likely distribution, of non-native fish in the Wet Tropics. A total of 850 additional records (91 presence, 3 unsure, 756 absence) were collated. The 91 presence records comprised new records on brown trout (*Salmo trutta* ; 1), Koi carp (*Cyprinus carpio*; 1), and an un-identified cyprinid, as well as additional records on *G. holbrookii* (9 records), *X. helleri* (20 records), *X. maculatus* (6 records), *T. mariae* (20 records), *O. mossambicus* (10 records), and *P. reticulata* (23 records) (Appendix 2a-e).

The workshop identified the following environmental attributes conducive to the establishment and spread of *non-native fish populations*. First, disturbance of the natural environment came up consistently as the main factor driving the establishment and spread of non-native species. As such, the presence and persistence of non-native species was considered a symptom, rather than the cause, of landscape disturbance. However, it was acknowledged that there is a difference between persistence and thriving, with some non-native fish species persisting in pristine environments, but thriving in disturbed environments. A disturbed environment could include lack of riparian zones, presence of aquatic weeds, presence of impoundments, modified environmental flows, modified aquatic habitats, as was well broader landscape modification. Rivers that are disturbed, such as the Burdekin, rather than degraded, such as the Barron, were considered 'ripe' for invasion by the workshop participants. The workshop further agreed that non-native fish species were more likely to be found closer to urban centres, due to (repeated) aquarium releases, the presence of more disturbed areas and increased pollution.

The workshop also discussed environmental and life history attributes conducive to the establishment and spread of *individual species*. First, non-native fish species that can alter their life history (e.g. stunt) are likely to do well in a new environment, although it is unclear whether this is because of advantages in resource competition or adaptation to environmental conditions. Second, the tilapia species were thought to be more abundant in degraded and artificial Wet Tropics habitats. Tilapia species are considered to be very adaptable to different environmental conditions, and very tolerant of low-oxygen environments. Snags appear to be a primary habitat for these species, but numbers appear to diminish after riparian bank restoration. Third, the Poecilid live bearers may have a competitive edge compared to egg-layers considering the feeding habits of native predators in the Wet Tropics region. Finally, *X. maculatus* appears to be more common in muddy and slow water

The workshop discussed the nomination of Wet Tropics catchments and sub-catchments that are at risk of invasion and prioritised areas of high conservation value for managers. Areas identified include (i) Walsh/Mitchell to prevent spread of tilapia into the Gulf and Northern Australia, (ii) Lake Eacham to prevent the attraction of birds and changes in ecosystem state, (iii) areas of high conservation importance and/or endemism (e.g. Daintree region and further north), and (iv) smaller catchments and smaller creeks in isolated catchments (e.g. Noah Ck, Winfield R). The discussion highlighted that management of non-native fish species in the Wet Tropics region needs to be better targeted and focussed on empirical scientific evidence. Current knowledge gaps include the impacts and effects of non-native species on the Wet Tropics ecosystems, with State and National noxious listings of tilapias based on overseas impacts. Hence, it is difficult to prioritise areas of management in the Wet Tropics region without understanding the local impacts and effects. The workshop identified that the reason for non-native species management is ultimately the protection of native species. Management should prevent further habitat disturbance and encourage habitat restoration. For example, local council and regional long-term plans should include guidelines to protect and restore drainage patterns and riparian buffers. Furthermore, rather than prioritising catchment and areas, prioritisation can be based on specific environmental traits such as (i) potential for protection and revegetation, (ii) biodiversity assets, and (iii) potential for success. Overall, the workshop acknowledged the importance of the interface between research and management.

3.3.3 RELATING NON-NATIVE FISH PRESENCE/ABSENCE TO ENVIRONMENTAL VARIABLES

To determine whether the presence of non-native fish species was related to certain environmental variables at the Wet Tropics regional scale, we intersected combined ‘presence’ records from the Fish Atlas and workshop with nine spatial layers. For most spatial layers, non-native fish were clearly present more often than not within certain categories, such as (i) 0-500 m in ‘road distance’, (ii) alluvial colluvial and basic volcanic in ‘geology’, (iii) mean annual temperatures ≥20ºC in ‘BC01’, (iv) freehold in ‘DCDB’, and (v) non-remnant in ‘BVG’ (Table 4.5). For a few spatial layers, the differential in presence records between different categories was small to non-existent, such as ‘residential distance’ and ‘barrier distance’. We created nine new spatial layers that reflected those environmental conditions where the majority of the ‘presence’ records fell for each of the nine layers. The intersection of these new nine layers showed those locations where values co-exist for nine environmental variables, representing conditions suitable for non-native fish presence within the Wet Tropics region and WT WHA (Figure 4.2).

To determine whether the absence of non-native fish species was related to certain environmental variables at the Wet Tropics regional scale, we intersected ‘absence’ records from the workshop with nine spatial layers separately. For most spatial layers, non-native fish were clearly absent more often than not within certain categories, such as (i) alluvial colluvial in ‘geology’, (ii) mean annual temperatures ≥23ºC in ‘BC01’ (iii) freehold in ‘DCDB’, (iv) distance ≥1,000 m in ‘residential distance’, and (v) non-remnant in ‘BVG’ (Table 4.5). For a few spatial layers, the difference in absence records between different categories was small to non-existent, such as ‘road distance’ and ‘barrier distance’. We created nine new spatial layers that reflected those environmental conditions where the majority of the ’absence’ records fell for each of the nine layers. The intersection of these new nine layers showed those locations where values co-exist for nine environmental variables, representing conditions less suitable for non-native fish presence within the Wet Tropics region and WHA (Figure 4.3).

Table 1. Pearson Correlation results, relating *Tilapia mariae* abundance with environmental variables of Freshwater Creek, Barron River, North Queensland, Australia. Bold indicates a significant correlation ($p<0.05$).

	r	*P*		r	*P*
Physical components			**Cover components**		
pH	0.367	0.418	Disturbance	-0.189	0.685
T (°C)	0.684	0.090	Sedimentation	0.284	0.537
O_2 (%)	-0.235	0.612	Continuity (l)	0.196	0.673
O_2 (ppm)	-0.626	0.133	Continuity (r)	-0.326	0.476
Conductivity (µS/cm)	-0.213	0.646	Trees (l)	-0.323	0.480
Turbidity (NTU)	0.671	0.099	Trees (r)	0.112	0.812
Site length (m)	0.276	0.549	Grass (l)	0.323	0.480
Width (l) (m)	0.189	0.684	Grass (r)	0.003	0.996
Width (r) (m)	0.191	0.682	Other (l)	0.000	1.000
Pool			Other (r)	-0.318	0.487
Total length (m)	0.383	0.396	No veg (l)	0.000	1.000
Max depth (m)	0.755	0.050	No veg (r)	0.000	1.000
Av depth (m)	0.712	0.073	Grass length	0.298	0.516
Max width (m)	0.958	**0.001**	Grass max width	0.241	0.602
Av width (m)	0.931	**0.002**	Canopy Cover	0.416	0.354
Reach			*Pool*		
Total length (m)	-0.299	0.515	Boulder/Cobble	0.308	0.502
Max depth (m)	0.401	0.373	Cobble/Gravel	-0.341	0.454
Av depth (m)	0.410	0.361	Sand	0.099	0.833
Max width (m)	0.523	0.229	Fine material	-0.130	0.781
Av width (m)	0.603	0.152	Bank cover	0.000	1.000
			Overhanging veg	0.502	0.251
			Macrophytes	0.671	0.099
			Snags	0.792	**0.034**
			Undercut Banks/Roots	0.165	0.724
			Grasses	0.382	0.397
			Rocks	-0.297	0.518
			Leaf Litter	0.356	0.433
			Reach		
			Boulder/Cobble	-0.161	0.730
			Cobble/Gravel	0.178	0.703
			Sand	-0.477	0.279
			Fine material	-0.354	0.435
			Bank cover	0.000	1.000
			Overhanging veg	0.502	0.251
			Macrophytes	0.573	0.179
			Snags	0.470	0.288
			Undercut Banks/Roots	0.367	0.418
			Grasses	0.502	0.251
			Rocks	-0.346	0.447
			Leaf Litter	0.502	0.251

Table 2. Correlation results, relating *Poecilia reticulata* abundance (in CPUE) with environmental variables of stream reaches (n=9) in the Mossman River, North Queensland, Australia. Correlations are Pearson or Spearman Rank Order (*). Bold indicates a significant correlation (p<0.05).

	r	*P*		r	*P*		r	*P*
Riparian condition			**Cover components**			**Catchment components**		
Riparian condition index	-0.486	0.185	Aquatic macrophytes	n/a		Distance to river mouth (km)	0.462	0.211
Physical components			Microphyto benthos	-0.243	0.528	Distance to forest (km)	-0.473	0.198
Mean T (°C)	0.443	0.232	Filamentous algae	n/a		Catchment area (ha)	-0.215	0.579
Mean DO (ppM)	0.409	0.275	Emergent vegetation	0.000 *	>0.05	Grazing (%)	**-0.708 ***	**<0.05**
Mean pH	0.432	0.245	Overhanging vegetation	0.548 *	>0.05	Horticulture (%)	0.068 *	>0.05
Mean conductivity (µS/cm)	0.117 *	>0.05	Submerged vegetation	0.411 *	>0.05	Urban (%)	0.207	0.592
Total phosphorous (mg/L P)	0.411 *	>0.05	Riparian cover	-0.639 *	>0.05	Protected (%)	0.533 *	>0.05
Orthophosphate (mg/L P)	0.303 *	>0.05	Root masses	**-0.725 ***	**<0.05**	Forested (%)	-0.533 *	>0.05
Total nitrogen (mg/L N)	0.017 *	>0.05	Leaf litter	**-0.730 ***	**<0.05**	Sugar (%)	-0.367	0.331
Nitrate (mg/L N)	-0.25 *	>0.05	Small woody debris	n/a				
Nitrite (mg/L N)	0.274 *	>0.05	Large woody debris	n/a				
Ammonia	0.390 *	>0.05	Undercut bank	n/a				
Mean reach depth (m)	-0.434 *	>0.05	Mud	n/a				
Maximum reach depth (m)	-0.166	0.669	Sand	n/a				
Reach depth variance (m^2)	-0.339 *	>0.05	Fine gravel	n/a				
Mean reach width (m)	0.044	0.911	Coarse gravel	-0.548 *	>0.05			
Reach length (m)	0.510	0.160	Cobbles	0.000 *	>0.05			
Reach area (m^2)	0.421	0.259	Rocks	0.456 *	>0.05			
Reach volume (m^3)	0.031	0.937	Bedrock	n/a				

Table 3. Spearman Rank Correlation results, relating relative abundance of *Poecilia reticulata*, *Tilapia mariae*, and *Xiphophorus maculatus* (in CPUE) with environmental variables of sampling sites (n=21) in the Mulgrave River, North Queensland, Australia. Note that environmental data was not collected or available for all sites. Bold indicates a significant correlation ($p<0.05$).

Physical components	*P. reticulata*	*T. mariae*	*X. maculatus*
pH	**-0.539**	0.009	**-0.638**
Water temp	-0.121	0.330	-0.196
O2 %	**-0.592**	-0.050	**-0.624**
O2 ppm	-0.478	-0.110	**-0.685**
Conductivity	0.389	-0.025	**0.574**
Turbidity (NTU)	0.342	0.036	0.320
Sedimentation	**0.504**	0.193	**0.564**
Site length (m)	0.029	0.071	-0.228
Width (l)	-0.421	-0.099	-0.351
Width (r)	-0.030	-0.184	0.023
Total length (p)	**0.453**	0.300	0.140
Total length (r)	**-0.527**	-0.029	**-0.603**
Max depth (p)	-0.354	0.087	**-0.468**
Max depth (r)	-0.086	0.136	0.045
Av depth (p)	-0.106	0.146	-0.090
Av depth (r)	-0.052	0.129	0.075
Max width (p)	-0.381	0.307	**-0.507**
Max width (r)	-0.266	0.089	**-0.492**
Av width (p)	**-0.447**	0.296	**-0.567**
Av width (r)	-0.388	0.063	**-0.491**

Catchment components	*P. reticulata*	*T. mariae*	*X. maculatus*
Stream order	**-0.643**	0.359	-0.423
Distance to ocean (m)	-0.138	-0.009	-0.205
Distance to barrier downstream (m)	-0.137	0.366	
Distance to barrier upstream (m)	**0.608**	-0.257	0.302

Cover components	*P. reticulata*	*T. mariae*	*X. maculatus*
Disturbance	-0.263	-0.331	-0.340
Continuity (l)	0.267	0.001	0.335
Continuity (r)	0.111	0.327	0.272
Trees (l)	-0.258	-0.058	-0.276
Trees (r)	0.008	0.012	-0.116
Grass (l)	0.275	0.104	0.272
Grass (r)	-0.223	0.021	-0.043
Other (l)	-0.046	-0.193	0.233
Other (r)	0.211	-0.126	**0.531**
No veg (l)	0.177	-0.201	-0.132
No ver (r)	0.087	-0.253	-0.165
Grass length	0.322	0.193	0.272
Grass max width	**0.489**	0.309	0.394
Boulder/Cobble (p)	**-0.472**	-0.244	-0.340
Boulder/Cobble (r)	**-0.467**	-0.068	-0.323
Cobble/Gravel (p)	-0.272	0.364	-0.206
Cobble/Gravel (r)	0.057	0.272	0.017
Sand (p)	**0.587**	0.069	0.393
Sand (r)	**0.553**	0.154	0.424
Fine material (p)	-0.070	0.181	0.079
Fine material (r)	0.401	-0.037	0.180
Canopy Cover	0.266	-0.028	0.358
Feral Animal Damage	-0.124	-0.139	-0.091
Undercut Banks/Roots (p)	-0.064	0.228	-0.162
Snags (p)	0.025	0.389	-0.008
Aquatic macrophytes (p)	**0.544**	0.313	0.409
Grasses (p)	**0.637**	-0.091	**0.556**
Rocks (p)	-0.418	-0.037	-0.312
Overhanging vegetation (p)	0.001	0.194	-0.170
Leaf Litter (p)	0.361	-0.109	**0.643**
Undercut Banks/Roots (r)	0.244	0.296	0.191
Snags (r)	**0.471**	0.300	0.061
Aquatic macrophytes (r)	0.344	0.074	0.173
Grasses (r)	**0.578**	-0.136	**0.491**
Rocks (r)	**-0.565**	-0.273	-0.269
Overhanging vegetation (r)	-0.150	0.076	0.034
Leaf Litter (r)	0.379	-0.211	0.435
Flow (p)	-0.101	0.153	-0.104
Flow (r)	-0.275	0.175	-0.294

Table 4. Names, organisations and positions of attendees at "*MTSRF expert workshop on non-native fish species in the Wet Tropics*" held at CSIRO, Atherton, 03 March 2010.

Name	Organisation	Position
Bart Dryden	Terrain NRM	Pest and Weeds Officer
Malcolm Pearce	Qld DEEDI	Senior Fisheries Biologist
Paul Godfrey	James Cook University	PhD student
Terry Vallance	Tropical River Consulting	Private consultant
Alf Hogan	Alf Hogan and Associates	Private consultant
Brendan Ebner	Griffith University	Research Fellow
John Pollock	North Queensland Pest Fish Working Group	Chair
Stephanie Januchowski	James Cook University	PhD student
Bruce Hansen	Australia New Guinea Fishes Association	Life Member
Bob Kroll	Aquarium Shop	Owner
David Westcott	CSIRO	Principal Research Scientist
Frederieke Kroon	CSIRO	Principal Research Scientist
Tina Lawson	CSIRO	Spatial Analyst
Caroline Bruce	CSIRO	Research Assistant
Fiona Thomson	Qld DEEDI	Fisheries Technician
John Russell	Qld DEEDI	Principal Fisheries Biologist
Paul Theusen	Qld DEEDI	Fisheries Biologist
Damien Burrows	James Cook University	Senior Research Scientist

Table 5. Spatial data layers, categories, and presence/absence records of all non-native fish species in the Wet Tropics region derived from the Fish Atlas and workshop. Categories with records highlighted were subsequently used in further spatial analyses.

Spatial data layer	Combined records	
Road Distance	**Present**	**Absent**
0 - 500	181	229
500 - 1000	64	137
1000 - 2000	49	223
2000 - 5000	36	141
Total	**330**	**730**

Spatial data layer	Combined records	
BC12 (rainfall)	**Present**	**Absent**
-9999	26	16
<1500	38	25
1501 - 2000	116	113
2001 - 2500	56	64
2501 - 3000	15	465
3001 - 3500	60	68
>3500	37	5
Total	**348**	**756**

Spatial data layer	Combined records	
BC01	**Present**	**Absent**
-9999	26	16
17 - 17.9	4	0
18 - 18.9	12	10
19 - 19.9	18	12
20 - 20.9	65	25
21 - 21.9	1	10
22 - 22.9	11	14
23 - 23.9	122	608
24 - 24.9	89	60
Total	**348**	**755**

Spatial data layer	Combined records	
Geology	**Present**	**Absent**
-	5	0
Alluvial Colluvial	187	641
Acid Plutonic	23	30
Acid Volcanic	7	20
Basic Volcanic	64	18
Metasedimentary Metamorphic	36	21
Tully Granite Complex	0	10
Total	**322**	**740**

Spatial data layer	Combined records	
DCDB	**Present**	**Absent**
Rd/Creek/River	81	110
Covenant	1	0
Easement	0	5
Freehold	168	498
Forest Reserve	25	22
Lands Lease	21	0
National Park	6	30
Reserve	11	55
State Forest	1	15
State Land	8	5
Total	**322**	**740**

Spatial data layer	Combined records	
Residential Distance	**Present**	**Absent**
0 - 500	94	25
500 - 1000	51	41
1000 - 2000	81	245
2000 - 5000	82	357
Total	**308**	**668**

Spatial data layer	Combined records	
Barrier Distance	**Present**	**Absent**
0 - 500	122	108
500 - 1000	81	232
1000 - 1500	65	141
1500 - 2000	40	71
Total	**308**	**552**

Spatial data layer	Combined records	
QLUMP	**Present**	**Absent**
Cropping	62	272
Grazing Natural Vegetation	49	93
Intensive Animal Production	18	7
Irrigated Cropping	19	35
Irrigated Perennial Horticulture	8	20
Managed Resource Protection	2	5
Manufacturing and Industrial	2	0
Marsh/wetland/water	34	86
Nature Conservation	33	57
Other Minimal Use (Non-Remnant)	63	150
Production Forestry	2	15
Residential	22	0
Services	8	0
Total	**322**	**740**

Spatial data layer	Combined records	
BVG	**Present**	**Absent**
Disturbed	13	15
Mangroves	2	2
Melaleuca	3	41
Non-remnant	224	551
Other	1	5
Plantation	0	30
Rainforest	35	45
Sclerophyll	31	80
Wet Sclerophyll	12	0
Total	**321**	**769**

Figure 1. Non-metric multidimensional scaling (nMDS) ordinations of species assemblages based on abundance data, in the Mulgrave River, in sites with (1) and without (0) non-native fish species. The ordinations are based on standardised, log $_{(x+1)}$ transformed abundances and Bray-Curtis similarities.

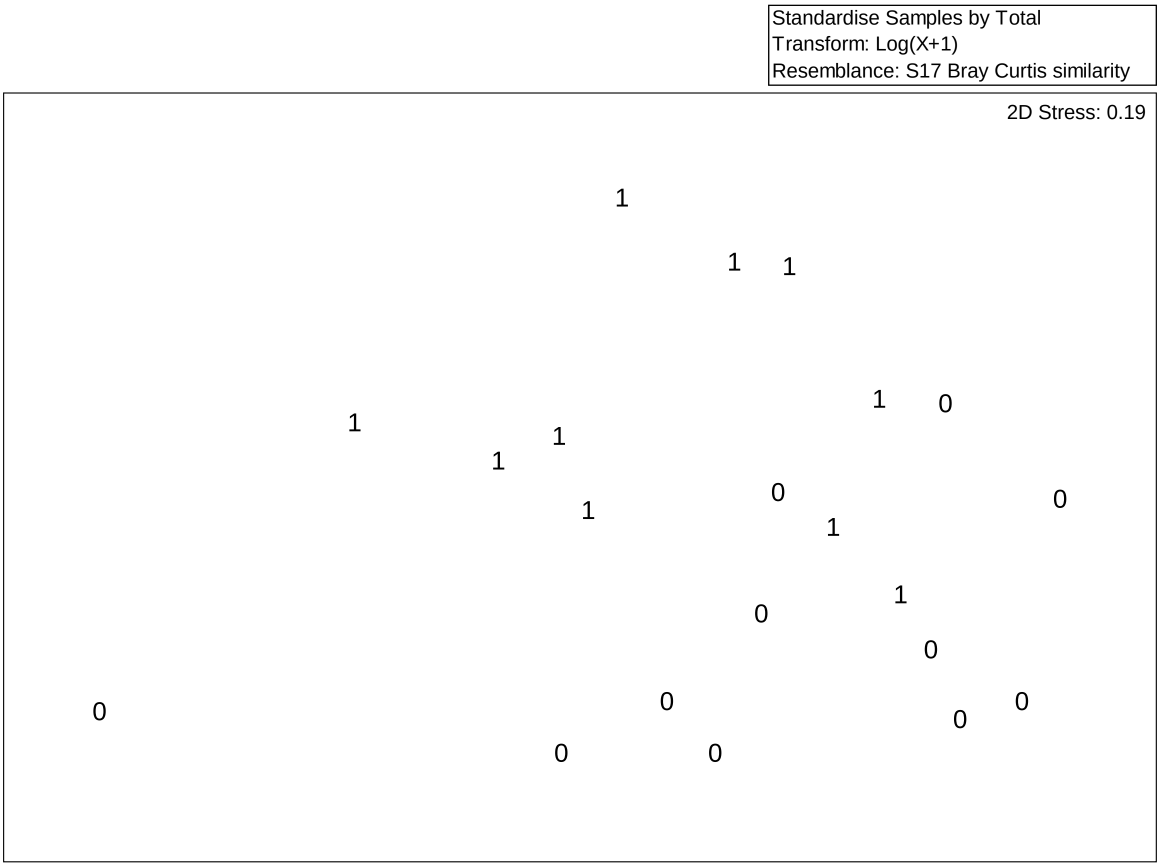


Figure 2. Streams and rivers in the Wet Tropics region and Wet Tropics World Heritage Area with environmental conditions conducive to non-native fish presence.

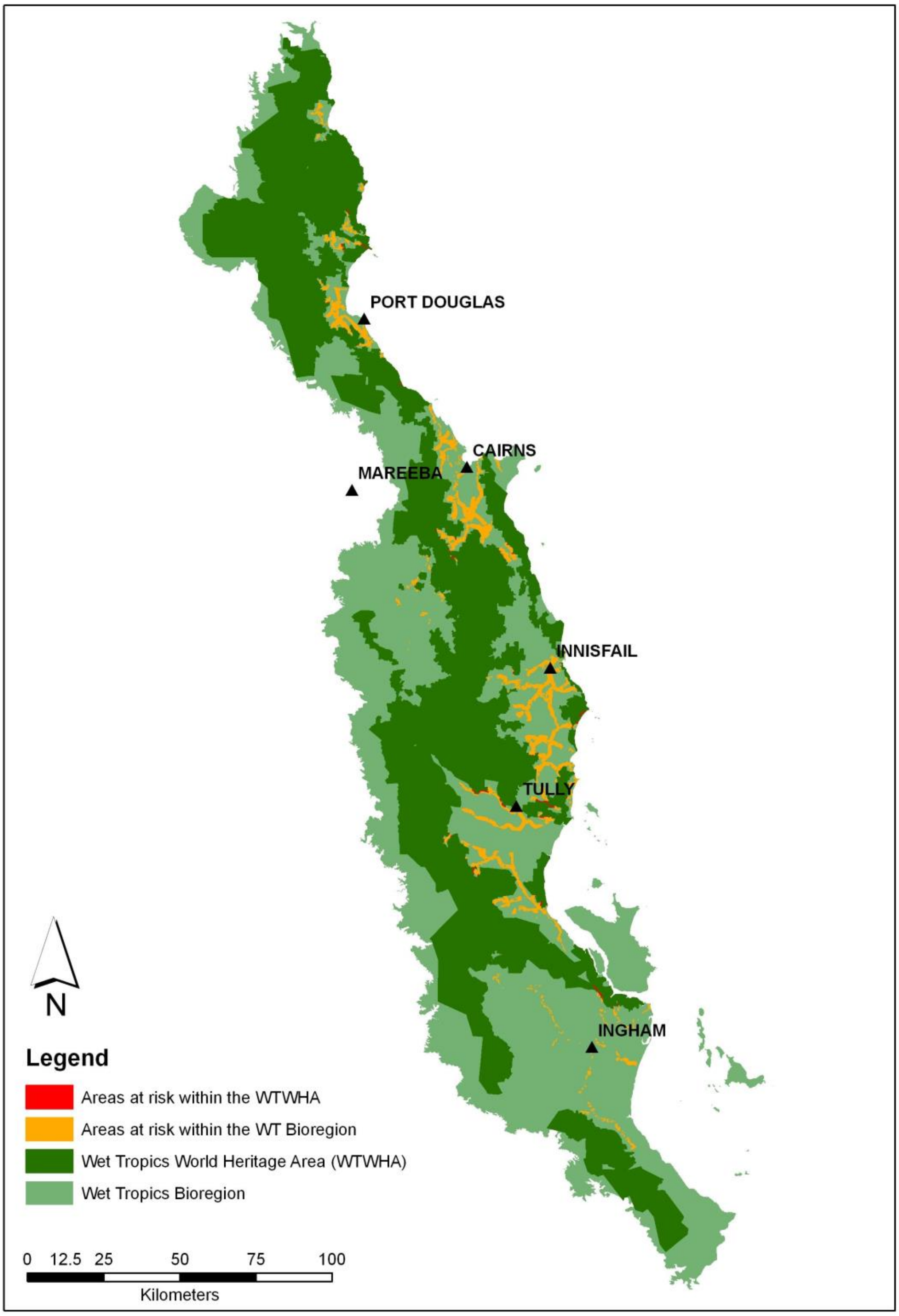
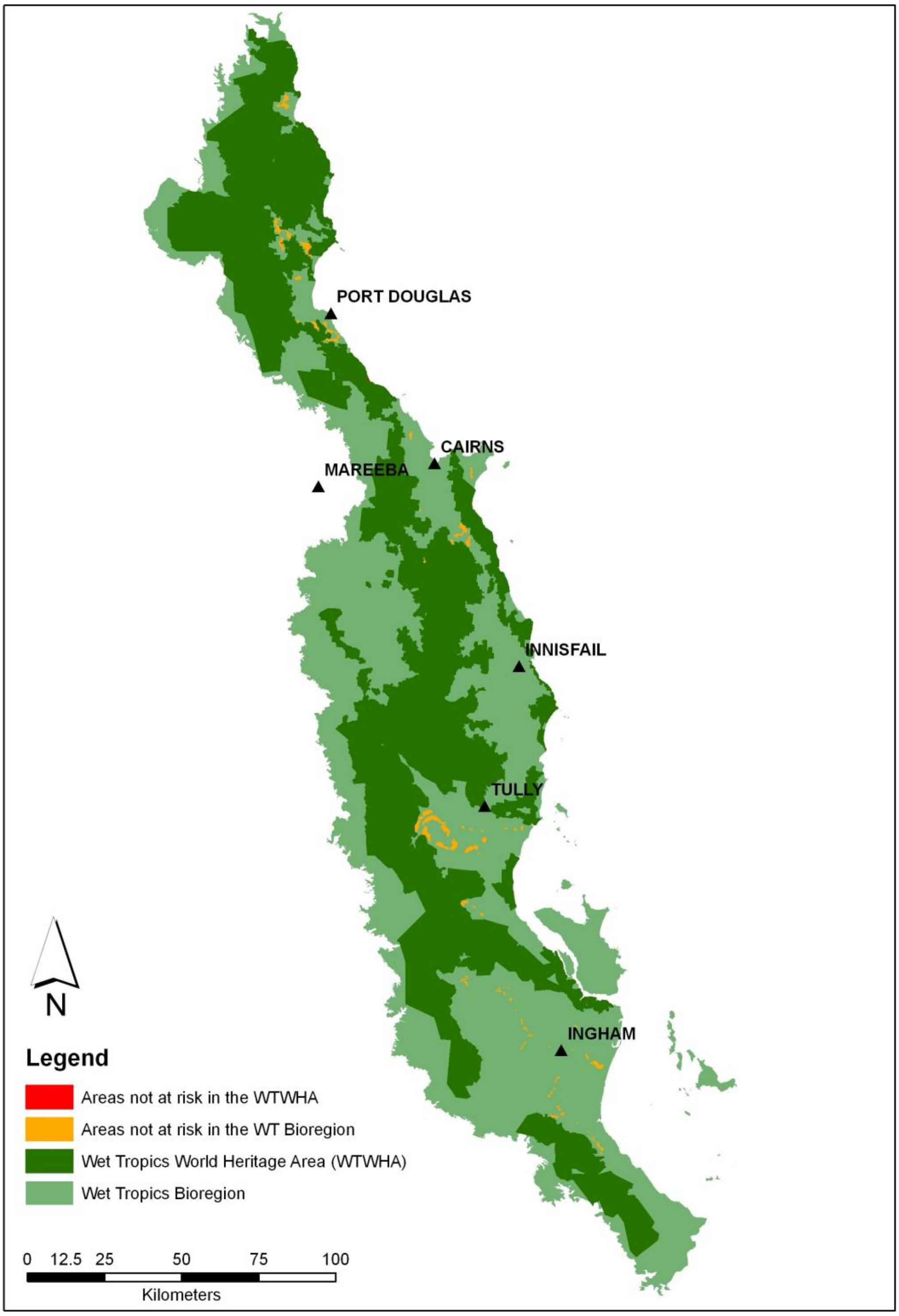


Figure 3. Streams and rivers in the Wet Tropics region and Wet Tropics World Heritage Area with environmental conditions not conducive to non-native fish presence.



4 Discussion

4.1 Distribution of non-native fish in the Wet Tropics region

This study consolidated our knowledge on the distribution, or likely distribution, of non-native fish species in the Wet Tropics region. The 258 presence records in the Fish Atlas were increased by 91 to a total of 349 following our expert workshop. Moreover, our workshop recorded the presence of three additional non-native species, comprising one brown trout (*Salmo trutta*), one Koi carp (*Cyprinus carpio*), and one un-identified cyprinid, and a total of 756 absence records. Species presence and absence records, including geographic locations where available, have been submitted to Qld DEEDI through the North Qld Pest Fish Advisory Group for inclusion in State-wide pest fish maps.

4.2 Environmental attributes conducive to non-native fish

Our study aimed to examine whether we could identify potential hot-spots for non-native fish at the catchment and regional scale, using predictor environmental variables identified at stream and catchment scale. Our results demonstrate significant relationships between relative abundance of non-native fish species and specific environmental variables at the stream and catchment scale, but not at the regional Wet Tropics scale. For example, the relative abundance of *T. mariae* increased with maximum pool width, average pool width, and snags in pools at the stream scale, but was not related to any environmental variables at the catchment scale. Similarly, the relative abundance of Poecilids (*P. reticulata* and *X. maculatus*) at the stream scale decreased with root masses, leaf litter, and proportion of upstream grazing land use, and at the catchment scale increased with sedimentation, grasses in pool, and grasses in reaches, and decreased with pH, O_2 (%), total length of reach, and average width of pool. At the Wet Tropics regional scale however, our GIS analysis did not reveal clear distinctions between environmental predictor variables for presence and absence, and areas susceptible and not susceptible to invasion. Irrespective, most experts at the workshop were of the opinion that disturbance of the natural environment is the main factor driving the establishment and spread of non-native species. Hence, we argue that our result at the regional scale may at least in part be due to our inability to detect any relationship with the data currently available. The main reasons underlying this inability include:

- The total number of records for presence (349) and absence (756) may not be large enough for spatial analysis covering an area close to 20,000 km^2;
- The spatial locations of the presence and absence records may not have been valid or valid in a consistent manner, compromising the accuracy and precision of the records;
- The spatial layers used were dependent on their availability, with many layers on predictor environmental variables relevant at stream and catchment scale (e.g. water quality, non-native weeds, in-stream habitat) currently non-existent or not available; and
- The resolution of the spatial layers used was not consistent across all layers, and may not have been at a fine enough scale.

To enable the identification of potential hot-spots for non-native fish at the regional scale, relevant spatial layers need to be developed at the appropriate resolution for robust spatial analysis. In the meantime, the results of our study point towards specific physical and cover components at the local scale, rather than catchment components at the regional scale, that could be used for hot-spot identification as well as for remediation strategies. For Poecilids these components include increased amounts of sedimentation, increased abundance of grasses in pools and reaches, and decreased levels of O2 (%). On the other hand, we did not find such specific physical and cover components relating to the relative abundance of *T. mariae*, supporting the workshop's assertion that tilapia species are very adaptable to different environmental conditions (Bradford *et al.*, 2011; Russell *et al.*, 2012).

The difference in correlative evidence between environmental variables and relative abundance of Poecilids and *T. mariae* may be related to the characteristics of the native environments of these species. The large number of significant correlations between *P. reticulata* (18 out of 63), *X. maculatus* (15 out of 63), and environmental variables may reflect the similarity between the species' native environment and Wet Tropics streams. For example, the environmental characteristics of *P. reticulata*'s native habitat in mountain streams in Trinidad, West Indies include similar DO concentrations, pH levels, and pool sizes (Reznick *et al.*, 2001) as Wet Tropics locations inhabited by *P. reticulata*. In Central American rivers, *X. maculatus* and *X. helleri* occur in a wide range of habitat and water quality (Schmitter-Soto *et al.*, 2011), although specific information on its native habitat in these rivers could not be found. In contrast, *T. mariae* is generally abundant in wider sections of watercourses with a silty and sandy substratum in its native West Africa (Bradford *et al.*, 2011), but was found to be a microhabitat generalist in lowland freshwater rivers in Queensland (Rayner *et al.*, 2008). Bradford *et al.* (2011) posit that *T. mariae*'s documented plasticity in reproductive and feeding behaviours, its tolerance of a wide range of temperatures, salinity and dissolved oxygen concentrations, and its aggressive behaviour to other piscine species, may contribute to the species' competitive advantage in both native and introduced regions.

4.3 Impacts of non-native fish on native fish species assemblages

In the Mulgrave catchment, the presence of the non-native fish species *T. mariae, P. reticulata*, and *X. maculatus* significantly changed the composition of species abundance assemblages. Five native fish species were more abundant at sites without these non-natives, namely *Tandanus tandanus*, *Hephaestus fuliginosus*, *Glossamia aprion,* and the endemics *Glossogobius bellendenensis* and *Cairnsichthys rhombosomoides*. This suggests that the presence of the three non-native fish species may detrimentally affect the presence and abundance of at least some native species, including species endemic to the Wet Tropics. Conversely, three native species were more abundant at sites with these non-natives, namely *Hypseleotris compressa*, *Pseudomugil signifier*, and *Melanotaenia splendida splendida*. These three species are all more generalist species, that is, having a generalist nature of habitat use and a wide range of environmental tolerances (Pusey *et al.*, 2004). Thus, relative to the other five native species they may be more likely to withstand disturbances in their aquatic environments, either directly or associated with the presence of non-native species. Here, we briefly discuss the ecological processes that may underpin the changes in presence and abundance of native and endemic species documented in this study.

First, the three non-native fish species may compete with native species for the available food sources in the Mulgrave River. *Tilapia mariae* is primarily herbivorous (Bradford *et al.*, 2011) with its main diet categories in the Mulgrave River comprised of macrophytes (31–54%), filamentous algae (17–25%), and detritus (21–26%) (Rayner *et al.*, 2009). The only other fish in the Mulgrave River classified as a herbivore, the native *Arrhamphus sclerolepis,* feeds on macrophytes such as *Vallisneria* sp. (95–100% of diet) (Rayner *et al.*, 2009). Both Poecilids are known to feed on aquatic and terrestrial invertebrates in Australia (Arthington, 1988), with *P. reticulata* also feeding on benthic algae (Dussault and Kramer, 1981). In the Mulgrave River, they are likely to compete with the aquatic invertivores *G. aprion*, *G. bellendenensis*, and *H. compressa* (Ryan et al. 2009), the terrestrial invertivore *C. rhombosomoides* (Pusey *et al.*, 2004), and possibly also with juveniles of the carnivorous *T. tandanus* (Pusey *et al.*, 2004). In contrast, food competition with *P. signifier* and *M. splendida splendida* is unlikely as they are surface invertivores (Rayner *et al.*, 2009). Hence, food competition is a likely pathway that non-native fish affect the presence and abundance of at least some native and endemic species in the Wet Tropics region.

Second, aggressive behaviour by non-native species may influence the abundance and distribution of native species. During courtship and mating established *T. mariae* pairs will aggressively defend their territory from conspecific individuals and other species (see references in Bradford *et al.*, 2011). *Tilapia mariae* attend to nests in the upper Mulgrave River (Lake Barrine) at least six months of the year (F. Kroon, personal observations), and can breed year-round in their native range (see references in Bradford *et al.*, 2011). During these periods, *T. mariae*'s aggressive behaviour could result in exclusion of native species, particularly those that share the same habitat such as *G. aprion, H. compressa*, and *M. splendida splendida* (Rayner *et al.*, 2008). Other native species that build nests in similar habitats, such as *T. tandanus* (Pusey *et al.*, 2004), could be prevented from breeding all together. For example, in Florida 30% of sunfish (*Lepomis* spp.), a species with similar territorial and spawning behaviour, are ejected from territories through competition with *T. mariae* (Brooks and Jordan 2010). Furthermore, workshop participants mentioned the uprooting of *Vallisneria* beds by breeding *T. mariae* in the nearby Johnstone River, with macrophyte beds returning when fish are removed. *Vallisneria* beds are now almost completely absent in the Mulgrave River (P. Thuesen, personal observation). Thus by disturbing macrophyte beds such as *Vallisneria*, *T. mariae* is also likely to affect the food source of the native *A. sclerolepis* (Rayner *et al.*, 2009).

Third, fish diseases and parasites have entered Australia via introductions of non-native fish (Arthington, 1991). *Poecilia reticulata* can act as a vector for diseases and parasites (e.g. Leberg and Vrijenhoek 1994). In North Queensland, non-native parasites (n=5 species) have been identified on non-native fish species, including *P. reticulata*, but not on native fish species (Webb 2003). We are currently not aware of native fish in the Mulgrave River or Wet Tropics region more widely having been impacted by the introduction of non-native diseases or parasites.

4.4 Implications for research and management of non-native fish

Our results suggest that relative abundance of non-native fish in the Wet Tropics region may be determined by physical and cover components at the local scale, rather than catchment components at the regional scale. However, our study was restricted by the availability of suitable spatial information at the regional scale and the influence of catchment components at the regional scale, such as in-stream barriers (Lawson *et al.*, 2010), on the distribution and abundance of non-native species needs to be further explored.

The relative abundance of Poecilids was clearly related to disturbances associated with the removal of riparian vegetation. Specifically, their relative abundance increased with sedimentation and presence of grasses, and decreased with root masses and leaf litter. Riparian zones influence a variety of ecological patterns and processes, including enhancement of bank stability (Prosser *et al.*, 2001), the provision of coarse woody material as habitat and substrate for aquatic flora and fauna (Crook and Robertson, 1999), mediation of changes in channel morphology and habitat diversity (Beechie and Sibley, 1997) and refuge from disturbance at a variety of scales (Seddell *et al.*, 1990). Key ecological processes influenced by riparian zones include thermal buffering (Lynch *et al.*, 1984), shading and in-stream primary production (Bunn and Davies, 1999), as well as nutrient interception, storage and release (Osborne and Kovacic, 1993). Shading has been shown to control invasive macrophytes in the Johnstone River (Bunn *et al.*, 1998), indicating that restoration of native riparian vegetation provides a long-term control mechanism for aquatic weeds in the Wet Tropics NRM region. Simultaneously, riparian rootmasses will provide bank stability thereby reducing sedimentation, while native riparian vegetation will enhance input of riparian leaf litter. While our study did not document a relationship between relative abundance of Cichlid species and specific riparian variables, previous work in the Upper Barron suggest that restoration of native riparian vegetation and fencing could reduce the abundance of *O. mossambicus* (Hogan and Vallance, 2002). Hence, similarly to the control of invasive macrophytes, restoration of native riparian vegetation is likely to provide a long-term control mechanism for non-native fish species in the Wet Tropics region. Follow-up surveys of the abundance of *O. mossambicus* at the rehabilitated sites in the Upper Barron (Hogan and Vallance, 2002) would provide a first indication of the effectiveness of this control mechanism for non-native fish species.

5 References

Allen, G. R., Midgley, S. H. & Allen, M. (2003). *Freshwater Fishes of Australia.* Collingwood, Australia: CSIRO Publishing.
Arthington, A. H. (1988). Diet of *Gambusia affinis holbrooki*, *Xiphophorus helleri*, *X. maculatus*, and *Poecilia reticulata* (Pisces: Poeciliidae) in streams of southeastern Queensland, Australia. *Asian Fisheries Science* **2**, 193-212.
Beechie, T. J. & Sibley, T. H. (1997). Relationships between channel characteristics, woody debris and fish habitat in north-eastern Washington streams. *Transactions of the American Fisheries Society* **126**, 217-229.
Bradford, M., Kroon, F. J. & Russell, D. J. (2011). The biology and management of Tilapia mariae (Pisces: Cichlidae) as a native and invasive species: a review. *Marine and Freshwater Research* **62**, 902-917.
Bunn, S. E. & Davies, P. M. (1999). Aquatic food webs. In *Riparian Land Management Technical Guidelines Vol 1: Principles of Sound Management* (Lovett, S. & Price, P., eds.), pp. 47-62. Canberra, Australia: Land and Water Resources Research Development Corporation.
Bunn, S. E., Davies, P. M., Kellaway, D. M. & Prosser, I. P. (1998). Influence of invasive macrophytes on channel morphology and hydrology in an open tropical lowland stream, and potential control by riparian shading. *Freshwater Biology* **39**, 171-178.
Clarke, K. R. (1993). Non-parametric multivariate analyses of changes in community structure. *Australian Journal of Ecology* **18**, 117-143.
Clarke, K. R. & Gorley, R. N. (2001). PRIMER (Plymouth Routines In Multivariate Ecological Research) v5: user manual/tutorial. Plymouth, U.K.: PRIMER Ltd.
Clarke, K. R. & Gorley, R. N. (2006). p. 190 pp. Plymouth, UK: PRIMER-E Ltd.
Clarke, K. R. & Warwick, R. M. (2001). Change in marine communities: an approach to statistical analysis and interpretation. Plymouth, U.K.: PRIMER-E.
Crook, D. A. & Robertson, A. I. (1999). Relationships between riverine fish and woody debris: implications for lowland rivers. *Marine and Freshwater Research* **50**, 941-953.
Dussault, G. V. & Kramer, D. L. (1981). Food and feeding-behavior of the guppy, *Poecilia reticulata* (Pisces, Poeciliidae). *Canadian Journal of Zoology-Revue Canadienne De Zoologie* **59**, 684-701.
Hogan, A. & Vallance, T. (2002). An assessment of an NHT project to re-establish riparian zones as a Tilapia control measure. p. 16. Walkamin, Australia: Freshwater Fisheries and Aquaculture Centre.
Lawson, T., Kroon, F., Russell, J., Thuesen, P. & Fakes, A. (2010). Audit and prioritisation of physical barriers to fish passage in the Wet Tropics region. Milestone report, MTSRF project 2.6.2. p. 14. Atherton, Australia: CSIRO Ecosystem Sciences.
Lynch, J. A., Rishel, G. B. & Corbett, E. S. (1984). Thermal alterations of streams draining clear-cut watersheds - quantification and biological implications. *Hydrobiologia* **111**, 161-169.
Osborne, L. L. & Kovacic, D. A. (1993). Riparian vegetated buffer strips in water-quality restoration and stream management. *Freshwater Biology* **29**, 243-258.
Prosser, I., Rutherford, I., JM, O., Young, W., Wallbrink, P. & Moran, C. (2001). Large-scale patterns of erosion and sediment transport in river networks, with examples from Australia. *Marine and Freshwater Research* **52**, 81-99.
Pusey, B., Kennard, M. & Arthington, A. (2004). *Freshwater Fishes of North-Eastern Australia*. Collingwood, Australia: CSIRO Publishing.

Pusey, B. J. & Kennard, M. J. (1994). The freshwater fish fauna of the Wet Tropics Region of northern Queensland. p. 97. Nathan, Australia: Griffith University.
Pusey, B. J. & Kennard, M. J. (1996). Species richness and geographical variation in assemblage structure of the freshwater fish fauna of the Wet Tropics region of Northern Queensland. *Marine and Freshwater Research* **47**, 563-573.
Rayner, T. S., Pusey, B. J. & Pearson, R. G. (2008). Seasonal flooding, instream habitat structure and fish assemblages in the Mulgrave River, North-East Queensland: towards a new conceptual framework for understanding fish-habitat dynamics in small tropical rivers. *Marine and Freshwater Research* **59**, 97-116.
Rayner, T. S., Pusey, B. J. & Pearson, R. G. (2009). Spatio-temporal dynamics of fish feeding in the lower Mulgrave River, north-eastern Queensland: the influence of seasonal flooding, instream productivity and invertebrate abundance. *Marine and Freshwater Research* **60**, 97-111.
Reznick, D., Butler IV, M. J. & Rodd, H. (2001). Life history evolution in guppies 7: The comparative ecology of high and low predation environments. *American Naturalist* **157**, 126-140.
Russell, D. J. & Hales, P. W. (1993). Stream Habitat and Fisheries Resources of the Johnstone River Catchment. p. 60. Brisbane, Australia: Queensland Department of Primary Industries.
Russell, D. J. & Hales, P. W. (1997). Fish Resources and Stream Habitat of the Liverpool, Maria and Hull Catchments. p. 68. Brisbane, Australia: Queensland Department of Primary Industries.
Russell, D. J., Hales, P. W. & Helme, S. A. (1996a). Fish Resources and Stream Habitat of the Moresby River Catchment. p. 50. Brisbane: Queensland Department of Primary Industries.
Russell, D. J., Hales, P. W. & Helmke, S. A. (1996b). Stream Habitat and Fish Resources in the Russell and Mulgrave Rivers Catchment. p. 58. Brisbane, Australia: Queensland Department of Primary Industries.
Russell, D. J., McDougall, A. J. & Kistle, S. E. (1998). Fish resources and stream habitat of the Daintree, Saltwater, Mossman and Mowbray catchments., p. 72. Brisbane, Australia: Queensland Department of Primary Industries.
Russell, D. J., McDougall, A. J., Ryan, T. J., Kistle, S. E., Aland, G., Cogle, A. L. & Langford, P. A. (2000). Natural Resources of the Barron River Catchment 1. Stream habitat, fisheries resources and biological indicators. p. 108. Brisbane, Australia: Queensland Department of Primary Industries.
Russell, D. J., Thuesen, P. A. & Thomson, F. E. (2012). A review of the biology, ecology, distribution and control of Mozambique tilapia, *Oreochromis mossambicus* (Peters 1852) (Pisces: Cichlidae) with particular emphasis on invasive Australian populations. *Reviews in Fish Biology and Fisheries* **22**, 533-554.
Schmitter-Soto, J. J., Ruiz-Cauich, L. E., Herrera, R. L. & González-Solís, D. (2011). An Index of Biotic Integrity for shallow streams of the Hondo River basin, Yucatan Peninsula. *Science of the Total Environment* **409**, 844-852.
Seddell, J. R., Reeves, G. H., Hauer, F. R., Stanford, J. A. & Hawkins, C. P. (1990). Role of refugia in recovery from disturbance: modern fragmented and disconnected river systems. *Environmental Management* **14**, 711-724.
Thuesen, P. A., Russell, D. J., Thomson, F. E., Pearce, M. G., Vallance, T. D. & Hogan, A. E. (2011). An evaluation of electrofishing as a control measure for an invasive tilapia (Oreochromis mossambicus) population in northern Australia. *Marine and Freshwater Research* **62**, 110-118.
Webb, A. C. (2007). Status of Non-native Freshwater Fishes in Tropical Northern Queensland, Including Establishment Success, Rates of Spread, Range and Introduction Pathways. *Journal & Proceedings of the Royal Society of New South Wales* **140**, 63-78.

Appendix A Data sheets DPI&F

A.1 Data sheets used by DPI&F for data collection in Freshwater Creek, Behana Creek and Mulgrave catchment

FISH INVENTORY DATASHEET (ELECTROFISHING)

Date: ___________ Site No: ____________ Stream Name: ______________________________________

Electofisher counter: Start: ____________ Finish: _______________ Substrate

(P)________(R)______

Length of stream assessed (m): _________ Flow: _____(S,M,F) Depth (P)______ (R)_____

Temp (°C):________ pH:______ Oxygen (ppm):________ Turbidity (NTU):_________Conductivity: ________

	Habitat Type	Secs	Species shocked	Number Tally	Size Range	Spp observed	Comments
Pool/Glide	Snag						
	Undercut						
	Rocks						
	Grass						
	Leaf litter						
	Roots						
	Open						
Rapids	Rocks						

Date Site No Stream Name Stream order

Lat/Long Zone Length of stream assessed (m)

WQ meter: Temp (C) pH Conductivity (uS) DO (pp/ml) (%SAT) Turbidity (NTU)

Disturbance rating Aquatic veg. species: Barrier present: y/n Type of barrier:

Photos taken: Site y/n Barrier y/n

RIPARIAN VEGETATION

LEFT BANK		RIGHT BANK
	WIDTH	
	CONTINUITY	
	% TREES / SHRUBS	
	% GRASSES	
	% OTHER	
	% NO VEG	

FISHERIES HABITAT RATING (1 (minor) to 4 (major)

	P	R
UNDERCUT BANKS/ROOTS		
SNAGS		
AQUATIC MACROPHYTES		
GRASSES		
ROCKS		
OVERHANGING VEGETATION		
LEAF LITTER		

CANOPY COVER

SEDIMENTATION

INVASIVE GRASSES

SPECIES	
TOTAL LENGTH	
MAX. WIDTH	

FERAL ANIMAL DAMAGE

MANGROVES PRESENT

STREAM STRUCTURE

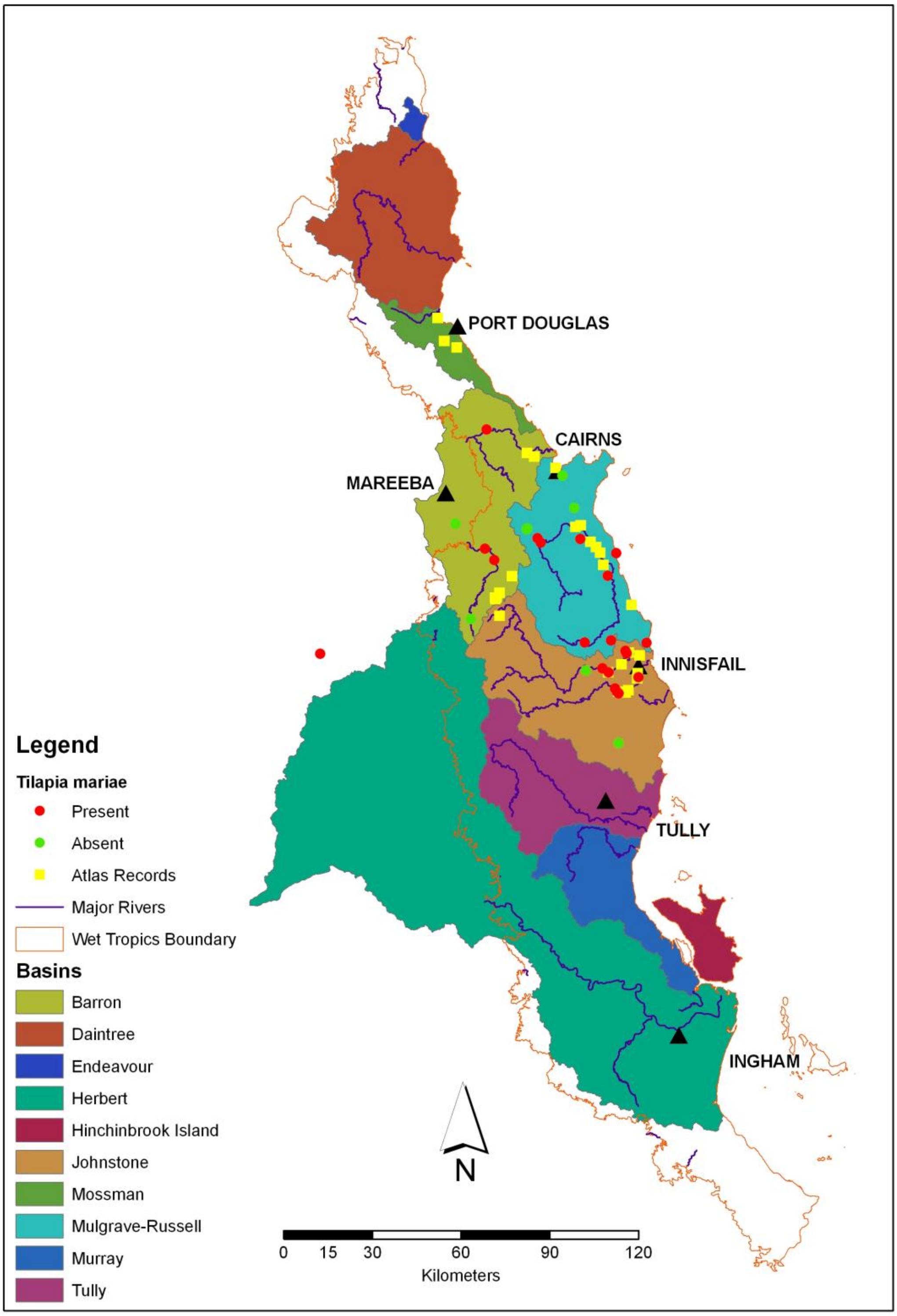
POOLS/DEEP		RIFFLES / SHALLOW
	TOTAL LENGTH	
	MAX. DEPTH	
	AV. DEPTH	
	MAX. WIDTH	
	AV. WIDTH	
	BOULDER/COBBLE	
	COBBLE/GRAVEL	
	SAND	
	FINE MATERIAL	

DISTURBANCES

COMMENTS

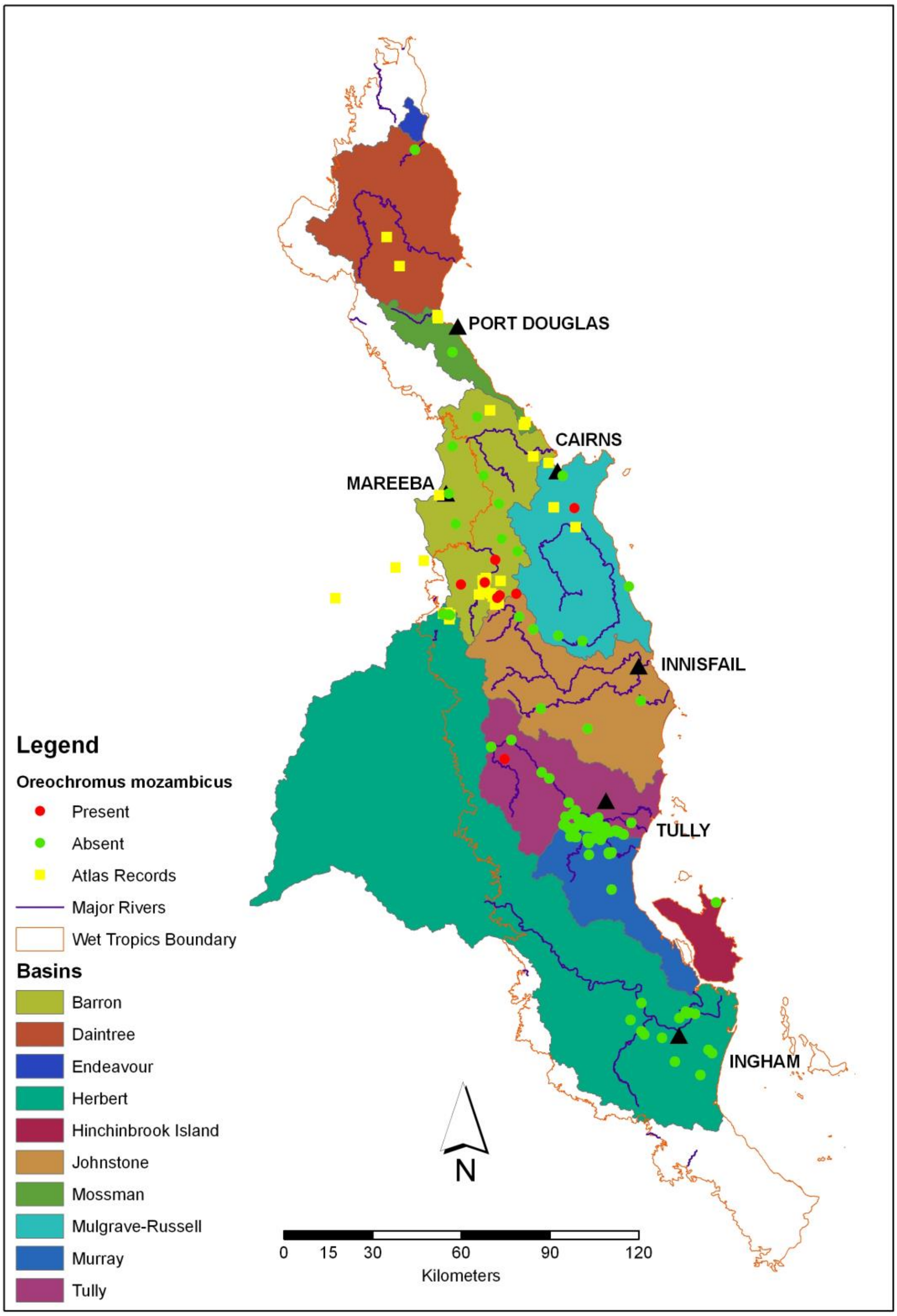
A.2 Presence/absence records for five non-native fish species in the Wet Tropics region. (a) *Tilapia mariae*, (b) *Oreochromus mossambicus*, (c) *Poecilia reticulata*, (d) *Xiphophorus maculatus*, and (e) *Gambusia holbrookii*.

(a)



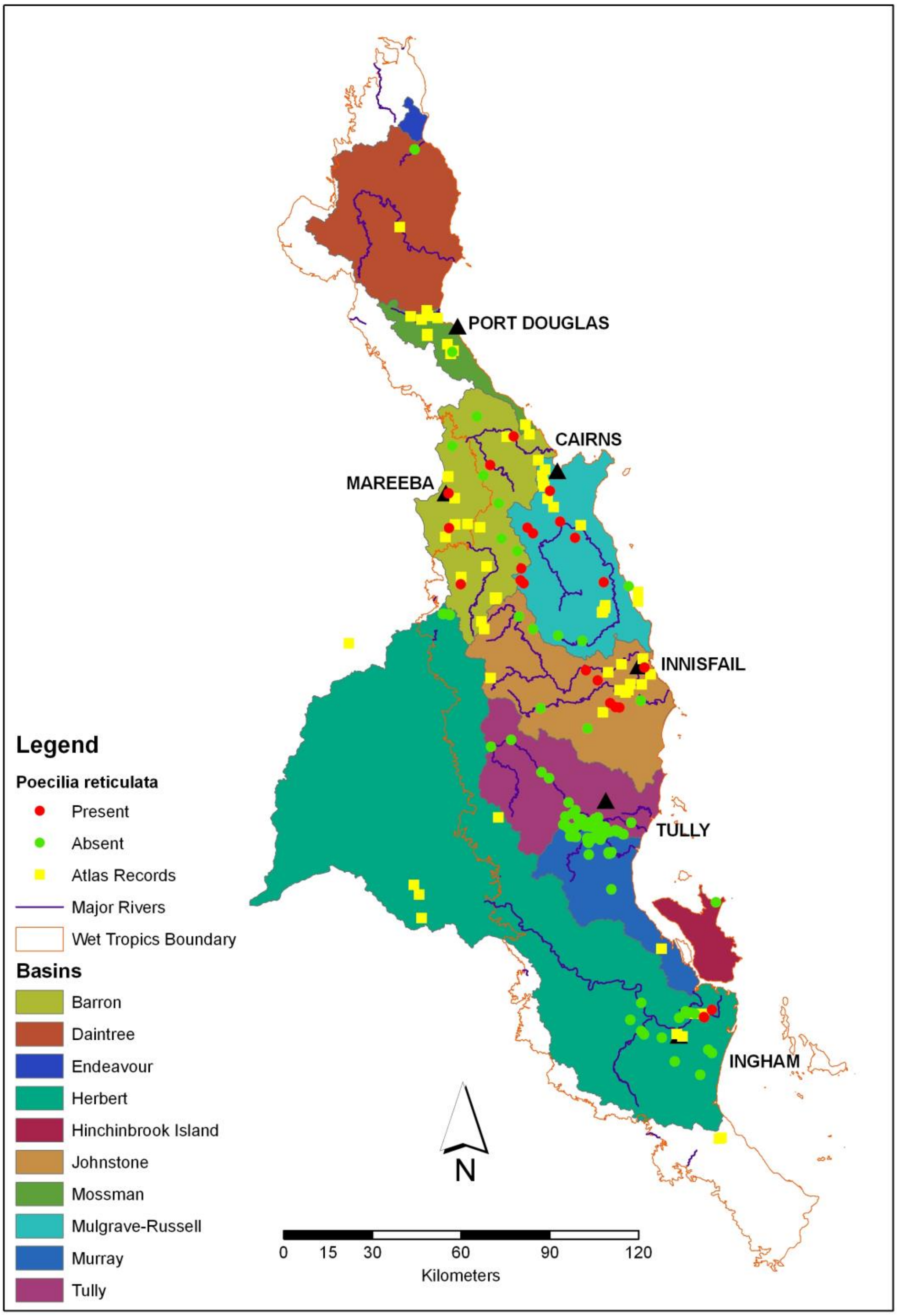
PORT DOUGLAS
CAIRNS
MAREEBA
INNISFAIL
TULLY
INGHAM
Legend
Tilapia mariae
Present
Absent
Atlas Records
Major Rivers
Wet Tropics Boundary
Basins
Barron
Daintree
Endeavour
Herbert
Hinchinbrook Island
Johnstone
Mossman
Mulgrave-Russell
Murray
Tully
N
0
15
30
60
90
120
Kilometers

(b)

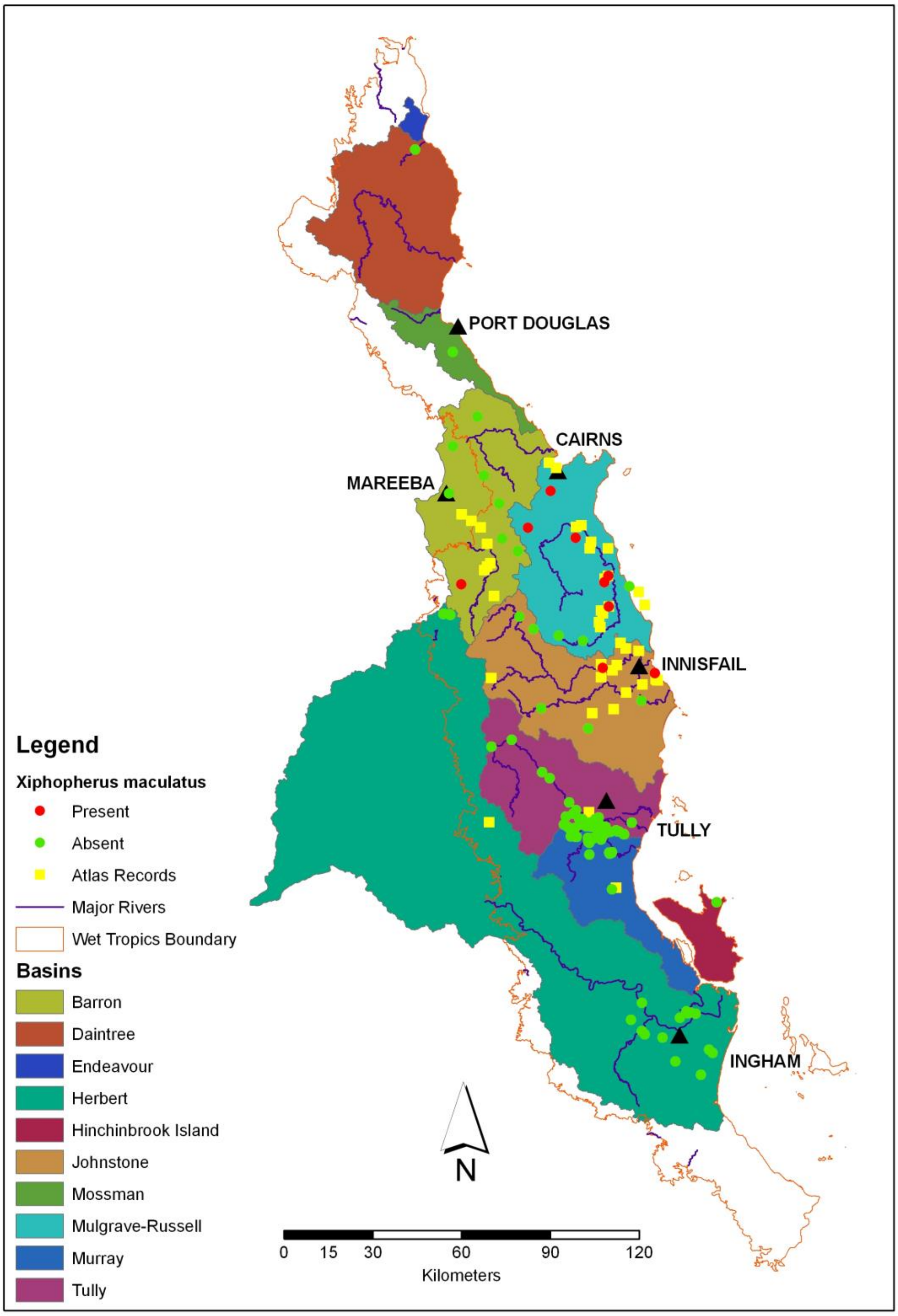


PORT DOUGLAS
CAIRNS
MAREEBA
INNISFAIL
TULLY
INGHAM
Legend
Oreochromus mozambicus
Present
Absent
Atlas Records
Major Rivers
Wet Tropics Boundary
Basins
Barron
Daintree
Endeavour
Herbert
Hinchinbrook Island
Johnstone
Mossman
Mulgrave-Russell
Murray
Tully
N
0 15 30 60 90 120
Kilometers

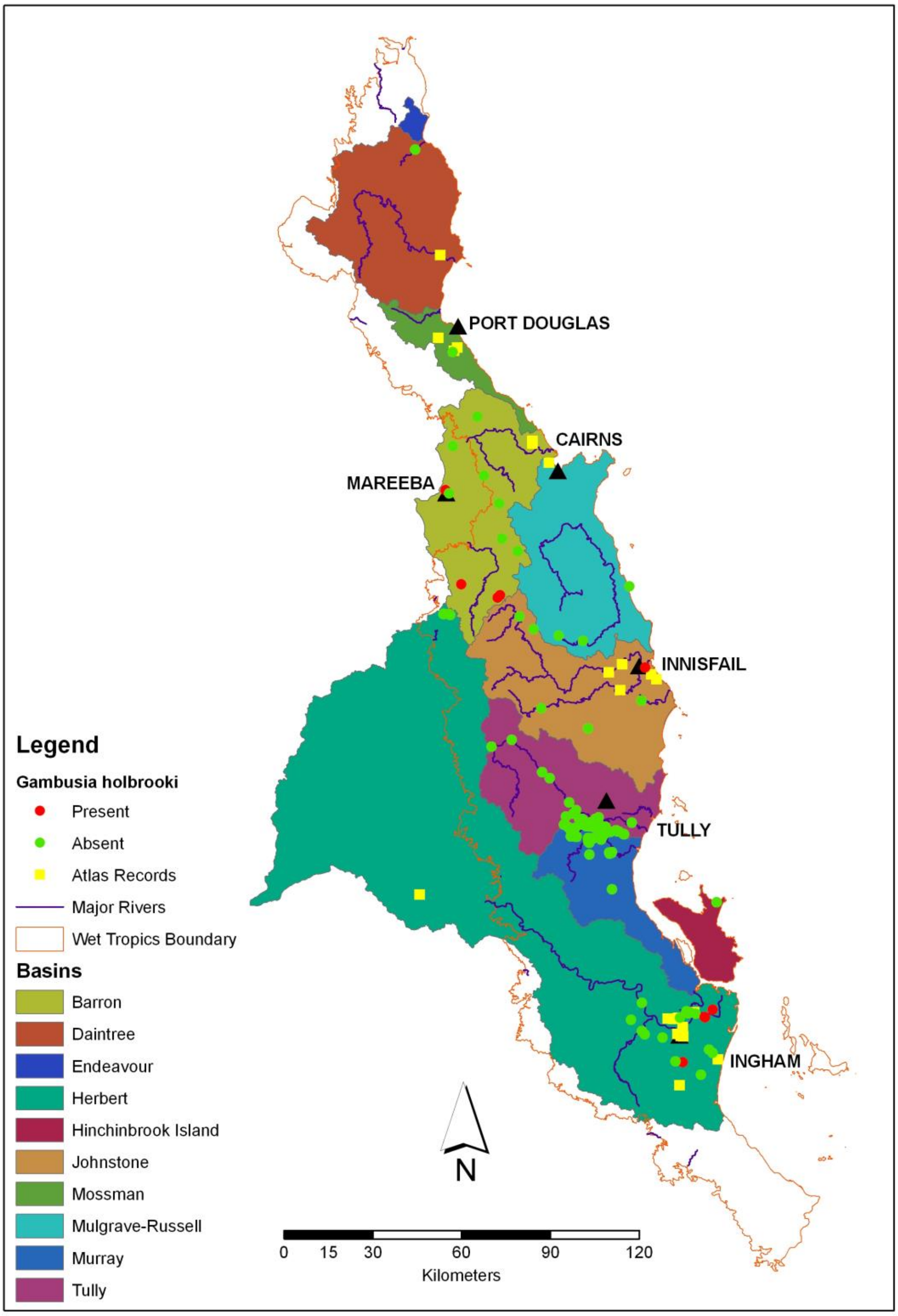
(c)


PORT DOUGLAS
CAIRNS
MAREEBA
INNISFAIL
TULLY
INGHAM
Legend
Poecilia reticulata
Present
Absent
Atlas Records
Major Rivers
Wet Tropics Boundary
Basins
Barron
Daintree
Endeavour
Herbert
Hinchinbrook Island
Johnstone
Mossman
Mulgrave-Russell
Murray
Tully
N
0 15 30 60 90 120
Kilometers

(d)


PORT DOUGLAS
CAIRNS
MAREEBA
INNISFAIL
TULLY
INGHAM
Legend
Xiphopherus maculatus
Present
Absent
Atlas Records
Major Rivers
Wet Tropics Boundary
Basins
Barron
Daintree
Endeavour
Herbert
Hinchinbrook Island
Johnstone
Mossman
Mulgrave-Russell
Murray
Tully
N
0 15 30 60 90 120
Kilometers

(e)


PORT DOUGLAS
CAIRNS
MAREEBA
INNISFAIL
TULLY
INGHAM
Legend
Gambusia holbrooki
Present
Absent
Atlas Records
Major Rivers
Wet Tropics Boundary
Basins
Barron
Daintree
Endeavour
Herbert
Hinchinbrook Island
Johnstone
Mossman
Mulgrave-Russell
Murray
Tully
N
0 15 30 60 90 120
Kilometers

CONTACT US

t 1300 363 400
+61 3 9545 2176
e enquiries@csiro.au
w www.csiro.au

YOUR CSIRO

FOR FURTHER INFORMATION

CSIRO Ecosystems Sciences
Frederieke Kroon
t +61 7-4091 8809
e frederieke.kroon@csiro.au
w http://www.csiro.au/Organisation-Structure/Divisions/Ecosystem-Sciences.aspx