Effects of alteration to catchments and streams on freshwater fish communities of Vanua Levu, Fiji

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Executive Summary

In October and November 2010, staff from the Wildlife Conservation Society, Wetlands International-Oceania, Department of Fisheries and Department of Forestry conducted riparian and stream surveys at 32 small stream sites in Wainunu, Kubulau, Macuata and Sasa districts of Bua and Macuata provinces on the island of Vanua Levu. The sites were chosen in areas of greater or less than 50% sub-catchment forest cover and with intact or degraded riparian zones to assess the impact of catchment and stream alteration on in-stream freshwater fish communities. We set out to address the question: "How does the size and composition of the riparian forest buffer strip in varying overall catchment cover conditions influence fish abundance, diversity, and water quality in the adjacent river?"

We found that the tree community size structure of the riparian zone may only have marginal influence on in-stream fish abundance. The factors that were most strongly related to fish presence/absence and abundance were: sub-catchment forest cover; conductivity; and the presence of downstream overhanging culverts.

Our prior research indicated that fish community composition is substantially affected when catchment forest cover falls below 50%. These findings were confirmed in our present study. This is likely due to increased sediment erosion from the adjacent lands into streambeds, which can impact feeding, breeding and resting habitat of Fiji's native fish. Our present survey found elevated conductivity at the most degraded sites, which can be related to concentrations of suspended sediment and dissolved organic material.

Secondly, we found reduced species richness and fish abundance at sites upstream from overhanging culverts, even in locations with high cover of primary forest and intact riparian zones. Overhanging culverts block upstream migrations of fish, and a large proportion of Fiji's freshwater fish fauna make obligate migrations from the upper or mid-reach of streams to the sea at some phase in their life cycles. Many species that were absent from the fish assemblages upstream from overhanging culverts are those with importance for subsistence or livelihoods for inland communities. Thus, there is a pressing need to think about improved culvert design to allow for safe fish passage.

From our research, we have developed two important rule of thumb recommendations to guide local communities to manage their freshwater systems. First, communities should aspire to protect waterways in sub-catchments with greater than 50% forest cover. It is much easier and more cost-effective to protect existing intact landscapes than to attempt to restore them. Secondly, communities should preferentially prioritize freshwater streams for protection that are clear of downstream overhanging culverts. We have been using these guidelines to assist communities throughout Vanua Levu to designate or expand terrestrial and freshwater protected areas.

Introduction

Riparian habitats are critically important as habitat corridors for wildlife (Catteral 1993) and sources of organic detritus for downstream secondary production (Caraco and Cole 2004). They additionally provide water quality benefits through bank stabilization and sediment trapping (McKergow et al. 2003) and nutrient and chemical filtering (Hubbard and Lowrance 1994), therefore potentially protecting downstream reef systems from sediment and nutrient pollution. Because Fiji's fishes are highly migratory (~99% of fishes found in freshwater make contact with saltwater during their life cycles; Jenkins et al. 2010), protection of riparian systems is also critical to protect biodiversity and important fisheries resources.

There is a large body of evidence which suggests that broad-scale catchment land-clearing has both direct and indirect effects on tropical, native in-stream community structure (Naiman and Decamps 1997). In Fiji, Jenkins et al. (2010) note a marked decline in fish diversity in mid-reaches of streams where catchment forest cover is reduced below 50%. These impacts are particularly pronounced in degraded catchments during the wet season, when seasonal flood pulses bring high volumes of sediments and associated pollutants into waterways (Jenkins and Jupiter 2011). Invertebrates are likely to be similarly affected: Haynes (1999) found consistently lower diversity in streams adjacent to logged areas over a three year study period. She hypothesized that the low abundance of neritid gastropods in streams of a logged catchment was due to sediment covering the periphyton on which they grazed (Haynes 1999). The decline of these prey species may strongly affect predator species such as gudgeons, which are important local freshwater fisheries resources in Fiji and feed preferentially on bottom-dwelling invertebrates (Jenkins et al. 2010).

A large question remains regarding the role and nature of riparian vegetation and processes in mitigating the effects of broader-catchment land clearing, particularly in tropical systems. Some studies have found riparian width and past disturbance histories to be important factors in determining impacts from land-clearing: for example, a study from Tasmania found an 80% reduction in macroinvertebrate abundance between control sites upstream of logging and downstream sites where riparian buffer width was less than 30 m (Davies and Nelson 1994). In a tropical example, Iwata et al. (2003) showed decreases in abundance and diversity of aquatic insects, shrimp, crabs, and benthic-dwelling fish in relation to increases in fine sediments, eroded banks, and depositional habitat as a result of previous slash-and-burn clearing within riparian zones in Borneo.

Local management can play a major role in halting these declines and, in one case, community-based management of catchment areas in Fiji was successful at preserving native fish diversity in freshwater systems. The small, coastal catchment of Macuata-i-wai, which is surrounded by heavily cultivated and degraded land, had much greater fish diversity than non-managed catchments with comparable forest cover (Jenkins et al. in 2010). For two years prior to sampling, the community leaders had strictly enforced a ban on logging, fishing and waste disposal within the vicinity of the stream, which may have preserved the clean, rocky substrate preferred by species such as the endemic *Stiphodon* sp. 1 and the overhanging riparian vegetation which provides leaf litter detritus on which specialized detritivores feed (such as *Ophiocara porocephala*). Yet following the lifting of this ban, all benefits of protection were rapidly removed (Jenkins and Jupiter 2011), indicating that riparian and freshwater protection must be consistent, long-term and enforced for it to be effective.

However, an assumption is often made that the water quality and community benefits from preserved and restored riparian vegetation will be universally applicable. They typically only occur where the vegetation communities are proximate to pollution sources and when surface runoff moves slowly across the root zone (Norris 1993; Lowrance et al. 1997; Jupiter and Marion 2008). In the section of Kubulau District's (Bua Province) ecosystem-based management plan on best practices for management of freshwater habitats, there is a recommendation to "restore degraded river banks and riparian zones by planting native trees and shrubs" (WCS 2009). Because this is a time consuming and expensive process, we need to first be confident that areas with more intact riparian zones will indeed support greater biological diversity in the context of broader land-clearing for agricultural activities and logging. Secondly, we need to be able to prioritize where would be the best places along freshwater corridors to protect existing riparian habitat and restore degraded habitat.

In this study, we collect a range of field data on in situ predictor variables (e.g. riparian vegetation composition, dissolved oxygen, conductivity, water temperature) and response variables (e.g. fish diversity and relative abundance) in order to better understand drivers of in-stream community composition. Secondly, we use the lessons from this current research and prior studies (Jenkins et al. 2010; Jenkins and Jupiter 2011) to set rules of thumb for identifying priorities for terrestrial and riparian protection across Fiji.

Methods

Study region and site selection

Our study region focused on the districts of Wainunu and Kubulau (Bua Province) and Macuata and Sasa (Macuata Province) on the island of Vanua Levu, Fiji. For site selection, we used spatial layers of Fiji forest cover, roads, villages and catchments boundaries, and referenced imagery within Google Earth, to identify locations that met the following criteria in our stratified sampling design:

Greater than 50% sub-catchment forest cover		**Less than 50% sub-catchment forest cover**	
Greater than 30 meters riparian width	Less than 30 meters riparian width	Greater than 30 meters riparian width	Less than 30 meters riparian width

We used this technique to select 32 sampling sites (8 sites for each treatment) and pre-uploaded the GPS coordinates to enable field location of the sampling areas. Upon arriving at the field sites in October and November 2010, the field team found that the actual width of the riparian zones in many cases was larger or smaller than anticipated, leading to an unbalanced site design (Figure 1, Appendix 1):

Greater than 50% sub-catchment forest cover		Less than 50% sub-catchment forest cover	
Greater than 30 meters riparian width (n = 13)	Less than 30 meters riparian width (n = 5)	Greater than 30 meters riparian width (n = 2)	Less than 30 meters riparian width (n = 12)

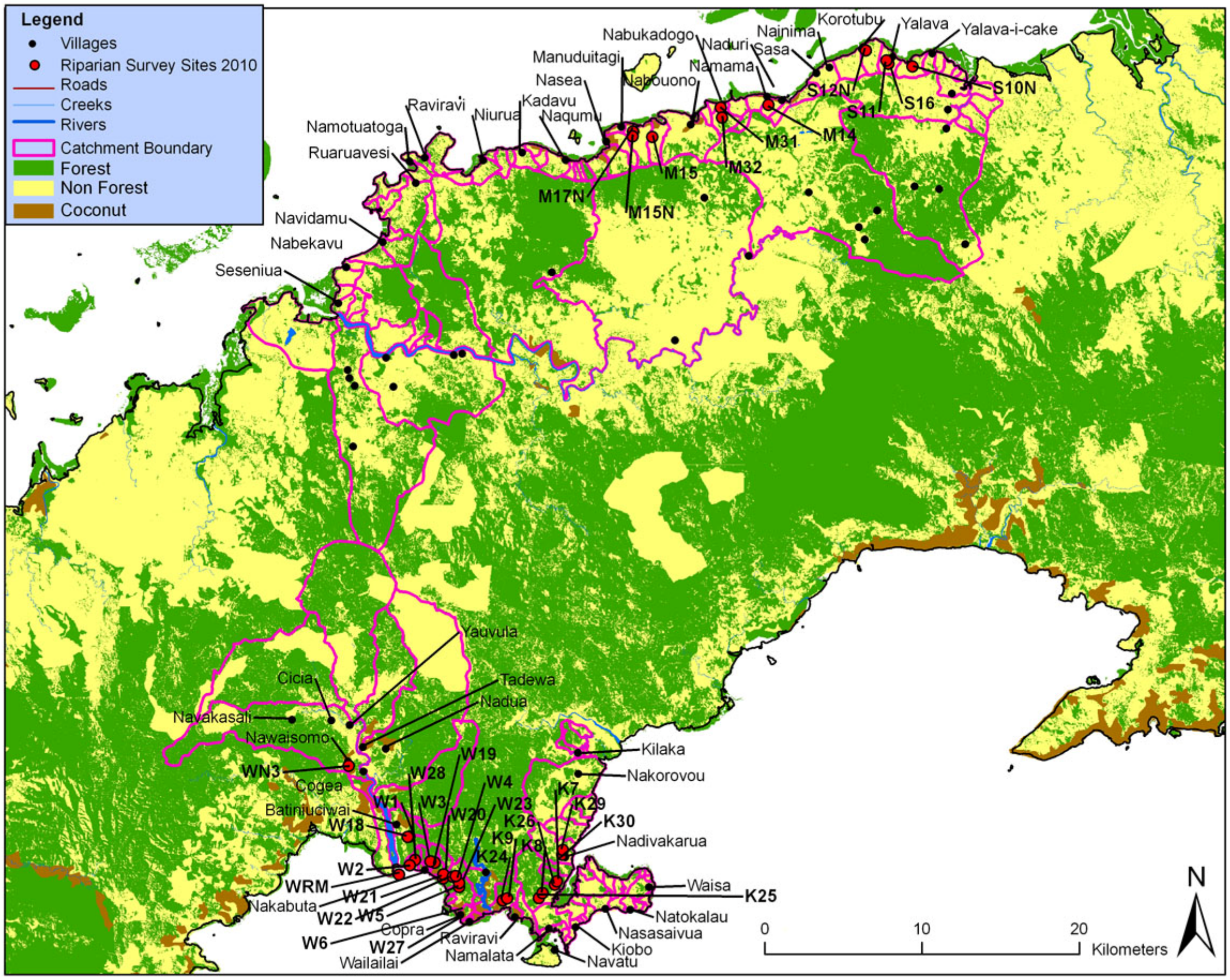

Figure 1. Location of riparian and instream field sites in Wainunu, Kubulau, Macuata and Sasa districts.

It was particularly difficult for the field team to locate more than 2 sites in areas of substantially cleared catchments where riparian buffer zones had been maintained at widths greater than 30 m. This type of site is extremely valuable as it simulates what restoration efforts might be able to provide. Unfortunately, both of the sites located were compromised by the presence of downstream overhanging culverts, which serve as barriers for upstream movements of most fish that cannot climb. Thus, our analysis focused on evaluating the biophysical determinants of similarities and differences between sites, using continuously distributed predictor variables (e.g., conductivity, water temperature, dissolved oxygen concentrations, mean stream depth, mean stream width), ranked qualitative measurements of stream characteristics (e.g., substrate type, overhanging canopy cover, number of root masses, number of undercuts), and categorical predictor variables (e.g., presence/absence of downstream overhanging culverts).

Riparian surveys

Diameter at breast height (dbh) was measured from all trees with diameter greater than 10 cm within four replicate 30 m x 2 m belt transects running perpendicular to the stream bank at each site (Figure 2a). Dominant trees and other vegetation types were noted for each transect, as well as remarks about landscape characteristics. Vegetation was crosschecked against Keppel (2005) and Keppel and Ghazanfar (2006) to determine whether species were endemic, indigenous or introduced.

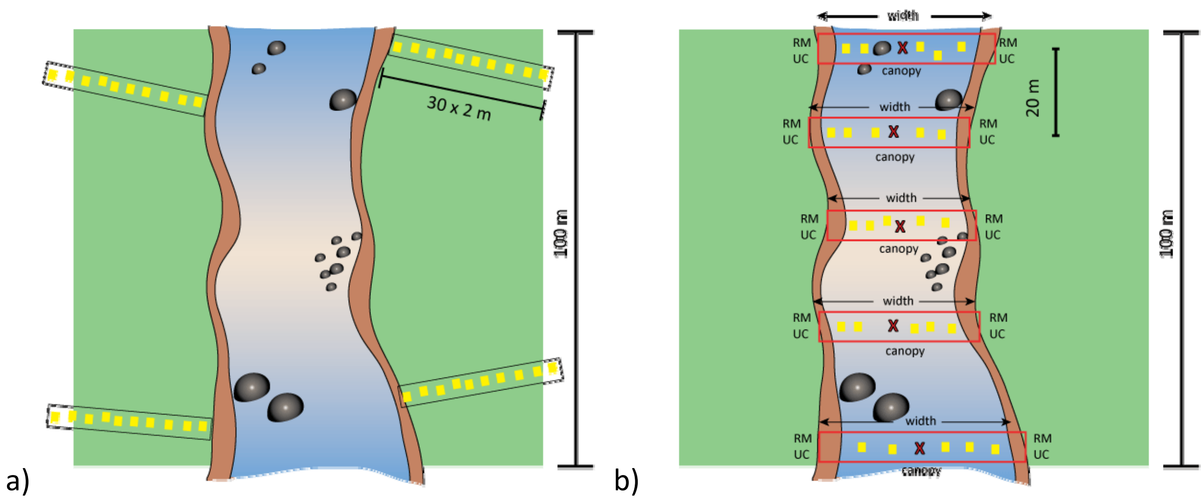

Figure 2. Schematic representation of measurements taken for (a) riparian zone surveys and (b) stream biophysical characteristics surveys. RM = root mass, UC = undercut, yellow square = quadrat.

Stream biophysical characteristics surveys

At each site, we collected measurements of water quality variables (temperature, conductivity, and dissolved oxygen) and stream characteristics (stream width, stream depth, substrate coarseness, canopy cover, number of root masses, and number of undercuts) predicted to influence fish community assemblages (Figure 2b). We measured water quality variables with a hand-held YSI multi-meter before entering the water to minimize disturbance. We measured stream width across 5 replicate transects spread at a minimum of 20 m apart. For each transect, we estimated canopy cover (0-20%, 20-40%, 40-60%, 60-80%, 80-100%) from the centre of the stream. We noted whether there were any root masses or undercuts present at each stream bank side along each transect. We measured stream depth from 5 quadrats spaced randomly across each transect. We ranked substrate coarseness into the following classes, evaluated for each quadrat: 1 – silt; 2 – sand; 3 – gravel; 4 – pebble; 5 – cobble; 6 – boulder; 7 – bedrock.

In-stream fish community surveys

We surveyed fish species richness and abundance in streams at study sites in Wainunu, Kubulau, Macuata and Sasa districts described above. We systematically sampled fish communities using the exact methods of Jenkins et al. (2010), modified from field protocols of Parham (2005) and Fitzsimons et al. (2007). In brief, we used a variety of techniques to collect fauna from the streams to ensure comprehensive presence/absence assessment. These techniques included: electrofishing using a Smith-Root (500 V, 10A) backpack unit; netting with gill nets (1 in mesh), large seine nets (0.4 cm^2 mesh), medium pole seine nets (1 mm^2 mesh) and small hand nets (1 mm^2 mesh); and observations by mask and snorkel. At each site, 4–6 surveyors made collections from downstream to upstream for 1 h total. We fixed all specimens that could not be identified in the field in 10% formalin solution and transferred them to 70% ethanol solution after 1–2 weeks fixation for accurate taxonomic verification.

Statistical analyses

We first conducted RELATE tests comparing Bray-Curtis resemblance matrices calculated for mean density of trees across dbh size classes distributions with Bray-Curtis resemblance matrices (with dummy variable added due to sites with no fish collected) for fish presence/absence and abundance data. A RELATE test operates on the null assumption that there is no underlying relationship between the two sets of site-based data being compared and is assessed based on the number of times the calculated rho (ρ) statistic exceeds that found in 95% of simulations based on 999 permutations of the data labels (Clarke and Gorley 2006). As per Jenkins and Jupiter (2011), we used the BIO-ENV procedure within the BEST function of PRIMER version 6 software to evaluate potential stream biophysical correlates of fish presence/absence and abundance data (Clarke and Ainsworth 2003). We compared Euclidean distance similarity matrices of normalised stream biophysical variables plus presence of downstream overhanging culverts with Bray-Curtis similarity matrices (with dummy variable added) for fish presence/absence and abundance over 999 permutations. The output statistic for the BIO-ENV procedure is also rho (ρ). We used non-metric dimensional scaling (nMDS) to ordinate fish presence/absence and abundance data and evaluated the significance of resulting clusters using cluster analysis with similarity profile (SIMPROF) tests (Clarke and Gorley 2006). Lastly, we conducted two-factor permutational multivariate analysis of variance (PERMANOVA) analyses with 4,999 permutations using log10 Modified Gower resemblance matrices (Anderson 2001) of fish presence/absence and abundance data. We conducted separate two-factor PERMANOVA analyses with catchment forest cover class and presence of culverts as fixed factors and with riparian zone width class and presence of culverts as fixed factors as there was not enough replication to evaluate the interaction of catchment forest class and riparian width class due to difficulties finding sites in heavily cleared catchments with remnant riparian zones (as described above).

Results

Riparian zone communities

Dominant vegetation is described for each district below. Unless otherwise indicated to be endemic or introduced, plants are of indigenous origin.

Wainunu. Wainunu District had the highest cover of primary forest near streams of any district surveyed. Dominant species in sites included: *Atuna racemosa* (**makita**); *Gironniera celtidifolia* (**sisisi**); *Pometia pinnata* (**dawa**); *Ficus vitiensis* (**lolo**; endemic); *Cyathea* spp. (**balabala**); *Miscanthus floridulus* (**gasau**); *Inocarpus fagifer* (**ivi**); *Myristica castaneifolia* (**kaudamu**; endemic); and *Intsia bijuga* (**vesi**). Other large trees noted included: *Garcinia pseudoguttifera* (**bulu m**); *Bischofia javanica* (**koka**); *Dysoxylum lenticellare* (**malamala**); *Endospermum macrophyllum* (**kaukula**; endemic); *Serianthes melanesica* (**vaivai ni veikau**); and *Dillenia biflora* (**kuluva**). There was additionally a sighting of the now rare indigenous hardwood *Fagraea gracilipes* (**buabua**) at site W3. Tree sizes were skewed towards saplings and on average, trees were present along each transect in every size class (Figure 3a,b).

Kubulau. Survey sites in Kubulau were located in a mix of primary and secondary forest, as well as land previously cleared for plantations. At sites with recent or prior disturbance, there was a large cover of the vine *Meremia peltata* on the forest canopy or creeping across open space. Dominant species in sites with greater than 50% sub-catchment forest cover included: *P. pinnata* (**dawa**); *G. celtidifolia* (**sisisi**); *I. fagifer* (**ivi**); *Cyathea* spp. (**balabala**); *D. biflora* (**kuluva**); *G pseudoguttifera* (**bulu m**); *A. racemosa* (**makita**); *F. vitiensis* (**lolo**; endemic); *Dysoxylum richii* (**sasawira**; endemic); *Parinari insularum* (**sa**); *M. castaneifolia* (**kaudamu**; endemic); *Aleurites moluccana* (**sikea**; aboriginal introduction); *Macaranga harveyana* (**gadoa**); *I. bijuga* (**vesi**); and *Pagiantha thurstonii* (**tadalo**; endemic). Other large trees noted included: *Balaka seemannii* (**balaka**; endemic); and *Heritiera ornithocephala* (**rosarosa**). More degraded landscapes included the trees, shrubs and grasses: *Piper puberulum* (**yaqoyaqona vula**); *Geoniostoma vitiense* (**boiboida**); *Cynometra insularis* (**cibicibi**; endemic); *I. fagifer* (**ivi**); *F. vitiensis* (**lolo**; endemic); *M. harveyana* (**gadoa**); *Cocos nucifera* (**niu**); *Piper methisticum* (**yaqona**); *Alocasia* sp. (**via**); *Syzygium malaccense* (**kavika**; aboriginal introduction); *Hibiscus tiliaceus* (**vau**); *Spathodea campanulata* (African tulip; introduced); *Pandanus tectorius* (**vadra**); *P. pinnata* (**dawa**); *Theobroma cacao* (cocoa); *Leucena leucocephala* (**vaivai**; introduced) and *Canaga odorata* (**makosoi**; possibly introduced from Hawaii). Like in Wainunu, tree sizes were skewed towards saplings and on average, trees were present along each transect in every size class (Figure 3c,d).

Macuata. Riparian landscapes in Macuata were fairly degraded, with sparse canopy adjacent to grazing lands and/or dry forest. Species found included a combination of mesic forest trees and trees cultivated for fruits, such as: *I. fagifer* (**ivi**); *Mangifera indica* (**maqo**; early European introduction); *S. malaccense* (**kavika**; aboriginal introduction); *C. nucifera* (**niu**); *D. richii* (**sasawira**; endemic); *Gyrocarpus americanus* (**wiriwiri**); *C. odorata* (**makosoi**; possibly introduced from Hawaii); *Psidium guajava* (guava; aboriginal introduction); *Decaspermum vitiensis* (**nuqanuqa**; endemic); *L. leucocephala* (**vaivai**; introduced); *A. moluccana* (**sikea**; aboriginal introduction); *Guioa sp.* (**drausasa**); *M. harveyana* (**gadoa**); *Casuarina equisetifoeia* (**nokonoko**); *Morinda citrifolia* (**kura**); *F. vitiensis* (**lolo**; endemic); *S. campanulata* (African tulip; introduced); *Pinus caribaea* (pine; introduced); *I. bijuga* (**vesi**); *P. insularum* (**sa**); *Premna protusa* (**yaro**; endemic); and *P. tectorius* (**vadra**). Sites had reasonable density of saplings, but few trees with dbh between 50 to 100 cm, suggesting considerable past disturbance (Figure 3e,f).

Sasa. The Sasa sites were the most disturbed, with highly cleared, largely open canopied, grassy riparian zones. Most larger trees were left standing likely because of food or fiber resources that they produce. Species included: *P. tectorius* (**vadra**); *P. guajava* (guava; aboriginal introduction); *Mangifera indica* (**maqo**; early European introduction); *Erythrina variegata* (**drala**); *P. caribaea* (pine; introduced); *S. campanulata* (African tulip; introduced); *C. odorata* (**makosoi**; possibly introduced from Hawaii); and *L. leucocephala* (**vaivai**; introduced). Cassava, yams, eggplants and paragrass were found throughout transects, with other grasses and herbs. Sasa had the lowest tree density, with the fewest saplings and low or missing values from many dbh size classes (Figure 3g,h).

Biophysical characteristics of streams

Wainunu and Kubulau had the highest mean canopy cover (80-100%) over streams, with slightly greater width and depth of streams than in Macuata and Wainunu (Table 1). Wainunu streams had the coarsest substrate and lowest conductivity. Temperature was notably elevated and dissolved oxygen notably lower in Sasa streams, which had very open canopy cover (20-40%). Macuata had the highest average number of root masses observed per site, while none of the districts had high mean numbers of undercuts along stream banks.

Table 1. Mean site stream biophysical parameters for each district for: stream width (m); stream depth (m); ranked substrate coarseness; estimated canopy cover; number of undercuts; number of root masses; conductivity (µS cm^{-1}), temperature (^{o}C); and dissolved oxygen (DO, mg L^{-1}).

	Stream width	Stream depth	Substrate Coarseness	Canopy cover	Undercuts	Root masses	Conductivity	Temperature	DO
Wainunu	3.837	0.306	5.043	80-100%	0.615	1.462	83.431	24.608	7.04
Kubulau	2.744	0.306	2.112	80-100%	0.667	2.556	122.479	24.856	6.076
Macuata	2.479	0.25	2.479	40-60%	0.167	3	370.2	24.633	6.375
Sasa	1.439	0.157	1.439	20-40%	0.25	0	217.85	28.575	0.987

Factors driving fish community assemblages

The RELATE tests maintained the null hypothesis that riparian tree size distribution is not related to in-stream fish presence/absence or abundance, however the rho values were only barely non-significant, particularly for fish abundance (abundance: ρ = 0.161, p = 0.051; presence/absence: ρ = 0.145, p = 0.072). No combination of stream biophysical variables significantly explained fish presence/absence distribution patterns in the BIO-ENV analysis. The two factors with the strongest correlation (ρ = 0.202, p = 0.284) were conductivity and the presence of downstream overhanging culverts. The patterns in site-level conductivity did, however, significantly relate to fish abundance (ρ = 0.311, p = 0.047). Cluster analyses of fish communities at the site level based on presence/absence and abundance data indicated that the sites can be separated into three significantly different groups (Figure 4): (1) sites (W21, K8, K29) with high species richness and abundance, despite lack of a 30 m riparian buffer zone, but without downstream overhanging culverts; (2) sites with extremely low species richness and abundance, containing only very hardy fish or no fish (M32, M31, S10, M15N) due to extreme environmental degradation and/or presence of a downstream overhanging culvert; and (3) everything else. Sites W21, K8 and K9 were the most speciose, with each site containing the following species that did not appear in any other sites: *Ambassis miops*; *Kuhlia munda*; and *Microphis brachyurus* (Appendix 2). Results from PERMANOVA show that catchment forest cover class and presence of downstream culverts both significantly influence site-based fish presence/absence and abundance, however there was no significant interaction between them

(Table 2). In the PERMANOVA analysis with riparian width class and presence of culverts, only culverts significantly influenced the fish community structures (Table 3).

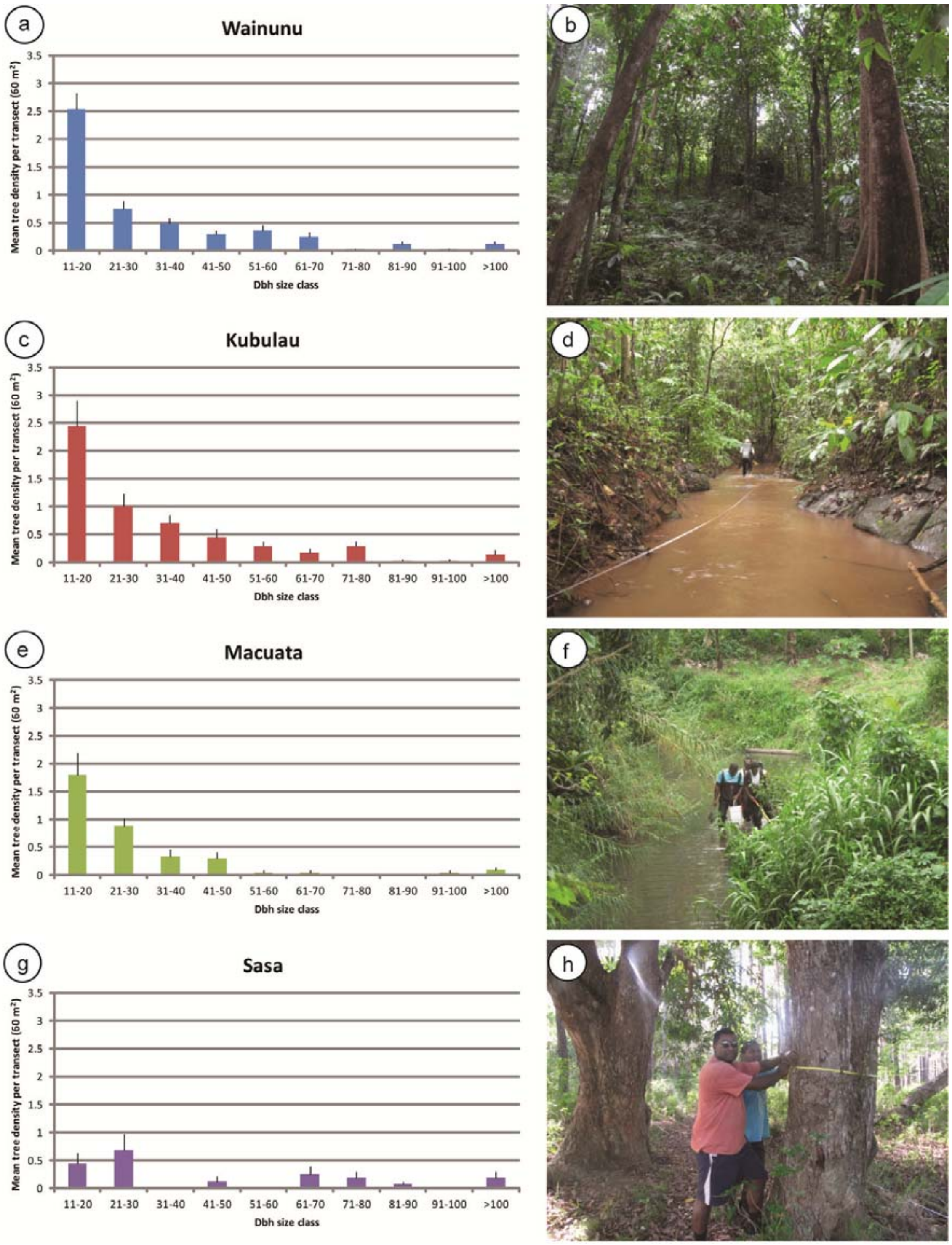

Figure 3. Size class distributions of mean tree density per transect (60 m^2) in diameter at breast height (dbh) and representative photograph of survey locations from (a) Wainunu, (b) Kubulau, (c) Macuata, and (d) Sasa districts.

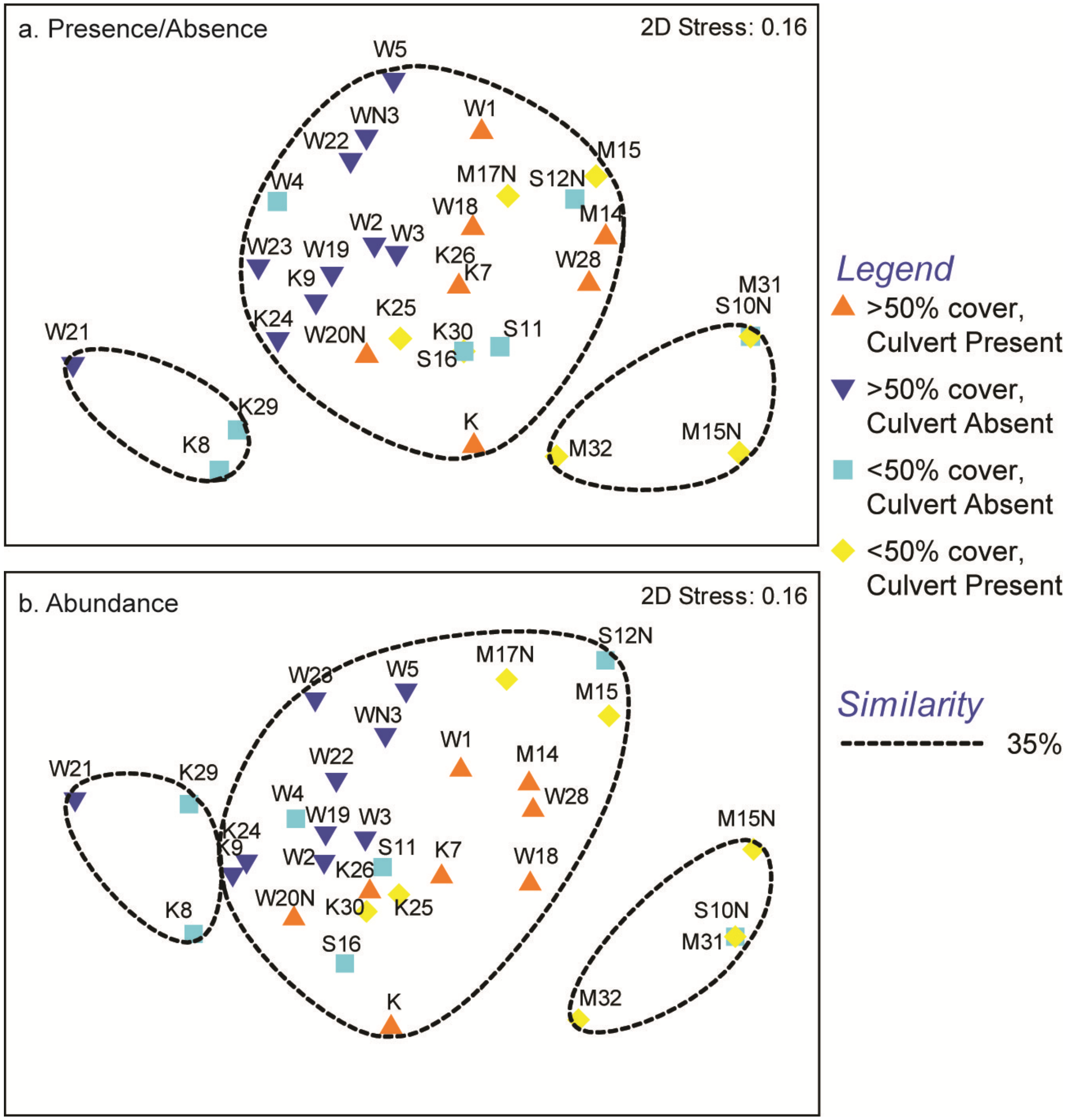

Figure 3. nMDS plots of (a) fish presence/absence and (b) fish abundance by site. Colours indicate: orange triangle – greater than 50% sub-catchment forest cover and presence of downstream overhanging culvert; dark blue triangle – greater than 50% forest cover and no downstream culvert; light blue square – less than 50% forest cover and no downstream culvert; and yellow diamond – less than 50% forest cover and presence of downstream culvert. Sites to the left of the plot have the most species and most numbers of fish. Dashed circles indicate clusters which are significantly different from one another.

Table 2. PERMANOVA results with sub-catchment forest cover class and presence of culvert as fixed factors for site-pooled (a) fish presence/absence and (b) fish abundance. Significant values are in bold.

(a) Fish Presence/Absence						**(b) Fish Abundance**				
Source	*df*	*SS*	*MS*	*Pseudo-F*	*P(perm)*	*df*	*SS*	*MS*	*Pseudo-F*	*P(perm)*
Catchment Forest Class	1	0.747	0.747	1.821	**0.046**	1	0.747	0.747	1.821	**0.046**
Culvert Presence	1	0.836	0.836	2.036	**0.022**	1	0.836	0.836	2.036	**0.020**
Forest x Culvert	1	0.359	0.359	0.874	0.587	1	0.359	0.359	0.874	0.576
Residual	28	11.490	0.410			28	11.490	0.410		
Total	31	13.498				31	13.498			

Table 3. PERMANOVA results with riparian width class and presence of culvert as fixed factors for site-pooled (a) fish presence/absence and (b) fish abundance. Significant values are in bold.

(a) Fish Presence/Absence						**(b) Fish Abundance**				
Source	*df*	*SS*	*MS*	*Pseudo-F*	*P(perm)*	*df*	*SS*	*MS*	*Pseudo-F*	*P(perm)*
Riparian Width Class	1	0.719	0.719	1.719	0.065	1	0.719	0.719	1.719	0.065
Culvert Presence	1	0.928	0.928	2.218	**0.013**	1	0.928	0.928	2.218	**0.012**
Riparian x Culvert	1	0.174	0.174	0.416	0.965	1	0.174	0.174	0.416	0.969
Residual	28	11.718	0.419			28	11.718	0.419		
Total	31	13.498				31	13.498			

Discussion

The major goal of this research was to address the question: "How does the size and composition of the riparian forest buffer strip in varying overall catchment cover conditions influence fish abundance, diversity, and water quality in the adjacent river?" We sought this information specifically to inform recommendations for riparian zone protection, restoration and freshwater management. However, while we were able to demonstrate several factors that influence freshwater fish community composition that confirm and build on prior research (Jenkins et al. 2010; Jenkins and Jupiter 2011), we found it difficult to specifically link conditions in the riparian zone alone to fish assemblage characteristics, although they are likely to play a contributing role.

There is a large body of literature that indicates that fragmentation and degradation within the riparian zone can affect biological communities and abiotic conditions within catchments and adjacent streams (Davies and Nelson 1994; Machtans et al. 1996; Debinski and Holt 2000; Heartsill-Scalley and Aide 2003; Iwata et al. 2003). When we assessed the condition of riparian communities in relation to fish community variables based on tree size structure, which can give a good indication of disturbance to the forest community, we found that tree size structure at our sites surveyed may only have a marginal impact on fish community assemblages.

There are a few reasons that could explain this phenomenon. First, we found that downstream overhanging culverts exerted strong influence on structuring fish communities because they represent a huge barrier to upstream migration. Culverts, dams and other natural barriers (e.g. waterfalls) have been previously shown to interrupt migration of diadromous fishes (Holmquist et al. 1998; Fitzsimons et al. 2005; Greathouse et al. 2006; Hein et al. 2011). This is particularly problematic in Fiji where freshwater ichthyofaunal communities are dominated by amphidromous fish that make obligate migrations downstream as larvae and upstream as post-larvae (Jenkins et al. 2010). Jenkins et al. (2010) postulated that overhanging culverts may strongly influence mid-reach fish assemblages, but they could not detect significant contribution of maximum downstream slope on fish species richness likely due to the coarseness of the slope data used. However, in our current survey at sites with good catchment and riparian forest cover where downstream overhanging culverts were documented (e.g. sites in Wainunu and Kubulau such as W18, W28, K7 and K), species richness and abundance were substantially lower than would have been otherwise predicted. Fish communities only included climbing species (*Anguila marmorata*); hardy species that may have been trapped and survived upstream (*Eleotris fusca*; *Giurus margaritacea*) and one of Fiji's two endemic freshwater residents (*Redigobius leveri*). We, therefore, are looking to start conversations with Fiji Government about best practices for constructing culverts and retrofitting existing culverts with fish passageways (e.g. Kapitzke 2010)

A second possible reason for the lack of strong influence of riparian and stream habitat in structuring fish assemblages may be due to lower overall diversity from reduced number of microhabitats in small stream systems compared with larger stream systems previously surveyed (Jenkins et al. 2010; Jenkins and Jupiter 2011). Niche partitioning through habitat and food specialization are important determinants of freshwater stream communities (Ross 1986). Our data indicated very few undercuts and root masses at any of the sites, which are important microhabitat features for many fish species (Pusey et al. 2004). Greater replication at the site level in future studies may help to uncover more of these important features.

Despite these findings, the condition of the riparian zone and overall condition of adjacent landscape may still indirectly influence assemblages. Iwata et al. (2003) found strong relationships between the degree of riparian disturbance and regeneration in tropical landscapes and in-stream depositional characteristics, with more eroded soil found in streams adjacent to disturbed areas. The most degraded riparian sites we surveyed in Macuata and Sasa districts had extremely elevated conductivity, which can increase with high sediment loads or high concentrations of dissolved organic material. Sediment may impact feeding, breeding and resting ability of many species of Fiji's freshwater fish (Jenkins et al. 2010). Conductivity on its own at least partially explained fish abundance patterns across all sites surveyed. An important corollary to the Iwata et al. (2003) study was that in-stream habitats adjacent to riparian areas well in progress of regeneration still had not recovered even one to two decades after agricultural activities ceased.

With higher replication of survey sites, particularly sites with low sub-catchment forest cover and intact riparian zones of at least 30 m width, we might be able to tease out impacts attributable to riparian zone condition apart from general catchment condition. Our finding that loss of sub-catchment forest cover has strong impact on in-stream communities echoes our prior work from Fiji that severe catchment degradation can result in near complete to complete loss of freshwater fish assemblages (Jenkins et al. 2010), and that these losses are pronounced in degraded catchments during the wet season (Jenkins and Jupiter 2011). Thus, our findings further give weight to our rule of thumb recommendation to protect waterways in sub-catchments with greater than 50% forest cover. From this study, we add a second rule of thumb recommendation to preferentially prioritize freshwater streams for protection that are clear of downstream overhanging culverts. We have been using these guidelines to assist communities to designate or expand terrestrial and freshwater protected areas. To date, communities of Kubulau, Wainunu, Nadi and Solevu districts of Bua Province and Wailevu District of Cakaudrove Province have found the data and the rules of thumb useful to comprehend the threats to their freshwater resources and assist in selection of areas for management.

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Appendix 1. Site location information, including: district; survey date; latitude and longitude; whether downstream overhanging culverts were present; percent sub-catchment forest cover (greater than or less than 50%); and riparian zone width (greater than or less than 30 m). Colours indicate site categories: green - greater than 50% forest cover and greater than 30 m riparian zone; blue – greater than 50% forest cover and less than 30 m riparian zone; purple – less than 50% forest cover and greater than 30 m riparian zone; brown – less than 50% forest cover and less than 30 m riparian zone.

Site Code	District	Survey Date	Lat	Lon	Culverts	Catchment Forest	Riparian width
W1	Wainunu	18-10-2010	178.92564 E	16.86486 S	Yes	>50	>30
W18	Wainunu	18-10-2010	178.92468 E	16.86502 S	Yes	>50	>30
W23	Wainunu	19-10-2010	178.95524 E	16.89368 S	No	>50	>30
W5	Wainunu	19-10-2010	178.95535 E	16.89136 S	No	>50	>30
W21	Wainunu	20-10-2010	178.94571 E	16.88878 S	No	>50	<30
W20N	Wainunu	20-10-2010	178.94601 E	16.88637 S	Yes	>50	>30
W19	Wainunu	21-10-2010	178. 94078 E	16.87970 S	No	>50	>30
W3	Wainunu	21-10-2010	178.93813 E	16.87899 S	No	>50	>30
WN3	Wainunu	21-10-2010	178.88951 E	16.82419 S	No	>50	<30
W28	Wainunu	22-10-2010	178.92910 E	16.87826 S	Yes	>50	>30
W2	Wainunu	22-10-2010	178.92590 E	16.88123 S	No	>50	>30
W4	Wainunu	25-10-2010	178.95535 E	16.89134 S	No	<50	<30
W22	Wainunu	25-10-2010	178.95339 E	16.88738 S	No	>50	<30
K24	Kubulau	28-10-2010	178.98128 E	16.90124 S	No	>50	>30
K9	Kubulau	28-10-2010	178.98396 E	16.90012 S	No	>50	<30
K25	Kubulau	29-10-2010	179.00279 E	16.89997 S	Yes	<50	<30
K8	Kubulau	29-10-2010	179.00494 E	16.89705 S	No	<50	<30
K	Kubulau	29-10-2010	N/A	N/A	Yes	>50	>30
K26	Kubulau	30-10-2010	179.01245 E	16.89235 S	Yes	>50	>30
K7	Kubulau	30-10-2010	179.01351 E	16.89041 S	Yes	>50	>30
K30	Kubulau	30-10-2010	179.01674 E	16.87512 S	Yes	<50	<30
K29	Kubulau	30-10-2010	179.01708 E	16.87243 S	No	<50	<30
S16	Sasa	03-11-2010	179.21018 E	16.42123 S	No	<50	<30
S11	Sasa	03-11-2010	179.20895 E	16.41939 S	No	<50	<30
S12N	Sasa	04-11-2010	179.19667 E	16.4137 S	No	<50	<30
S10N	Sasa	04-11-2010	179.22433 E	16.42274 S	No	<50	<30
M17N	Macuata	08-11-2010	179.05821 E	16.46054 S	Yes	<50	>30
M15N	Macuata	08-11-2010	179.05811 E	16.46322 S	Yes	<50	<30
M31	Macuata	09-11-2010	179.11042 E	16.44657 S	Yes	<50	<30
M32	Macuata	09-11-2010	179.11123 E	16.42501 S	Yes	<50	>30
M14	Macuata	10-11-2010	179.13868 E	16.44509 S	Yes	>50	<30
M15	Macuata	10-11-2010	179.06970 E	16.46349 S	Yes	<50	<30

Appendix 2. Freshwater fish species presence (dark grey) for each site in each of the four districts surveyed.

	Wainunu													Kubulau									Sasa				Macuata					
Species	W1	W18	W23	W5	W21	W20N	W19	W3	WN3	W28	W2	W4	W22	K24	K9	K25	K8	K	K26	K7	K30	K29	S16	S11	S12N	S10N	M17N	M15N	M31	M32	M14	M15
Ambassis miops					■												■					■										
Anguilla marmorata	■	■			■	■	■	■	■		■			■	■	■	■	■			■		■									
Anguilla megastoma										■											■	■	■	■				■			■	■
Anguilla obscura	■							■					■											■	■						■	■
Apogon laterallis					■																											
Awaous guamensis														■																		
Butis butis					■												■															
Eleotris fusca	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■		■				■	■
Eleotris melanosoma	■				■				■		■		■																			■
Giurus margaritacea			■		■	■	■	■			■	■	■	■	■	■	■	■	■	■	■	■	■	■						■		
Glossogobius sp.																	■					■										
Gymnothorax polyuranodon							■							■			■					■										
Hypseleotris guentheri			■	■	■							■		■	■	■	■					■		■								
Kuhlia marginata			■		■	■								■	■							■										
Kuhlia munda					■												■					■										
Kuhlia rupestris			■		■		■	■	■		■	■	■	■	■							■					■					
Liza vagiensis					■																											
Lutjanus argentimaculatus					■																											
Microphis brachyurus					■												■					■										
Moringua macrochir					■																											
Ophiocara porocephala					■												■															
Periopthalmus kalolo					■																											
Redigobius bikolanus					■																											
Redigobius leveri		■		■			■	■	■		■				■				■	■												
Scatophagus argus					■																											
Schismatogobius vitiensis				■																												
Sicyopterus lagocephalus																												■				
Sicyopus zosterophorum	■					■	■					■	■																			
Siganus vermiculatus					■																											
Sphraena flavicauda					■																											
Stenogobius sp.			■														■															
Stiphodon rutilaureus												■																				
Stiphodon sp.			■	■					■			■	■																			
Yirrkala sp.																	■															
Zenarchopterus dispar					■																	■										