Tropical floodplain food webs - connectivity and hotspots | Final report

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Photographs by Michael Lawrence-Taylor and Michael Douglas

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Contents

Summary

This project delivered new understanding of the contributions of floodplains to the maintenance of biodiversity and fish biomass in river-floodplain systems, meeting both pure and applied scientific objectives. For the floodplains of the Alligator Rivers region (Kakadu) the project delivered:

- Clarification of the food web implications of water resource development by quantification of the importance of different habitats in sustaining fish and other consumers in river-floodplain systems
- Remote sensing methods to map, monitor and asses the seasonal connectivity between catchments, floodplains and coastal receiving waters
- Methods to identify and map seasonally available 'hotspots' of floodplain primary productivity that are critical to the maintenance of food webs, and implications of the loss of such habitats
- Understanding of the movement patterns of key fauna that use floodplains and the freshwater-saltwater interface in estuaries
- A global context on how the predictability of flood magnitude and timing drives ecosystem responses in tropical floodplain riverscapes.

The outputs of the project can feed directly into wetland management and conservation planning processes, providing end users with methods and tools to quantify the importance of different landscape elements towards overall system biodiversity.

1 Principal focus and significance

Linkages among habitats and fluxes of materials across ecosystem boundaries often have major implications for the production of animal and plant biomass and resultant biodiversity (Polis *et al*. 1997, Nakano and Murakami 2001). Fully-aquatic species which typically inhabit the river channel, floodplain billabongs and estuarine waters in the dry season move onto floodplains during the wet season. As these floodwaters recede, aquatic production that has been assimilated by consumers such as fish is often transferred back into the river systems and exported offshore (Jardine *et al.* 2012b). These types of subsidies can therefore represent a significant transfer of aquatic carbon and nutrients from floodplains to other parts of the river system and indeed to other aquatic systems over hundreds or thousands of kilometres (Bunn *et al*. 2003, Douglas *et al*. 2005, Warfe *et al*. 2011). Yet it is very difficult to quantify the importance of these linkages and fluxes.

By measuring sources of energy and trophic level of predators along with underlying sources of production such as algae, and the movement patterns of key fauna species, this project generated ecosystem-level science needed for management. The tools used in this project such as stable isotope analysis to measure energy flow, and archival remote sensing to identify hot spots of productivity also integrate highly variable information through time, and as such can simplify some of the complexity of these systems. The outputs of this project provide key knowledge and methods that facilitate prediction of how natural and human-induced changes to ecosystem connectivity might affect biodiversity and fisheries productivity in tropical floodplain systems.

2 Distinctiveness of issue to this landscape

The project study area comprised the Alligator Rivers region (here after referred to as Kakadu) in the wet-dry tropics along the coastal zone of northern Australia (Fig. 1). This region includes the iconic Kakadu National Park which is World Heritage listed and has been designated as internationally important under criteria established by the Ramsar Convention on Wetlands. Covering an area of approximately 20,000 km^2, the region includes the floodplains of the West, South and East Alligator Rivers and the Wildman River to the west (Finlayson *et al*. 2006). Under the Ramsar Convention, the Kakadu National Park was deemed to contain representative, rare, and unique examples of wetland types that support vulnerable and endangered species, as well as populations of plant and animal species important for maintaining the biological diversity of this biogeographical region. The region is Aboriginal land and has World Heritage listed cultural values including more than 40,000 years of continuous human habitation through to present-day Aboriginal traditional society (Roberts *et al*. 1993).

The large floodplain systems such as those associated with the extensive wetland areas of Alligator Rivers region are typical of other floodplain systems in the equatorial zone (the 'top end') of northern Australia. These include major floodplain systems of the Daly, Mary, Adelaide and the Goyder (Arafura Swamp) river systems (Ward *et al*. 2011). These systems are unique in that they have extensive floodplains that remain flooded for many months each year. These floodplain regions provide habitat across a range of trophic levels, from small invertebrates to large predators such as crocodiles, not found in other areas of Australia. However, the floodplain systems of the 'top end' are increasingly affected by multiple anthropogenic stressors such as invasive animals, weeds (Setterfield REF), altered fire regimes, mining, and the potentially acute impact of sea level rise due to climate change on seawater intrusion into the freshwater wetlands (Tockner *et al*. 2010, Vorosmarty *et al*. 2010). There is a real need for baseline ecological and hydrological information for the region to support the development of natural resource management regimes and climate change adaption strategies.

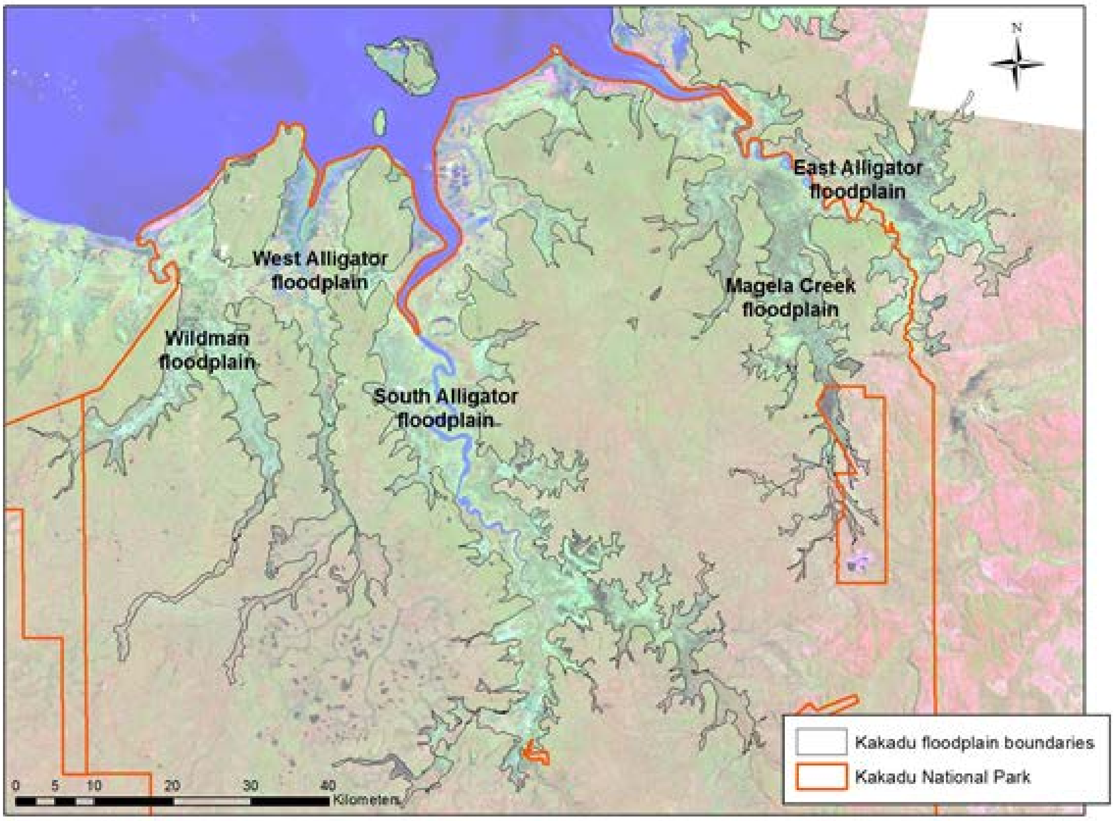

Figure 1: Alligator River region (Kakadu) floodplains

3 Knowledge status and constraints

Previous research within Tropical Rivers and Coastal Knowledge (TRaCK) program identified that there is great variability in floodplain inundation duration across northern Australian rivers, with some systems typically inundated for less than one month (e.g. Fitzroy River, WA) and others with areas inundated for more than half the year (e.g. Daly River, NT) (Ward *et al*. 2011, Jardine *et al*. 2012b). Using stable isotope analysis, the TRaCK program showed that organic matter produced in these floodplains is exported by fish both upstream to low productivity main channels and offshore to coastal food webs (Jardine *et al*. 2012a), in many cases sustaining consumers through the dry season.

Systems with floodplains inundated for longer periods and with higher overall connectivity appear to allow considerable movement of biota within the river network to exploit seasonally available resources. What is still poorly understood is how rates of productivity within floodplains compare with those in permanent waterbodies (e.g. main river channels and billabongs), whether the presence of long periods of inundation lead to higher biodiversity, and the extent to which large-bodied consumers (e.g. predatory fish) use the various components of the river network (floodplains, rivers, estuaries and coasts).

4 Methodological approaches

This project expanded on the findings of the TRaCK program by: 1) identifying where, and how long water resides on floodplains, 2) determining the rates of floodplain primary productivity and resultant biomass produced in these flooded areas, 3) calculating how that material is exported to, and used in the remainder of the system and offshore areas, 4) measuring any tangible benefits to food webs (e.g. greater biodiversity, higher biomass and better condition of animals), and 5) determining the amount of movement of large keystone predators between habitats.

We hypothesize that the export of floodplain-derived organic matter to the remainder of the catchment and estuarine/coastal areas will be linked to the extent, duration and connectivity of flooding. Further, this contribution will lead to higher biodiversity and higher fish yields (biomass, density) in systems with greater inundation, and large mobile predators will show extensive movements that relates to hydrological connectivity.

4.1 Global context

The focus of this study was the unique floodplain systems in the equatorial zone of northern Australia. In understanding these Australian floodplain systems, it is useful to place these systems in a broader global context, thereby providing a comparative context for interpreting the results. To this end, a desk-top study and publication was developed that investigated how flood rhythm, or the predictability of flood magnitude and timing, drives ecosystem responses in tropical floodplain riverscapes. The massive floodplains of South America have been reasonably well studied and formed the majority of the comparative analysis with the Australian floodplains.

4.2 Food web stable isotopes analysis

Stable isotope analysis methods provide novel tools to measure energy flow in aquatic systems (Lewis *et al*. 2001, Bunn *et al*. 2003). Stable isotope analysis was applied to construct food webs for the Kakadu region and quantify the transfer of aquatic carbon and nutrients from floodplains to other parts of the river systems in Kakadu. Field site collections were made of food web producers (e.g. algae, leaf litter, macrophytes, plankton) and consumers (e.g. insects, prawns, fish) and analysed for stable isotopes to assess whether animals are feeding locally or if they are carrying biomass derived from elsewhere. Remote sensing was used to identify the most likely floodplain areas where productivity is highest and sampling was undertaken there.

Dry season field work sampling was conducted in main channels and waterholes where there is most likely to be an isotope distinction between potential foraging areas. Isotope mixing models were used to calculate the percent of each species' diet derived from marine, floodplain, and dry season freshwater sources, and these measures are linked to individual body sizes of organisms (ranging from mm-sized insects to 4m crocodiles) to determine if different species capitalize on externally produced subsidies in different ways.

4.3 Floodplain periphyton (algal) productivity

Primary productivity, and in particular algal productivity has been shown to be important for maintenance of aquatic food webs in tropical rivers and floodplains (Bunn *et al*. 2003, Douglas *et al*. 2005). A series of measures were applied to quantify rates of primary productivity on the seasonally inundated floodplains of the Kakadu region. The productivity of the main primary producers of the floodplains of the region, namely macrophytes, periphyton (algae and bacterial communities attached to plants) and phytoplankton was assessed using three complementary methodologies: 1) Experiments with ^{13}C enrichment to determine carbon assimilation; 2) measurements of dissolved oxygen (DO) variations in light/dark bottles; and 3) estimations of ecosystem productivity with diel DO variations measured with in-situ loggers (Cattaneo and Kalff 1980, McCormick *et al*. 1998, Burford *et al*. 2011).

Different wetlands that were categorised according to the structure, complexity and position in the water column of the dominant macrophyte were compared: 1) Simple emerging vertical, e.g. wild rice, native *Hymenachne*; 2) Simple emerging horizontal e.g. *Pseudoraphis*; 3) Complex submerged, e.g. *Ceratophyllum* ("hornwort"), *Najas* (najas), *Utricularia* ("bladderwort"), and 4) Simple floating, e.g. *Nymphae*, *Nymphoidies* (waterlilies). Invasive Para grass and Olive hymenachne, both of them with a simple vertical structure were also included. It was predicted that primary productivity would be variable among different wetland types, with highest productivity in wetlands dominated by submerged complex plants. We also predicted that periphyton would have a significant contribution to the primary production budget.

4.4 Remote sensing floodplain inundation and vegetation dynamics

Extensive satellite image archives facilitate the application of remote sensing to capture the long-term dynamics of flood inundation (Hamilton *et al*. 2002, Alsdorf *et al*. 2007). Remote sensing techniques are also increasingly being applied to estimate floodplain productivity and biomass (Costa *et al*. 2002). The remote sensing component of the project comprised two parts: 1) the development of long-term time series of seasonal and inter-annual floodplain inundation and connectivity, and 2) landscape scale spatial estimation of the seasonal variability in floodplain periphyton (algal) productivity and the identification of potential 'hot spots' of periphyton production.

The capacity to map and asses the seasonal connectivity between catchments, floodplains and coastal receiving waters is an important tool in understanding river to landscape connections and aquatic biodiversity. To capture floodplain inundation extents and connectivity for the Kakadu region, microwave and optical satellite data were combined with field-sampled aquatic vegetation and depth logger data to predict the seasonal and inter-annual dynamics of aquatic plant cover and inundation extent in the Kakadu region (Ward *et al.* 2014). The USGS Landsat TM 5 image archive was sampled between 1985 and 2011 using three seasonal samples per year to create a comprehensive long-term time series of seasonal and inter-annual floodplain inundation extents. This information was then summarized into a single map layer showing long-term flood inundation frequency of the Kakadu region.

Wetland management and conservation planning processes require spatial estimations of the relative importance of different aquatic habitats to the maintenance of aquatic biodiversity. Estimation of the spatial and temporal variability in floodplain periphyton productivity was modelled using remotely sensed optical data and field measurements of macrophyte cover, and estimates of periphyton productivity associated with macrophyte structural groups (Ward *et al*., in prep). The macrophyte structural groupings used in the analysis were emergent vertical, emergent horizontal, submerged and floating vegetation. Only freshwater areas of the Kakadu floodplains that were not covered by tree canopies were considered in the analysis. The results of the modelling provided a spatial estimate of periphyton biomass per unit area within the photic zone, over the entire flooded freshwater floodplains for the Kakadu region (at the time of satellite image capture). To capture the seasonal dynamics of periphyton productivity, this procedure was applied to satellite imagery captured in May, July and September 2014.

4.5 Fish movement

Stable isotope analyses provide critical information regarding the sources and pathways of energy flow within aquatic ecosystems (e.g. Bunn *et al*. 2003; Jardine *et al*. 2011). However, such approaches do not provide direct information about the movements of biota across the landscape. This information is necessary to understand how energy is transported by biota, and the relative importance of different habitats (e.g. inundated floodplains) in supporting fish populations. For example, the transport of energy from inundated floodplains to fish populations in the river channel might be driven by the movement of large-bodied fish onto the inundated floodplain during the wet season. Alternatively, energy (in the form of small fish, insects, organic carbon, etc.) may be washed into the main channel as the floodwaters recede at the end of wet season. Data on the movements of large-bodied fish during the wet season were integrated with the stable isotope and remote sensing data to address these fundamental questions.

Two approaches to studying the movements of barramundi (*Lates calcarifer*) and forktail catfish (*Neoarius leptaspis*) were employed. Firstly, radio telemetry was used to provide high-spatial resolution information on fish locations throughout the wet season. A total of 40 barramundi and 30 catfish had radio-transmitters surgically implanted and were tracked every two weeks using a boat and helicopter. 25 barramundi and 25 catfish with acoustic transmitters were also tagged, which allowed for continuous monitoring of fish movement at discrete locations. Thirty acoustic receivers were deployed in the South Alligator River from the upper freshwater reaches to the estuary mouth. Spatially and temporally explicit state space models investigated habitat associations and movement patterns of fish using the radio- and acoustic telemetry data.

5 Lessons learnt for this landscape

5.1 Global context

The comparative analysis of Australian and South American rivers shows how flood rhythm drives ecosystem responses in tropical floodplain riverscapes. In large rivers, floods are significant agents of change, not only causing considerable physical and biotic disturbance yet often also enhancing productivity and diversity. The study showed that the relative balance between these seemingly divergent outcomes can be explained by the 'rhythmicity', (Fig. 2) or predictability of both the timing and magnitude, of flood events (Jardine *et al*., 2015). By analysing biological data for large rivers that span a gradient of rhythmicity in South America and Australia, we found that systems with rhythmic annual floods have higher fish species richness, more stable avian populations and elevated rates of riparian forest production compared with those with arrhythmic flood pulses. Intensification of the hydrological cycle driven by climate change, coupled with reductions in runoff due to water extractions for human use, will alter the hydrologic rhythmicity of floodplain rivers with significant consequences for both biodiversity and productivity.

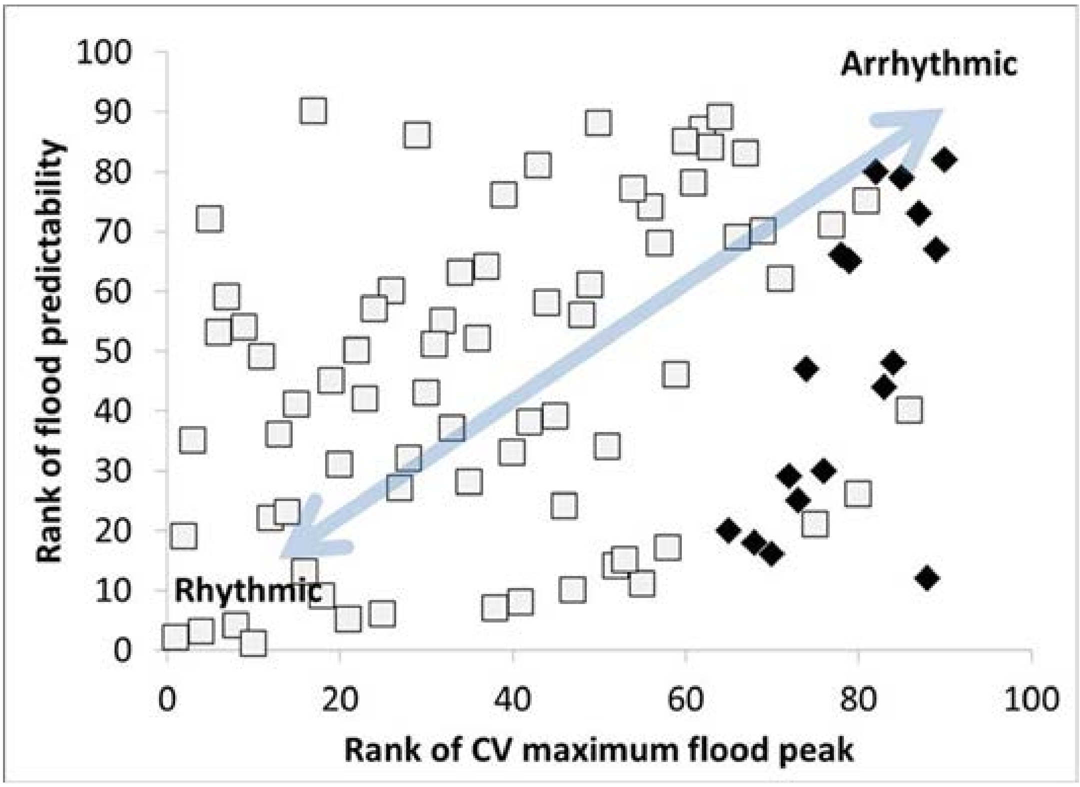

Figure 2: The rhythmicity of river floodplains in South America (open squares) and Australia (solid diamonds), as indicated by statistics on river discharge over periods of >20 years.

5.2 Food web stable isotopes analysis

The focused food web work in Kakadu shows that large animals captured during the dry season have obtained as much as 80% of their diet from sources outside of their home waterhole. This is illustrated by the comprehensive food web sampled in Bucket Billabong, a small waterhole in the South Alligator floodplain (Fig. 3). Small insects, crustaceans and fish can be sustained by production within the waterhole (from periphyton, plankton and detritus) but the larger animals (saratoga, barramundi and crocodiles) require access to external food sources including marine fish and invertebrates, small floodplain-grown fishes, and, in the case of the crocodiles, various land mammals such as wallabies and feral pigs.

This story, revealed by carbon and nitrogen isotope analysis, is supported by sulfur isotopes that also show crocodiles having a mixed diet of marine, floodplain and savannah sources. The significant increase in the importance of external sources with increasing body size is a common feature of Kakadu food webs, as well as the Mitchell River in north Queensland. The Mitchell River lies in a region with flood connectivity that is shorter than the rivers in Kakadu, but nonetheless also contains large animals heavily reliant on external subsidies to maintain such high biomass.

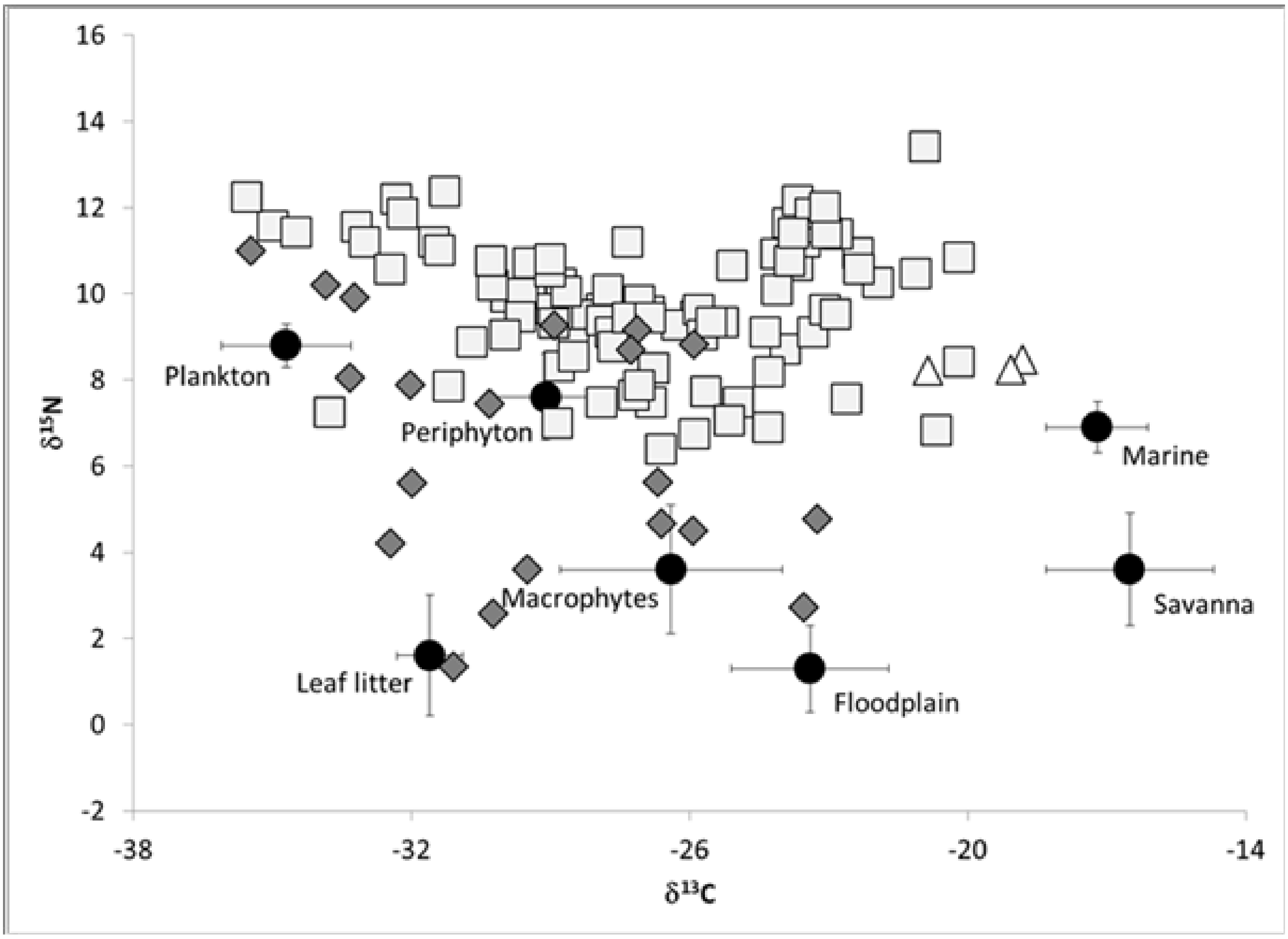

Figure 3: An example dry-season food web (Bucket Billabong, August 2012) from Kakadu. Different sources available to animals (circles) include those produced within the waterhole (plankton, periphyton, macrophytes) and those produced outside the waterhole (floodplain, marine, savanna). As illustrated by their relative “closeness” in dual-isotope space, invertebrates (diamonds) feed mostly on internal sources. Fish (squares) feed on a mix of sources – smaller fish are largely supported by internal sources, whereas large fish are shifted towards external sources. Crocodiles (triangles) feed almost exclusively on foods produced outside the waterhole.

5.3 Floodplain periphyton (algal) productivity

The assessment of floodplain primary productivity indicates that macrophyte structural form was critical to light penetration into the water column and the attachment of epiphytic algae and consequently periphyton production. Emergent grasses (*Oryza*, *Hymenachne* & *Urochloa*) with a combination of simple vertical structure and high density stands, limits light penetration and attachment sites and therefore the biomass and productivity of periphyton. In contrast the submerged macrophytes, such as *Ceratophyllum demersum*, grows just below the water surface allowing greater light penetration and its complex architecture provides a large surface area for the development of a dense covering of periphyton. Other plant structural forms such as floating plants (*Nymphaea* spp) have a simple structure but with some light penetration. The emergent grass *Psuedoraphis spinescens* also had low light penetration but the horizontally orientated stems allow the development of periphyton. These findings indicate that macrophyte structure (plant architecture) plays a major role in the production and abundance of periphyton in these floodplain systems (Pettit *et al*. in prep).

The quantification of rates of primary productivity on floodplains of the Kakadu region showed that lowest primary productivity was measured in macrophytes, followed by periphyton; phytoplankton had the highest productivity rates, which were 50 times higher than those of macrophytes. However, biomass of phytoplankton was very low, resulting in a similar contribution to the overall productivity of the wetland as macrophytes and periphyton (Fig. 4). Macrophyte productivity was highest for submerged plants (e.g. *Ceratophyllum*) and lowest for emerging vertical grasses. Periphyton productivity was highest in floating and emerging horizontal structures. When accounting for the biomass of each component within the water column, we found that the most productive wetlands were those dominated by horizontal grasses and submerged plants. Emerging vertical grasses (including Para grass) had the lowest plant and periphyton production and the lowest periphyton biomass, both of which resulted in emerging vertical grasses being the least productive of all the wetland types assessed. Primary production on the Kakadu floodplains was relatively high, however, respiration rates were also high, thus overall the floodplains were heterotrophic (Adame *et al*., in prep).

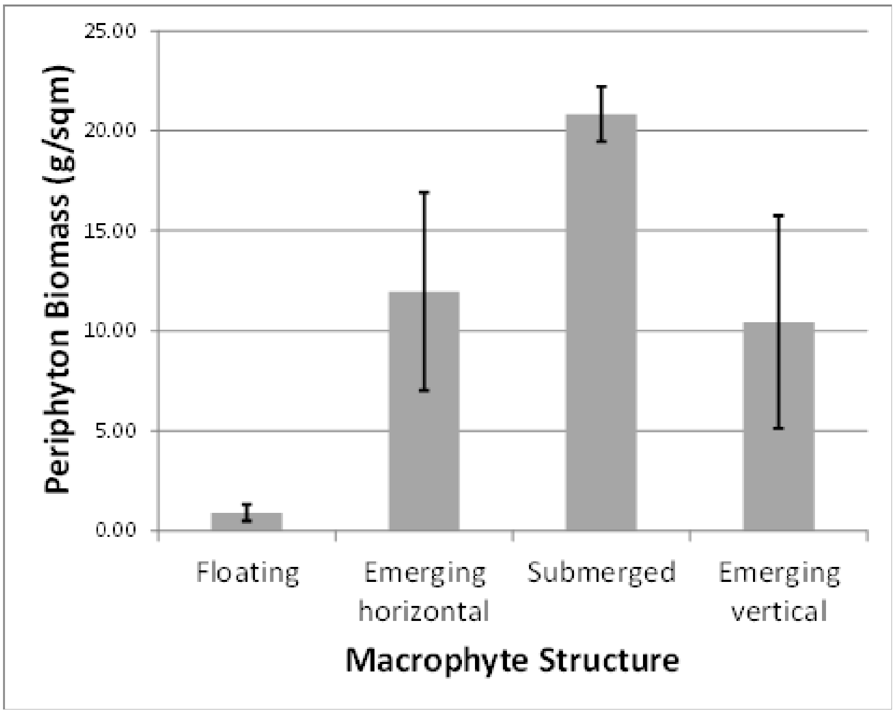

Figure 4: Productivity (gC m^{-2} d^{-1}) (phytoplankton, periphyton and macrophyte) for floodplain wetlands dominated by different macrophyte structural groups: floating plants, emerging horizontal grasses, submerged plants and emerging vertical grasses.

In terms of floodplain productivity hotspots (i.e. food for fish and invertebrates), habitats dominated by emerging horizontal vegetation (e.g. *Pseudoraphis*) and submerged vegetation (e.g. *Ceratophyllum*) are likely good feeding grounds due their capacity to carry periphyton (Fig. 5). Consequently, the spatial distribution of potential food 'hot spots' is strongly influenced by differences in the spatial distribution of different macrophyte structural groups. Invasion of Para grass, Olive hymenachne, and other exotic macrophytes with vertical emergent structures is likely to reduce fish feeding grounds in the Kakadu floodplain. Para grass and Olive hymenachne had lowest overall productivity, and lowest periphyton productivity.

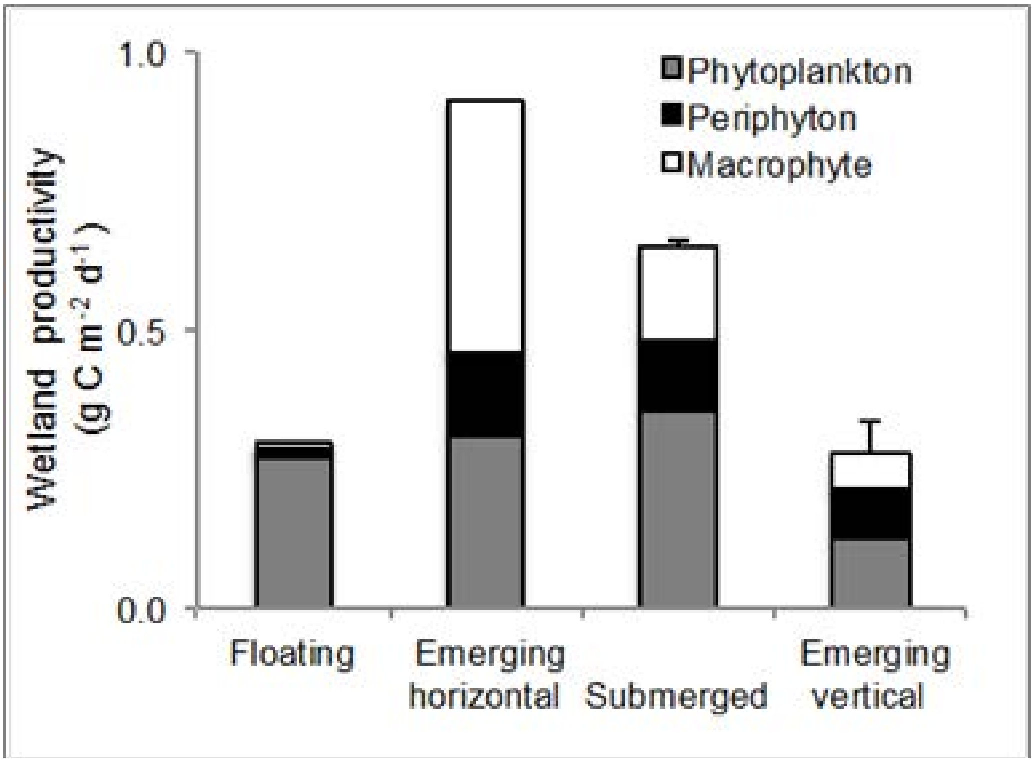

Figure 5: Periphyton productivity (g m^{-2}) for macrophyte structural groups.

5.4 Remote sensing floodplain inundation and vegetation dynamics

For the Kakadu region, the classification of flooded inundation states from imagery sampled between 1985 and 2011 resulted in the average post-wet-season flooded extent for March / April for the entire Kakadu region of 1,784 km^2 (range 1,309 - 2,283 km^2), receding, on average, to approximately 25% -30% of its extent by August / September (Ward *et al*., 2014). Further recession of flooded areas to isolated billabongs and swamps continues into the late dry season. However, the results indicate that the degree of recession to isolated waterbodies is highly variable. In wetter years substantial areas of the Magela Creek, West Alligator and Wildman floodplains remained flooded into the following wet season. The East and South Alligator River floodplains had the greatest average flooded area extent, and the West Alligator the least. The results of the inundation frequency analysis (Fig. 6) for the Kakadu region indicate that the East Alligator (particularly Magela Creek), West Alligator and Wildman River floodplains have the largest areas of long duration inundation. The inundation frequency for the Kakadu region shows a general pattern of seasonal recession of inundation into 'backswamp' areas on the edges of the floodplains. Backswamp areas with the longest duration of inundation occur in the Nourlangie, Yellow Water, and Boggy Plain regions of the South Alligator floodplain, and the upper Magela Creek floodplain. The remote sensing methods and outputs developed in this project were applied to provide information specific for the Kakadu region. However, these methods have wide applicability for other tropical floodplain regions in Australia and elsewhere in the world.

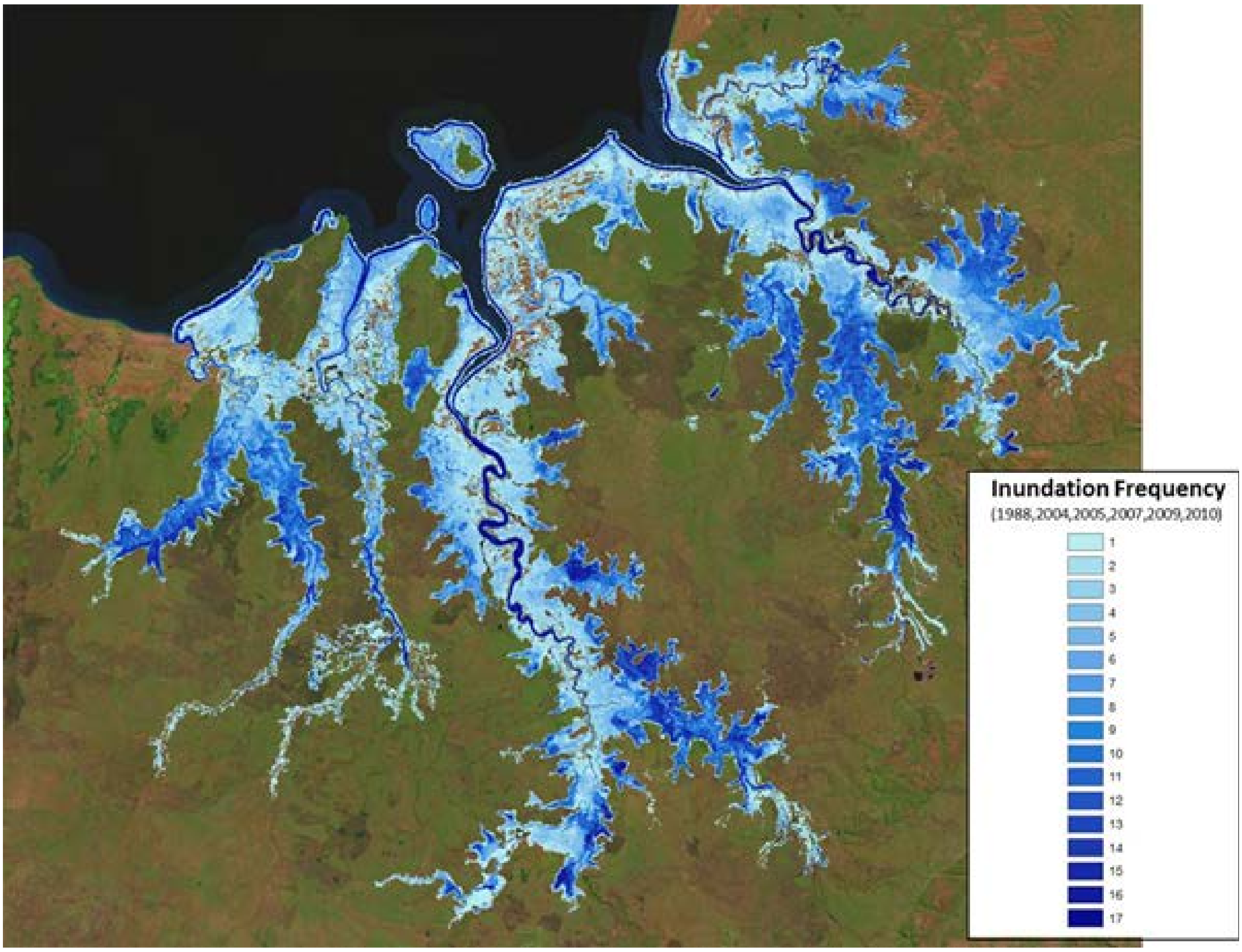

Figure 6: Inundation frequency for the Alligator River region (Kakadu) floodplains derived from three seasonal image captures per year (March/April, June/July, and August/September) for 1988, 2004, 2005, 2009, 2007 and 2010. Inundation frequency was calculated by assigning 1 to a flooded state and 0 to a non-flooded state, and then adding the incidence of inundation over the 17 image captures.

For the Kakadu region, the spatial estimations of the seasonal variability in floodplain periphyton productivity (g m^{-2}) tended to be correlated with inundation frequency, with the most productive areas being in the 'backswamp' areas on the edges of the floodplains (Fig. 7). These backswamp areas are deeper and hold water from much longer than areas dominated by the emergent grasses, which tend to occur in the more shallow areas of the Kakadu floodplains. The seasonal variation in flooded extent showed a 65% decline in the flooded area available for periphyton production between May and September 2014. While there was a significant reduction in the spatial extent of periphyton biomass, the seasonal ranges in estimated periphyton biomass were relatively similar (Fig. 7). The reason for this is that the areas of high periphyton biomass remaining in September 2014 were largely the deeper backswamp areas that carry the most extensive areas of the submerged macrophytes. These backswamp areas appear to remain highly productive throughout the growing season and going into the dry season. The results indicate that these backswamp areas with the highest periphyton productivity (Nourlangie, Yellow Water, and Boggy Plain regions of the South Alligator floodplain, and the upper Magela Creek floodplain) are 'hot spots' of productivity and act as important freshwater aquatic refugia, maintaining fauna populations through the dry season, prior to the onset of the next wet season.

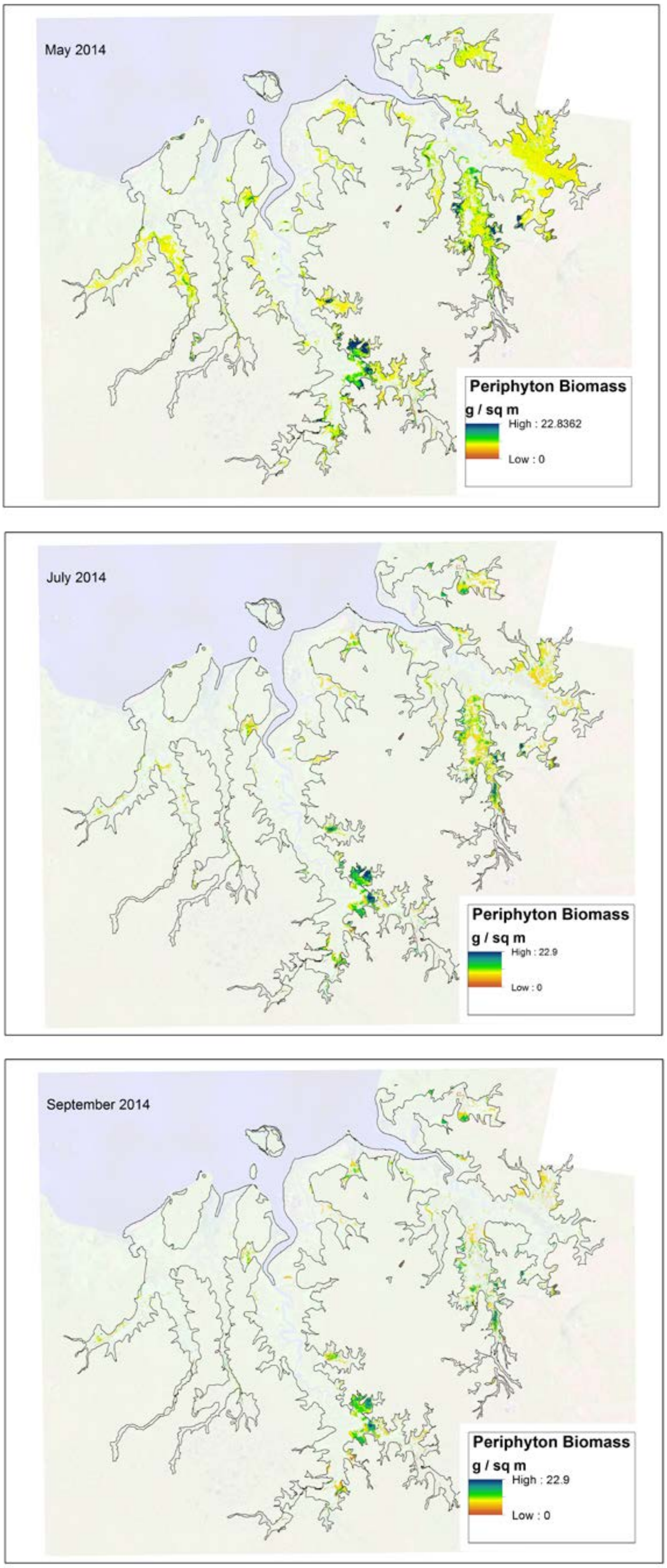

Figure 7: Distribution of periphyton biomass (mg m^{-2}) for Kakadu freshwater floodplains for May, July, and September 2014

5.5 Fish movement

The results of the fish telemetry study showed that large-bodied fishes utilise inundated floodplains as habitat during the wet season and, in combination with the stable isotope analyses, demonstrate that movement by fish is a key energy transport mechanism in northern Australian rivers. The radio-tracking data showed that both barramundi and catfish undertook localized (up to 5km) movements among the connected freshwater billabongs in which they were tagged during the late dry season. When the South Alligator River began to flow and the floodplain became inundated early in the wet season, most fish responded immediately by moving large distances (up to ~80km) away from their normal home ranges (Fig. 8, 9). Both species used inundated floodplain habitats extensively during the wet season and then returned back to their "home" billabong once the water had begun to recede (Fig. 8, 9).

Results of the acoustic tracking study were consistent with the radio-tracking data, with most fish recorded frequently on acoustic receivers within the freshwater billabongs during the late dry season. During the wet season, tag detections in the billabongs decreased as the fish moved downstream and out onto the inundated floodplains. As the wet season flooding receded, fish were once again detected frequently on the receivers within their home billabong. Receivers installed along the main channel of the South Alligator River detected catfish up to 25km downstream of their tagging location during the wet season. Barramundi were detected up to ~80km downstream (Fig. 10), but even fish that moved such large distances eventually returned to their home billabong by the end of the wet season. None of the tagged barramundi appear to have entered saline water during the study. As barramundi require salinities > 20‰ for spawning, these results suggest high levels of non-participation in spawning by freshwater resident fish.

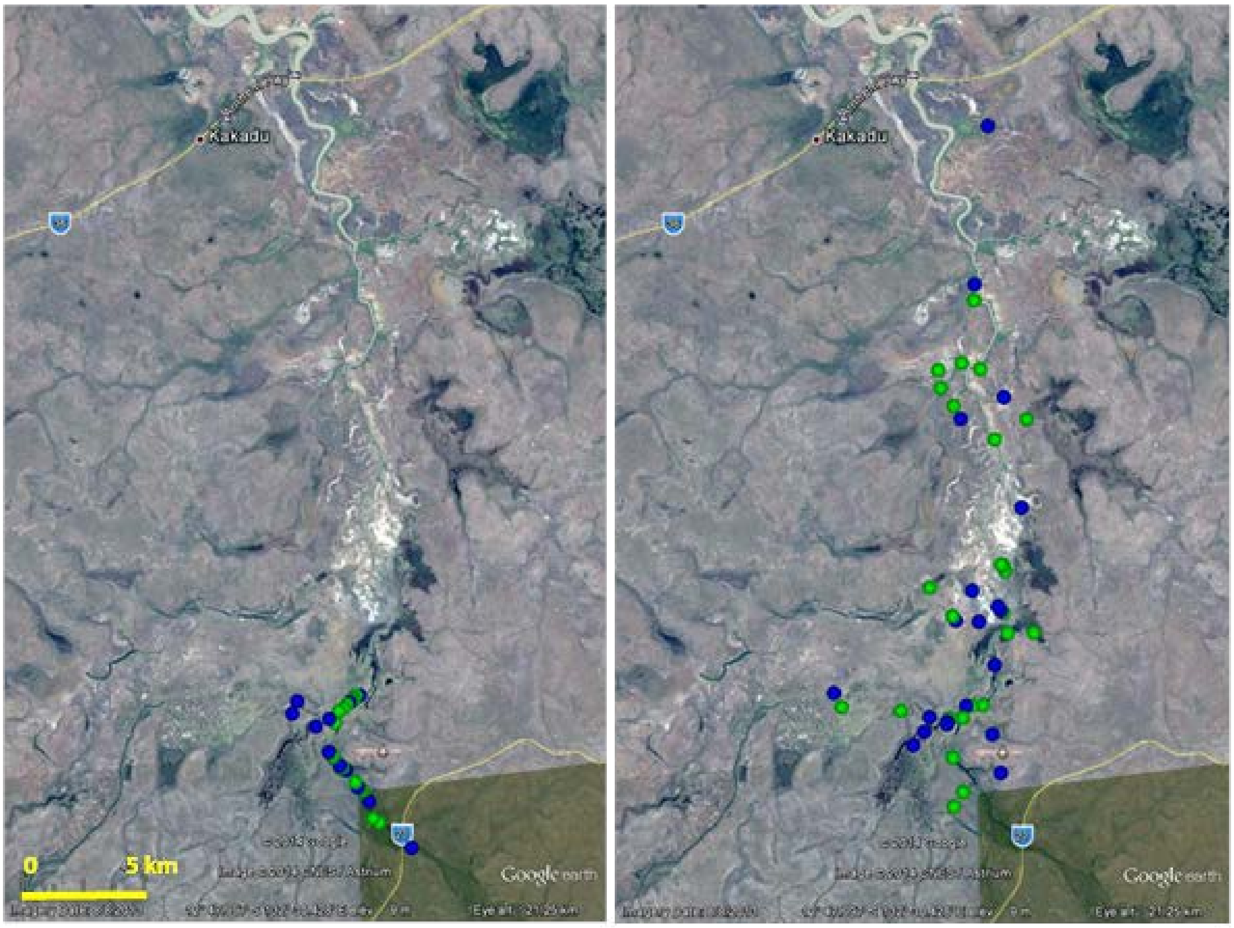

Figure 8: Maps showing locations of radio-tagged barramundi (blue dots) and forktail catfish (green dots) in the late dry season (left, 24th October 2013) and the wet season (right, 4th February 2014).

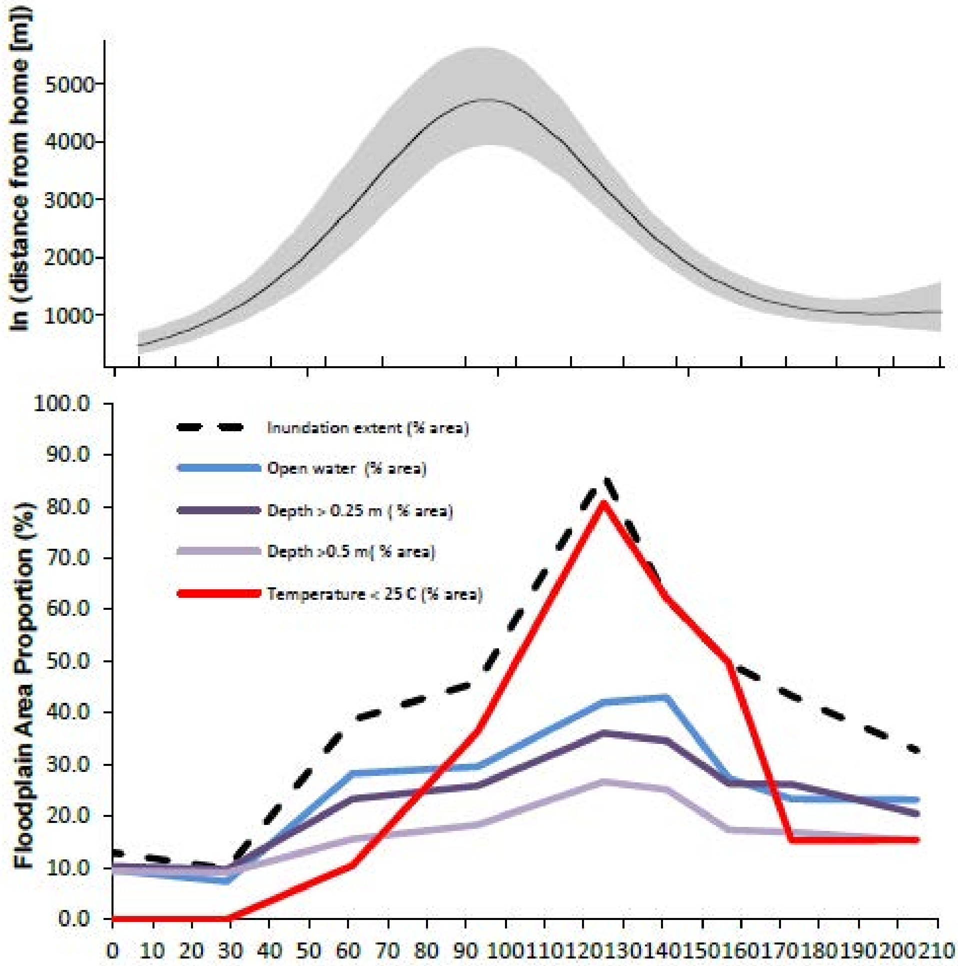

Figure 9: Graphs showing modelled distance from home over study period for radio-tagged barramundi (top) and the changing proportions of various habitat attributes on the South Alligator floodplain over the same period (bottom graph). These graphs show that most barramundi moved out onto the floodplain soon after inundation commenced and began to return to their home billabongs prior to the peak in floodplain inundation extent.

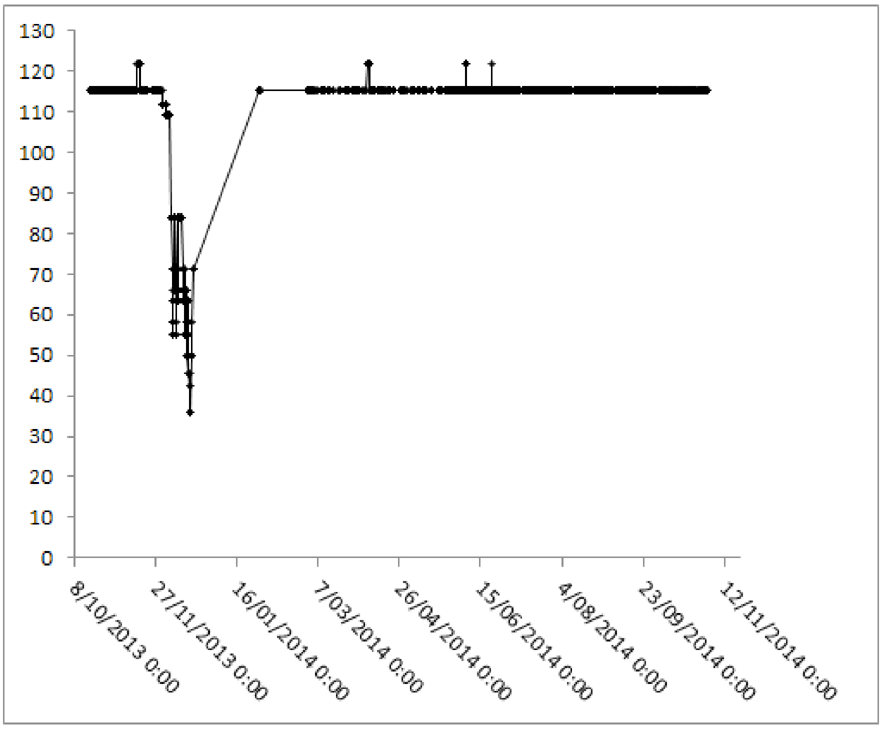

Figure 10: Detections of an acoustically tagged barramundi that moved ~80 km downstream during the early wet season before returning to its home billabong later in the wet season.

6 Summary of results

6.1 Food web stable isotopes analysis

The food web analyses illustrate the importance of connectivity between oceans, estuaries, floodplains, waterholes and the savannah as a critical feature maintaining animal productivity and diversity in these complex food webs. Notably, the iconic aquatic species of the region (e.g. barramundi, crocodiles) appear most dependent on this connectivity and are therefore the most vulnerable to hydrological modification, as is occurring or planned in other tropical regions of the world such as South America and southeast Asia (Dudgeon 2000).

Regions with more rhythmic (predictable timing and magnitude) floods contain food webs that more clearly demonstrate a flood pulse advantage, suggesting that organisms in these webs are adapted to capitalize on the annual flood by foraging in temporary habitats (Jardine *et al*. 2015). Consequently, food webs in more rhythmic rivers contain a greater number of fish species, which partially explains the high species richness in northern Australia in general and Kakadu in particular. All of these findings highlight the vulnerability of these systems to upstream water resource development that could lessen or otherwise alter the flood pulse, and the warnings posed by climate change that is predicted to increase the severity of extreme events, with implications for flood rhythms.

6.2 Remote sensing floodplain inundation and vegetation dynamics

The remote sensing tools developed in this project facilitate the mapping, monitoring and assessment of the seasonal connectivity between catchments, floodplains and coastal receiving waters. The remote sensing outputs for this project provided spatial products that have been directly applied in the Kakadu region in applications such as:

- Habitat suitability mapping for weed spread modelling
- Assessment of spatial and temporal connectivity of Kakadu floodplains
- Calibration of hydrodynamic models for assessment of salt water intrusion
- Inputs to aquatic vegetation mapping
- Inputs to the modelling fish movement patterns.

While remote sensing spatial outputs for this project are specific to the Kakadu region the remote sensing tools that were developed and published from this project have wide applicability for other tropical floodplain regions in Australia and other regions of the world.

6.3 Floodplain periphyton (algal) productivity

The assessment of floodplain periphyton (algal) productivity undertaken in this project delivered methods and spatial data products that enable the quantification of primary productivity for different aquatic habitats. This type of information is essential for wetland management and conservation planning processes both nationally and internationally. For the Kakadu region the application of these methods showed that:

- Submerged aquatic plants (e.g. ceratophyllum) carry 3-4 times the mass of periphyton compared to other structural types (e.g emergent grasses)
- Spatially dominant emergent vertical species (eg. grasses like wild rice, para grass) carry the least periphyton
- Light profile measurements indicate that light penetration is a major determinant of periphyton productivity
- The deeper floodplain backswamp areas had the highest periphyton productivity and can be considered 'hot spots' of periphyton productivity
- The deeper floodplain backswamp areas with highest periphyton productivity also hold water for the longest periods and consequently remain highly productive into the dry season
- The 'hot spots' areas of high periphyton productivity act as important aquatic refugia, maintaining fauna populations through the dry season, prior to the onset of the next wet season.

6.4 Fish movement

The fish telemetry study provided new information on fish behavioural responses to wet season flows with broad applicability to the conservation of floodplain habitats and the management of water resources in tropical Australian rivers. In combination with the stable isotope analyses and remote sensing aspects of the project, the fish telemetry research clearly demonstrated the importance of fish migration as a key process in delivering energy derived from floodplain sources to fish populations in the main channel. This information provides empirical evidence of the link between floodplain health and fisheries productivity in rivers of northern Australia. Other key findings of the research include:

- Immediate movement response of barramundi and catfish to first significant rises in river flow of the wet season
- Widespread use of inundated floodplain habitats in the early wet season by both species
- Preference for highly productive floodplain areas immediately downstream of Yellow Water, including the closed-access area known as "the Forks"
- Return movement to home ranges prior to the maximum floodplain extent
- Non-participation in spawning by freshwater resident barramundi.

Radio-tracking of both barramundi and catfish showed that when floodplains became inundated early in the wet season, most fish responded immediately by moving large distances (up to ~80km) away from their normal home ranges.

7 National implications of lessons learnt

The outputs of this project provide a better understanding of the maximum and minimum contributions of floodplains to the maintenance of biodiversity and fish biomass, meeting both pure and applied scientific objectives. The outputs can feed directly into the conservation planning by providing end users with knowledge and spatial data to quantify the importance of different landscape units towards overall system biodiversity.

This project provides information that will be of value to the Parks Operations and Tourism Branch, Parks Australia. It can also contribute knowledge of the ecology and resources supporting species (e.g. sawfish) listed under the EPBC Act, as well as broader coastal, estuarine and riverine fisheries covered under the Sustainable Fisheries Section.

The project addresses a range of Federal Government interests and responsibilities, including biodiversity conservation within the Parks Australia estate, research and science management (Parks and Biodiversity Science), the health of aquatic ecosystems (Aquatic Systems Health), the protection of the environment and people of the Alligator Rivers region (Supervising Scientist Division), and the management of invasive species (Environmental Biosecurity).

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The spread of the exotic grasses para grass (shown here) and olive hymenachne into areas of submerged aquatic plants will reduce periphyton production and primary productivity

Kakadu National Park's floodplains cover an area of approximately 20,000km^2

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