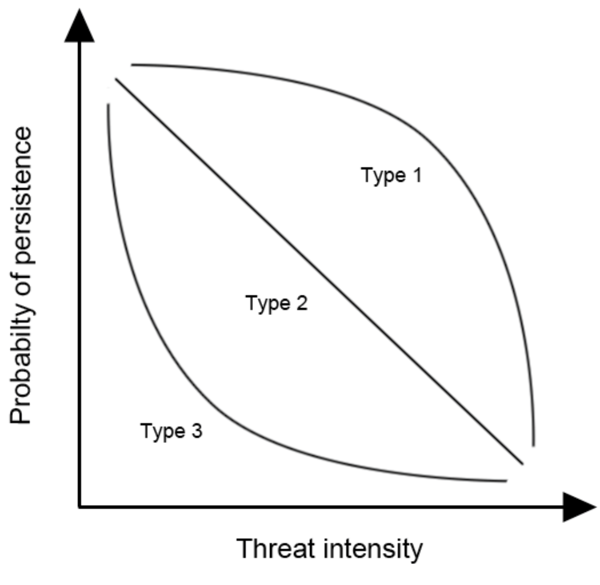
Expert elicitation to estimate the response of terrestrial species and ecosystems to threats in focal catchments of northern Australia

What is the goal of this research?

Our project aims to prioritise the spatial allocation of management actions to increase the persistence of terrestrial biodiversity in northern Australia. We will use a systematic conservation planning approach[1] to prioritise management actions in specific areas to achieve defined conservation objectives, while minimising costs and socioeconomic impacts[2].

The planning process involves prioritising actions to manage multiple threats to maximise benefits for several species and ecosystems[3]. This process requires information about the distribution of species, ecosystems and threats, as well as their potential responses to different threatening processes[4,5]. We will identify potential **responses of species and ecosystems to threats** using state-of-the-art expert elicitation techniques[6,7] and use this information to generate **response curves**[8] (**Figure 1**) that describe the relationship between probability of **persistence** of species/ecosystems and **threat intensity**.

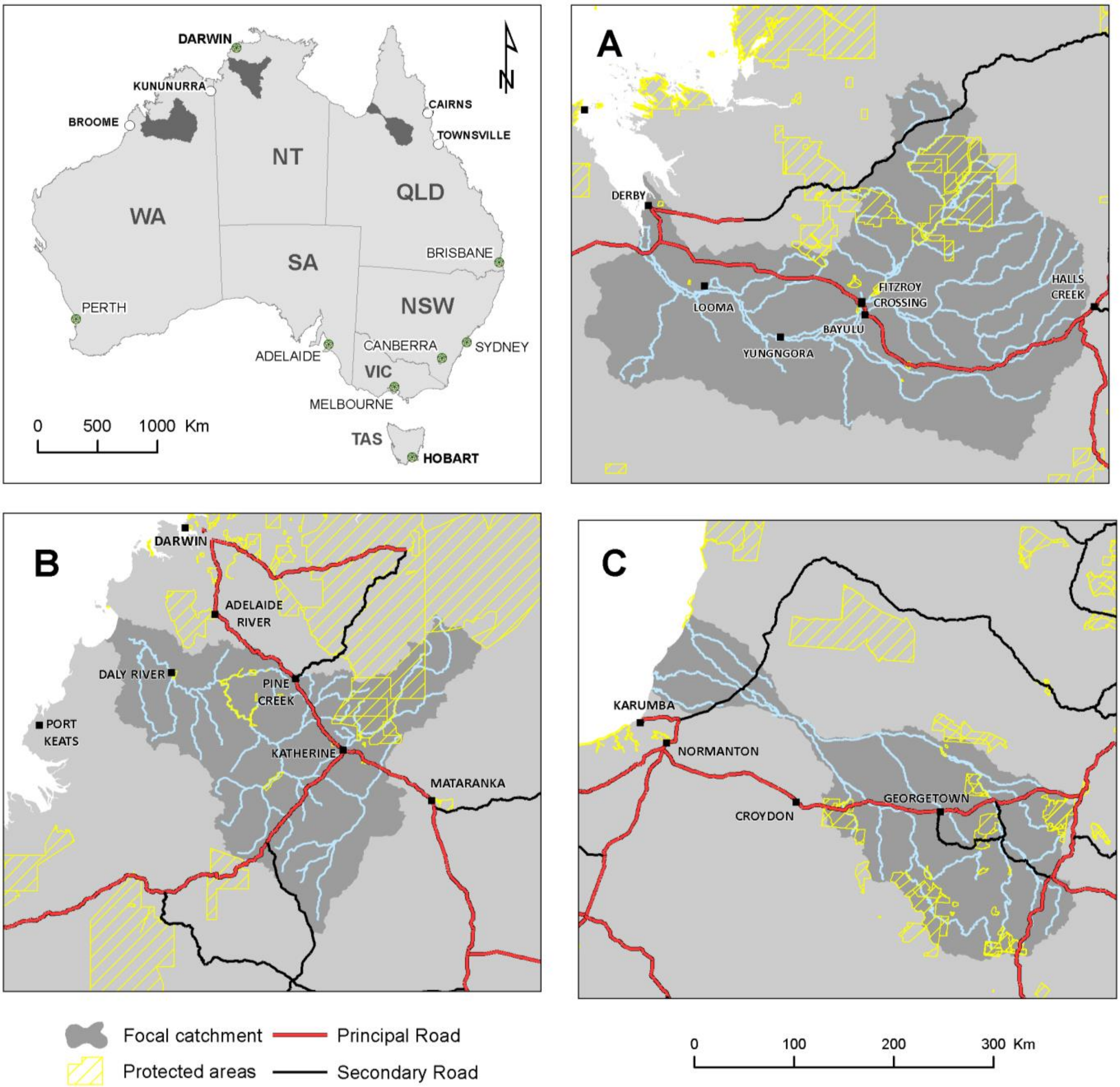
Figure 1. Graphic representation of response curves corresponding to changing probabilities of persistence for three hypothetical species or ecosystems along a threat intensity gradient



Where is the research happening?

Our study focuses on three catchments in northern Australia (**Figure 2**) that share ecological, cultural, and socioeconomic values[9-12], and face similar threats, including extensive grazing, altered fire regimes, and invasive species[13]. These catchments also face potential conflict between development and conservation[14-16], and offer opportunities for emerging stewardship programs that will likely play an important role in the conservation of northern Australia's biodiversity[17,18].

Figure 2. The three focal northern Australian catchments: (A) Fitzroy River, Kimberley, Western Australia; (B) Daly River, Northern Territory; and (C) Gilbert River, Northern Gulf, Queensland



Why this research is needed?

Northern Australia's biodiversity has high conservation value and provides important ecosystem services, but is threatened by many factors[4,19-21] including invasive animals[22-31], weeds[32-37], grazing[38-41], and changes to fire regimes[42-53]. The effects of these threats vary depending on their spatial distribution and co-occurrence of species and ecosystems. Therefore, it is essential to manage diverse threats to maximise benefits for multiple species and ecosystems[3,19,35]. Progress has been made in understanding the importance of different threats in some areas of northern Australia[3,19], including interactions between threats[31,37,50,52]. However, further research is needed to synthesise knowledge about the responses of biodiversity for conservation planning across northern Australia[8]. This information is essential for effective conservation planning, allowing managers to identify the benefits of different actions to mitigate the diversity of threats[8], and prioritise actions and areas accordingly[9]. This approach has rarely been followed, but is necessary for more effective and efficient conservation interventions[8,54].

What are we planning to do?

We are conducting a survey to elicit expert knowledge about the potential responses of terrestrial species and ecosystems to different threats. This information will be used to create response curves (**Figure 1**) that describe the relationship between the probability of persistence of species or ecosystems and threat intensity. The information will be used to improve methods to prioritise the spatial allocation of actions to promote the persistence of terrestrial biodiversity in the focal catchments. While implementation of actions is outside the scope of this project, we expect the results will assist natural-resource managers to make decisions about conservation investments that will benefit biodiversity in the region. The research group is working closely with Natural Resource Management (NRM) groups in the region, including updating of NRM plans and guiding conservation planning in the focal catchments.

Expert selection criteria

The experts selected for this survey comprise specialists in one or more ecosystems, faunal groups (amphibians, reptiles, birds, mammals) and/or threats (e.g. fire, weeds, pests), and have been identified by their track record, experience and knowledge of northern Australian ecosystems. Preference was also given to those with knowledge about the potential ecological responses to threatening processes and conservation management actions.

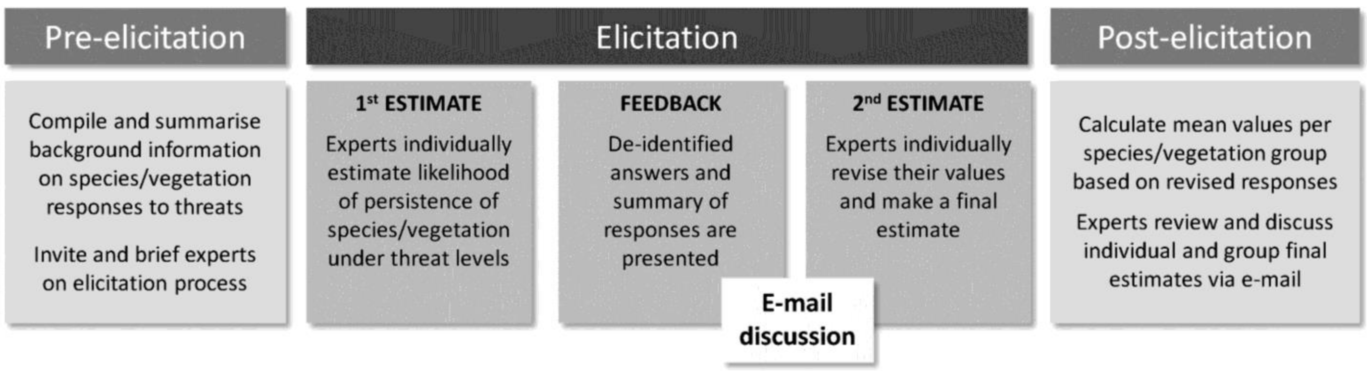
What will you be asked to do?

We ask you to use your expert knowledge to estimate the likelihood that an ecosystem or species in each functional group[55,56] will persist under different threat intensities. We define persistence as the maintenance of ecosystems[57] or populations of species at levels sufficient to perform their ecological function[58-60] over 20 years[3] (see '*Instructions for estimating the probability of persistence*' below).

Elicitation process

We are using state-of-the-art elicitation techniques[6,7] to gather expert knowledge on the vulnerability of terrestrial species and ecosystems to selected threats, including a literature review and an electronic consultation (**Figure 3**) following a structured expert elicitation procedure[7].

Figure 3. Expert elicitation process conducted remotely via e-mail (modified from McBride et al. 2012)



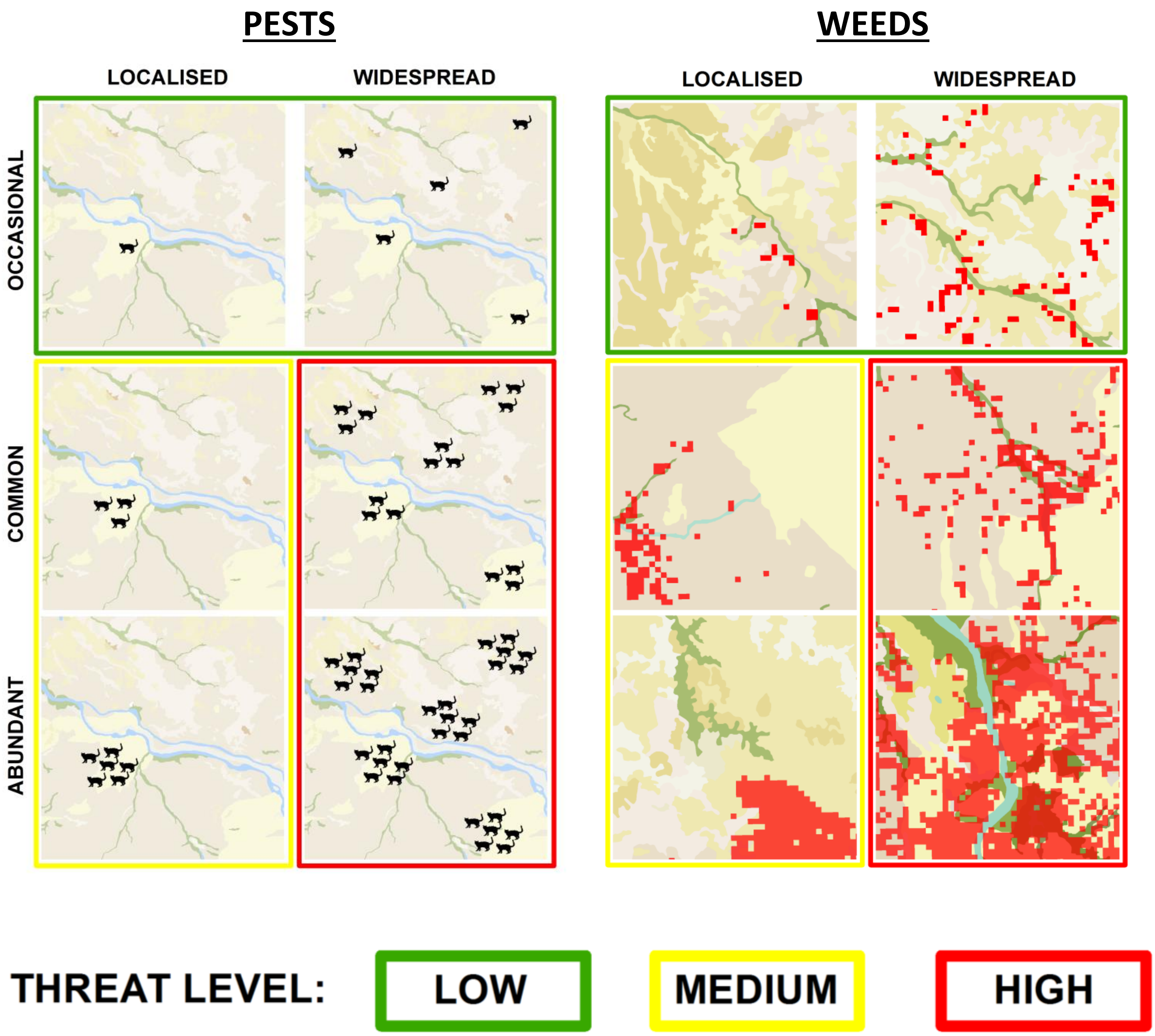
The survey focuses on species/ecosystem responses to four **threats**: invasive animals, hereafter 'pests' (e.g. cane toads, feral pigs, feral cats), weeds (e.g. grader grass, rubber vine, mimosa), grazing pressure, and altered fire regimes. To reduce discrepancy in the interpretation of threat intensity, we define intensity for each threat and provide a visual guide representing threat intensity. We also provide a summary of known mechanisms of impact for each threat (**Appendix 1**) to support your assessments.

Invasive species

Our definition of threat intensity for invasive species is based on the *extent* (localised or widespread) and *abundance* (rare, moderate or abundant) of **pests** and **weeds**. The abundance of invasive species can be "naturally" more or less patchy, and their association with certain habitats (e.g. riparian systems, grasslands) can be stronger (specialists) or weaker (generalists). Furthermore, seasonal variations in both extent and abundance (e.g. due to rainfall, vegetation cover) can be substantial for some pests or weeds, and accentuated by differences in their life strategies and behaviour. Therefore, threat intensity should be interpreted as the *average extent-abundance of the pest or weed being assessed* for any given area.

When completing the survey you will be asked to assess the response of species or ecosystems based on 3 levels of threat intensity for each invasive species, as defined in **Figure 4** based on a combination of extent (columns) and abundance (rows).

Figure 4. Visual guide for assessing species or ecosystems responses to invasive species

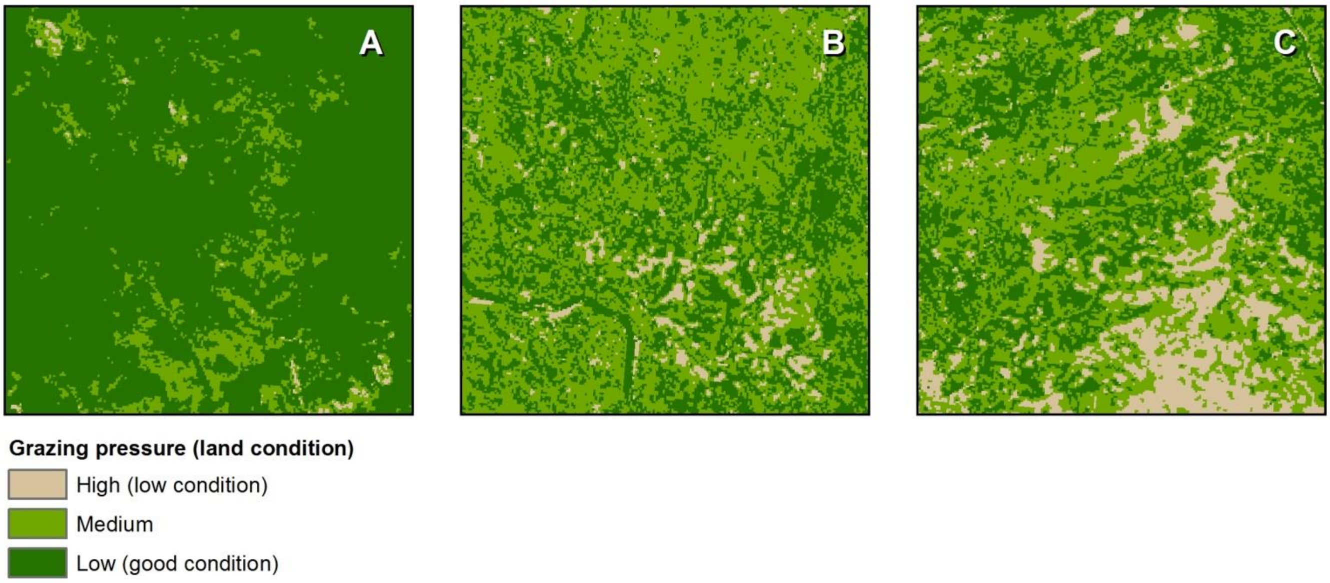


Grazing pressure

Our definition of threat intensity for grazing is based on the notion that land condition (assessed using remotely-sensed ground cover) can serve as proxy for grazing pressure, provided that changes in land condition associated with climatic (e.g. rainfall) and ecosystem (e.g. bioregions) variability are taken into account[61,62]. We define three levels of grazing pressure based on *land condition*, which is assumed to reflect the effect of grazing practices after discounting natural variability.

When completing the survey you will be asked to assess the response of species or ecosystems based on the three levels of grazing pressure (A: Low, B: Medium, C: High) defined based on the land condition of any given area (**Figure 5**).

Figure 5. Visual guide for assessing species or ecosystems responses to grazing pressure



Altered fire regimes

Our definition of threat intensity regarding fire regime is based on studies showing that frequent and very hot (late dry season) fires can have detrimental effects on various components of terrestrial biodiversity in northern Australia's tropical savannas[42-53]. Therefore, we define threat intensity based on the frequency of late-season (hot) fires and the interval between fires, which can be estimated based on remotely-sensed fire-scar history[a].

When completing the survey you will be asked to assess the response of species or ecosystems to altered fire regimes defined based on a combination of hot fire frequency and inter-fire intervals (**Table 1**).

Table 1. Criteria for defining threat intensity regarding altered fire regimes

LOW	MEDIUM	HIGH
Relatively small and rare late-season fires with long inter-fire intervals	Medium sized and sporadic late-season fires with medium inter-fire intervals	Relatively large and frequent late season fires with short inter-fire intervals

[a] Based on North Australian Fire Information (NAFI), which provides information on fire history from 2000 to 2013 (years burnt, late burnt, last burnt)

Species and ecosystems assessed

To expedite the expert elicitation process, we defined **functional groups**[55,56] of species with similar ecological requirements and potential responses to threats. We focused on species recorded for the three focal catchments, but functional groups are those generally found in other northern catchments. Our classification in functional groups resulted in 4 amphibian groups (60 species), 19 reptile groups (210 species), 12 bird groups (286 species), and 11 mammal groups (102 species). For ecosystems we used **major vegetation groups**[63] (14 ecosystems). A complete list of the ecosystems and species in each functional group is included in the attached '**03_survey_groups**' file.

***Note**: Excel files are named using the functional group (e.g. Survey_BIRDS) and you will be provided only with the files corresponding to the groups that you agreed to assess.*

To minimise the workload, we reduced the number of functional groups as much as possible without disregarding important ecological differences. However, some experts may consider that a particular species within a functional group requires a specific assessment because it is expected to respond very differently to some threats. If considered necessary, experts can add species of special concern and assess their response in addition to the assessment of the functional group to which that species belongs.

Instructions for completing the survey

See how it works: First, open '**04_survey_form.xlsx'** and look at the worksheet named '**Worked_ examples**' describing two examples of *correct* answers and two examples of *incorrect* answers. This demonstrates how to enter the information during your assessments.

To complete the survey: In the same Excel file you will find one worksheet per threat (named after each threat) that you need to fill in with your estimates on probability of persistence (with automatically-updating plots similar to example below). There are five Excel files, one per taxonomic group (amphibians, reptiles, birds and mammals) and one for ecosystems.

Remember, you will be provided only with the files corresponding to the groups that you agree to assess.

First, for each threat, ***estimate the probability of persistence*** of each species group or ecosystem under each of the three levels of threat intensity. For each threat intensity, ***give your best guess*** (between 0 and 1), which represents the probability that a species within each functional group (or ecosystem) will maintain a population level (or state) sufficient to perform its ecological function over 20 years under a given threat intensity; ***assess the expected response if threat intensity remains constant over the 20-year period***. Please refer to **Figure 4** (pests and weeds), **Figure 5** (grazing pressure), and **Table 1** (altered fire regimes).

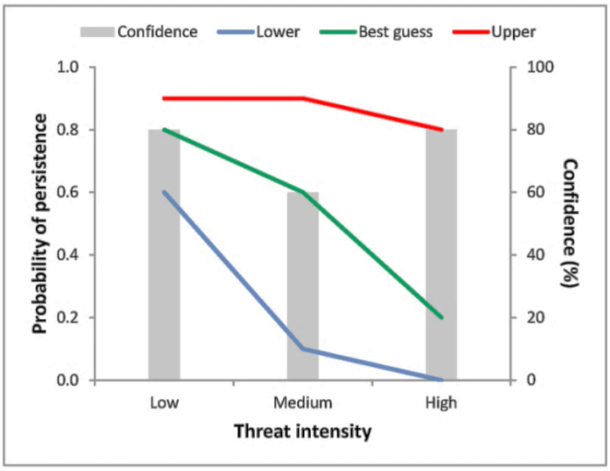
Following, ***give a lower and upper bound***, which represent the lowest and highest probability of persistence you expect a species or ecosystem to have (i.e. worst and best-case scenarios). Figure below shows a worked example of how the relationship between probability of persistence and threat intensity might look.

Finally, for each species or ecosystem you also need to **provide a level of confidence** (50 to 100%) that the true probability of persistence is located between these bounds. ***Your level of confidence for each estimate should always be >50%, otherwise it means that you are more confident that your answer is wrong than right.*** Also it should be <100% as there will always be uncertainty around the true estimate. Confidence can only be 100% when lower and upper bounds are 0 and 1, respectively.

The probability of persistence should generally not go up as the intensity of a threat increases. However, if you consider that increasing the intensity of a threat can increase the probability of persistence a given functional group or ecosystem, please justify. Also, note that the probability can remain flat for species unaffected by a threat or can be low (e.g. <0.5) even at the 'Low' threat intensity.

******Remember, you can add individual species and assess their probability of persistence if you think that their response to threats will differ significantly from other species within their functional group******

Probability of persistence	Threat intensity: Low	Medium	High
Upper	0.9	0.9	0.8
Best guess	0.8	0.6	0.2
Lower	0.6	0.1	0.0
Confidence	80	60	80



Additional interpretation guidelines

Confidence values (why not 100% confidence?): Experts should be able to be fully confident in some cases, but we assumed that one cannot be 100% sure that something is going to happen given our incomplete knowledge. In those cases, experts assigned a very high confidence (e.g. 99%), which means they are completely sure of their assessment and (effectively) has the same effect as giving a 100% confidence.

Species persistence: We define persistence as the maintenance of ecosystems or populations of species at levels sufficient to perform their ecological function over 20 years. However, in some cases, the extent/abundance of some species (or populations) has already been reduced to levels not sufficient to perform their ecological function anymore. Their current population status could be the product of one or more of the threats that we are assessing. *For species that have already declined to an extent/abundance that is too low to perform their ecological function, experts assessed how the species would respond to different threat intensities as if the species were at an extent/abundance in which they could perform their ecological function.*

Species groupings: Assessing some species groups (or vegetation types) can be difficult and substantially reduce sensitivity when individual species (or subgroups) can respond significantly different to the rest of the group (more resilient or sensitive to a threat). While we dedicated quite some time grouping and regrouping species to minimise the above situation, we understand there might be some of these cases or alternative ways of grouping. We considered subdividing further, but this would significantly increase the number of assessments. *In very few cases experts decided to assess certain species/subgroups individually because they could respond significantly different to a threat (compared with their corresponding functional group). In these cases, an additional (specific) assessment with the values for those species was included in the records; for summary purposes, these data were treated as an additional assessment for the corresponding functional group/threat combination..*

Threat interactions: We discussed the possibility of assessing interactions and decided against due to the complexity and additional time demand (i.e. possible combinations). This is a limitation of our approach that need to be explicitly acknowledged and considered carefully when interpreting or using the results, for example when assessing and integrating multiple threats. *Some experts considered that, for some species/threat combinations, it was necessary to incorporate interactions implicitly in their assessment (e.g. increased fire risk associated with invasive grasses, increased risk of cat predation associated with fires, higher cat predation following increase in rabbits through hyper-predation). Very few assessments included interactions and it was only when experts considered it was very difficult to isolate the interaction while doing their assessment; these are noted when applicable in the individual responses.*

Threat/group combinations: Some threats vs. species combinations are very unlikely or would never occur (e.g. moles occur in habitats that aren't used by buffalo) and some species will definitely not be affected by certain threats under any circumstances (e.g. parrots are not affected by cane toads). *In these cases, experts generally assigned a high (e.g. best guess 0.95, low 0.90 and max 1.0) and uniform probability of persistence across threat intensities (thus indicating the species group/vegetation is not sensitive to a given threat independently of the intensity) and also high confidence (e.g. 99%). In a few of these cases, experts decided to skip the assessment for a particular group/threat combination.*

Threat occurrence: As noted before, some threats tend to be localised within specific areas even when they are at the highest possible extent/abundance (e.g. dense infestations of weeds may primarily occur along riparian or heavily disturbed areas). *In these cases, experts were asked to imagine the conditions for a given area or vegetation type are such that the threat is allowed to reach its maximum level (i.e. for the high threat intensity) and, under this situation, estimate the likelihood that the species of a given group or vegetation community will persist/maintain its ecological function.*

Fire regimes: Identifying levels of fire return intervals and intensity that affect species or communities across all regions consistently is not possible due to natural differences in the occurrence of fires across regions and vegetation types. In other words, what could be a relatively benign inter-fire interval for one ecosystem/community, could be detrimental for another. For these reasons, experts assessed the response of functional groups/vegetation types against a relative measure of fire threat intensity that incorporates extent, frequency and seasonality/intensity as defined below. This partially addresses the issue of extent and natural variation (excluding reference to specific inter-fire intervals) and is consistent with the way experts decided to interpret fire threat intensity for this assessment.

References

1 Margules, C. R. & Pressey, R. L. Systematic conservation planning. *Nature* **405**, 243-253 (2000).

2 Wilson, K. A. *et al.* Conserving biodiversity efficiently: what to do, where, and when. *PLoS Biol* **5**, e223 (2007).

3 Carwardine, J. *et al.* Prioritizing threat management for biodiversity conservation. *Conservation Letters* **5**, 196-204, doi:10.1111/j.1755-263X.2012.00228.x (2012).

4 Franklin, D. C. *et al.* Geographic patterns and correlates of the decline of granivorous birds in northern Australia. *Wildlife Research* **32**, 399-408, doi:http://dx.doi.org/10.1071/WR05052 (2005).

5 Firth, R. S., Brook, B. W., Woinarski, J. C. & Fordham, D. A. Decline and likely extinction of a northern Australian native rodent, the Brush-tailed Rabbit-rat< i> Conilurus penicillatus</i>. *Biological Conservation* **143**, 1193-1201 (2010).

6 Martin, T. G. *et al.* Eliciting Expert Knowledge in Conservation Science. *Conservation Biology* **26**, 29-38, doi:10.1111/j.1523-1739.2011.01806.x (2012).

7 McBride, M. F. *et al.* Structured elicitation of expert judgments for threatened species assessment: a case study on a continental scale using email. *Methods in Ecology and Evolution* **3**, 906-920, doi:10.1111/j.2041-210X.2012.00221.x (2012).

8 Adams, V. M. *et al.* Planning across freshwater and terrestrial realms: co-benefits and tradeoffs between conservation actions. *Conservation Letters* **In press** (2014).

9 Carwardine, J. *et al.* *Priority threat management to protect Kimberley wildlife*. (CSIRO Ecosystem Sciences Brisbane, 2011).

10 Kennard, M. J. *Priorities for identification and sustainable management of high conservation value aquatic ecosystems in northern Australia - Final Report for the Department of Sustainability, Environment, Water, Populations and Communities and the National Water Commission*. (Tropical Rivers and Coastal Knowledge (TRaCK) Commonwealth Environmental Research Facility, Charles Darwin University, 2011).

11 Vanderduys, E. P. & Kutt, A. S. Biodiversity condition in the Northern Gulf. 119 pp (CSIRO Ecosystem Sciences, Townsville, QLD, 2011).

12 CENRM. Fitzroy River Catchment Management Plan. 103 pp (Centre of Excellence in Natural Resource Management, The University of Western Australia, Albany, WA, 2010).

13 Pusey, B. *Aquatic biodiversity in Northern Australia: patterns, threats and future*. (Charles Darwin University Press (CDU Press), 2011).

14 Stoeckl, N. *et al.* An integrated assessment of financial, hydrological, ecological and social impacts of 'development' on Indigenous and non-Indigenous people in northern Australia. *Biological Conservation* **159**, 214-221, doi:http://dx.doi.org/10.1016/j.biocon.2012.12.007 (2013).

15 Petheram, C., Watson, I. & Stone, P. Agricultural resource assessment for the Gilbert catchment: a report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment, part of the North Queensland Irrigated Agriculture Strategy. (CSIRO Water for a Healthy Country and Sustainable Agriculture Flagships, Australia, 2013).

16 Dale, A. *et al.* Catchment-scale governance in northern Australia: a preliminary evaluation. *Journal of Economic and Social Policy* **16**, Article 2 (2014).

17 Adams, V. M., Pressey, R. L. & Stoeckl, N. Estimating land and conservation management costs: The first step in designing a stewardship program for the Northern Territory. *Biological Conservation* **In Press** (2012).

18 Greiner, R. in *Contributed Paper at the 58th AARES Annual Conference, Port Macquarie, New South Wales.* 4-7.

19 Woinarski, J. C. Z. *et al.* The disappearing mammal fauna of northern Australia: context, cause, and response. *Conservation Letters* **4**, 192-201, doi:10.1111/j.1755-263X.2011.00164.x (2011).

20 Ziembicki, M., Woinarski, J. & Mackey, B. Evaluating the status of species using Indigenous knowledge: Novel evidence for major native mammal declines in northern Australia. *Biological Conservation* **157**, 78-92 (2013).

21 Burbidge, A. A. & McKenzie, N. L. Patterns in the modern decline of western Australia's vertebrate fauna: Causes and conservation implications. *Biological Conservation* **50**, 143-198, doi:http://dx.doi.org/10.1016/0006-3207(89)90009-8 (1989).

22 Bradshaw, C. J. A., Field, I. C., Bowman, D. M. J. S., Haynes, C. & Brook, B. W. Current and future threats from non-indigenous animal species in northern Australia: a spotlight on World Heritage Area Kakadu National Park. *Wildlife Research* **34**, 419-436, doi:http://dx.doi.org/10.1071/WR06056 (2007).

23 Forsyth, D. M., Duncan, R. P., Bomford, M. & Moore, G. Climatic Suitability, Life-History Traits, Introduction Effort, and the Establishment and Spread of Introduced Mammals in Australia. *Conservation Biology* **18**, 557-569 (2004).

24 Norris, A. & Low, T. Managing feral animals and their impacts. (2007).

25 Fordham, D., Georges, A., Corey, B. & Brook, B. W. Feral pig predation threatens the indigenous harvest and local persistence of snake-necked turtles in northern Australia. *Biological Conservation* **133**, 379-388 (2006).

26 Urban, M. C., Phillips, B. L., Skelly, D. K. & Shine, R. The cane toad's (Chaunus [Bufo] marinus) increasing ability to invade Australia is revealed by a dynamically updated range model. *Proceedings of the Royal Society B: Biological Sciences* **274**, 1413-1419 (2007).

27 West, P. *Assessing invasive animals in Australia 2008*. (National Land & Water Resources Audit, 2008).

28 Cowled, B. D. *et al.* Feral pigs: predicting future distributions. *Wildlife Research* **36**, 242-251 (2009).

29 Wicks, S., Mazur, K., Please, P., Ecker, S. & Buetre, B. An integrated assessment of the impact of wild dogs in Australia. (2014).

30 Price-Rees, S. J., Brown, G. P. & Shine, R. Predation on toxic cane toads (Bufo marinus) may imperil bluetongue lizards (Tiliqua scincoides intermedia, Scincidae) in tropical Australia. *Wildlife Research* **37**, 166-173, doi:http://dx.doi.org/10.1071/WR09170 (2010).

31 Kennedy, M., Phillips, B. L., Legge, S., Murphy, S. A. & Faulkner, R. A. Do dingoes suppress the activity of feral cats in northern Australia? *Austral Ecology* **37**, 134-139 (2012).

32 Brooks, K. J., Setterfield, S. A. & Douglas, M. M. Exotic Grass Invasions: Applying a Conceptual Framework to the Dynamics of Degradation and Restoration in Australia's Tropical Savannas. *Restoration Ecology* **18**, 188-197, doi:10.1111/j.1526-100X.2008.00470.x (2010).

33 Adair, R. J. & Groves, R. H. *Impact of environmental weeds on biodiversity: a review and development of a methodology*. (Biodiversity Group, Environment Australia Canberra, 1998).

34 Grice, A. C., Vanderduys, E. P., Perry, J. J. & Cook, G. D. Patterns and processes of invasive grass impacts on wildlife in Australia. *Wildlife Society Bulletin* **37**, 478-485, doi:10.1002/wsb.314 (2013).

35 Rossiter, N. A., Setterfield, S. A., Douglas, M. M. & Hutley, L. B. Testing the grass-fire cycle: alien grass invasion in the tropical savannas of northern Australia. *Diversity and Distributions* **9**, 169-176, doi:10.1046/j.1472-4642.2003.00020.x (2003).

36 Lonsdale, W. M. Inviting trouble: introduced pasture species in northern Australia. *Australian Journal of Ecology* **19**, 345-354 (1994).

37 Setterfield, S. A., Rossiter-Rachor, N. A., Hutley, L. B., Douglas, M. M. & Williams, R. J. Turning up the heat: the impacts of Andropogon gayanus (gamba grass) invasion on fire behaviour in northern Australian savannas. *Diversity and Distributions* **16**, 854-861, doi:10.1111/j.1472-4642.2010.00688.x (2010).

38 Sharp, B. R. & Whittaker, R. J. The irreversible cattle-driven transformation of a seasonally flooded Australian savanna. *Journal of Biogeography* **30**, 783-802, doi:10.1046/j.1365-2699.2003.00840.x (2003).

39 Woinarski, J. C. Z. & Ash, A. J. Responses of vertebrates to pastoralism, military land use and landscape position in an Australian tropical savanna. *Austral Ecology* **27**, 311-323, doi:10.1046/j.1442-9993.2002.01182.x (2002).

40 Garnett, S. T., Woinarski, J. C., Crowley, G. M. & Kutt, A. S. Biodiversity conservation in Australian tropical rangelands. *Wild rangelands: conserving wildlife while maintaining livestock in semi-arid ecosystems*, 191-234 (2010).

41 Legge, S., Kennedy, M. S., Lloyd, R., Murphy, S. A. & Fisher, A. Rapid recovery of mammal fauna in the central Kimberley, northern Australia, following the removal of introduced herbivores. *Austral Ecology* **36**, 791-799 (2011).

42 Andersen, A. N. *et al.* Fire frequency and biodiversity conservation in Australian tropical savannas: implications from the Kapalga fire experiment. *Austral Ecology* **30**, 155-167, doi:10.1111/j.1442-9993.2005.01441.x (2005).

43 Parr, C. L. & Andersen, A. N. Patch Mosaic Burning for Biodiversity Conservation: a Critique of the Pyrodiversity Paradigm. *Conservation Biology* **20**, 1610-1619, doi:10.1111/j.1523-1739.2006.00492.x (2006).

44 Legge, S. *et al.* The short-term effects of an extensive and high-intensity fire on vertebrates in the tropical savannas of the central Kimberley, northern Australia. *Wildlife Research* **35**, 33-43 (2008).

45 Murphy, B. P. & Bowman, D. M. J. S. What controls the distribution of tropical forest and savanna? *Ecology Letters* **15**, 748-758, doi:10.1111/j.1461-0248.2012.01771.x (2012).

46 Murphy, B. P. *et al.* Fire regimes of Australia: a pyrogeographic model system. *Journal of Biogeography* **40**, 1048-1058, doi:10.1111/jbi.12065 (2013).

47 Murphy, B. P., Russell-Smith, J. & Prior, L. D. Frequent fires reduce tree growth in northern Australian savannas: implications for tree demography and carbon sequestration. *Global Change Biology* **16**, 331-343, doi:10.1111/j.1365-2486.2009.01933.x (2010).

48 Prior, L. D., Murphy, B. P. & Russell-Smith, J. Environmental and demographic correlates of tree recruitment and mortality in north Australian savannas. *Forest Ecology and Management* **257**, 66-74, doi:http://dx.doi.org/10.1016/j.foreco.2008.08.015 (2009).

49 Russell-Smith, J., Whitehead, P. J., Cook, G. D. & Hoare, J. L. Response of Eucalyptus-dominated savanna to frequent fires: lessons from Munmarlary, 1973-1996. *Ecological Monographs* **73**, 349-375 (2003).

50 Vigilante, T., Bowman, D. M. J. S., Fisher, R., Russell-Smith, J. & Yates, C. Contemporary landscape burning patterns in the far North Kimberley region of north-west Australia: human influences and environmental determinants. *Journal of Biogeography* **31**, 1317-1333, doi:10.1111/j.1365-2699.2004.01104.x (2004).

51 Woinarski, J. & Legge, S. The impacts of fire on birds in Australia's tropical savannas. *Emu* **113**, 319-352 (2013).

52 Woinarski, J., Brock, C., Fisher, A., Milne, D. & Oliver, B. Response of birds and reptiles to fire regimes on pastoral land in the Victoria River District, Northern Territory. *The Rangeland Journal* **21**, 24-38, doi:http://dx.doi.org/10.1071/RJ9990024 (1999).

53 Yates, C. P., Edwards, A. C. & Russell-Smith, J. Big fires and their ecological impacts in Australian savannas: size and frequency matters. *International Journal of Wildland Fire* **17**, 768-781 (2008).

54 Carwardine, J. *et al.* Avoiding Costly Conservation Mistakes: The Importance of Defining Actions and Costs in Spatial Priority Setting. *PLoS ONE* **3**, 1-6 (2008).

55 Blondel, J. Guilds or functional groups: does it matter? *Oikos* **100**, 223-231 (2003).

56 Blaum, N., Mosner, E., Schwager, M. & Jeltsch, F. How functional is functional? Ecological groupings in terrestrial animal ecology: towards an animal functional type approach. *Biodiversity and Conservation* **20**, 2333-2345 (2011).

57 RodrÍguez, J. P. *et al.* Establishing IUCN Red List criteria for threatened ecosystems. *Conservation Biology* **25**, 21-29, doi:10.1111/j.1523-1739.2010.01598.x (2011).

58 Conner, R. N. Wildlife Populations: Minimally Viable or Ecologically Functional? *Wildlife Society Bulletin* **16**, 80-84, doi:10.2307/3782359 (1988).

59 Soulé, M. E., Estes, J. A., Berger, J. & Del Rio, C. M. Ecological Effectiveness: Conservation Goals for Interactive Species. *Conservation Biology* **17**, 1238-1250, doi:10.1046/j.1523-1739.2003.01599.x (2003).

60 Redford, K. H. *et al.* What Does It Mean to Successfully Conserve a (Vertebrate) Species? *Bioscience* **61**, 39-48, doi:10.1525/bio.2011.61.1.9 (2011).

61 Bastin, G. *et al.* Separating grazing and rainfall effects at regional scale using remote sensing imagery: A dynamic reference-cover method. *Remote Sensing of Environment* **121**, 443-457 (2012).

62 Ward, D. P. & Kutt, A. S. Rangeland biodiversity assessment using fine scale on-ground survey, time series of remotely sensed ground cover and climate data: an Australian savanna case study. *Landsc. Ecol.* **24**, 495-507 (2009).

63 Australian Government, D. o. t. E. (Australian Government Department of the Environment, Canberra, ACT, 2012).

EXPERT SURVEY TO ESTIMATE FRESHWATER SPECIES RESPONSES TO THREATS IN THE DALY RIVER CATCHMENT

Why is the research being conducted?

The aim of our research project is to prioritize the spatial allocation of conservation management actions to sustain freshwater-dependent species in the Daly River catchment, Northern Territory, Australia. The project is led by Griffith University in collaboration with CSIRO.

We invite you to participate in this survey to elicit information on the potential responses of freshwater-dependent species to different threats. The elicited information will be used to create simple response curves that describe the relationship between the probability of persistence of functionally similar species and the intensity of a particular threatening process. This information will be used to prioritize the spatial allocation of conservation management actions to improve persistence of freshwater biodiversity in the Daly River catchment.

The results of this analysis will be published as a research paper, which we will invite expert participants to be acknowledged on if they wish. Implementation of threat abatement actions is outside the scope of this project, but we hope that the results from our research will be useful to assist with decision making on freshwater conservation in the Daly region.

What you will be asked to do

We ask you to use your expert knowledge to estimate the likelihood that species in each functional group will persist for at least 20 years under increasing intensities of threat (see section "*Instructions for estimating the probability of persistence of species in each ecological group*").

The basis by which participants will be selected or screened

The experts selected for this survey comprise specialists in one or more faunal groups (i.e. waterbirds, fish and/or turtles) and have been identified by their track record, experience and preferably, knowledge of the fauna in northern Australia. Preference was also given to those with experience in expert elicitation as well as knowledge of ecological responses to threatening processes and conservation management actions. We aim to survey at least five experts for each of the three faunal groups (maximum of 20 experts will be surveyed). You have already been contact by telephone/email and agreed to consider participating in this expert survey. After responses from the present survey will have been collected and summarised, we may need to contact participants a second time, to allow them to revise their responses, if there is need to.

The expected benefits of the research

The Daly River catchment is widely recognised for its high ecological values and sustains important cultural, spiritual, and socioeconomic activities for Indigenous and non- Indigenous people. However, several major threatening processes are potentially affecting the long-term persistence of freshwater species and the important goods and services they provide for people living in the Daly River catchment. The outcomes of this project will assist natural resource managers make decisions about prioritising conservation management actions to improve persistence of freshwater biodiversity in the Daly River catchment.

Risks to you

By participating in this project we assert that you will not be exposed to physical, economic or legal harms. We consider that by expressing your personal expert opinions the risks to you of psychological harms, devaluation of personal worth or social harms to be negligible. This is because we have an appropriate management strategy in place to protect your anonymity and the confidentiality of your responses to the fullest possible extent, within the limits of the law (see next section).

Your confidentiality

We intend to protect your anonymity and the confidentiality of your responses to the fullest possible extent, within the limits of the law. Your name and contact details will be kept in a separate, password-protected computer file from any data that you supply, which will only be accessible to the researchers. You are welcome to access any information you provide on request to the researchers. No information that can be used to identify you as an individual will be published in any publications or audio-visual presentations. The data will be kept securely at the Australian Rivers Institute, Griffith University for five years from the date of publication, before being destroyed.

The rest of this document provides further details about project background and aim, and instructions on how to complete the survey.

Project background and aim

Despite their high biodiversity value and role in providing important ecosystem services to different stakeholders, freshwaters are among the most threatened and modified environments on the planet, and require immediate conservation action. As threats to freshwater systems are diverse and spatially heterogeneous - while resources for conservation are finite - it is critical to identify priority management actions, as well as where these should be implemented, especially dealing with financial and socio-economic constraints. Unfortunately, traditional conservation planning does not identify the specific actions required to meet a particular conservation target, and rarely considers the cost and socio-economic impacts of multiple actions.

A key step, in order to prioritize management actions, is to evaluate their effectiveness, i.e. the expected responses of biodiversity to those actions. This is important because different species respond differently to different threats and therefore likely benefit differently to different management actions. For example, barriers to movement caused by weirs or road crossings might have a greater impact on the persistence of migratory fish species than non-migratory fish species. Therefore, restoring fish passage should be a priority in areas where it is likely to have a greater benefit to migratory fishes (e.g. in the downstream reaches of river systems), because that can contribute more towards achieving conservation targets (assuming that the cost of the action is constant across space). Incorporating the response of species to threats into the spatial prioritization of conservation actions is essential in order to develop more effective and efficient conservation plans.

The aim of this project is to prioritize the spatial allocation of conservation management actions to increase persistence of freshwater-dependent species in the Daly River catchment, Northern Territory, Australia, while minimizing costs and socio-economic impacts. We define persistence as the maintenance of populations of species at high enough levels to perform their ecological function over 20 years. The Daly River catchment is widely recognised for its high ecological values, with many species of waterbirds, fishes and turtles of high conservation importance. The land and water systems of the Daly also sustain important cultural, spiritual, and socioeconomic activities for Indigenous and non- Indigenous people. Several major threatening processes are potentially affecting the long-term persistence of freshwater dependent species in the Daly River catchment. The major primary threats include introduced animals (including swamp buffalo - *Bubalus bubalis*, feral pigs - *Sus scrofa*, and cane toads - *Bufo marinus*), agricultural land use (particularly grazing), alteration of natural flow regimes (particularly due to dry season water extraction of surface- and ground-water systems), barriers to longitudinal connectivity (caused by weirs and road crossings) as well as proliferation of aquatic weeds and alteration of fire regimes. Some of the mechanisms by which these threats affect freshwater biodiversity in the Daly River catchment are briefly reviewed in Appendix 3.

The spatial scale of analysis (i.e., planning unit) is the stream sub-catchment. The project focuses on 6 different major threats, which include: buffalos, pigs, cane toads, grazing land use, altered flow regimes, barriers to longitudinal connectivity and aquatic weeds. We quantified the intensity of each threat within each planning unit, using information on the relative abundance of feral species (buffalo, pig, cane toad), the proportion of the planning unit occupied by a certain land use and the level of river flow disturbance (see Appendix 1 for criteria used to define threat intensity for different threats). To expedite the expert elicitation process, we defined 6 functional 'ecological groups' of freshwater fishes, waterbirds and turtles with similarities in ecological requirements and behaviour. The ecological groups are non-mutually exclusive, in the sense that a species can belong to different groups. A complete list of the species in each ecological group is reported in Appendices 3 in the attached excel file. To support the experts in quantifying the response of species to threats we have included a list of mechanisms of impact for each threat as a table in Appendix 2.

Instructions for estimating the probability of persistence of species in each ecological group

1. Estimate the probability of persistence of species in each ecological group under three different threat intensities. For each threat intensity, give your best guess (between 0 and 1), which represents the average probability of persistence of a species in an ecological group. Give also a lower and upper bounds, which represent the lowest and highest probability of persistence you expect each species in a specific ecological group to have (i.e., worst-case and best-case scenarios). Figure 1 shows three examples of how the relationship between probability of persistence and threat intensity might look like (i.e., response curves). Finally, give a level of confidence (between 0 and 100%) that the true probability of persistence is located between these bounds.

2. Probability of persistence estimates should never go up as the intensity of a threat increases (however, they can remain flat for a species group that is not affected by a threat).

3. You should be at least more than 50% confident (otherwise you are more confident that your answer is wrong, than right!) but less than 100% confident. Aim for between 60-90%.

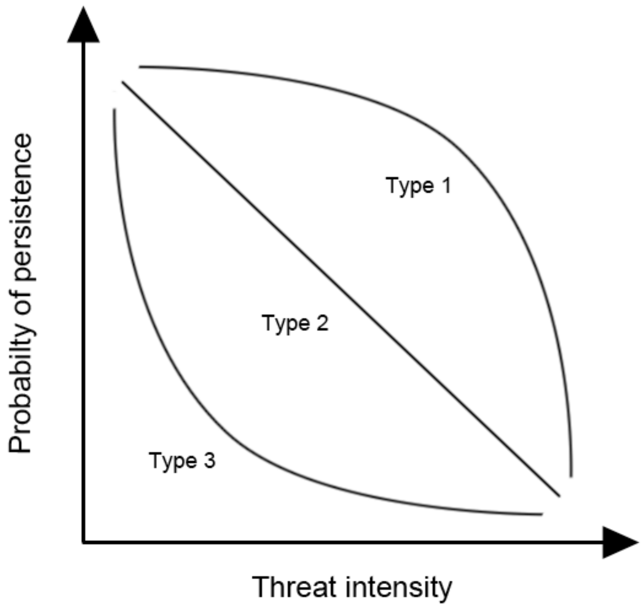


Figure 1. Graphic representation of three examples of the response of a species group's probability of persistence to threat intensity.

To complete the survey open the excel file "Daly_survey_form_FaunalGroupName.xlsx". The file contains worked examples and the tables to fill in with information on probability of persistence (with automatically-updating plots). The excel file also contains details about the nature of the threats and criteria for defining threat intensity (Appendix 1), a table summarizing the potential mechanisms of impact of different threats (Appendix 2), and a list of species in each ecological group for turtles (Appendix 3). Appendices 1 and 2 are also included below for easy print out.

If you have any queries about completing the survey, please email Lorenzo Cattarino (l.cattarino@griffith.edu.au).

Appendix 1. Criteria to define intensity of threats

	Threat intensity		
Threat	Low	Medium	High
Water buffalo	absent/localized occurrence	common/widespread	abundant and widespread
Pig	absent/localized occurrence	common/widespread	abundant and widespread
Cane toad	absent/localized occurrence	common/widespread	abundant and widespread
Grazing	Proportion of a planning unit occupied by grazing < 30%	Proportion of a planning unit between 30 and < 60%	Proportion of a planning unit > 60%
Altered flow regime (dry season water extraction)	Minor increase in flow intermittency, minor reduction in waterhole persistence	Moderate increase in flow intermittency, moderate reduction in waterhole persistence	Major increase in flow intermittency, major reduction in waterhole persistence
Longitudinal barriers[1]	no barrier or very few small barriers that frequently drown out (multiple times per wet season)[2]	few small - medium sized barriers that drown out periodically (i.e. each wet season)	multiple large barriers that rarely drown out
Aquatic weeds[3]	absent/localized occurrence	common/widespread	abundant and widespread

Note

[1] Longitudinal barriers include road crossings and gauging weirs. The Daly River catchment has no major barriers that interrupt river connectivity all year round and relatively few in-stream structures that are barriers to fish movement during the dry season. There are likely to be other road crossings that cause barriers but this depends on the characteristics of the structure (e.g. culvert or bridge design). The largest structures are gauging weirs on the Katherine River (at Donkey Camp Pool) and on Green Ant Creek, and the road crossings on the Daly River at Claravale, Beeboom and Daly River (at Nauiyu Nambiyu community). During the wet season these structures are 'drowned out', and no longer impede fish and other fauna movement. Not all flow gauges cause barrier, only those associated with a weir (concrete barrier).

[2] Intensity of the threat "Longitudinal barriers" depends on height of the barrier, number of barriers within the planning unit, frequncy and timing of drownout

[3] Salvinia (*Salvinia molesta*) is the only truly aquatic weed in the Daly catchment. It is present in billabongs, rather than in rivers and streams. Another important weed species is Mimosa (*Mimosa pigra*), which is concentrated on the river's floodplains, especially in the lower Daly.

Appendix 2. Summary of mechanisms of impact of different threats

<table>
<tr><th rowspan="2">Primary threats</th><th colspan="2">Mechanisms of impact on freshwater biodiversity</th><th rowspan="2">Implications for ecological resources and processes</th></tr>
<tr><th>Direct</th><th>Indirect</th></tr>
<tr><td rowspan="9">Swamp Buffalo</td><td rowspan="6">Trampling</td><td>suspension of sediments leading to elevated turbidity and reduced primary production</td><td>Water quality, Food availability (plants & animals)</td></tr>
<tr><td>direct damage to nests/eggs (all taxa) and juveniles (birds, turtles)</td><td>Habitat availability (refuge, reproduction)</td></tr>
<tr><td>accelerated soil erosion on land and in Riparian zone leading to increased sedimentation of aquatic habitats</td><td>Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)</td></tr>
<tr><td>channelling of runoff on floodplains and loss of local floodplain inundation</td><td>Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals), Connectivity</td></tr>
<tr><td>saltwater intrusion into freshwater habitats,</td><td>Water quality, Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals), Connectivity</td></tr>
<tr><td>loss of aquatic and riparian vegetation</td><td>Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)</td></tr>
<tr><td>Competition for food</td><td>grazing of aquatic and riparian vegetation</td><td>Food availability (plants)</td></tr>
<tr><td>Defecating & Urinating</td><td>nutrient enrichment and increased algal growth</td><td>Water quality, Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)</td></tr>
<tr><td>Defecating</td><td>addition of fine particulate organic matter leading to smothering of benthic aquatic habitat</td><td>Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)</td></tr>
<tr><td rowspan="3">Feral pigs</td><td>Predation</td><td>direct predation on waterbirds and turtles (adults, juveniles, eggs)</td><td>direct decline in abundance</td></tr>
<tr><td rowspan="2">Competition for food</td><td>grazing of aquatic and riparian vegetation</td><td>Food availability (plants)</td></tr>
<tr><td>consumption of aquatic and riparian animals (e.g.</td><td>Food availability (animals)</td></tr>
</table>

		molluscs, crustaceans, insects, vertebrates)	
	Trampling and rooting	suspension of sediments = elevated turbidity	Water quality, Food availability (plants & animals)
		accelerated soil erosion on land and in Riparian zone leading to increased sedimentation of aquatic habitats	Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)
		channelling of runoff and loss of local floodplain inundation	Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals), Connectivity
		saltwater intrusion into freshwater habitats,	Water quality, Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals), Connectivity
		loss of aquatic and riparian vegetation	Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)
	Defecating & Urinating	addition of nutrient rich organic matter leading to elevated nutrients, smothering of benthic aquatic habitat	Water quality, Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)
Cane toads	Predation	direct predation on fish eggs (& juveniles & adults?)	Direct decline in abundance
	Poisoning	predation by fish (& turtles?) on toad eggs & tadpoles (& adults?)	Direct decline in abundance
	Competition for food	tadpole grazing of aquatic detritus and algae	Food availability (algae & detritus)
		adult consumption of aquatic and riparian animals (e.g. crustaceans, insects, vertebrates)	Food availability (animals)
Grazing (and other agricultural land use)	Trampling	suspension of sediments leading to elevated turbidity	Water quality, Food availability (plants & animals)
		direct damage to nests/eggs (all taxa) and juveniles (birds, turtles)	Habitat availability (refuge, reproduction)
		accelerated soil erosion on land and in Riparian	Habitat availability (refuge, feeding, reproduction), Food

		zone leading to increased sedimentation of aquatic habitats	availability (plants & animals)
		loss of aquatic and riparian vegetation	Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)
	Competition for food	grazing of aquatic and riparian vegetation	Food availability (plants)
	Defecating & Urinating	nutrient enrichment and increased algal growth	Water quality, Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)
	Defecating	addition of fine particulate organic matter leading to smothering of benthic aquatic habitat	Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)
Altered flow regimes (dry season water extraction)	Reduced river baseflow	Reduction in habitat volume	Habitat availability (refuge, feeding, reproduction)
		Reduced extent of shallow fast-flowing habitats	Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)
		Reduced depth of deep slow-flowing habitats	Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)
		Exposure of submerged bankside structures (e.g. wood, root masses undercut banks)	Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)
		Reduced longitudinal connectivity over shallow riffle areas	Movement
		Increased risk of exposure to predation, competition for resources, transmission of diseases	direct decline in abundance
		Risk of exposure eggs and nests if rapid reduction in water levels	Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)
	Reduced groundwater-surfacewater	Reduced persistence of waterholes as aquatic refugia	Habitat availability (refuge)
		Reduced integrity of riparian vegetation	Habitat availability (refuge, feeding, reproduction), Food

	connectivity		availability (plants & animals)
Barriers to longitudinal connectivity (weirs and road crossings)	Reduced ability to move within river networks	restricted access to habitats for spawning, rearing or growth for diadromous species (large scale)	Habitat availability (feeding, reproduction), Food availability (plants & animals)
		restricted access to habitats for spawning, rearing or growth for non-diadromous species (local scale)	Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)
Aquatic weeds	Proliferation and blanketing of water surface (e.g. *Salvinia*)	reduced light transmission into water column, curtailing photosynthesis and primary production (algae and native macrophytes)	Water quality, Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)
	Proliferation on floodplains and waterhole margins (e.g. *Mimosa*)	dense thickets monopolise space and nutrients and prevent access to permanent water by species such as waterbirds	Habitat availability (refuge, feeding, reproduction), Food availability (plants & animals)

Appendix 3. Mini-review of major threatening processes and mechanisms of impact on freshwater biodiversity in the Daly River catchment

Source: *Pusey, B., Warfe, D., Townsend, S., Douglas, M., Burrows, D., Kennard, M. & Close, P. (2011). Condition, impacts and threats to aquatic biodiversity. Chapter 10 In: Aquatic Biodiversity in Northern Australia: Patterns, Threats and Future. (Ed) B.J. Pusey. Charles Darwin University Press, Darwin. Pp. 151–172. ISBN: 9780980864113.*

Swamp buffalo

Swamp buffalo (*Bubalus bubalis*) and feral pigs (*Sus scrofa*) are the most conspicuous alien vertebrate pests that degrade aquatic ecosystems of northern Australia. Buffalo have caused severe damage to wetland environments in the Northern Territory, including accelerated soil erosion and sedimentation, channelling of floodwaters, saltwater intrusion into freshwater habitats, loss of wetland vegetation, and reductions in the diversity of wetland plants and animals (Petty et al 2007).

Feral pigs

Feral pigs represent another significant threat to waterways throughout the wet–dry tropics, particularly as their distribution is largely limited by access to water, as they are easily heat stressed. Like buffalo, pigs increase riverbank erosion and the spread of weeds through trampling and rooting. Pigs are omnivorous, consuming a variety of wetland and riparian seedlings, freshwater invertebrates and amphibians, and eggs of ground-nesting turtles, crocodiles and birds (Bayliss et al 2006, Pusey and Kennard 2009, Mitchell 2010). Pigs have relatively small home ranges (Caley 1997), which results in herds congregating around permanent waterholes and wetlands during the dry season (Cowled et al 2009), thus concentrating their activity and increasing their local impact. They uproot and eat riparian seedlings as they root along riverbanks in search of food. During the hottest months, pigs wallow in the wet margins of waterholes, dramatically increasing the amount of suspended sediment in the water column and reducing water clarity. The physical disturbance associated with wallowing may reduce the capacity of wetlands to rejuvenate with the onset of summer rains.

Cane toads

The impacts of the cane toad (*Bufo marinus*) may be greater on terrestrial organisms than on aquatic organisms. However, reports of declines in abundance of freshwater crocodiles (*Crocodylus johnstoni*) (Letnic et al 2008) and two species of water monitor (*Varanus mertensi* and *V. panoptes*) are known, and the latter were listed as threatened in the Northern Territory in 2006 (Fox 2008). Cane toads have been shown to rapidly reduce local populations of water monitors and alter their occupancy of suitable sites (Griffiths and McKay 2007). Interestingly, there is recent evidence that the omnivorous fish *Hephaestus fuliginosus* (black bream, or sooty grunter) can consume cane toads with no ill effects (Davis and Perna 2009). Recent research has indicated that the impact of toads may not be as great as previously thought.

Toads were originally introduced into Queensland in the early 1930s to control insect pests in cane fields—which seemed like a good idea at the time. While we still do not know whether they fulfilled this role of cane beetle consumers, we do know that they have spread widely from the point of introduction, and continue to do so. Moreover, they are now spreading at a faster rate, due to both rapid physical and behavioural change. Toads on the invasion front now have longer legs, move in a straighter line, stay in one place for less time, use existing road networks, and are not averse to hitching a ride in vehicles (Brown et al 2006, Phillips et al 2006, Alford et al 2009, White and Shine 2009) The invasion front now moves at about 55 km each year, compared with 10 km each year when toads were restricted to Queensland. Urban et al (2007) predicted that toads will eventually colonise every mainland state.

Toads are highly toxic at all life stages. The toxins—a variety of bufogenins or bufodienolides—are rapidly acting and frequently cause death upon ingestion. Declines in native wildlife associated with toads have occurred, although no species has been driven to extinction. Mass mortality in native anuran tadpoles has been reported, because tadpoles eat the highly toxic eggs (Crossland et al 2008). Presumably, the many anecdotal accounts of fish kills associated with high toad densities may also be associated with egg predation.

Declines in the abundance of monitor lizards have coincided with the appearance of toads (Ujvari and Madsen 2009). Doody et al (2009) found that, within a year of the cane toad colonising the Daly River catchment, some species of monitor lizards (*Varanus panoptes, V. mitchelli and V. mertensi*) all greatly decreased in abundance. Notably, they also found that the freshwater crocodile, *Crocodylus johnstoni*, did not also decline at this time, despite the fact that seven dead specimens had eaten toads shortly before they died. Other studies reported declines in *C. johnstoni* due to toads in the Daly River (Letnic et al 2008), and that this species is highly susceptible to toad toxins (Smith and Phillips 2006). Interesting indirect effects of the reduction in *V. panoptes* abundance include increased survivorship of pig nosed turtle nests (Doody et al 2006) and an increase in abundance of the dragon lizard, *Lophognathus gilberti* (Doody et al 2009). Both turtle eggs and dragons are a major food source of *V. panoptes*. Such indirect effects are likely to be common and perhaps very important in changing patterns of biodiversity in toad infested areas. Greenlees et al (2006) reported that toads reduce the abundance of grounddwelling invertebrates, but only to the same extent as the equivalent biomass of native frogs. However, toads may attain extraordinary densities on floodplains (more than 2000 per hectare; Phillips et al 2003), and may become a major sink for carbon (in the form of insects) that becomes unavailable to other higher-order consumers until the toads die and re-enter the food web via decomposer organisms. Given their mobility, toads may also export energy from the ecosystem.

***Grazing* (and other Agricultural land use)**

Agriculture can affect aquatic ecosystems in many ways, including increased sedimentation, nutrient enrichment, contamination with biocides and other chemicals, changes in run-off rates and increased likelihood of alien weed invasions. Importantly, the effects of agriculture on aquatic systems may be persistent and difficult to correct; thus agriculture may have significant negative legacy effects (Allan 2004).

Sediment mobilised by agricultural and pastoral activity is delivered to aquatic environments via run-off, causing a variety of deleterious physical and ecological effects. Suspended sediments reduce water clarity and hence the availability of light needed for photosynthesis. Thus, increased sediment loads can depress primary production and hence impair ecosystem function. Sedimentation can reduce habitat quality for bottom-dwelling animals (e.g. by infilling the interstitial spaces of sand and gravel streambeds), and suspended sediments may also clog the gills and respiratory surfaces of invertebrates and fishes. Prolonged increases in sediment loads can ultimately result in changes in river channel form, loss of pools through infilling and overall reduction in habitat diversity.

Nutrients applied to crops often find their way into aquatic environments, sometimes in large and damaging quantities. Nutrient enrichment can massively increase rates of primary production (the process of eutrophication), potentially causing proliferation of filamentous algae and blooms of toxic blue-green algae. Ganf and Rea (2007) assessed the potential for blooms to occur in rivers of northern Australia. They found that nutrients were limiting—that is, in short supply—in natural circumstances, and were consumed by plants and algae before large algal blooms could occur. More importantly, they found that the necessary inoccula for algal blooms, including species of toxic cyanobacteria (blue-green algae), were present in northern Australian rivers, but were kept at very low biomass because of nutrient limitation. These findings indicate that algal blooms could occur if nutrient levels increased as a result of human activities so that they were no longer limiting. This is of particular concern in the generally nutrient-poor systems of northern Australia (Douglas et al 2005).

Contaminants arising from agricultural practices include pesticides, herbicides and heavy metals. Biological impacts on aquatic organisms (e.g. invertebrates and fish) from these chemicals include increased rates of physical deformities, impacts on behaviour (such as the propensity for larval invertebrates to disperse, or drift, in the water current), reduced growth rates, reductions in reproductive capacity and a host of other effects. In tropical Australia, the rate of delivery of contaminants from agricultural lands to aquatic ecosystems may be significant.

Many of the impacts described above are particularly associated with broadacre agriculture, although they are not limited to this type of agriculture. Despite the patchy nature of mosaic-style agriculture, it may still have widespread impacts across river–floodplain ecosystems. Although best practice irrigation should see no water exiting from cropped areas during the dry season, high-intensity rainfall events during the wet season will still result in the mobilisation of sediments and residual fertiliser and toxicants. In addition, the development of road infrastructure to service widespread and patchy mosaic-style development is likely to have its own suite of impacts (e.g. barriers to movement, increased rates of erosion). Widespread extraction of groundwater to irrigate mosaic-style agriculture is likely to reduce groundwater inputs to river systems and cause drawdown of groundwater in subterranean systems. Careful monitoring of aquifers may regulate the extent of this impact, but this may be difficult in areas with diffuse, poorly recognised aquifers; where the links between aquifer recharge and subsequent discharge to river systems are poorly understood; where the distribution and needs of groundwater-dependent ecosystems are unknown; and where there may be significant time lags in groundwater recharge and hence responses to extraction.

***Altered flow regimes* (particularly dry season water extraction)**

Maintenance of the natural flow regime is critical to the integrity of aquatic ecosystems and biodiversity. Changes in natural patterns of river flow due to changing land use, water resource development and projected global climate change are at the forefront of the many processes that threaten aquatic habitats and biota regionally, nationally and globally. The distinctive flow regimes of northern Australia thus remain largely unaffected by human activities; however, impoundments, riparian extraction (i.e. direct pumping from the river) and groundwater extraction have the potential to affect the natural run-off and recharge rates in particular areas.

Dry season water extraction reduces baseflow, dewatering important flow-sensitive habitats that are critical for many fish species, and for aquatic algae and invertebrates, which provide food for larger species such as freshwater crocodiles, barramundi and black bream (Douglas et al 2005, Webster et al 2005, Townsend and Padovan 2009, Chan et al 2010). Extreme reductions in flow can disconnect river reaches, preventing the movement and migration of numerous species of crustaceans, fish and turtles, and resulting in isolated populations that are more at risk from localised disturbances.

Water extraction can affect groundwater recharge rates and riparian vegetation communities that rely on groundwater (O'Grady et al 2006, Tien 2006). Groundwater extraction may disturb subterranean and groundwater ecosystems, which are thought to play important roles in filtering and water purification (Humphreys 2008, Pusey and Kennard 2009). Naturally isolated waterholes are a common feature of many intermittent rivers in northern Australia. They are critical refuges for water-dependent biota and are key watering points for many terrestrial animals during the dry season. Waterholes are often sustained by connection to groundwater once surface flow has ceased. When this connection is prevented by lowered groundwater levels, the waterholes dry out more quickly and their value as a refuge can be compromised by an unnaturally rapid deterioration in water quality (e.g. low dissolved oxygen and increased concentration of salts). Dry-season waterholes may be the only source of aquatic refuge over many hundreds of kilometres of otherwise dry streambed. The refuge provided by isolated waterholes is very important as they are the point from which recolonisation and dispersal along the river occurs once connectivity is restored by wet season flows. Human impacts on the spatial distribution and persistence of dry-season waterholes can therefore have widespread and prolonged ecological consequences.

Barriers to movement caused by physical infrastructure **(weirs and road crossings)**

Many northern Australian species of fish, crustaceans and other biota move extensively throughout river networks, on and off seasonally inundated floodplains, and between freshwater and marine ecosystems. Such movements are necessary to complete life cycles and are vital for maintaining viable population sizes and genetic integrity. Water infrastructure developments such as dams, weirs and tidal barrages can be significant barriers to such movement. These barriers can prevent access to upstream riverine habitats, which are vital for development of fish that spawn in estuaries (barramundi, sawfish, bullsharks and a host of other species) but can also spend much of their early lives in fresh water, often far upstream. Barriers may therefore affect commercial fishery values.

Cascading impacts throughout the riverine ecosystem can occur because many such species are top predators and play an important role in the structure of natural communities and the movement of carbon and energy through aquatic food webs (Douglas et al 2005, Pusey and Kennard 2009). Freshwater prawns also migrate upstream after they have developed from larvae into juveniles in estuarine or downstream river habitats. Freshwater fish such as black bream (*Hephaestus fuliginosus*) and eel-tailed catfishes (*Neosilurus* spp.) can be prevented from accessing tributary streams required for spawning. Without such movement, local populations diminished by seasonal drought or flooding cannot be replenished.

Although there are relatively few large dams in northern Australia, there are numerous smaller dams and weirs that can pose a barrier to the movement of aquatic organisms. Road crossings can also form artificial barriers to movement, particularly during low-flow periods when many species of fish disperse throughout river networks (Lamche 2006, van Dam et al 2008a, Pusey and Kennard 2009). Any development of northern Australia is likely to involve expansion of the existing road network, which may place further pressure on these migratory species.

Reservoirs, weirs and barrages may also act as barriers to the movement of materials other than biota. For example, reservoirs act as sinks or storage sites for suspended sediment and the nutrients attached to them, and also trap sand being transported along the riverbed. When fine sediment becomes trapped and is no longer available for downstream and lateral transport in floodwaters, the annual replenishment of floodplain habitats, which is vital for natural communities and agricultural production, is reduced. Transmission of sediment is also important for the maintenance of natural geomorphological processes and downstream habitat. Without continual replenishment, features such as sandbars gradually become smaller and less abundant. These habitats are crucial for reproductive success of freshwater crocodiles and turtles in northern Australia.

Aquatic weeds

Many plant species now recognised as invasive weeds were deliberately introduced into the environment to support pastoralism (Cook and Dias 2006). Invasive plants pose a serious threat to the waterways and floodplains of northern Australia. The release of aquarium plants by the public and their dispersal from fish ponds to waterways during the wet season also poses a major risk to the aquatic environment. Fishing equipment and boats are a common means of spread of invasive weeds. Five such weed species in northern Australia— *Mimosa pigra, Hymenachne amplexicaulis, Cabomba caroliniana, Salvinia molesta* and *Cryptostegia grandiflora*—are listed as weeds of national significance because their impacts on natural and agricultural systems are so severe. These five species illustrate the spectrum of the impact of weeds on aquatic systems.

Salvinia molesta is a surface-dwelling plant that also grows and reproduces extraordinarily rapidly. It may completely blanket the surface of waterbodies in a very short time, doubling its dry weight every 2.5 days under optimal conditions (Room et al 1981). Prolific stands may prevent the transmission of sunlight into the water column and effectively curtail photosynthesis and primary production. *Mimosa pigra* (prickly mimosa) forms dense thickets on floodplains and on the margins of waterholes, monopolising space and nutrients and preventing access to permanent water by species such as waterbirds and wallabies. It is estimated that mimosa now infests about 800 square kilometres of coastal floodplains across the Northern Territory. The combined pressures of climate change, land use and feral animals may facilitate the growth and spread of this weed (van Dam et al 2008a).

Hymenachne amplexicaulis is an introduced pasture grass that invades permanent waterbodies and seasonally inundated wetlands. Because it is capable of growing in several metres of water, hymenachne can choke waterways sufficiently to prevent water movement and intensify flooding. It forms dense stands that reduce native plant diversity and available habitat for native animals, particularly fish (Ferdinands et al 2005). It can also out-compete important native grasses. *Cabomba caroliniana* is a fully aquatic plant that grows prolifically and is highly invasive. It is present in Darwin River. Its profuse growth ensures that it is able to quickly dominate waterways, and it is a serious problem in irrigation canals and impoundments as well as natural waterways. The plant secretes a sticky mucus around its leaves, which inhibits consumption by herbivorous animals and reduces its value as fish habitat. In dense stands in still waters, it may cause dissolved oxygen levels to fall so low through nocturnal respiration that fish kills occur (due to asphyxiation), although this feature is not restricted to alien aquatic plants. Its potential to disrupt aquatic food webs is extremely high. *Cryptostegia grandiflora* (rubber vine) is a serious pest species that occurs as isolated outbreaks in the Kimberley region and the eastern edge of the Northern Territory but is especially widespread in the Gulf region of Queensland. In Queensland, the Queensland Land Protection (Pest and Stock Route Management) Act 2002 requires landholders to control its spread and abundance. Rubber vine is a vigorous growing shrub whose seeds are spread in waterways. It forms dense, impenetrable thickets along streambanks, preventing stock access to water and reducing riparian biodiversity. From streambanks, it may spread to the surrounding savanna (Doak et al 2004).

Many other weeds have serious impacts on northern Australia's aquatic ecosystems, even though they are not listed as weeds of national significance. These alien plants include water lettuce (*Pistia stratiotes*), para grass (*Urochloa mutica*) and water hyacinth (*Eichorna* *crassipes*). Water hyacinth is of considerable concern as it may quickly establish surface mats that then become the substrate for other weeds, such as para grass. This alien vegetation complex then becomes an impenetrable, stable cover on the water's surface, which can only be dislodged by the very largest of floods. Such mats have been a persistent problem in irrigation areas such as the Burdekin delta and have been shown to depress water quality (Perna and Burrows 2005) and eliminate native fish communities (Perna 2003).

In 2009, five tropical invasive pasture grasses were listed as a key threatening process under the Environment Protection and Biodiversity Conservation Act 1999. Four of these species pose serious threats to inland waters in the region, including para grass and olive hymenachne (*Hymenachne amplexicaulis*), which threaten wetland and floodplain habitats, decreasing native biodiversity. Other weeds have also become a concern in recent years, including the introduced pasture grass gamba grass (*Andropogon gayanus*), Noogoora burr (*Xanthium occidentale*) and the perennial and annual mission grasses (*Pennisetum polystchoin* and *P. pedicellatum*, respectively) (van Dam et al 2008a). Gamba grass and mission grass threaten riparian habitats, monopolising space and increasing fire intensity and risk (Rossiter et al 2003, van Dam et al 2008a).

In contrast to feral animals, which are mostly very widespread across the region, most of the weeds that have serious impacts are not yet so widely distributed. Some are currently quite restricted in distribution. Riparian areas provide an ideal habitat for such species to establish, since they are relatively cool and moist. The spread of weeds from riparian areas is greatly facilitated by the annual dispersal of propagules in floodwaters. Thus riparian areas may act as a staging point for further spread.