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Applying a versatile, comprehensive, attribute-based waterhole classification scheme to ecosystem-based management challenges

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ABSTRACT

Context. Understanding habitat suitability for feral animals across a landscape is important for conservation planning because the spatial and temporal availability of water provides critical limits to native biodiversity and the processes that threaten it. Previous attempts to support management actions on feral pig populations through predictions of population abundance, distribution and seasonal resource constraints have been confounded by a lack of knowledge, classification and mapping of waterholes – which are critical to their survival. **Aims.** In this paper, we aimed to apply a waterhole classification scheme for feral pig management to address gaps in our understanding of water and food availability through space and time, at scales relevant to feral animal movement and resource use. **Methods.** We utilise an attribute-based waterhole classification scheme for ecosystem-based management by defining a waterhole typology of feral pig habitat suitability and applying it spatially. **Key results.** Five attributes (water permanence, predictability of inundation, oceanic influence, dominant vegetation and shading) reflect many of the critical requirements for feral pig habitat in northern Australia. The attributes directly relate to the environmental constraints that exert population and behavioural pressure on feral pigs. These attributes were applied spatially in a specific hierarchy to group waterholes into 21 types. **Conclusions.** A waterhole typology that characterises within the context of their suitability for feral pig populations is foundational for systematic adaptive management and monitoring programs that aim to reduce the impact of threatening processes on freshwater ecosystems. **Implications.** Refining the mapping of important feral pig habitat variables (water and food) will greatly improve modelling approaches that aim to support data-driven management approaches, such as connectivity analysis and estimating population dynamics to inform culling programs. Here we demonstrate a significant increase in overlap with known feral pig distributions using a much smaller mapped effective management area when compared with previous best available spatial products.

Keywords: adaptive management, Australia, classification, feral pigs, habitat, typology, waterholes, wetlands.

Introduction

Freshwater ecosystems provide critical ecosystem services, including cultural, social and economic benefits (Daily *et al.* 2009). Despite an international focus on wetland conservation, freshwater ecosystems are under threat, and lack consistent universal planning, management and reporting frameworks (Acreman *et al.* 2020). This makes it difficult to objectively assess the status and trends in aquatic systems between regions, and to establish universally accepted methods for ecosystem management and monitoring.

With the establishment of market-based instruments for nature-based solutions, it is increasingly important to establish flexible trusted classification schemes that can underpin reporting systems (Farley *et al.* 2010).

Ecosystem-based management is an integrated approach that supports decision making; it considers the range of relationships and interactions within an ecosystem

(Foley et al. 2013), including: human communities as part of an ecosystem; multiple spatial and temporal scales; and the dynamic nature of ecosystems (Price et al. 2009). The principle of ecosystem-based management has been widely applied globally and within Australia (Slocombe 1998; Granek et al. 2010; Fletcher et al. 2011; Kenchington and Hutchings 2012).

Classification systems and/or schemes are often integral to the implementation and success of ecosystem-based management by supporting an understanding of the characteristics of different ecosystems, and by providing a common language from which we can synthesise and consolidate information into practical, ecologically meaningful categories. Typologies extend classification schemes applying hierarchical rules around categories that group similar ecosystems into types for a particular purpose (Aquatic Ecosystems Task Group 2012; Department of Environment and Heritage Protection 2017). Numerous typologies can be applied to the same classification to fulfil different management or research purposes, and not all parts of a classification will be required for each typology. Mapping is produced by the spatial extension of classification using available data, including aerial photography, satellite imagery and ground-based observations (Neldner et al. 2019; Department of Environment and Science 2020b). The clear delineation and separation of classification, typology, and mapping enables a single classification scheme to be used for multiple purposes (including as an a-spatial field identification tool), maximising its potential usefulness and value for ecosystem-based management (Department of Environment and Heritage Protection 2017).

Water resources and associated aquatic ecosystems provide fundamental ecosystem services, and as such are the focus of conservation efforts. Planning for management of water resources is usually completed at a catchment scale, relying on broad wetland categories to define management units. However, from a practical management perspective, management activities are often focused on waterholes within wetlands because individual waterholes hold values that are important to people, animals, plants and ecosystem function (Sheldon et al. 2010).

Waterholes are referred to by many names (e.g. billabongs, lagoons and waterbodies) due to their wide geographic range (Gibling et al. 1998; Jardine et al. 2012), their morphological variability, and presence within different wetland types (Costelloe et al. 2007; Box et al. 2008; Medeiros and Arthington 2008). Waterholes are often a component within a larger wetland, providing important aquatic refugia to enable the persistence of organisms within the landscape during dry periods or droughts, and facilitating their recolonisation of the broader landscape when favourable conditions return (Davis et al. 2002; Sheldon et al. 2010). Understanding the role of waterholes is important for conservation planning because the spatial and temporal availability of water provides critical limits to native biodiversity and the processes that threaten it.

Despite previous attempts to classify waterholes (Knighton and Nanson 2000; Bohnet and Kinjun 2009; Warfe et al. 2011; Davis et al. 2013), a clear and consistent definition and classification system is yet to be widely accepted and adopted, resulting in discrepancies in terminology and confusion within the literature, and presenting a further challenge for management agencies. Recognising this issue, the Queensland Government developed a comprehensive attribute-based classification for waterholes (within Queensland, Australia; Department of Environment and Science 2020a) that can be used for multiple purposes and is consistent and integrated with classification systems used for other aquatic systems. This classification scheme defined waterholes as wetlands 'where water pools in a depression within a landform element at a defined spatial scale' (Department of Environment and Science 2020a). This classification scheme includes attributes defined in the interim National Aquatic Ecosystem Classification Framework (Aquatic Ecosystems Task Group 2012), and 27 additional attributes at the four scales: (1) region; (2) seascape/landscape; (3) habitat; and (4) community (Department of Environment and Science 2020a).

Here we apply this waterhole classification scheme to the challenge of feral animal management and impact assessment in northern Australia. Australia supports some of the largest populations of feral pigs (*Sus scrofa*) in the world that are recognised as a critical threat to biodiversity, biosecurity, and agriculture (Choquenot et al. 1996; Barrios-Garcia and Ballari 2012; Bengsen et al. 2014). Despite the clear and well documented threats and significant public expenditure on management programs, the impacts of feral pigs have remained high (Bengsen et al. 2014; McLeod 2004). Previous attempts to support management planning through predictions of population abundance, distribution, and seasonal resource constraints have been confounded by the spatial and temporal resolution of existing wetland mapping (Froese et al. 2017a), as well as the lack of some spatial features that are critical to their survival. Additionally, impact assessments have been challenging due to a lack of detail in the available mapping, which does not account for natural species turnover across environmental gradients. This spatio-temporal mismatch has made it difficult to separate the impact of feral pigs from the natural variation in wetland biodiversity due to environmental and temporal ecological compositional turnover. It is critically important that the underlying ecological processes are well defined and consistent to adequately assess the impact of management interventions for restoring aquatic habitats.

In this paper we demonstrate the utility of the attribute-based waterhole classification scheme for ecosystem-based management by defining a waterhole typology of feral pig habitat suitability and applying it spatially across the Archer River Basin in Cape York Peninsula, Queensland, Australia (141.871, −13.762). We explore the implications of using this refined spatial product for accurately describing the distribution and abundance of feral pigs.

An accurate and consistent waterhole typology can underpin the development of robust impact monitoring and planning for feral animal management. Feral animal management aims to reduce impacts on natural systems (Negus *et al.* 2019; Nordberg *et al.* 2019), agricultural assets (Bengsen *et al.* 2014), and/or cultural assets (Ens *et al.* 2010). To adequately assess the impacts of management actions, it is important to understand the reference state to develop credible metrics of success. In the context of feral pig management, the presence and type of waterhole and associated resources can be used to predict the abundance and distribution of feral pigs (Froese *et al.* 2017*a*). The density and location of waterhole types that are high value for feral pigs provide a means of quantifying habitat connectivity and likely movement paths, likelihood of re-invasion following control, connectivity between populations for epidemiological models, and limits to breeding success (Froese 2017).

The Archer River catchment covers over 10 000 km^2 and contains approximately 504 km^2 of wetland ecosystems (Department of Environment and Science 2013), including palustrine, estuarine, and riverine systems. The Archer River is characterised by distinct hot, humid, wet summers, and dry winters (Bureau of Meteorology 2016). The Archer River catchment was chosen as a pilot area due to the availability of feral pig data, but the outcomes of this work can be applied in similar ecosystems across Australia and the approach applied globally.

Materials and method

Development of the waterhole typology

A typology of waterholes was developed to support spatio-temporal modelling of seasonal feral pig distribution and their vulnerability to control measures. A critical aspect of this typology is the ability to characterise the late dry season location of freshwater 'refuges' that likely provide habitat for feral pig populations. In northern Australia, these refuges comprise such places as permanent wetlands, river waterholes, and groundwater dependent ecosystems.

In consultation with subject matter experts, attributes in the waterhole classification scheme (Department of Environment and Science 2020*a*) were reviewed for their relevance and usefulness as feral pig habitat. Four attributes were selected for the waterhole typology: (1) water permanence; (2) timing predictability (i.e. reliability of water presence); (3) dominant vegetation; and (4) available shading. These attributes reflect many of the critical requirements for feral pig habitat in northern Australia, which can be simplified to food, water, shade, and protection from threats (Froese 2017). The attributes selected directly relate to the environmental constraints that exert population and behavioural pressure on feral pigs. Feral pigs have few sweat glands and easily overheat, relying on behavioural thermoregulation to limit exposure (Department of Primary Industries and Fisheries 2008). Breeding success is dependent on the availability and abundance of digestible energy and crude protein (Choquenot *et al.* 1996). Feral pigs are omnivorous and opportunists, with 80–95% of their diet consisting of vegetation (reflecting vegetation abundance and availability in the landscape) and opportunistic vertebrate and invertebrate consumption, which is likely to be an important element for breeding success (Choquenot *et al.* 1996; Ross 2009). Froese (2017) indicates that the complementarity and density of habitat with these variables are important for determining feral pig distribution. A new attribute was also identified, oceanic influence on the waterhole. This attribute was incorporated into the waterhole typology to reflect the role of tidal regime in the variability in resource availability, fresh water, and food in intertidal habitats.

Once attributes were selected, experts considered each attribute category and merged categories (Table 1) where the distinction was not relevant for feral pig habitats, that is their usefulness as proxies for predicting temporal habitat suitability. Categories for water permanence and timing predictability were reviewed with permanent and near-permanent categories merged, and intermittent split based on the predictability of water availability. The availability of water in the late dry season can result in greater impacts on the remaining waterholes but also concentrates feral pig populations, which can then be used to plan management responses (Froese 2017). The grass, herb or sedge category in dominant vegetation attribute was further split for the typology to identify preferred feral pig diet (e.g. *Eleocharis* sp. dominated ecosystems from other wetlands in this category), supported by available literature and field data (Choquenot *et al.* 1996; Ross 2009). Three categories were defined for the oceanic influence on the waterhole attribute reflecting the oceanic inundation regime (i.e. daily, monthly, or seasonally).

Subject matter experts then informed the establishment of an attribute hierarchy for the selected attributes that groups waterholes into types for the purpose of feral animal habitat assessment and management. The typology resulted in 21 theoretical waterhole types across northern Australia (Fig. 1).

For each attribute selected for the typology, the suitability of available spatial data was reviewed, including existing ecological data, time-series remote sensing data, and field data. Available spatial data was processed and applied spatially, detailed below, to existing ecosystem data sets to create a spatial model of habitat suitability for feral pigs.

Field data collection

In the 2018 dry season, aerial survey of the Archer River catchment was undertaken to record the point location (latitude and longitude) of 2324 field observations of standing water. Undertaking the survey in the dry season limited the observation of intermittent or ephemeral standing water.

Table 1. Attributes and attribute categories selected for inclusion in the waterhole typology of northern Australia to support feral animal management.

Classification (from Department of Environment and Science 2020a)		Typology	
Attribute	**Category**	**Attribute(s)**	**Category**
Permanence of water	Permanent	Water permanence	Permanent or Near-permanent
	Near-permanent		
	Intermittent		Intermittent
	Ephemeral		
	Unknown		
Timing predictability	Regular (annual)	Timing predictability	Predictable
	Regular (non-annual)		
	Irregular		Un-predictable
	Unknown		
		Oceanic influence on the waterhole	Daily oceanic inundation
			Monthly oceanic inundation
			Seasonal oceanic inundation
Surrounding vegetation	Grass, herb or sedge	Dominant vegetation	Preferred flora species (e.g. *Eleocharis* sp.) dominated ecosystems
			Grass, herb or sedge
	Shrubs		Other (e.g. trees and shrubs)
	Trees		
	Unknown		
Shading	Very high	Shading	High
	High		
	Moderate		
	Low		Low
	Very low		
	Unknown		

Spatial application of the waterhole typology

Five data sets were identified to represent the selected suite of attributes. The following subsections detail the source data, processing, and analysis undertaken to apply each attribute to existing spatially delineated ecosystem data sets. The use of existing aquatic ecosystem data sets as the base geometry, derived from Biodiversity of Remnant Regional Ecosystems (V11.1) and Queensland Wetland Data (V4.0), ensured that ecologically relevant boundaries were used in this analysis. All analysis was undertaken with ESRI ArcGIS® 10.5 (Redlands, California, USA: Environmental Systems Research Institute).

Water permanence and predictability in the landscape

Two data sets were identified to spatially delineate water permanence and predictability: Water Observations from Space product (source: Geoscience Australia) derived from Landsat 5 and 7 satellite imagery obtained between 1987 and 2019, and collected field data. Water Observations from Space contains information on the frequency of water detected in satellite imagery from 1987 to the present. The application of the Water Observations from Space algorithm is limited to the location of large areas of water rather than small or narrow water bodies due to the 30-m spatial resolution of Landsat satellite imagery (United States Geological Survey n.d.). Therefore, complementary field observations as previously outlined were used to provide supplementary information on permanent or near-permanent water in the landscape that was below the spatial resolution of the available satellite imagery time series.

A review of the Water Observations from Space product was undertaken, with reference to field observations of aquatic ecosystems with known water permanence, to identify hydrologically relevant thresholds that translate the count of water observations in the Water Observations from Space product with 'water permanence' attribute categories. A threshold of 30% was applied to the Water Observations from Space data across the whole landscape to identify areas of permanent and near-permanent standing water.

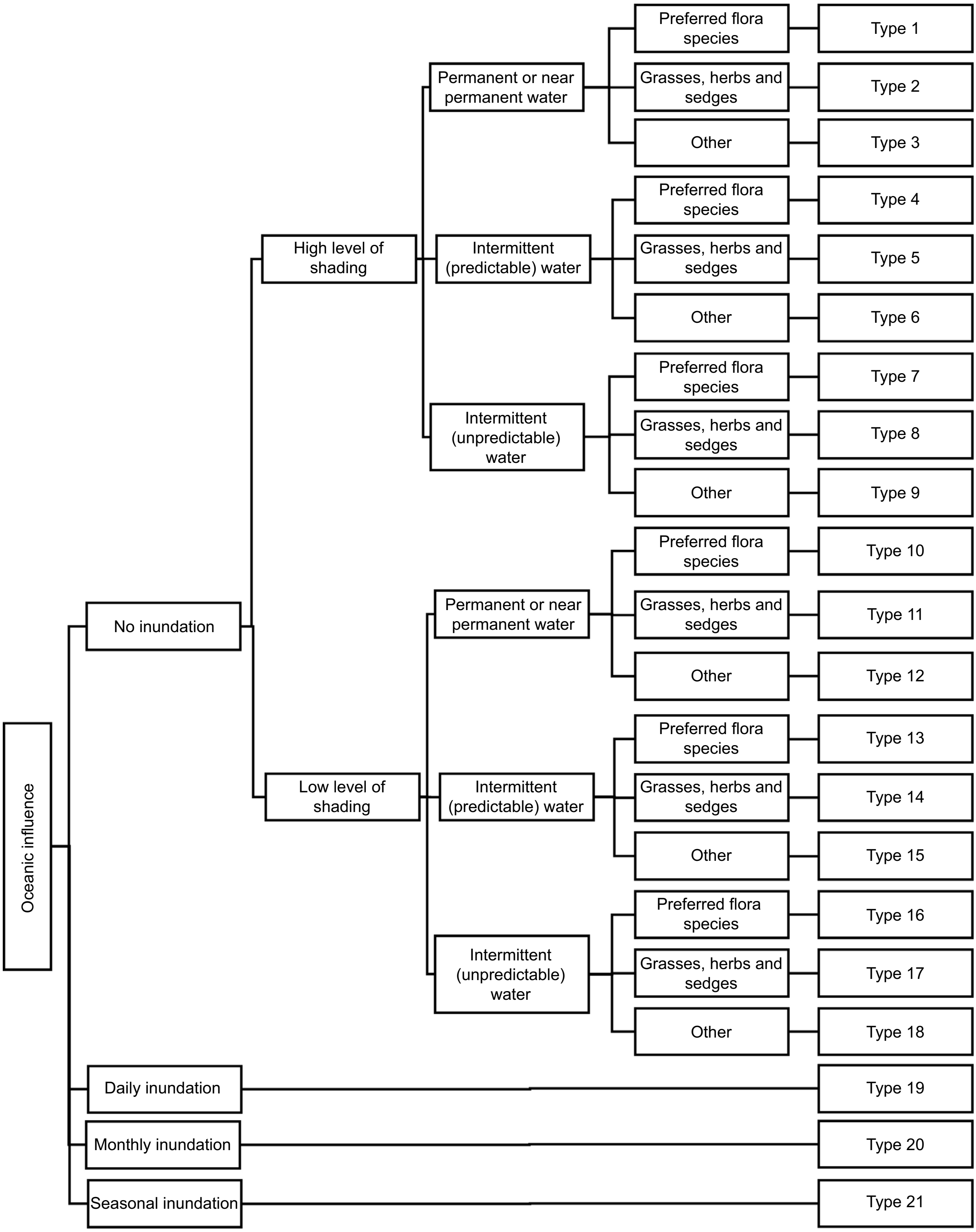

Fig. 1. Hierarchical application of attributes for the waterhole typology of northern Australia to support feral animal management.

A threshold of 5% was also applied to identify areas that feature predictable standing water (>5% and <30%) and unpredictable intermittent standing water (<5%). This reclassified data was then used to attribute available aquatic ecosystem data with summarised information on water permanence. Field observations were integrated in this step, overriding the satellite imagery-derived information with finer scale information. Locations with intermittent, near-permanent, or permanent water identified in the Water Observations from Space product that did not correspond to an existing mapped aquatic ecosystem were visually reviewed and incorporated as new ecosystem features in the base ecological mapping if they met certain thresholds. Generally, these represented aquatic ecosystems currently below the scale of available ecosystem data sets.

Oceanic influence on waterhole habitats

Two existing ecological data sets, Biodiversity of Remnant Regional Ecosystems (V11.1) and Queensland Wetland Data (V4.0), contained information that was used to identify ecosystems subject to periodic tidal inundation as the regime of oceanic influence. These datasets specifically identify those ecosystems where oceanic influence is reflected in the ecology of vegetation communities. Extracted information on tidal inundation was used to attribute available aquatic ecosystem data with summarised information on oceanic influence.

Dominant vegetation

The two ecological data sets, Biodiversity of Remnant Regional Ecosystems (V11.1) and Queensland Wetland Data (V4.0), also contained information that was used to identify the dominant floristics and structure of these aquatic ecosystems. Dominant floristics and structure were extracted from the ecological data sets and used to attribute available aquatic ecosystem data with summarised information on dominant vegetation. These source ecological data sets contain intra-polygon heterogeneity, whereby more than one vegetation community may occur within a defined area. In this case, the precautionary principle was applied with the full extent of an area attributed based on the ecosystem determined to be most floristically preferable for feral pig habitat.

Available shading

Three data sets were used to spatially delineate shading, the two ecological data sets (i.e. Biodiversity of Remnant Regional Ecosystems (V11.1) and Queensland Wetland Data (V4.0)) and Persistent Seasonal Greenness Cover (source: Joint Remote Sensing Research Program with remote sensing groups supporting the Queensland, New South Wales and Victorian governments) derived from Landsat 5, 7 and 8 satellite imagery. The Persistent Seasonal Greenness Cover estimates the 'proportion of vegetation that does not completely senesce within a year, which primarily consists of woody vegetation' (Department of Environment and Science 2021). An expert-specified threshold of 30% shading representing ecological requirements, including thermoregulation (Karfs *et al.* 2009), was applied to the Persistent Seasonal Greenness Cover. The data was vectorised and used to attribute available aquatic ecosystem data with summarised information on available shading. Supplementary information on shading was derived from ecosystem structure in the two ecological data sets based on their associated foliage projective cover per Neldner *et al.* (2019). This supplementary information was integrated with the satellite imagery-derived dataset, resolving any conflicts by attributing the full extent of an area based on which data set was considered to have the most preferable shade conditions for feral pig habitat.

Determination of waterhole types

For each spatially delineated ecosystem, the attributes were used to apply the hierarchical rules (Fig. 1) to assign each with a waterhole type. The presence of all waterholes types were identified in the Archer River (Fig. 2).

Assessment of the spatial application of the waterhole typology

We tested the potential for refining predictive models by comparing the extent and specificity of proxy spatial layers used to parameterise a published feral pig habitat model (Froese *et al.* 2017*a*). Froese *et al.* (2017*a*) modelled changes in extent of feral pig habitat in the wet and dry seasons in northern Australia using expert elicitation to parameterise a Bayesian Belief Network. Spatial layers representing the habitat variables, defined and scored by the expert panel, were derived through the combination of best available spatial data. The derived model variables included proxies for the availability and accessibility of fresh water, availability and quality of food, and extent and density of cover (see Froese *et al.* 2017*a*, supporting information s2.2–s2.6 tables for detailed information on spatial products and categorisation approaches used to derive the variables described above).

Feral pig distribution and abundance data was collected during feral pig management aerial culling events between 2014 and 2018 (Perry *et al.* 2021). Latitude, longitude, species, count, and observer name were collected using the DistanceSampler iPad application (Ver. 1.4–1.5, UgMedia, https://apps.apple.com/app/distance-sampler/id947811415?ign-mpt=uo%3D4) by an independent observer seated directly behind the shooter.

The published habitat suitability index, water quality (dry season) index, food quality (dry season) index and heat quality (dry season) index were downloaded from the supplementary material (Froese *et al.* 2017*b*). Froese *et al.* (2017*a*) also derive a heat quality index, but because the heat quality variable did not greatly influence the model predictions we use the water quality and food quality indices here for comparison. Froese *et al.* (2017*a*) provide thresholds for the water and food indices that indicate areas with very highly suitable late-dry season habitat (i.e. those areas that reflect very good dry season feral pig habitat for food quality, water quality and protection

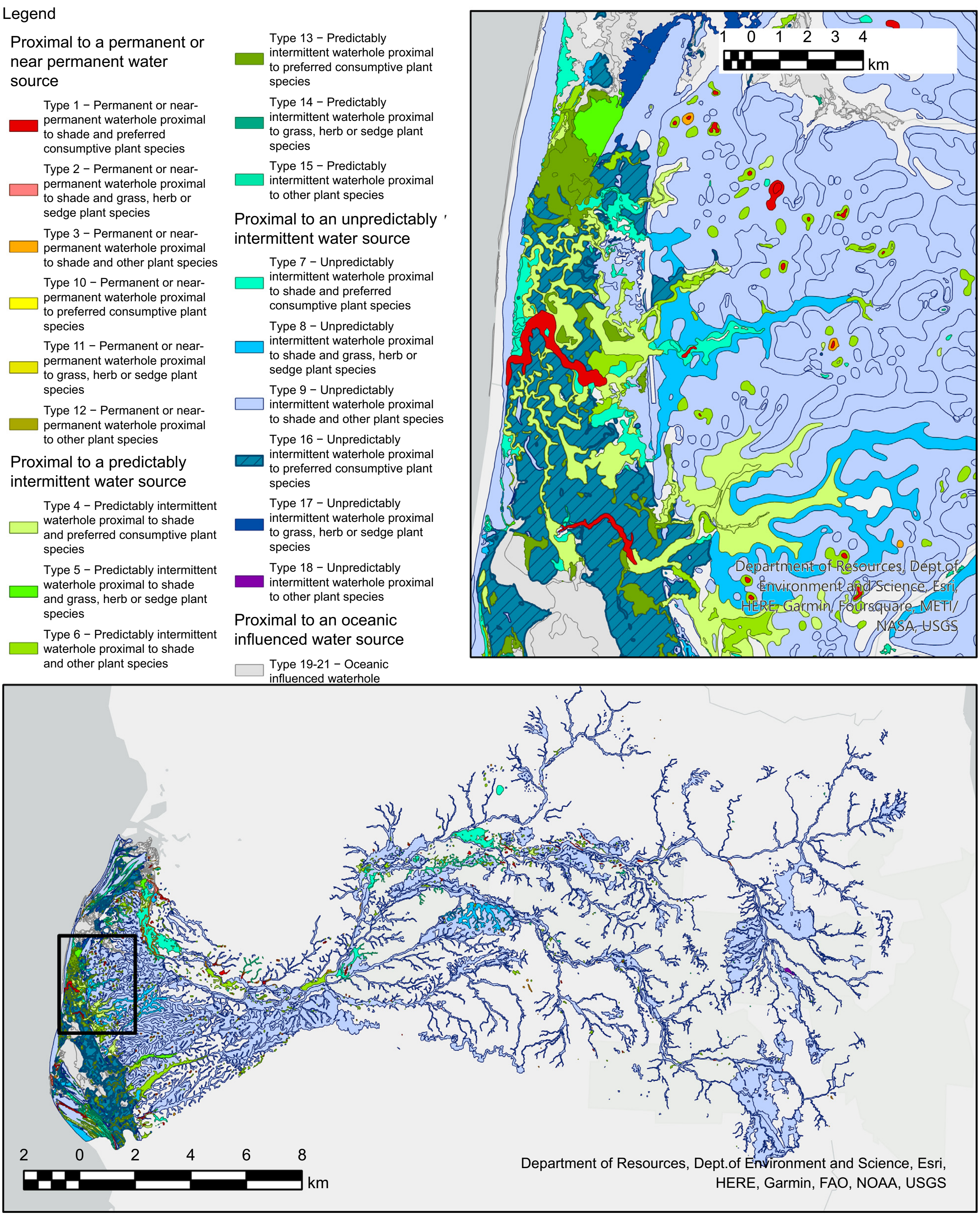

Fig. 2. Outcomes of the spatial application of a waterhole typology for feral pig management in northern Australia.

from heat and disturbance). We explore the potential improvement to the Froese *et al.* (2017*a*) predictions by filtering the waterhole typology mapping for high quality late dry season habitat that using refined classification and mapping products (waterholes with permanent or near-permanent water with nutritious consumptive plant species and proximity to shade). We compare the extent and specificity of the input layers used by Froese *et al.* (2017*a*) with the refined waterhole typology classification. We do this by defining an area of interest that includes feral pig distribution and abundance data (Perry *et al.* 2021) overlapping with the water quality index and food quality index (Froese *et al.* 2017*a*) and the waterhole typology mapping (this paper). The area of interest (141 688 ha) includes woodlands, rivers, floodplains, and coastal dunes to reflect the diversity of landscapes in the region. Within the area of interest, ESRI® ArcMap was used to calculate the total area (hectares) of the published very highly suitable dry season habitat, water quality and food quality index (Froese *et al.* 2017*a*), the total area of the waterhole typology late-dry season categories, the number of intersecting records of feral pigs (count of records) and total pigs observed (sum of recorded abundance). A 250-m and 1-km buffer is applied to the two derived spatial products to account for the movement of feral pigs near high-quality habitat, which can lead to point data falling outside of polygons due to detection errors and induced movement during culling operations. The total area (hectares) for each of the spatial layers is presented along with the number of overlapping pig records to assess the potential for increasing the specificity of predictive models through the refinement of water and food mapping presented here.

Results

The dry season water quality index mapped 18 297 ha of high-quality dry season water and 31 617 ha of high-quality food (Fig. 3, Table 2). The food and water indices were combined with 13 579 ha (10%) of the total area of interest characterised as having both very high habitat value for dry season food and water. In contrast, the waterhole typology method characterised 2% of the area of interest as having both highly suitable food and water, which represented an 8% decrease in the mapped extent of highly suitable pig habitat (Table 2).

When considering overlap with feral pig locations and abundance (Fig. 4), the waterhole typology mapping, without a buffer, overlapped with 30% of total pigs recorded (sum of all pigs including clusters and individual animals) and 34% of the pig groups (point records of sounders). The combined food and water mapping without a buffer overlapped with 35% of the total pigs recorded and 29% of the pig groups (Table 2). The unbuffered food and water mapping accounted for 5% more of the total abundance and overlapped with 5% less of the total encounters. However, the unbuffered combined food mapped 10% of the total area as high-quality food and water compared with only 2% of the total area for the unbuffered waterhole typology approach (Fig. 3). Further, 76% of total abundance overlapped with waterhole types 9, 1, 4, 7, and 6, all of which are waterhole types characterised as close to shade and preferred consumptive plant species (Table 3). 5.47% of total abundance did not overlap with waterhole typology; however, a manual reviewed indicated many of these were close (but not within) mapped waterhole types 1, 3, 4, and 8.

The mapped habitat area was substantially higher for the combined food and water mapping with a 250-m buffer (20%) and 1-km buffer (39%), with the expanded area accounting for 59% (250 m) and 78% (1 km) of total abundance, and 48% (250 m) and 66% (250 m) of total records. The waterhole typology method made substantial gains in specificity, with the 250-m buffer accounting for 67% of the total records and 70% of the total abundance and the 1-km buffer accounting for 87% of total records and 90% of total abundance. This means that with 8% less

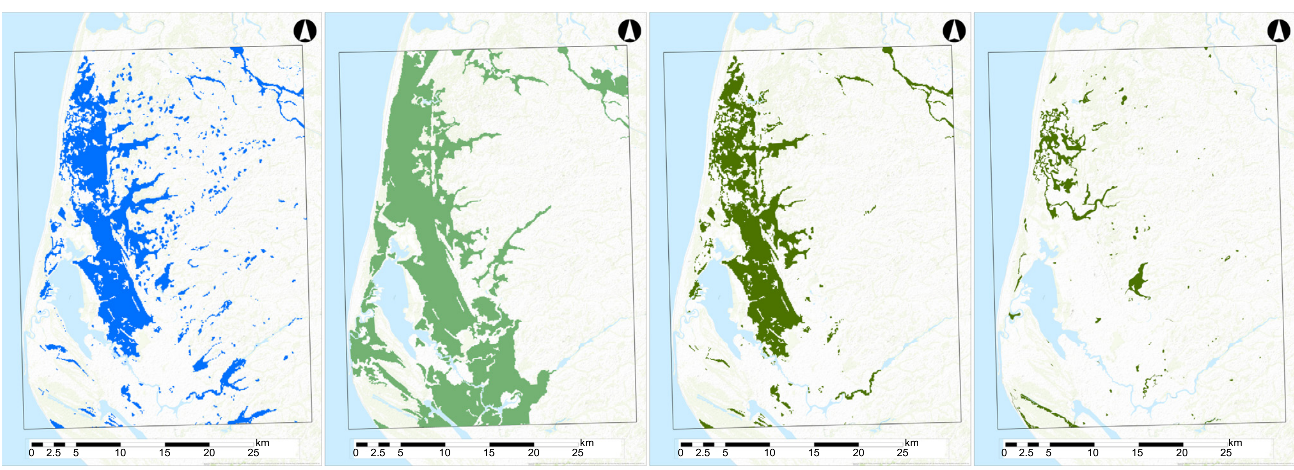

Fig. 3. Map of the underlying habitat classification used to predict very highly suitable habitat in Froese *et al.* (2017*a*). Dry season water quality index (left), Dry season food quality index (second from left), Combined dry season water quality and food quality (third from left) and the waterhole typology mapping presented in this paper (far right).

Table 2. Comparison of area of dry season highly suitable habitat mapped using published habitat suitability index (Froese 2017) and waterhole typology method for the Archer River basin.

Dry season highly suitable habitat	Count of pig records	% of total	Sum of pigs shot	% of total	Ha	% of total
Water quality index					18 297	13
Food quality index					31 617	22
Food and water overlap (no buffer)	74	29	584	35	13 579	10
Food and water overlap (250 m buffer)	121	48	967	59	28 125	20
Food and water overlap (1 km buffer)	167	66	1285	78	54 579	39
Waterhole typology dry season habitat (250-m buffer)	169	67	1149	70	12 798	9
Waterhole typology dry season habitat (1-km buffer)	221	87	1481	90	43 508	31
Waterhole typology dry season habitat (no buffer)	86	34	496	30	3205	2
Area of interest total	**253**	**100**	**1646**	**100**	**141 688**	**100**

Feral pig distribution and abundance overlapping with the published and refined products presented. The waterhole typology categories are buffered by 250 m to reflect the movement of feral pigs near important habitat types for comparing overlapping pig sightings.

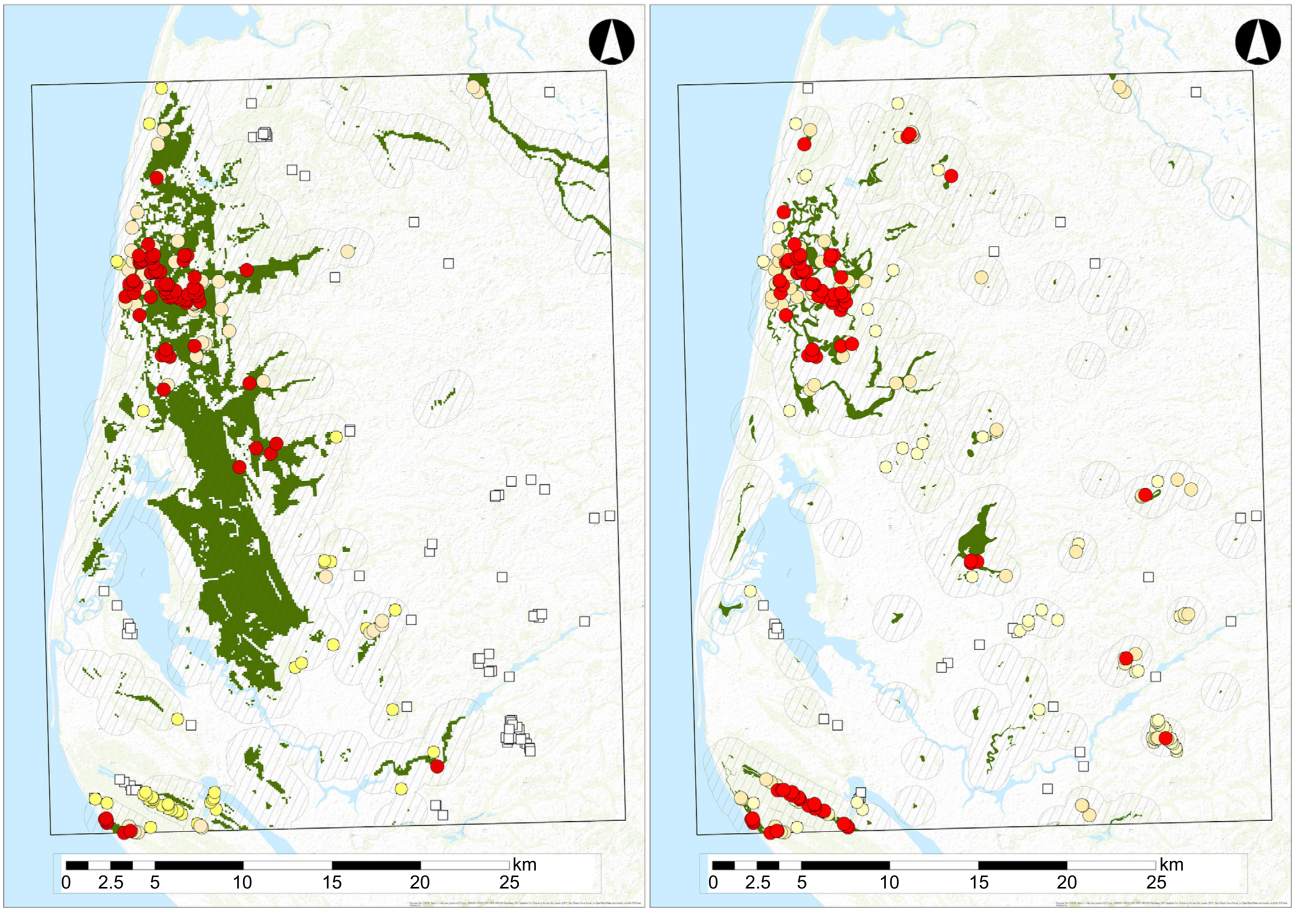

Fig. 4. Comparison of observed feral pig encounters within overlapping areas mapped as very highly suitable feral pig habitat for water quality and food quality (Froese *et al.* 2017*a*; left) and the refined waterhole typology product (right). Red points are feral pig observations within mapped high-quality habitat without a buffer, light orange points are within a 250-m buffer and yellow points are within a 1-km buffer. The 1-km buffer area is highlighted with a grey hashed polygon. Observed feral pig encounters not falling within the mapped preferred habitat are shown with black-bordered white squares.

area mapped, almost all the recorded pigs are within 1 km of the mapped high quality dry season types. When considering the 250-m buffer, the mapped area is far less (only 9% of the total area), and this accounts for 70% of the total abundance

Table 3. Comparison of area of dry season highly suitable habitat mapped using waterhole typology method for the Archer River basin.

Waterhole type	Count of pig records	% of total pig records
9 – Unpredictably intermittent waterhole proximal to shade and other plant species	399	24.24
1 – Permanent or near-permanent waterhole proximal to shade and preferred consumptive plant species	288	17.50
4 – Predictably intermittent waterhole proximal to shade and preferred flora species	222	13.49
7 – Unpredictably intermittent waterhole proximal to shade and preferred consumptive plant species	202	12.27
6 – Predictably intermittent water source proximal to shade and other plant species	140	8.51
16 –Unpredictably intermittent waterhole proximal to preferred consumptive plant species	104	6.32
8 – Unpredictably intermittent waterhole proximal to shade and grass, herb or sedge plant species	68	4.13
3 – Permanent or near-permanent waterhole proximal to shade and other plant species	41	2.49
13 –Predictably intermittent waterhole proximal to preferred flora species	41	2.49
5 – Predictably intermittent waterhole proximal to shade and grass, herb or sedge plant species	1	0.06
19–21 – Oceanic influenced waterhole	50	3.04
None	90	5.47
Total	1646	100.00

Feral pig distribution and abundance overlapping with the products presented.

and 67% of the total records. The waterhole typology method identified small refugial waterholes in woodland areas (such as in the western area of the area of interest) that are not picked up using the higher-level wetland categories underlying the published habitat suitability index mapping (Fig. 3).

Discussion

We developed and applied a waterhole typology to characterise different waterholes within the context of their suitability for feral pig populations. The outcomes of this work, including a waterhole typology for feral pig management and a spatial data set of habitat suitability, addressed a gap in our understanding of water and food availability through space and time, at scales relevant to feral animal movement and resource use. The results expanded on existing wetland mapping to synthesise spatio-temporal information on food, water, shade, and protection from threats into a spatial data set of the distribution of 21 waterhole types. These data can then be used to inform public expenditure on management programs including selection of appropriate management interventions to restore aquatic habitats.

This work used the existing attribute-based waterhole classification scheme (Department of Environment and Science 2020*a*), demonstrating the importance of classification schemes in the implementation and success of ecosystem-based management by providing a common language from which to synthesise available information and characterise ecosystem types for a particular purpose. This classification scheme was sufficiently flexible to support its application to a specific ecosystem-based management issue through the lumping of attribute categories, with the addition of new attributes where required.

The spatial application of the waterhole typology was limited by the availability of relevant data. For example, the attribute 'slope' was selected by subject matter experts as relevant to feral pig habitat with steeper edges around waterhole restricting feral pig access. However, insufficient spatial data were available at an appropriate scale to enable its inclusion in the mapping. A similar issue was encountered with water permanence; however, the finer-scale aerial surveys undertaken provided supplementary data to the existing available satellite imagery.

The developed waterhole typology can be applied at multiple scales depending on the availability of data. The resolution of the generated spatial data set of waterhole habitat suitability presented in this paper was limited by the scale of input data sets, including ecological data sets and satellite imagery. All remote sensing-derived data used were developed based on Landsat 5 and 7 satellite imagery with a resolution of 30 m. The underlying ecological data used are developed from extensive field survey, analysis of aerial photographs, satellite imagery and detailed site data, and assessment of other data (such as geology and soil mapping, and historical survey plans; Neldner *et al.* 2019). Available ecological data (such as the Biodiversity of Pre-Clearing and Remnant Regional Ecosystems), upon which to build and apply the waterhole classification scheme, are extremely valuable for simplifying and streamlining the process. The positional accuracy of these input data – mapped at a scale of 1:100 000 – is 100 m; therefore, this scale constraint applies to all derived products, and the generated spatial data set can be used to guide selection of target areas for management interventions. However, its use should be supported by an assessment of high-resolution imagery to determine the specific location of feral pig habitat within the mapped area at a scale relevant to on-ground feral animal control actions.

By refining the mapping of seasonality and function of wetlands at fine spatial scales we observe a substantial reduction in the mapped extent of high value habitat for feral pigs and connectivity in the late dry season. This is important when considering feral pig management in large remote areas where resources and access are limited. The waterhole typology approach described here can be used to underpin systematic adaptive management and monitoring programs that aim to reduce the impact of threatening processes on freshwater ecosystems.

Published predictive models of feral pig distribution have been limited by coarse mapping that was a poor predictor of water persistence and food quality. Here we demonstrate potential improvements in the specificity of feral pig distribution mapping through the refinement of environmental variables that account for ecological function. This method can also be used to support more accurate impact assessments, by providing a method for the systematic monitoring of elements of biodiversity associated with waterhole types likely to be impacted by feral pigs or other threatening processes.

The availability of food and water spatially contracts throughout the dry season, augmenting the value of late dry season refugial wetland waterholes at landscape scales. This is important for connectivity analysis that aims to identify discrete management units and reinvasion pathways. The refinement of the mapping using typologies has demonstrated the potential to reduce the effective management planning area by 55%.

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Data availability. The data that support this study are available in the Queensland Spatial Catalogue at https://qldspatial.information.qld.gov.au/catalogue/, Terrestrial Ecosystem Research Network at https://www.tern.org.au/, and the Water Observations from Space web services at https://nationalmap.gov.au/.

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