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Supplementary material

Defining the importance of ecological processes for monitoring aquatic habitats for conservation and rehabilitation objectives at the Ranger uranium mine, Kakadu Region, Australia

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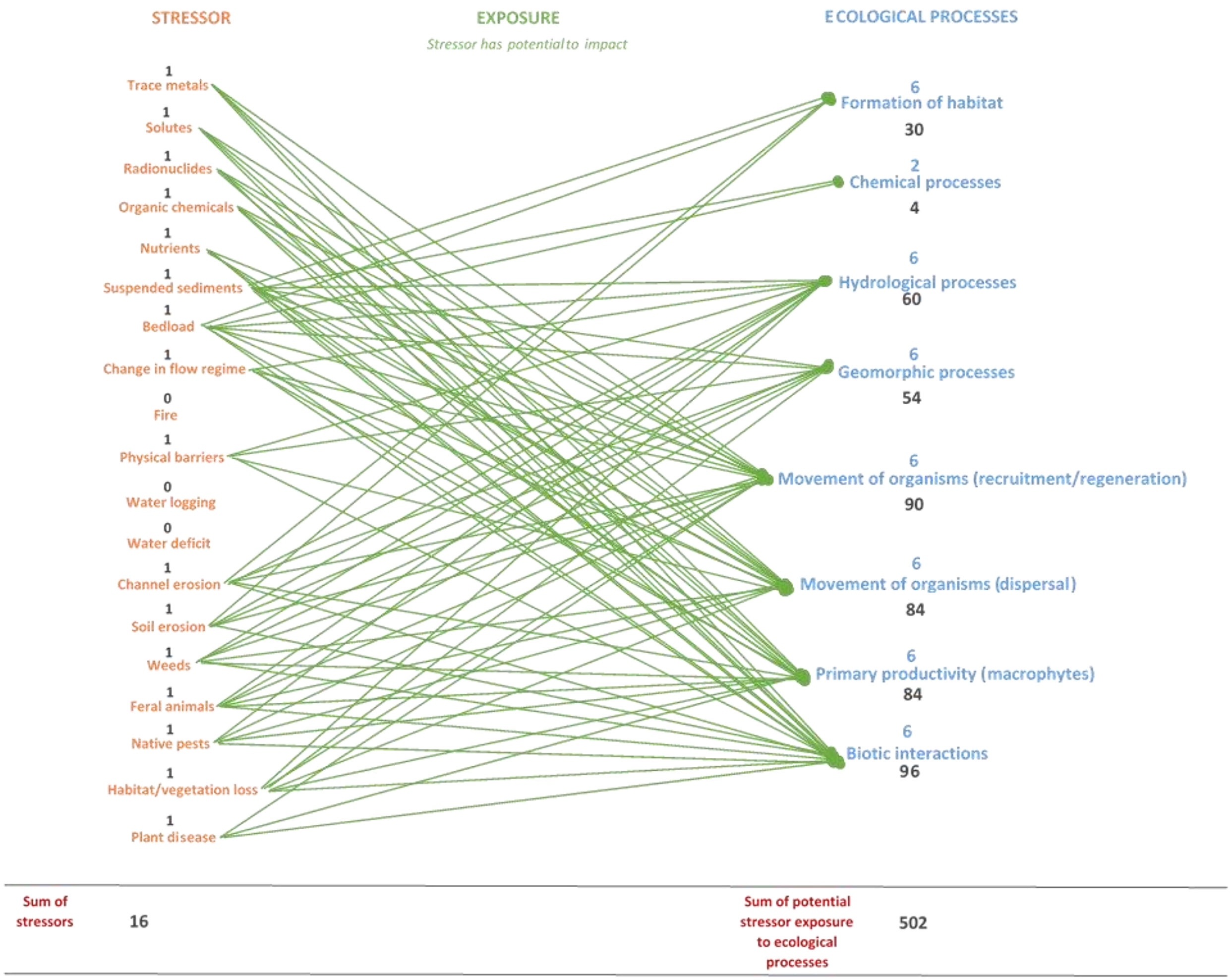

Fig. S1. Example conceptual model, showing exposure of ecological processes to stressors for the sandy creek-channel habitat during the wet season.

Fig. S2. Location of habitats.

Fig. S3. Stone country: riffle rock-pool sequence spanning 10.5 km from Bowerbird Billabong upstream to Magela Creek Falls.

Fig. S4. Stone country: riffle rock-pool sequence spanning 1.5 km at Radon Springs.

Fig. S5. Stone country: riffle rock-pool sequence spanning 1 km of the upper south arm of the Magela Creek.

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Fig. S6. Stone country: Bowerbird Billabong (photos: Mike Saynor).

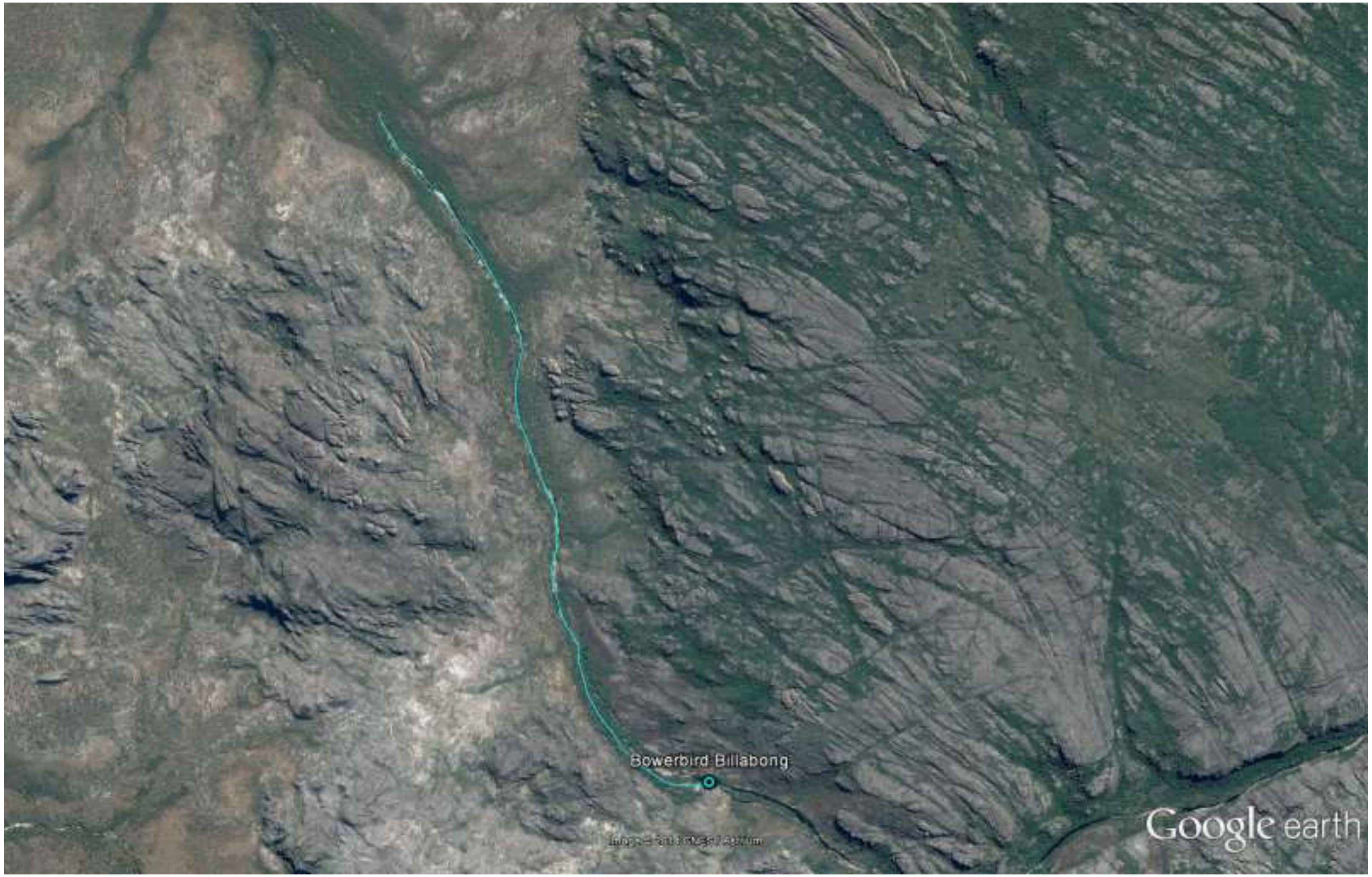

Fig. S7. Stone country: sandy creek channels downstream of Bowerbird Billabong.

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Fig. S8. Shallow lowland billabongs (backflow billabongs): Georgetown Billabong (photos: Duncan Buckle). April 2009 (top), October 2009 (bottom).

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Fig. S9. Shallow lowland billabongs (backflow billabongs): Coonjimba Billabong (photo: Mike Saynor).

Fig. S10. Shallow lowland billabongs (backflow billabongs): Gulungul Billabong.

Fig. S11. Shallow lowland billabongs (backflow billabongs): Gurndurrk (Corndorl) Billabong.

Fig. S12. Shallow lowland billabongs (backflow billabongs): Wirrnmuyurr Billabong.

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Fig. S13. Shallow lowland billabongs (backflow/channel billabongs): Baralil Billabong.

Fig. S14. Permanent waterbody (channel billabongs).

Fig. S15. Permanent waterbody (channel billabongs): Mudginberri Billabong (photo: Linda Da Costa).

Fig. S16. Permanent waterbody (channel billabongs): Buffalo Billabong.

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Fig. S17. Permanent waterbody (floodplain billabongs): Jabiluka Billabong.

Fig. S18. Riparian *Melaleuca*-dominated forest (Magela Creek Crossing).

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Description of aquatic habitats

Stone country

The stone country refers to the (predominantly) quartz sandstone-exposed portions of the Arnhem Land Plateau and its outliers. Aquatic habitats in the stone country include small seeps and springs, waterfalls, rock pools and watercourses of permanent flow classified as channel or escarpment rock pools by Walker and Tyler (1984), of Kombolgie Formation. The permanent surface waters are important refugia for aquatic organisms (see also Humphrey *et al*. 2017).

Sandy creek channels

The sand channel between the stone country and Mudginberri Billabong flows for typically 6–7 months of the year. In the upper portions of this sand channel, there are creek pools that persist in the dry season but the vast remainder of the sandy creek channel downstream usually dries out completely for a few months of the mid–late dry season. The sandy channel is a key breeding and feeding zone for freshwater fishes in the wet season, transports macroinvertebrates downstream for recolonisation of the channel during the wet season and is the conduit for two-way energy flow in Magela Creek, viz. fish migrations and downstream transport of other carbon and nutrient sources during the period of creek flow (Humphrey *et al*. 2017).

Shallow lowland billabongs

The shallow lowland billabongs are generally intermittent, and some may dry out each year, or be reduced to very shallow pools of poor water quality. For this reason, the billabongs are not significant refugial sites at a landscape scale (Humphrey *et al*. 2017). Very often, shallow lowland billabongs are of the 'backflow' type, because during high-flow periods in the wet season, water from the main creek (and tributary) backs up in the tributary where the billabong is located, by overtopping the sandy levee separating the tributary from the creek. Shallow lowland billabongs tend to have zones of dense macrophytes colonising the shallow littoral zones, which senesce as the water level drops after the wet season.

Permanent waterbodies

The permanent waterbodies contain water all year and can be grouped into channel, channel–floodplain and floodplain permanent waterbodies. These habitats were identified as key dry-season refugia for aquatic biota by Humphrey *et al*. (2017). The permanent waterbodies are located on both the lowlands and the seasonally inundated flood basins. Channel billabongs are found in the lowlands and are located within the alluvial sandy drainage lines. They have uniform good water quality in both the dry and wet seasons (in particular, low turbidity and generally high dissolved oxygen concentrations). Floodplain billabongs are located on relictual

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meandering channels of Magela Creek floodplain and during the wet season, these are subsumed by the flood waters to become part of the inundated floodplain. These billabongs have dissolved oxygen suppression at certain times of the year, and high primary production, whereas most show an increase in turbidity as the dry season progresses.

Seasonally inundated floodplain

The seasonally inundated Magela Creek floodplain is a coastal floodplain characterised by its cracking clays. Due to the drying and wetting of large areas of the floodplain, the habitats and vegetation in this environment are very dynamic, with areas drying out over the course of the dry season. As a result, these habitats are controlled largely by inundation and depth (microtopography; Finlayson *et al*. 1989). The route of first flow for the Magela Creek floodplain is shown in Fig. S19, available as Supplementary material for this paper. Humphrey *et al*. (2017) estimated that the surface waters remaining on Magela floodplain by the end of the dry season, including in channel, floodplain and floodplain billabongs, and 'backswamp' areas on the edges of the floodplains, constituted over 95% of those in Magela Creek system. This collective zone, therefore, constitutes important refugia for aquatic organisms.

As with other tropical floodplain systems, regular seasonal inundation and drying of the Magela floodplain is a major driver of ecological processes, including the substantial increases in primary productivity that support higher trophic groups in food webs, return of subsidies to all components of the broader creek system and enhanced biodiversity (Junk *et al.* 1989, Pettit *et al*. 2011, Bunn *et al*. 2015).

The seasonally inundated floodplain is a complex mosaic of the following aquatic plant communities: *Eleocharis*; *Hymenachne*; *Leerisa*; *Melaleuca* open forest; *Melaleuca* woodland; *Nelumbo*; *Oryza*; para grass; *Pseudoraphis*; *Pseudoraphis* and *Hymenachne*; and *Salvinia.*

Upper floodplain

The upper floodplain extends downstream of Mudginberri Billabong to just north of Nankeen Billabong. This area is dominated by *Melaleuca* woodland, *Pseudoraphis* and *Pseudoraphis* and *Hymenachne*. The *Melaleuca* woodlands can remain inundated for long periods of time.

The upper floodplain is a depositional zone in the context of geomorphic processes. In comparison to the whole floodplain, there are more geochemical processes occurring in the upper floodplain because the gradient of the creek is reduced and chemicals fall out, as depicted in strong radiochemical signals used as markers in this part of the floodplain (Murray *et al*. 1993). The lower floodplain in contrast is an erosional zone.

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Lower floodplain

The lower floodplain extends from north of Nankeen Billabong to the coast. It is an erosional zone compared with the depositional zone of the upper floodplain. This landscape is structurally dominated by grasslands and sedgelands and has large 'backswamp' areas on the edges of the floodplain.

*Riparian (*Melaleuca*-dominated forest)*

These are the *Melaleuca*-dominated woodlands and forest of the lowlands upstream of the floodplain that predominantly fringe creek lines, but are also located on the floodplain fringes.

Lowland woodlands

The eucalypt-dominated lowland woodlands occupy the deeply weathered and eroded Koolpinyah surface. Over the dry season, the groundwater table can fall between 2–4 m, which is recharged as wet-season rainfall commences McQuade *et al*. (1996). A perched water table forms as the wet season continues, and results in surface runoff during intense rainfall events. During the dry season, the surface soils dry out and fires become prevalent, fuelled by the grassy understorey. The lowland woodlands are the source of significant infiltration of rainfall to groundwaters and host groundwater-dependent ecosystems for this region. Potential long-term impacts to groundwater have been highlighted for the area.

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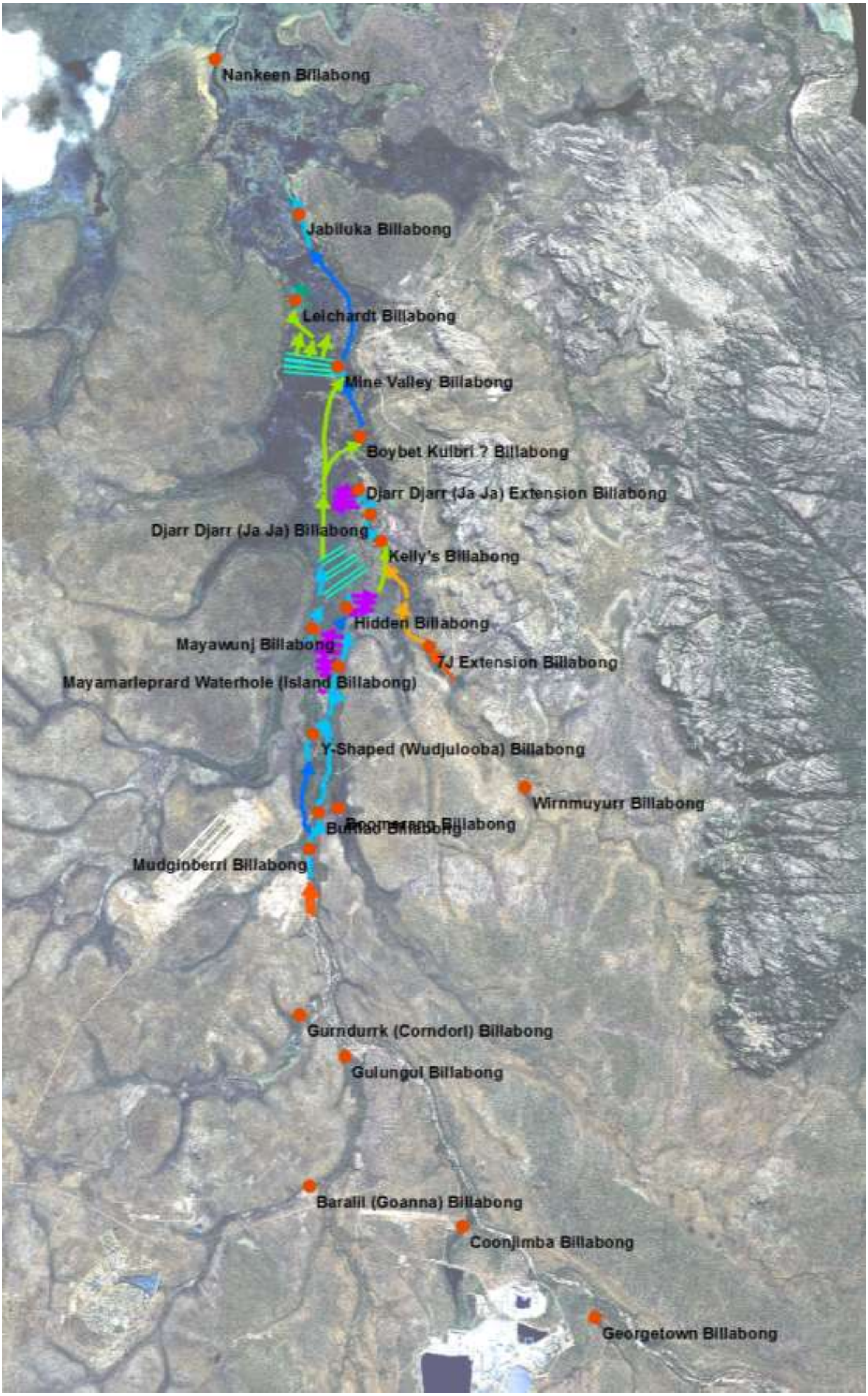

Fig. S19. Magela Creek first flow.

Table S1. Importance ranking of ecological processes across habitats during the dry season

Process type	Description	Sandy channel	Shallow lowland billabong	Permanent waterbody (channel)	Permanent waterbody (floodplain)	Upper floodplain	Lower floodplain	Lowland woodlands	Riparian	Stone country
Abiotic ecological processes	Formation of habitat	1	3	3	3	3	3	3	3	3
	Chemical processes	1	3	1	3	3	3	1	3	1
	Hydrological processes	2	2	1	1	3	3	1	3	1
	Natural disturbance: fire	2	3	1	1	3	3	3	3	3
	Natural disturbance: cyclone	1	1	1	1	1	1	1	1	1
	Natural disturbance: drought	1	3	1	1	3	3	1	3	1
	Natural disturbance: flood	1	1	1	1	1	1	1	1	1
	Geomorphic processes	1	1	1	1	1	1	1	1	1
Biotic ecological processes	Movement of organisms: recruitment and regeneration	2	2	2	2	2	2	3	2	3
	Movement of organisms: dispersal	1	2	2	2	2	2	2	2	2
	Primary productivity: macrophytes	1	3	3	3	3	3	2	3	2
	Predation, herbivory, competition, parasitism, mutualism	3	3	3	3	3	3	3	3	3

Table S2. Importance ranking of ecological processes across habitats during the wet season

Process	Description	Sandy channel	Shallow lowland billabong	Permanent waterbody (channel)	Permanent waterbody (floodplain)	Upper floodplain	Lower floodplain	Lowland woodlands	Riparian	Stone country
Abiotic ecological processes	Formation of habitat	3	2	2	2	3	3	3	3	3
	Chemical processes	1	1	1	1	2	2	1	3	1
	Hydrological processes	3	3	2	2	3	3	1	3	1
	Natural disturbance: fire	1	1	1	1	1	1	2	3	2
	Natural disturbance: cyclone	3	2	1	1	1	1	3	3	1
	Natural disturbance: drought	1	1	1	1	3	3	1	3	1
	Natural disturbance: flood	3	1	3	1	1	1	1	3	3
	Geomorphic processes	3	2	3	1	1	1	1	2	2
Biotic ecological processes	Movement of organisms: recruitment and regeneration	3	3	3	3	3	3	3	3	3
	Movement of organisms: dispersal	3	3	3	3	3	3	3	3	3
	Primary productivity: macrophytes	3	3	3	3	3	3	2	3	2
	Predation, herbivory, competition, parasitism, mutualism	3	3	3	3	3	3	3	3	3

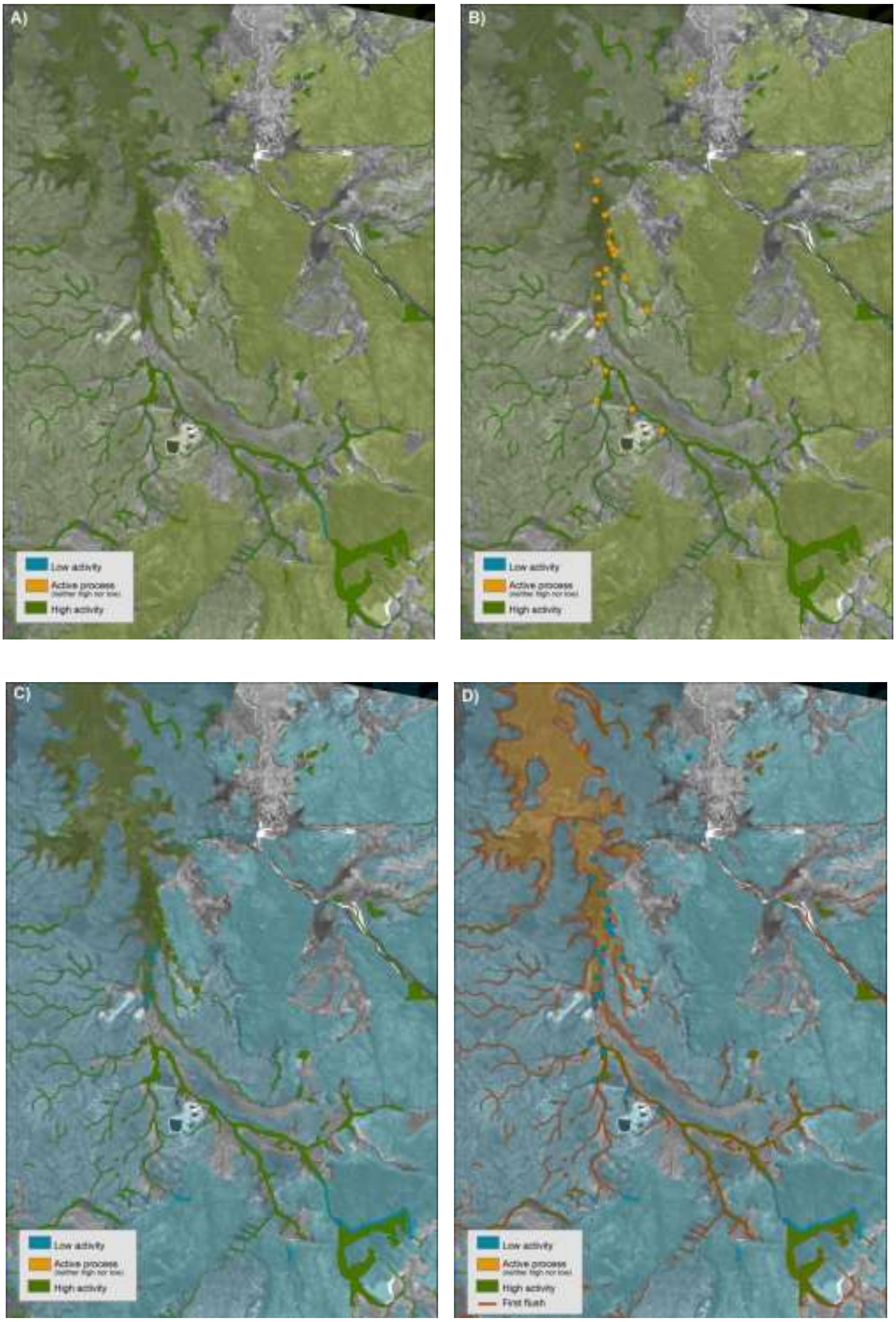

Fig. S20. Habitat rankings for ecological process, showing seasonal differences in importance of processes. (*a*) Formation of habitat (dry); (*b*) formation of habitat (wet); (*c*) chemical processes (dry); (*d*) chemical processes (wet); (*e*) hydrological processes (dry); (*f*) hydrological processes (wet); (*g*) fire (dry); (*h*) fire (wet); (*i*) cyclone (dry); (*j*) cyclone (wet); (*k*) drought (dry); (*L*) drought (wet); (*m*) flood (dry); (*n*) flood (wet); (*o*) geomorphic processes (dry); (*p*) geomorphic processes (wet); (*q*) recruitment and regeneration (dry); (*r*) recruitment and regeneration (wet); (*s*) dispersal (dry); (*t*) dispersal (wet); (*u*) primary productivity: phytoplankton (dry); (*v*) primary productivity: macrophytes (wet).

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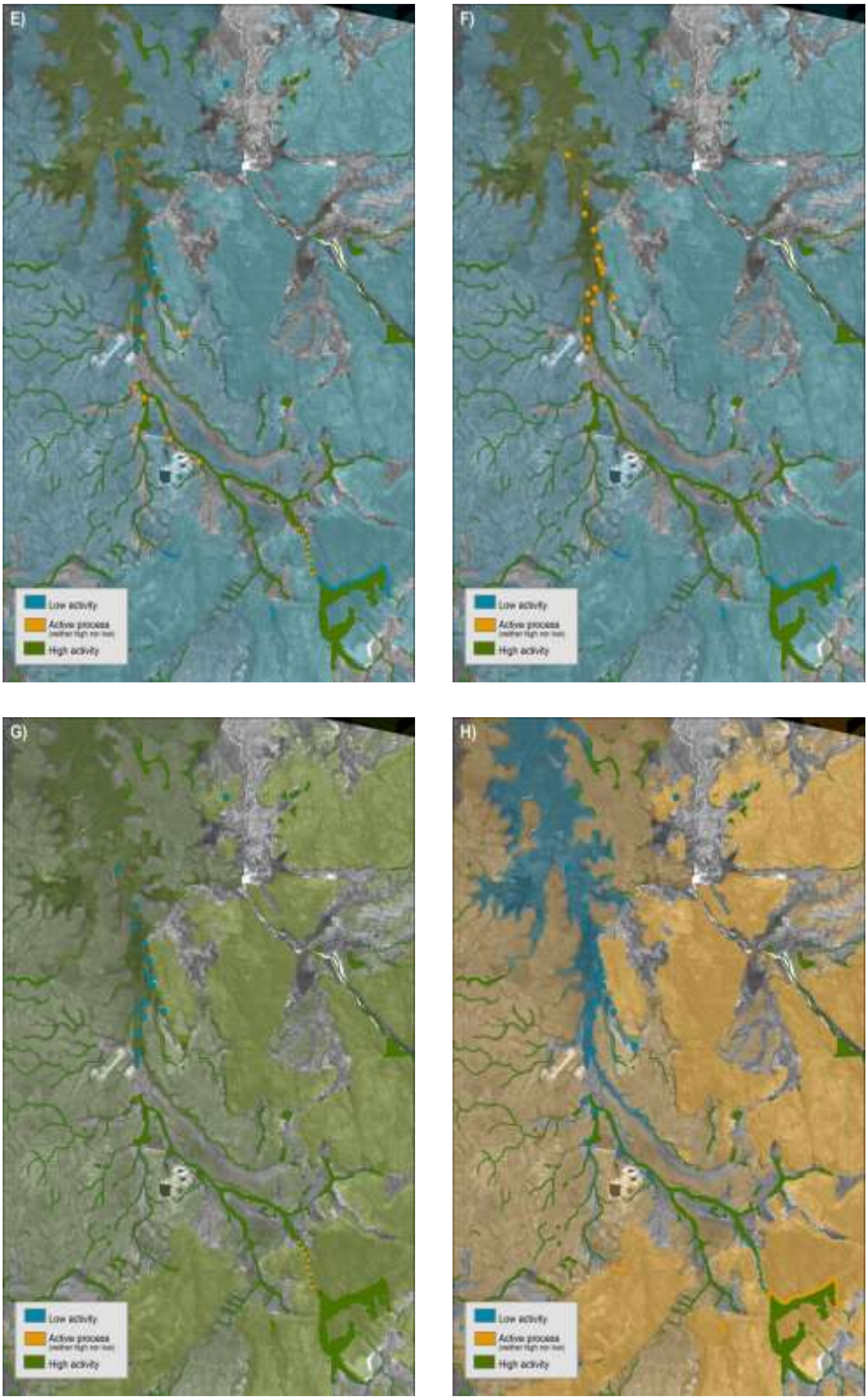

Fig. S20. *(Cont.)*

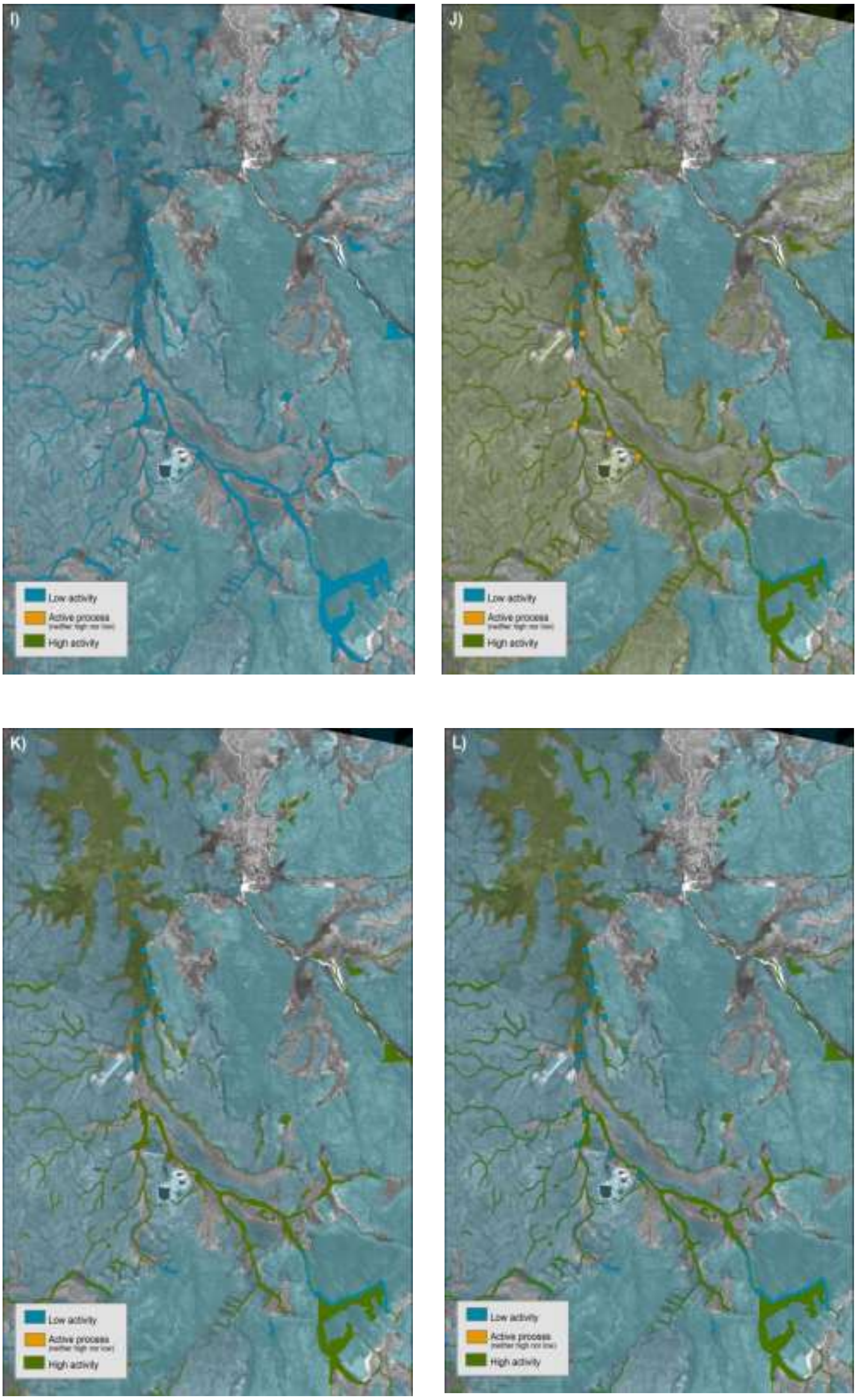
I)
Low activity
Active process
High activity
J)
Low activity
Active process
High activity
K)
Low activity
Active process
High activity
L)
Low activity
Active process
High activity

Fig. S20. *(Cont.)*

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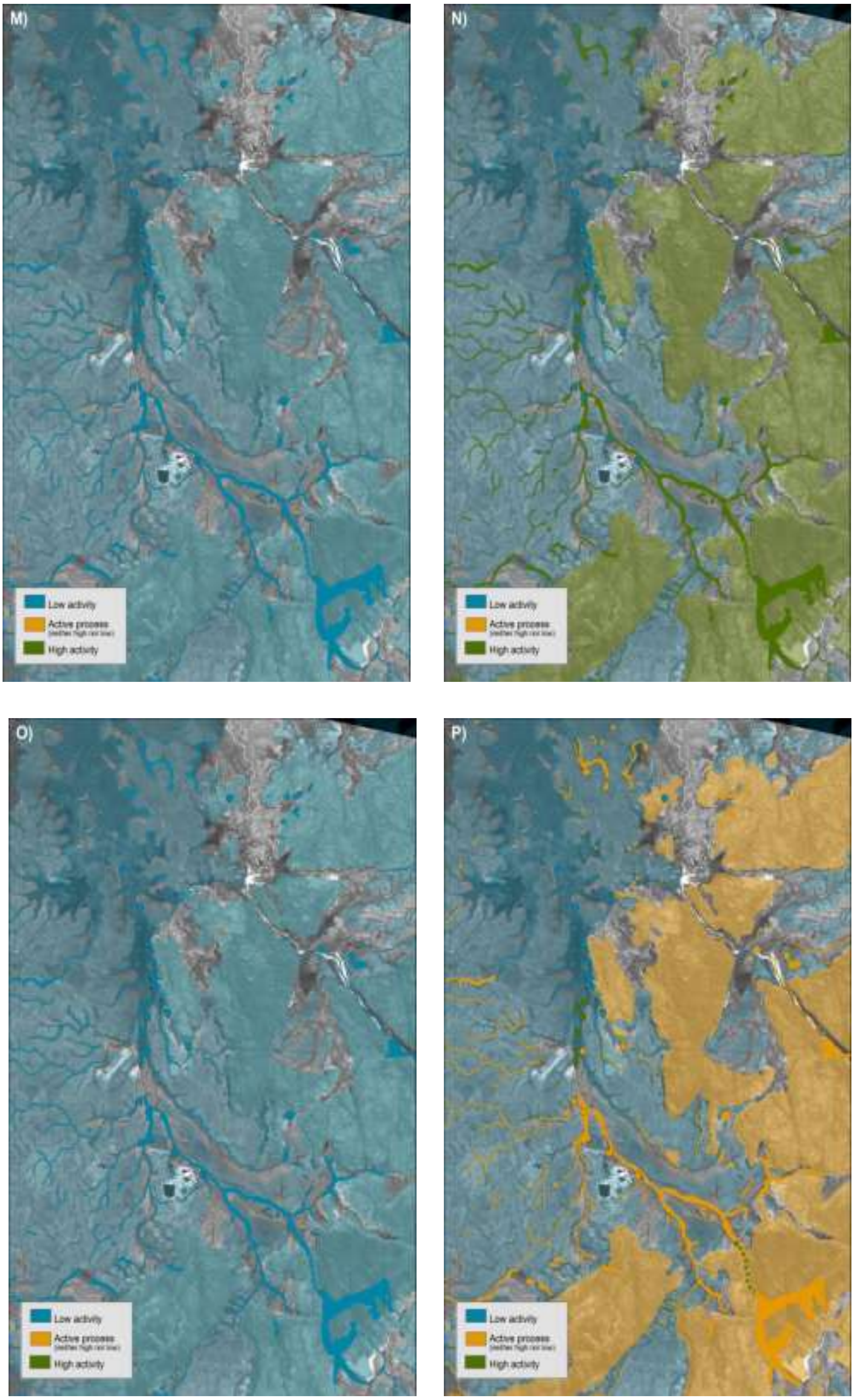

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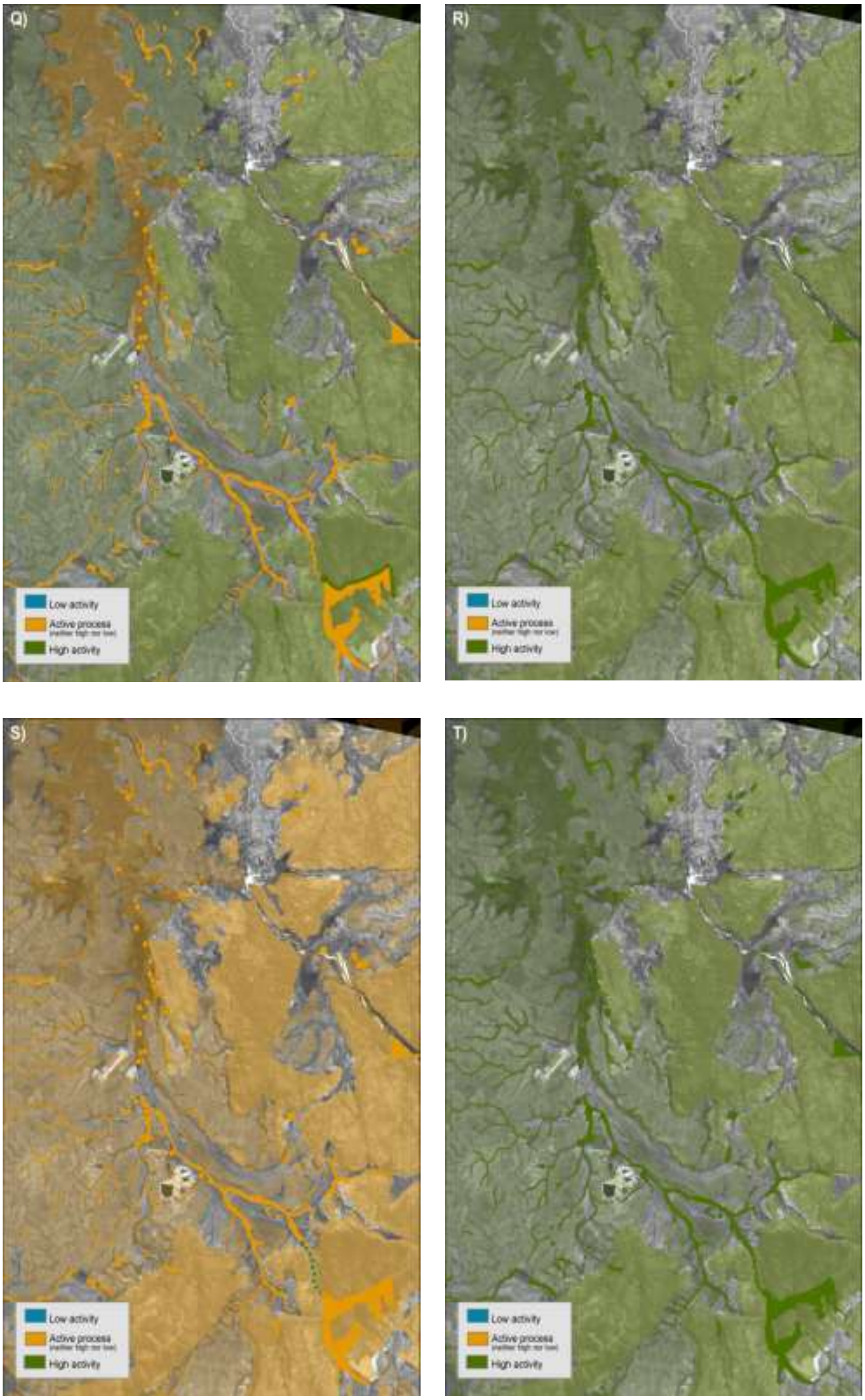

Fig. S20. *(Cont.)*

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Fig. S20. *(Cont.)*

Table S3. Dry-season assessment of potential stressor impacts on habitats

Process type	Parameter	Sandy channel	Shallow lowland billabong	Permanent waterbody (channel)	Permanent waterbody (floodplain)	Upper floodplain	Lower floodplain	Lowland woodlands	Riparian	Stone country
Abiotic ecological processes	Formation of habitat	3	2	2	2	3	3	3	3	3
	Stressor	Physical (B1, B2, B8, B9), biological (C1–C4)	Physical (B1–B3, B8, B9), biological (C1–C4)	Biological (C1, C2)	Biological (C1, C2)	Physical (B1, B3, B5, B8, B9), biological (C1, C2, C4)	Biological (C1, C2)	Chemical (A1–A5), physical (B2, B3, B6 (onsite)), biological (C1–C5)	Chemical (A1–A5), physical (B8–B9), biological (C1–C5)	
	Chemical processes	1	1	1	1	2	2	1	3	1
	Stressor	Physical (B1,B2)	Chemical (A1, A2. A5), physical (B1–B3), biological (C1)					Physical (B1–B3,B5, B8-B9), biological (C1, C2, C4)	Chemical (A1, A2), physical (B6, B7), biological (C2)	
	Hydrological processes	3	3	2	2	3	3	1	3	1
	Stressor	Physical (B1–B3, B5, B8, B9), biological (C1–C4)	Physical (B1–B3, B5, B8, B9), biological (C1–C4)	Physical (B1, B2)				Physical (B8, B9), biological (C1, C2, C4)	Physical (B1–B3, B5 B8, B9), biological (C1, C2, C4)	
	Geomorphic processes	3	2	3	1	1	1	1	2	2
	Stressor	Physical (B1–B3, B5, B8, B9),	Physical (B1–B3, B5, B8, B9),			Physical (B1–B3, B5, B8, B9),		Physical (B1–B3, B5, B8, B9),	Physical (B1–B3, B5, B8, B9),	

Process type	Parameter	Sandy channel	Shallow lowland billabong	Permanent waterbody (channel)	Permanent waterbody (floodplain)	Upper floodplain	Lower floodplain	Lowland woodlands	Riparian	Stone country
		biological (C1, C2, C4)	biological (C1, C2, C4)			biological (C1, C2, C4)		biological (C1, C2, C4)	biological (C1, C2, C4)	
Biotic ecological processes	Movement of organisms: recruitment and regeneration	3	3	3	3	3	3	3	3	3
	Stressor	Chemical (A1–A5), physical (B1–B3, B8-B9), biological (C1–C5)	Chemical (A1–A5), physical (B1–B3, B8-B9), biological (C1–C5)			Physical (B1–B3, B5, B8, B9), biological (C1, C2, C4)		Chemical (A1–A5), physical (B1–B3, B8, B9), biological (C1–C5)	Chemical (A1–A5), physical (B1–B3, B8, B9), biological (C1–C5)	
	Movement of organisms: dispersal	3	3	3	3	3	3	3	3	3
	Stressor	Chemical (A1-A5), physical (B1-B3, B5), biological (C1-C5)	Chemical (A1-A5), physical (B1-B3, B5), biological (C1-C5)			Physical (B3, B5), biological (C1-C4)		Chemical (A1-A5), physical (B3, B5), biological (C1-C5)	Chemical (A1-A5), physical (B2-B3, B5), biological (C1-C5)	
	Primary productivity: macrophytes	3	3	3	3	3	3	2	3	2
	Stressor	Chemical (A1–A5), physical (B1–B3, B8), biological (C1–C4)	Chemical (A1–A5), physical (B1–B3, B8), biological (C1–C4)			Physical (B3), biological (C1–C4)		Chemical (A1–A5), physical (B6, B7 (onsite), B9), biological (C1–C5)	Chemical (A1–A5), physical (B2, B6, B7 (onsite), B8, B9), biological (C1–C5)	

Process type	Parameter	Sandy channel	Shallow lowland billabong	Permanent waterbody (channel)	Permanent waterbody (floodplain)	Upper floodplain	Lower floodplain	Lowland woodlands	Riparian	Stone country
	Predation, herbivory, competition, parasitism, mutualism	3	3	3	3	3	3	3	3	3
	Stressor	Chemical (A1–A5), Physical (B1–B3, B5, B8, B9), Biological (C1–C5)	Chemical (A1–A5), Physical (B1–B3, B5, B8, B9), Biological (C1–C5)			Physical (B1–B3, B5, B8, B9), Biological (C1–C4)		Chemical (A1–A5), Physical (B1–B3, B5, B8, B9), Biological (C1–C5)	Chemical (A1–A5), Physical (B1–B3, B5, B8, B9), Biological (C1–C5)	

Table S4. Wet-season assessment of potential stressor impacts on habitats

Process	Parameter	Sandy channel	Shallow lowland billabong	Permanent waterbody (channel)	Permanent waterbody (floodplain)	Upper floodplain	Lower floodplain	Lowland woodlands	Riparian	Stone country
Abiotic ecological processes	Formation of habitat	3	2	2	2	3	3	3	3	3
	Stressor	Physical (B1, B2, B8, B9), biological (C1–C4)	Physical (B1–B3, B8, B9), biological (C1–4C)	Biological (C1–C2)	Biological (C1, C2)	Physical (B1, B3, B5, B8, B9), biological (C1, C2, C4)	Biological (C1,C 2)	Chemical (A1–A5), physical (B2, B3, B6 (onsite)), biological (C1–C5)	Chemical (A1–A5), physical (B8, B9), biological (C1–C5)	
	Chemical processes	1	1	1	1	2	2	1	3	1
	Stressor	Physical (B1, B2)	Chemical (A1, A2, A5), physical (B1–B3), biological (C1)					Physical (B1–B3, B5, B8, B9), biological (C1, C2, C4)	Chemical (A1, A2), physical (B6, B7), biological (C2)	
	Hydrological processes	3	3	2	2	3	3	1	3	1
	Stressor	Physical (B1–B3, B5, B8, B9), biological (C1–C4)	Physical (B1–B3, B5, B8, B9), biological (C1–C4)	Physical (B1, B2)				Physical (B8, B9) Biological (C1, C2, C4)	Physical (B1–B3, B5, B8, B9), biological (C1, C2, C4)	
	Geomorphic processes	3	2	3	1	1	1	1	2	2
	Stressor	Physical (B1–B3, B5, B8, B9), biological (C1, C2, C4)	Physical (B1–B3, B5, B8, B9), biological (C1, C2, C4)			Physical (B1–B3, B5, B8, B9), biological (C1, C2, C4)		Physical (B1–B3, B5, B8, B9), biological (C1, C2, C4)	Physical (B1–B3, B5, B8, B9), biological (C1, C2, C4)	

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Process	Parameter	Sandy channel	Shallow lowland billabong	Permanent waterbody (channel)	Permanent waterbody (floodplain)	Upper floodplain	Lower floodplain	Lowland woodlands	Riparian	Stone country
Biotic ecological processes	Movement of organisms: recruitment and regeneration	3	3	3	3	3	3	3	3	3
	Stressor	Chemical (A1–A5), physical (B1–B3, B8, B9), biological (C1–C5)	Chemical (A1–A5), physical (B1–B3, B8, B9), biological (C1–C5)			Physical (B1–B3, B5, B8, B9), biological (C1, C2, C4)		Chemical (A1–A5), physical (B1–B3, B8, B9), biological (C1–C5)	Chemical (A1–A5), physical (B1–B3, B8, B9), biological (C1–C5)	
	Movement of organisms: dispersal	3	3	3	3	3	3	3	3	3
	Stressor	Chemical (A1–A5), physical (B1–B3, B5), biological (C1–C5)	Chemical (A1–A5), physical (B1–B3, B5), biological (C1–C5)			Physical (B3, B5), biological (C1–C4)		Chemical (A1–A5), physical (B3, B5), biological (C1–C5)	Chemical (A1–A5), physical (B2, B3, B5), biological (C1–C5)	
	Primary productivity: macrophytes	3	3	3	3	3	3	2	3	2
	Stressor	Chemical (A1–A5), physical (B1–B3, B8), biological (C1–C4)	Chemical (A1–A5), physical (B1–B3, B8), biological (C1–C4)			Physical (B3), biological (C1–C4)		Chemical (A1–A5), physical (B6, B7 (onsite), B9), biological (C1–C5)	Chemical (A1–A5), physical (B2, B6, B7 (onsite), B8, B9), biological (C1–C5)	

Process	Parameter	Sandy channel	Shallow lowland billabong	Permanent waterbody (channel)	Permanent waterbody (floodplain)	Upper floodplain	Lower floodplain	Lowland woodlands	Riparian	Stone country
	Predation, herbivory, competition, parasitism, mutualism	3	3	3	3	3	3	3	3	3
	Stressor	Chemical (A1–A5), physical (B1–B3, B5, B8, B9), biological (C1–C5)	Chemical (A1–A5), physical (B1–B3, B5, B8, B9), biological (C1–C5)			Physical (B1–B3, B5, B8, B9), biological (C1–C4)		Chemical (A1–A5), physical (B1–B3, B5, B8, B9), biological (C1–C5)	Chemical (A1–A5), physical (B1–B3, B5, B8, B9), biological (C1–C5)	

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