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Supplementary material

An integrated risk-assessment framework for multiple threats to floodplain values in the Kakadu Region, Australia, under a changing climate

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S1. Supporting methods, tables, figures and analyses 2
- S1.1. Assessment and measurement endpoints used in the integrated risk assessment (IRA) of threats from invasive species to freshwater-floodplain natural and cultural values 2
- S1.2. Quantification of measurement endpoints in Table S1 used in the integrated risk assessment for the present-day, 2070 and 2100 sea level-rise scenarios 3
- S1.3. Uncertainty analyses for the 2070 and 2100 sea level-rise (SLR) scenarios 7
- S1.4. Use of Bayesian belief networks (BBNs) to undertake integrated risk assessments (IRAs) and to set risk-management targets 8
- S1.5. Parameterisation of invasive species bioeconomic control models, Kakadu National Park (KNP) 12
- S1.6. Invasive-species management scenarios examined in the integrated risk assessment–Bayesian belief network (IRA–BBN) framework for freshwater floodplain habitats 15
- S1.7. Conceptual Bayesian belief network (BBN) model of the integrated risk assessment (IRA) framework with management nodes for invasive species (para grass and pigs), and summary of scenario simulations (Figs S5, S6, Table S4) 16
- S1.8. Assessing structural uncertainty in the Kakadu socio-ecological system (SES) model using qualitative modelling (QM) methods 18

S2. Climate change and tourism 22

References 27

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S1. Supporting methods, tables, figures and analyses

S1.1. Assessment and measurement endpoints used in the integrated risk assessment (IRA) of threats from invasive species to freshwater-floodplain natural and cultural values

Table S1. Assessment and measurement end points used in the integrated risk assessment (IRA; and associated uncertainty analyses) of invasive-species impacts on magpie goose seasonal habitats and Indigenous cultural hunting and fishing sites in Kakadu National Park

Pig damage and para grass-cover data are from 2009 park-wide surveys (Boyden *et al*. 2008; Bayliss *et al*. 2012). See Eqns 1–3 in the main paper for calculation of measurement endpoints when combining ≥2 risk factors. SLR, sea level-rise

	Assessment end point	Measurement end point
Values	Extent of all floodplains in KNP (present-day SLR, 2013)	Area of freshwater and saline floodplain habitats
	Extent of freshwater floodplains in KNP	Area of freshwater floodplain habitats
Pmgws	Magpie goose wet-season nesting colonies (Pmgws)	Area hotspot GiBws ≥2 (95% CI)[A]
Pmgds	Magpie goose dry-season feeding refuges (Pmgds)	Area hotspot GiBds ≥1 (95% CI)[B]
Ph	Hunting and fishing sites on freshwater floodplains (Ph)	Proportion of freshwater floodplain area used
Threats	*Pigs*	
	Extent of pig damage on freshwater floodplains	Area where pig damage occurs
Pp (≥0)	Risk pig damage: intensity (percentage cover) in extent (+0s)	Pp ≥ 0: mean percentage cover pig damage
Pp (>0)	Risk of pig damage: intensity (percentage cover) adjusted for area (>0s)	Pp > 0: mean percentage cover pig damage > 0%
Pmgws	Risk of pig damage to goose wet-season nesting habitats	Pp & Pmgws overlap: Ppmgws
Pmgds	Risk of pig damage to goose dry-season feeding habitats	Pp & Pmgds overlap: Ppmgds
Ppmg	Combined risk of pig damage to both magpie goose habitats[C]	Ppmg = Ppmgds × Ppmgws – (Ppmgds × Ppmgws)
Pph	Risk of pig damage to hunting–fishing sites	Pp & Ph overlap: Pph
	Para grass	
	Extent para grass on freshwater floodplains	Area where para grass occurs
Ppg (>0)	Risk of para grass: intensity of percentage cover in extent (+0s)	Ppg ≥ 0: mean percentage cover para grass

	Assessment end point	Measurement end point
Ppg (>0)	Risk of para grass: intensity of percentage cover adjusted for area (>0s)	Ppg > 0: mean percentage cover para grass > 0%
Ppgmgws	Risk of para cover to goose wet-season nesting habitats	Ppg & Pmgws overlap: Ppgmgws
Ppgmgds	Risk of para cover to goose dry-season feeding habitats	Ppg & Pmgds overlap: Ppgmgds
Ppgmg	Combined para grass risk to both goose habitats[C]	Ppgmg = Ppgmgds × Ppgmgws – (Ppgmgds × Ppgmgws)
Ppgh	Risk of para grass to hunting–fishing sites	Ppg & Ph overlap: Ppgh
	Combine[C]	
Pimg	Combined invasive-species risk to magpie goose habitats	Pimg = Ppmg + Ppgmg – (Ppmg × Ppgmg)
Pih	Combined invasive-species risk to hunting–fishing sites	Pih = Pph + Ppgh – (Pph × Ppgh)
Pimgh	Combined risk to goose habitats and hunting–fishing sites	Pimgh = Pimg + Pih – (Pimg × Pih)

[A]GiBws (≥2) and [B]GiBds (≥1) are long-term magpie goose nesting and dry-season feeding 'hotspot' sites identified by Bayliss and Ligtermoet (2018) using a Getis-Ord Gi* test statistic (percentage *z* score significant at 95%, after Getis and Ord 1992).

[C]The risk probabilities of ≥2 factors were combined using Eqns 2 and 3 (after Bayliss *et al*. 2011, 2012).

S1.2. Quantification of measurement endpoints in Table S1 used in the integrated risk assessment for the present-day, 2070 and 2100 sea level-rise scenarios

Table S2. Sea level-rise scenarios for present-day (2009–2013) 2070 and 2100

Summary of the quantitative metrics used to characterise floodplain attributes and risk profiles (exposure probability, *P*) of those attributes for each assessment and measurement endpoint used in the integrated risk assessment (mean *P* ± s.d.; *N* of spatial cells in the 2.7-km grid; and the probability density function, pdf). Data were derived for each grid cell (n = 610) from GIS maps. BestFit software (Palisade 2002, 2010) was used to parameterise pdfs used in uncertainty analysis. FW, freshwater floodplain; see Table S1 for definitions of other variables

Parameter	Assessment end point	Measurement end point (km^2)	Area (km^2)	Percentage freshwater	Mean *P*	s.d.	*n* (cells)	*P* (pdf)	BestFit	Notes
2009–2013										
Values	Area of floodplain, Kakadu National Park		2285							
	Area of freshwater floodplain		1998	87						
	Magpie goose wet-season nesting colonies (Pmgws)	Area of hotspot GiBws ≥ 2	318	16	0.744	0.021	66	0.700	Logistic	GiBws HS index re-scaled 0–1
	Magpie goose dry-season feeding refuges (Pmgds)	Area of hotspot GiBds ≥ 1	309	15	0.891	0.113	90	0.858	Logistic	GiBds HS index re-scaled 0–1
	Hunting and fishing FW sites 2009 (Ph)	Area of FW floodplain used	1109	56	0.561					
Threats	*Pigs (2009)*									

Parameter	Assessment end point	Measurement end point (km^2)	Area (km^2)	Percentage freshwater	Mean *P*	s.d.	*n* (cells)	*P* (pdf)	BestFit	Notes
	Extent of pig damage on freshwater floodplains	Area where pig damage occurs	1110	56						
	Intensity of pig damage (percentage cover) on freshwater floodplains	Pp ≥0: mean percentage cover pig damage			0.090	0.151	610	0.090	Exponential	
	Intensity of pig damage (percentage cover) on freshwater floodplains	Pp > 0: mean percentage cover pig damage of >0%			0.192	0.171	287	0.187	Exponential	
	Pig damage to goose wet-season nesting habitats	Pp & Pmgws overlap: Ppmgws			0.039	0.095	66	0.039	Exponential	
	Pig damage to goose dry-season feeding habitats	Pp & Pmgds overlap: Ppmgds			0.135	0.148	90	0.132	Exponential	
	Combined pig damage to goose habitats	Ppmg = Ppmgds × Ppmgws – (Ppmgds × Ppmgws)			0.169			0.166		
	Pig damage to hunting–fishing sites	Pp & Ph overlap: Pph	643	58	0.112	0.160	307	0.111	Exponential	
	Para grass (2009)									
	Extent of para grass on freshwater floodplains	Area where para grass occurs	262	13						
	Intensity of para grass cover on freshwater floodplains	Ppg ≥ 0: mean percentage cover para grass			0.014	0.048	610	0.014	Exponential	
	Intensity para grass cover freshwater floodplains	Ppg > 0: mean percentage cover para grass > 0%			0.106	0.085	82	0.105	Exponential	
	Para grass damage to goose wet-season nesting habitats	Ppg & Pmgws overlap: Ppgmgws			0.014	0.038	66	0.014	Exponential	
	Para grass damage to goose dry-season feeding habitats	Ppg & Pmgds overlap: Ppgmgds								Does not exist
	Combined para damage to goose habitats	Ppgmg = Ppgmgds × Ppgmgws –(Ppgmgds × Ppgmgws)			0.014			0.014		
	Para grass damage to hunting–fishing sites	Ppg & Ph overlap: Ppgh	270	24	0.014	0.054	307	0.014	Exponential	
	Combined (2009)									
	Combined invasive-species risk to magpie goose habitats	Pimg = Ppmg + Ppgmg – (Ppmg × Ppgmg)			0.180			0.178		
	Combined invasive-species risk to hunting–fishing sites	Pih = Pph + Ppgh – (Pph × Ppgh)			0.124			0.124		
	Combined risk to goose habitats and hunting sites	Pimgh = Pimg + Pih – (Pimg × Pih)			0.282			0.280		
2070										
Values	Area of freshwater floodplain		1190	52						
	Magpie goose wet-season nesting colonies (Pmgws)	Area of hotspot GiBws ≥ 2	147	12	0.907	0.108	75	0.875	Logistic	GiBws HS index re-scaled 0–1
	Magpie goose dry-season refuge (Pmgds)	Area of hotspot GiBds ≥ 1	234	20	0.698	0.215	33	0.667	Uniform	GiBds HS index re-scaled 0–1
	Hunting–fishing freshwater sites 2009 (Ph)	Area of freshwater floodplain used	791	66	0.664					
Threats	*Pigs*									
	Extent of pig damage on freshwater floodplains	Area where pig damage occurs	1110	52						
	Intensity of pig damage (percentage cover) on freshwater floodplains	Pp ≥ 0: mean percentage cover pig damage			0.079	0.136	382	0.079	Exponential	
	Intensity of pig damage (percentage cover) on freshwater floodplains	Pp > 0: mean percentage cover pig damage > 0%			0.164	0.156	183	0.162	Exponential	

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Parameter	Assessment end point	Measurement end point	Area (km^2)	Percentage freshwater	Mean *P*	s.d.	*n* (cells)	*P* (pdf)	BestFit	Notes
	Pig damage to goose wet-season nesting habitats	Pp & Pmgws overlap: Ppmgws			0.011	0.036	33	0.011	Exponential	
	Pig damage to goose dry-season feeding habitats	Pp & Pmgds overlap: Ppmgds			0.133	0.152	75	0.131	Exponential	
	Combined pig damage to goose habitats	Ppmg = Ppmgds × Ppmgws – (Ppmgds × Ppmgws)			0.143			0.141		
	Pig damage to hunting–fishing sites	Pp & Ph overlap: Pph	429	54	0.096	0.148	233	0.096	Exponential	
	Para grass									
	Extent of para grass on freshwater floodplains	Area where para grass occurs	299	25						
	Intensity of para grass cover on freshwater floodplains	Ppg ≥ 0: mean percentage cover para grass			0.013	0.051	382	0.011	Exponential	
	Intensity of para grass cover freshwater floodplains	Ppg > 0: mean percentage cover para grass > 0%			0.073	0.101	67	0.093	Exponential	
	Para grass damage to goose wet-season nesting habitats	Ppg & Pmgws overlap: Ppgmgws			0.029	0.050	33	0.028	Exponential	
	Para grass damage to goose dry-season feeding habitats	Ppg & Pmgds overlap: Ppgmgds								Does not exist
	Combined para grass damage to goose habitats	Ppgmg = Ppgmgds × Ppgmgws –(Ppgmgds × Ppgmgws)			0.029			0.028		
	Para grass damage to hunting–fishing sites	Ppg & Ph overlap: Ppgh	256	32	0.019	0.062	233	0.019	Exponential	
	Combined									
	Combined invasive-species risk to magpie goose habitats	Pimg = Ppmg + Ppgmg – (Ppmg × Ppgmg)			0.167			0.164		
	Combined invasive-species risk to hunting–fishing sites	Pih = Pph + Ppgh – (Pph × Ppgh)			0.113			0.113		
	Combined risk to goose habitats and hunting sites	Pimgh = Pimg + Pih × (Pimg × Pih)			0.262			0.259		
2100										
Values	Area of freshwater floodplain		818	36						
	Magpie goose wet-season nesting colonies (Pmgws)	Area of hotspot GiBws ≥ 2	0.2	0.2	0.907	0.105	19	0.899	Extreme value	GiBws HS index re-scaled 0–1
	Magpie goose dry-season refuge (Pmgds)	Area of hotspot GiBds ≥ 1	9.4	1.1	0.698	0.515	2	n.a.	n.a.	Not enough samples for pdf
	Hunting–fishing freshwater sites 2009 (Ph)	Area of freshwater floodplain used	263	33	0.664	2.630				
Threats	*Pigs*									
	Extent of pig damage on freshwater floodplains	Area where pig damage occurs	1110	52						
	Intensity of pig damage (percentage cover) on freshwater floodplains	Pp ≥ 0: mean percentage cover pig damage			0.056	0.109	188	0.056	Exponential	
	Intensity of pig damage (percentage cover) on freshwater floodplains	Pp > 0: mean percentage cover pig damage > 0%			0.115	0.132	92	0.114	Exponential	
	Pig damage to goose wet-season nesting habitats	Pp & Pmgws overlap: Ppmgws								Does not exist
	Pig damage to goose dry-season feeding habitats	Pp & Pmgds overlap: Ppmgds			0.004	0.018	19	0.004	Exponential	
	Combined pig damage to goose habitats	Ppmg = Ppmgds × Ppmgws – (Ppmgds × Ppmgws)			0.004			0.004	Exponential	
	Pig damage to hunting–fishing sites	Pp & Ph overlap: Pph	429	54	0.065	0.127	114	0.014	Exponential	

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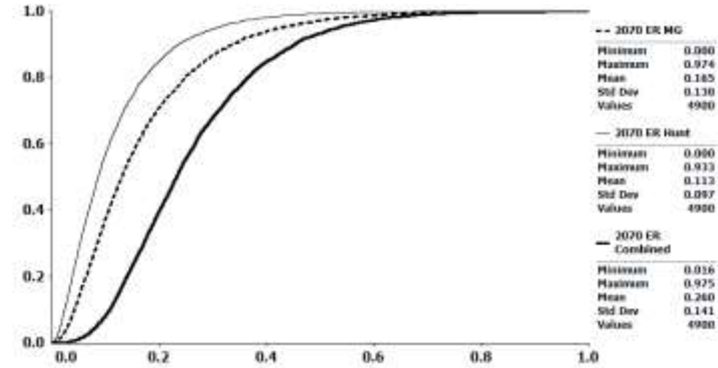
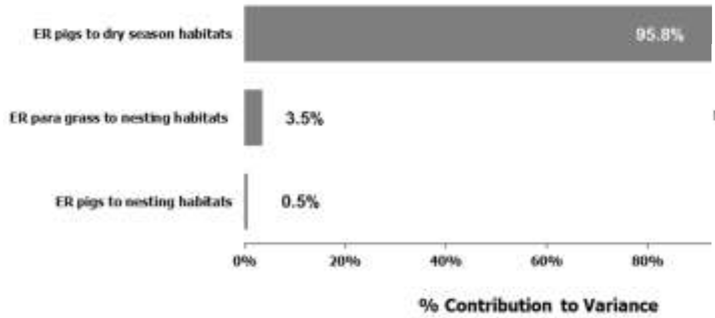
Parameter	Assessment end point	Measurement end point (km^2)	Area (km^2)	Percentage freshwater	Mean *P*	s.d.	*n* (cells)	*P* (pdf)	BestFit	Notes
	Para grass									
	Extent of para grass on freshwater floodplains	Area where para grass occurs	299	25						
	Intensity of para grass cover on freshwater floodplains	Ppg ≥ 0: mean percentage cover para grass			0.011	0.045	188	0.011	Exponential	
	Intensity of para grass cover freshwater floodplains	Ppg > 0: mean percentage cover para grass > 0%			0.098	0.098	21	0.093	Exponential	
	Para grass damage to goose wet-season nesting habitats	Ppg & Pmgws overlap: Ppgmgws								Does not exist
	Para grass damage to goose dry-season feeding habitats	Ppg & Pmgds overlap: Ppgmgds								Does not exist
	Combined para grass damage to goose habitats	Ppgmg = Ppgmgds × Ppgmgws –(Ppgmgds × Ppgmgws)								Does not exist
	Para grass damage to hunting–fishing sites	Ppg & Ph overlap: Ppgh	256	32	0.014	0.053	114	0.065	Exponential	
	Combined									
	Combined invasive-species risk to magpie goose habitats	Pimg = Ppmg + Ppgmg – (Ppmg × Ppgmg)			0.065			0.014		
	Combined invasive-species risk to hunting–fishing sites	Pih = Pph + Ppgh – (Pph × Ppgh)			0.014			0.065		
	Combined risk to goose habitats and hunting sites	Pimgh = Pimg + Pih – (Pimg × Pih)			0.078			0.078		

S1.3. Uncertainty analyses for the 2070 and 2100 sea level-rise (SLR) scenarios

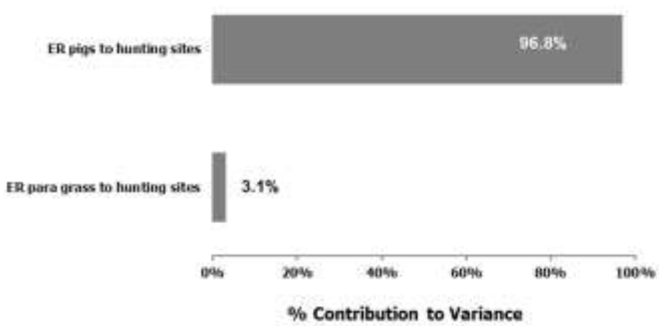
2070



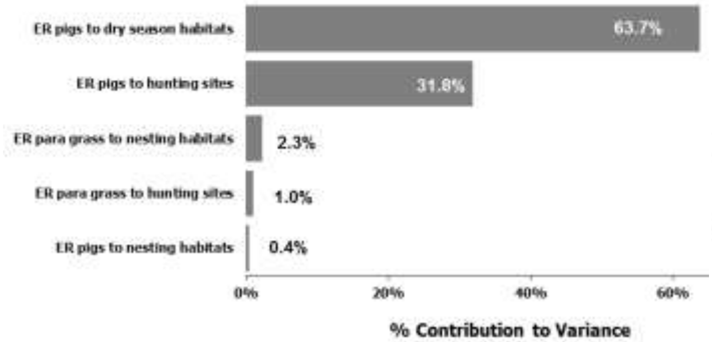
(*a*) Cumulative risk to goose habitats and hunting sites



(*b*) Risk to goose habitats from invasive species

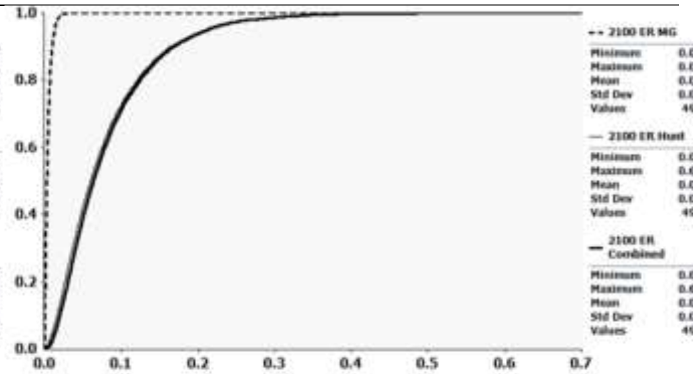


(*c*) Risk to hunting sites from invasive species

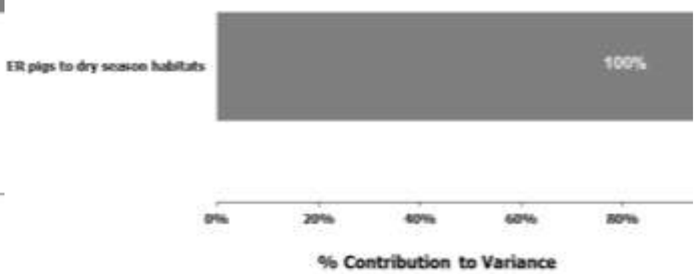


(*d*) Combined risks from invasive species

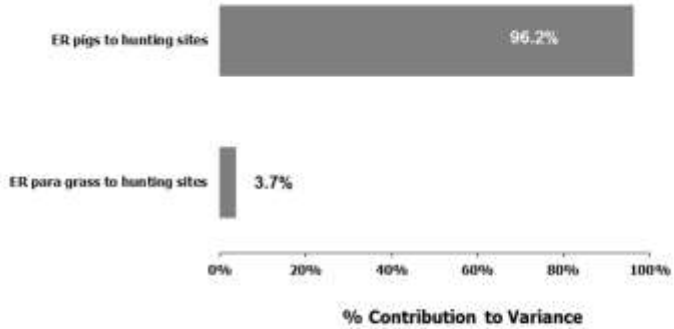
2100



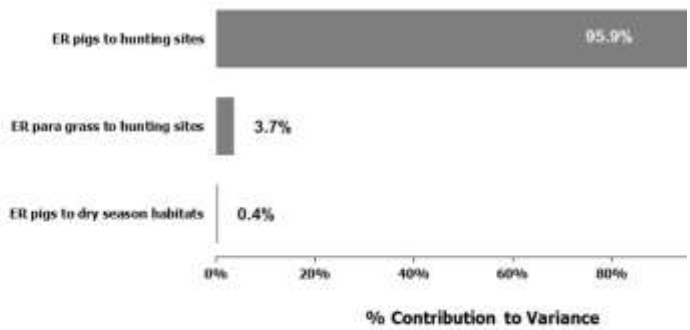
(*e*) Cumulative risk to goose habitats and hunting sites



(*f*) Risk to goose habitats from invasive species



(*g*) Risk to hunting sites from invasive species



(*h*) Combined risks from invasive species

Fig. S1. Cumulative distribution function (cdf) used to characterise risk profiles for magpie goose seasonal habitats (dashed line) and cultural hunting–fishing sites (fine solid line) from the impacts of two invasive species (pigs and para grass) in the (*a*) 2070 and (*b*) 2100 Sea level-rise (SLR) scenarios. The risk to both assets combined from both invasive-species risks combined is heavy solid line. The variance contribution of each risk factor to the risk model used in Monte Carlo simulations are illustrated by Tornado sensitivity graphs for the following: the combined risk of both invasive species to (*b*, *f*) magpie goose seasonal habitats; similarly, for (*c*, *g*) cultural hunting–fishing sites; and for (*d*, *h*) both invasive-species risks combined to both assets combined. Similarly, for the present-day (2009–2013) SLR scenario (Fig. 4*a*–*d* in the paper). See Table S2, available as Supplementary material for this paper, for probability density function (pdf) and cdf equations.

S1.4. Use of Bayesian belief networks (BBNs) to undertake integrated risk assessments (IRAs) and to set risk-management targets

All steps in an ecological risk assessment (ERA) need to be guided at the outset by appropriate conceptual models (Burgman 2005), and this caveat applies to both qualitative and quantitative methods, single risks within a regulatory framework and multiple risks within a more complex socio-ecological system (SES) framework. The general approach to ERA has been to first develop a conceptual model with stakeholders and end-users that captures multiple threats and their pathways to multiple assets, and then to prioritise or rank them on the basis of a qualitative or a semi-quantitative risk-analysis process where lesser or trivial risks are filtered. The structure of a BBN is based on a conceptual model where causal relationships are made explicit and the probabilistic relationships between variables can be updated using Bayes' theorem (Hart 2004). Node or variable values in a BBN are determined by mutually exclusive discrete states (McCann *et al*. 2007) such as 'high' and 'low' risk levels. Each 'parent' node takes as input a particular set of values from 'child' nodes to give the probability of the variable state that they represent (Bayliss *et al*. 2012). The conditional relationships, or dependencies, between parent and child nodes are defined by conditional probability tables (CPTs) that underlie each node.

Bayesian belief networks provide a flexible risk-management tool in that they can integrate quantitative information with qualitative expert knowledge and, hence, facilitate stakeholder engagement and communication (Baran and Jantunen 2004; Uusitalo 2007). Van Putten *et al*. (2013) used a Bayesian model of factors influencing indigenous participation in the Torres Strait tropical rock lobster fishery, demonstrating the utility of the method to capture Indigenous cultural values.

Bayliss *et al*. (2012) argued that although BBNs are not amenable to advanced modelling techniques, they are a much more powerful communication tool than most risk software because they are graphically based and, so, more suitable as a decision-making tool for stakeholders. The cascade effect of a change in a variable state, or the subjective value of a decision, or the uncertainty associated with it, can be observed instantaneously.

Incorporating uncertainty in risk variables

The probability density functions (pdfs; see Table S1 for symbols and Table S2 for equations) characterise the innate uncertainty of each risk factor used in the BBN, and the equations embedded in their underlying CPTs were solved using 5000 random samples drawn from each pdf. For ease of presentation in this demonstration, the mean and standard deviation of normal distributions were used as pdfs for each risk variable in the BBN, although their BestFit (Palisade 2002, 2010) distributions were exponential. In the BBN, P_{i} is the overall integrated risk (dark grey node), P_{n} is the risk to natural systems (blue node; magpie goose habitats, plant biodiversity), P_{ch} is the risk to cultural hunting–fishing sites; P_{swi} is the risk from saltwater inundation (SWI) for the three sea level-rise (SLR) scenario years; P_{cpmg} is the combined risk from pigs to goose seasonal habitats; P_{cpb} is the combined risk from pigs and para grass to plant biodiversity; P_{cpgmg} is the combined risk to goose seasonal habitats from para grass; P_{pmgds} and P_{pmgws} are the risks from pigs to goose dry-and wet-season habitats respectively; P_{pgmgds} and P_{pgmgws} are the risks from para grass to goose dry- and wet-season habitats respectively; P_{ppb} and P_{pgpb} are the risks to plant biodiversity from pigs and para grass respectively. For the present-day scenario (Fig. S2), the values are as follows: 20 and 11% covers for pigs and para grass respectively; P_n = 0.53; P_{ch} = 0.29; and P_i = 0.66. These risks relate only to the area that each threat occupies and are not adjusted for unoccupied areas across the park.

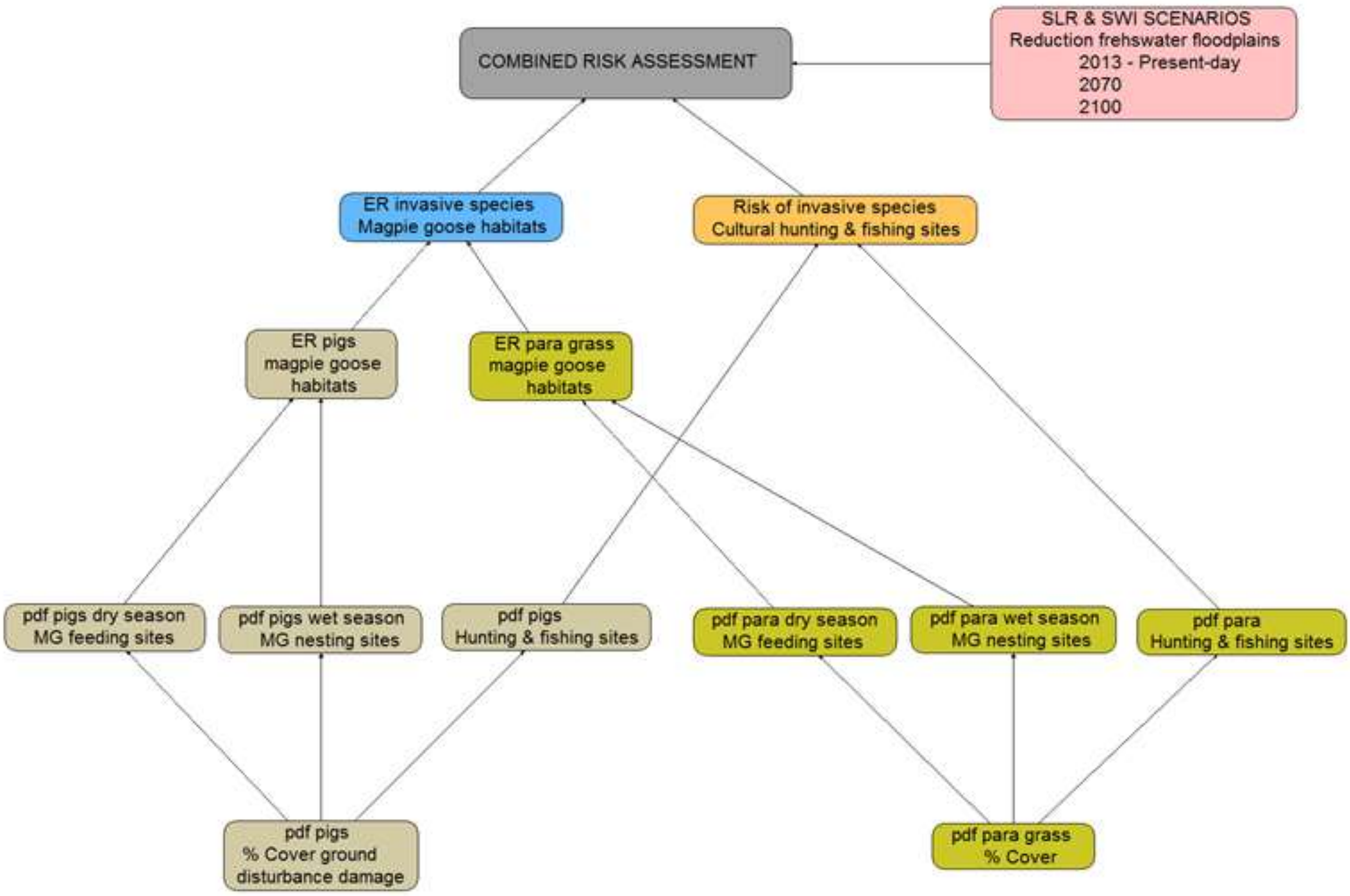


Fig. S2. Conceptual Bayesian belief network (BBN) model for a combined ecological risk assessment (ERA) of invasive-species impacts (pigs and para grass) and future sea level-rise–saltwater-inundation (SLR–SWI) impacts (present-day 2013, 2070 and 2100, after Bayliss *et al*. 2018) to natural (seasonal magpie goose habitats) and cultural (hunting sites) values (see Table S2 for risk-node variable settings for each SLR scenario). This is Fig. 1*b* in the paper, but without the invasive-species management node. MG, magpie geese; pdf, probability distribution function; ER, ecological risk); combined or integrated risk (grey) to natural (extent of magpie goose seasonal habitats, blue) and cultural (extent of hunting–fishing sites, orange) values; ER of pig damage (percentage cover ground disturbance) to geese feeding and nesting sites (brown); ER of para grass (percentage cover) to goose seasonal habitats (olive green); and risk from SLR–SWI at the three scenario time frames (pink). Risks to plant biodiversity on floodplains is not included in this BBN to simplify demonstration of accompanying uncertainty analyses (see Fig. 4*a*–*d* in the paper and Fig. S1*a*–*h*).

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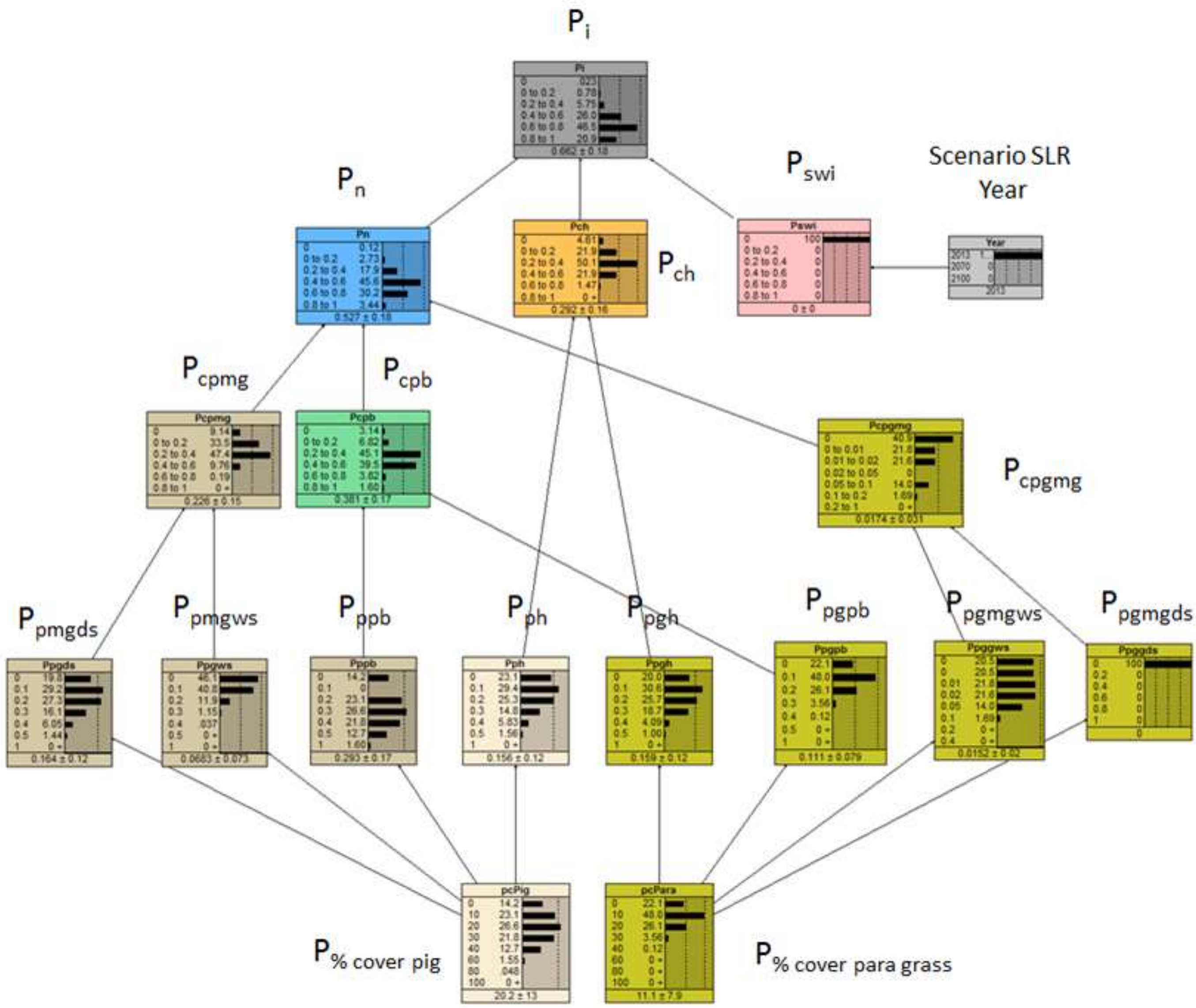

Fig. S3. A parameterised Bayesian belief network (BBN) for the conceptual risk model (Fig. S2), same as Fig. 1*a* in the paper, without invasive-species management node) underlying the integrated risk assessment (IRA) of the KNP natural and cultural floodplain values from invasive species (para grass (olive green) and pigs (brown)) and sea level rise-induced saltwater inundation (SLR–SWI; P_{swi} (red)) for three future scenarios (present-day 2009–2013, 2070 and 2100). Plant biodiversity on freshwater floodplains is included as an extra natural value or asset node at risk. The BBN illustrated here is for the present-day scenario (i.e. no SLR impacts). The underlying bottom-up invasive-species risks are driven by percentage cover of para grass ($P_{\%\ \mathrm{cover\ para\ grass}}$) and ground-disturbance damage caused by feral pigs ($P_{\%\ \mathrm{cover\ pigs}}$). Probability distribution functions (pdfs; Table S2) characterise the innate uncertainty of each risk factor (natural node) in the BBN and their equations were solved using 100 random samples drawing on the s.d. of means. P_{i} is the overall integrated or combined risk (dark grey node); P_{n} is the risk to natural systems (blue node; magpie goose habitats, plant biodiversity (bright green node)); P_{ch} is the risk to cultural hunting–fishing sites (orange node); P_{swi} is the risk from SWI for three SLR-scenario years (pink node; scenario year switch (light grey node)); P_{cpmg} is the combined risk from pigs to magpie goose seasonal habitats; P_{cpb} is the combined risk from pigs and para grass to plant biodiversity; P_{cpgmg} is the combined risk to magpie goose seasonal habitats from para grass; P_{pmgds} and P_{pmgws} are the risks from pigs to magpie goose dry- and wet-season habitats respectively; P_{pgmgds} and P_{pgmgws} are the risks from para grass to magpie goose dry- and wet-season habitats respectively; P_{ppb} and P_{pgpb} are the risks to plant biodiversity from pigs and para grass respectively. Para grass-risk nodes are olive green and that for pigs is brown.

Use of recursive properties of BBNs in risk assessment

A demonstration of the recursive properties and power of a BBN in an IRA is illustrated by comparing the actual present-day risks (Fig. S3) to acceptable levels of risk (Fig. S4). 'Downstream' levels of risk needed to obtain 'upstream' target levels of risk in the two key assessment endpoints can be estimated using all available data and knowledge embedded in each BBN node. The BBN includes a node for future SLR–SWI risks at the three scenario time frames, and in this example the risk (P_{swi}) is set to zero (present-day SLR scenario), although it can also be set for the 2070 and 2100 SLR scenarios. Hence, the BBN commences at the present-day (2009) exposure levels (percentage cover as a proportion of available freshwater floodplain habitat) of both invasive species (para grass P_{pg} and pig damage P_{pig}), and shows all subsequent pathways and dependent risk factors to natural and cultural values that contribute to the final IRA endpoint. An additional natural value at risk is included in this BNN (floodplain plant biodiversity) to align with the conceptual risk pathways model (Fig. S5) that underpins the IRA–BBN framework used to evaluate different invasive-species management scenarios at different SLR-scenario time frames (Fig. S6 for the present-day SLR scenario and Fig. S7 for 2100).

The 'socially acceptable' landscape-scale risks to natural and cultural systems on World Heritage KNP are both arbitrarily set to 0.10 (Fig. S3); however, higher levels of protection associated with lower levels of risk can also be adopted. To achieve these risk targets, the 'downstream' risks from pigs and para grass to magpie goose habitats (combined and separately), cultural hunting–fishing sites and plant biodiversity values on floodplains are calculated from the CPTs of all parent nodes as determined by their pdf equations or state levels. The damage (percentage cover) caused by pigs is 0 (i.e. where pig density is smaller than some detectable level, see 'thresholds' in section S1.5) and the percentage cover of para grass (pcPara) < 10% (here ~7% or equivalent to the low weed of national significance (WONS) weed-density classification; see NTG Weed Management Branch 2015). Overall $P_i = 0.18$ (Fig. S4) and is reduced by a factor of 4.

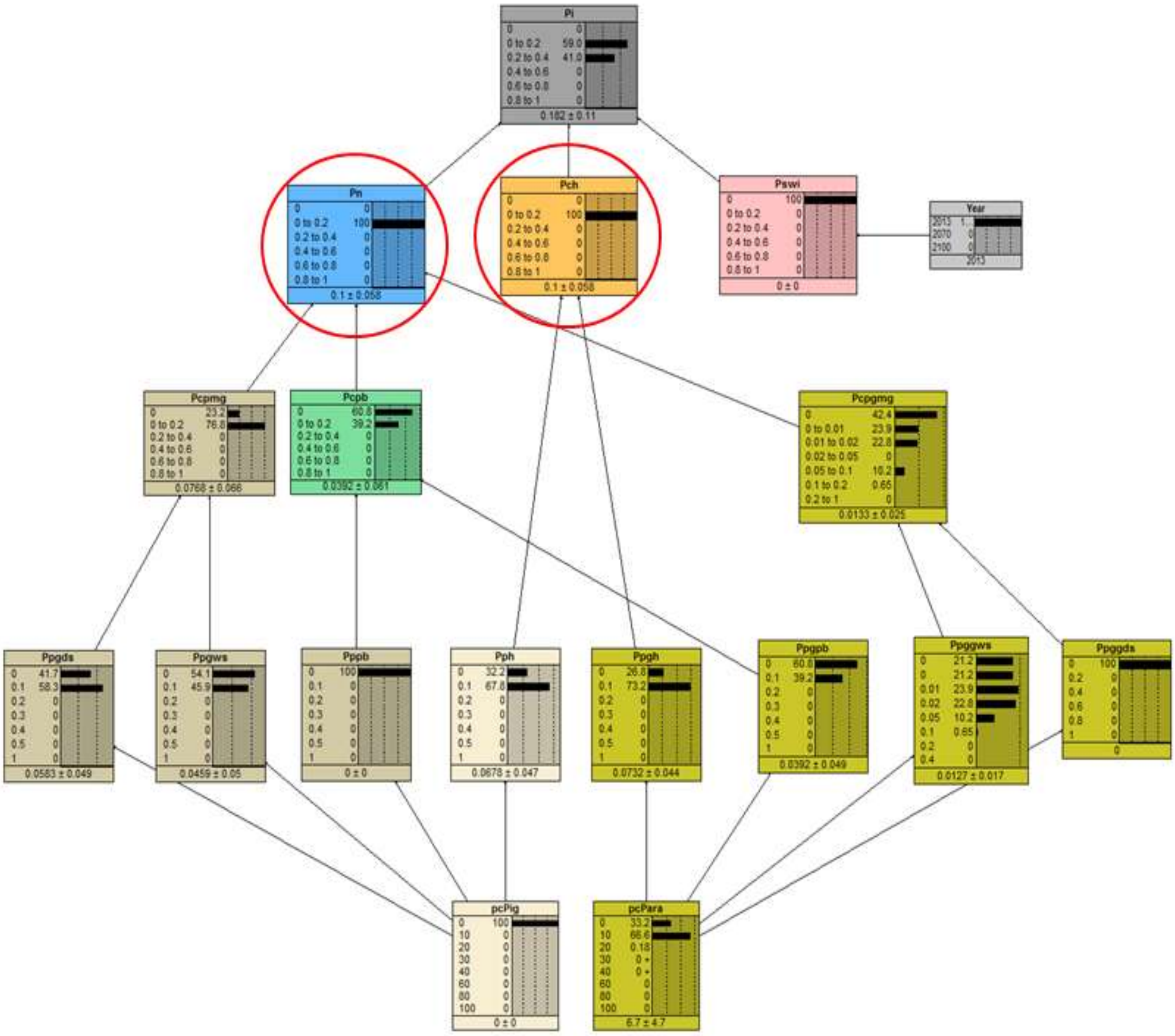

Fig. S4. Demonstration of the recursive properties and power of a Bayesian belief networks (BBNs) in an integrated risk assessment whereby 'downstream' levels of risk need to obtain target risk levels in the two key assessment endpoints can be estimated using all available data and knowledge embedded in each node (see node colour scheme in Figs S2 and S3). The risk from saltwater indundation (SWI; P_{swi}) is set to zero (present-day sea level-rise (SLR) scenario). The 'socially acceptable' arbitrary risk to natural (blue node) and cultural (orange node) systems on World Heritage Kakadu National Park are both set to 0.10 (red circles). To achieve these higher-level risk targets, the downstream risks from pigs (brown nodes) and para grass (olive green nodes) to magpie goose habitats, cultural hunting–fishing sites and plant biodiversity on floodplains are determined from the conditional probability tables of all parent nodes as set by their pdf equations or their state levels. The percentage cover damage caused by pigs (pcPig) is 0 (i.e. where pig density < the damage-density threshold value of 1.4 km^{-2}) and the percentage cover of para grass (pcPara) < 10% (here ~7% or the low weeds of national significance (WONS) weed-density classification, see NTG Weed Management Branch 2015).

S1.5. Parameterisation of invasive species bioeconomic control models, Kakadu National Park (KNP)

Methods

Although mimosa and feral buffalo now occur only at trace levels in KNP, they are included in the risk models to capture a moderate level (2-species interactions) of complexity in ecological risk assessments (ERAs) and to highlight

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the opportunity cost of not implementing management action now *v.* at some time in the future. The following three linked submodels of an invasive-species bioeconomic control model were developed for each invasive species examined in the integrated risk assessment (IRA): (1) a population-dynamic model that captures the rate of spread or colonisation of new habitats; (2) a damage-density function to determine socially acceptable control targets; and (3) a cost-of-control *v.* abundance function, typically a negative exponential curve based on predator–prey theory (see Bayliss and Yeomans 1989 for buffalo; Choquenot *et al*. 1996 for pigs; Hone 1994; Choquenot and Hone 2000).

Feral animals

Published and unpublished historical aerial survey datasets from the region were used to assess trends in the observed densities of pigs and buffalo, to determine whether or not there was an ecological interaction between the two. Pigs are very difficult to detect during fixed-wing aerial surveys, especially when they occupy dense cover during hot days (Choquenot 1995). Bayliss and Yeomans (1989) argued that there are too few pig sightings during fixed-wing aerial surveys to reliably map their distribution and abundance. Hence, their highly visible ground-disturbance damage ('pig damage') recorded on a percentage cover basis along survey transects in 2008–2009 was mapped instead of observed densities (P. Bayliss and K. Saalfeld, unpubl. data, as reported in Boyden *et al*. 2008). Percentage cover scores of pig damage were converted to exposure risk probabilities, and mean values were derived for each 2.7-km-grid cell.

Logistic population growth (and spread) was assumed for both species, given the lack of data to parameterise more appropriate consumer-resource models (see Bayliss and Choquenot 2002). The damage-density function developed by Bayliss *et al*. (2006) for pigs incorporating all historical published and unpublished data is used here (Bayliss and Yeomans 1989; P. Bayliss and K. Saalfeld, unpubl. aerial-survey data, 2003; the 2008–2009 aerial surveys cited above; and J. Russell-Smith, unpubl. data, 2008). The mean percentage (%) cover of pig damage could be correlated with overall mean pig density (numbers km^{-2}) on floodplains only for three time periods. Nevertheless, each density point was derived from sample transects comprising a 10% sampling intensity, so are considered robust point estimates. All observed densities were corrected for visibility bias by using results from an exotic-disease control exercise of buffalo and pigs in western Arnhem Land in the mid-1980s (Bayliss 1986), and unpublished data of helicopter culls of pigs on KNP between 1998 and 2001. Pre-control feral-animal densities in both exercises were derived from the regression between the number of new animals culled and the cumulative sum of numbers culled, whereby the *X*-intercept estimates numbers before control (essentially the Leslie's 'catch-out' method; see Caughley 1977, p. 44). A control-cost function for pigs culled from helicopters (A\$ kill^{-1}) was derived from all control data between 1998 and 2001.

Aquatic weeds

The distribution and abundance of para grass (percentage cover) were surveyed by helicopter in 2009 across a 250-m grid (NTG Weed Management Branch 2015; Parks Australia Kakadu, unpubl. data), and these data were averaged up to the 2.7-km aerial-survey grid. Similar helicopter survey data were also obtained in 2012; however, the 2009 data are used here to align with aerial-survey data obtained on pig damage in 2009, and the mapping of hunting–fishing sites in 2010. Bayliss *et al*. (2006, 2007) fitted a logistic population-growth and spread-rate model to historical para grass cover data across the Magela Creek (MC) floodplain, and used parks chemical-control data at nearby Nourlangie wetland between 1992 and 1995 to develop a control-cost function (A\$ ha^{-1}), both of which are used in the present assessment.

Bayliss *et al*. (2006) used multivariate analysis to model the negative effect of para grass cover on the cover of native floodplain plants, and argued that most plant classes (e.g. *Oryza* spp., *Eleocharis* spp., native *Hymenachne* and open water-lily habitats) had a threshold-effect detection level of ~20% (i.e. a reduction in their cover could not be detected unless para grass cover was >20%), and this was used as a pragmatic control target in management scenario simulations where para grass cover exceed this level.

Although mimosa has been successfully managed to trace levels in Kakadu National Park since the mid-1980s, a bioeconomic control model was developed for the Oenpelli floodplain on the East Alligator River (EAR) adjacent to the park between 1980 and 1991, and was included in the economic assessment to examine the opportunity cost of not undertaking pre-emptive weed control when their extent is restricted and cover densities are low (see Bayliss *et al*. 2006, 2007).

Threshold and non-linear effects

Choquenot and Parkes (2001) argued that threshold control targets for feral animals based on resource-damage thresholds need to be set because of the exponentially rising unit control costs as pest densities are substantially lowered. The damage–density relationship reported by Bayliss *et al*. (2006) for pigs exhibits a threshold effect of 1.4 pigs km^{-2} (i.e. damage is not observed below this threshold and can be used as the target control density). There is no published damage–density function for buffalo and, hence, an arbitrary control target is set at 10% of assumed carrying capacity (~17 buffaloes km^{-2}; see Bayliss and Yeomans 1989; McMahon *et al*. 2010; appendix B in Woodward *et al*. 2011). The visibility-bias correction factors of Bayliss and Yeomans (1989) for buffalo were used to derive absolute density estimates. The control-cost function for buffalo (A$ kill^{-1}) derived by Bayliss and Yeomans (1989) was used also in the final economic assessment, with 1986 unit costs adjusted to 2009 prices (costs had doubled in 23 years).

The dynamics of pest-control systems are clear examples of complex, non-linear socio-ecological systems (SESs) encompassing real-world uncertainties, even without the underlying and confounding effects of future sea-level rise (SLR). For example, the assumption of most pest-control programs is that a reduction in pest density will result in a concomitant reduction in pest ‘damage’. Hence, by default, the control objective often becomes density reduction rather than damage mitigation (or some other index of derived ‘benefit’). However, Hone (1994) reviewed the literature for explicit pest damage–density relationships and found that it was demonstrated only in approximately half of reported studies, suggesting that more complex relationships are likely to exist. Additionally, Choquenot and Parkes (2001) argued that ‘threshold’ pest-control targets based on resource-damage thresholds need to be used, given the exponentially rising unit control costs as pest densities are substantially lowered, and this may be especially true if damage–density thresholds exist, below which damage either does not manifest or cannot be measured. Even so, Ramsey *et al*. (2009) argued caution when using thresholds to decide whether or not to terminate a control program, given the implications of being incorrect. Hence, they used a Bayesian risk approach to assess the eradication success of feral pigs from Santa Cruz Island, California, under the constraint that pigs could no longer be detected. If necessary, the adaptive Bayesian belief network (BBN) approach used in the present study could be adapted to incorporate alternative levels of acceptable risk, damage or pest density as new management targets. Needless to say, without clear control targets in the first place, or objectives that are inextricably linked to pest damage, there is no way of measuring the performance of the control program and, hence, optimising, or even justifying, control costs. Caughley (1983) described this sort of approach as 'idiotic culling', as exemplified by the history of deer control in New Zealand.

S1.6. Invasive-species management scenarios examined in the integrated risk assessment–Bayesian belief network (IRA–BBN) framework for freshwater floodplain habitats

Table S3. Management scenarios examined in the integrated risk assessment–Bayesian belief network (IRA–BBN) framework for para grass and pigs on floodplain habitats at Kakadu National Park, and two additional invasive species, mimosa and feral buffalo, are used to compare the opportunity costs of not controlling these species with potential sunk costs of managing floodplains that will be lost to sea-level rise–saltwater inundation (SLR–SWI) in the future

Species	Control target (percentage cover weeds, percentage density reduction feral animals)	Control interval (years)	Control area 2009–2013 (km^2)	Control area 2070 (km^2)	Control area 2100 (km^2)
Para grass	0 – no control				
	10% cover (LOW density). Less than 20% average detection level of loss of native plants.	Annual – after 1st year of growth. In perpetuity until control areas inundated by SLR–SWI.	26.2	15.0	0
Pigs	0 – no control				
	20% of maximum carrying capacity density on floodplains; 80% reduction from maximum carrying capacity 6 km^{-2} on floodplains; ≤0.5 km^{-2} and is below threshold ground-disturbance damage-detection level.	Annual – after 1st year of population increase. In perpetuity until control areas inundated by SLR–SWI.	2627	1621	1160
Mimosa	0 – no control				
	<1% cover, current ground control (Storrs *et al*. 1999; Setterfield *et al*. 2013) at A$500 000 $year^{-1}$ or A$2 ha^{-1}.	In perpetuity until control areas inundated by SLR–SWI.	2500 check	1550	1100
	<10% assume uncontrolled outbreak as for Oenpelli in the 1990s.	Annual – after 1st year of growth. In perpetuity until control areas inundated by SLR–SWI.	2500	1550	1100
Buffalo	0 – no control				
	Density <3 km^2, 80% reduction of maximum carrying capacity density (17 km^{-2}) on floodplains (McMahon *et al*. 2010). No damage–density relationship exists.	Annual – after 1st year of population increase. In perpetuity until control areas inundated by SLR–SWI.	2627	1621	1160
Years since 2013			0	57	87

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S1.7. Conceptual Bayesian belief network (BBN) model of the integrated risk assessment (IRA) framework with management nodes for invasive species (para grass and pigs), and summary of scenario simulations (Figs S5, S6, Table S4)

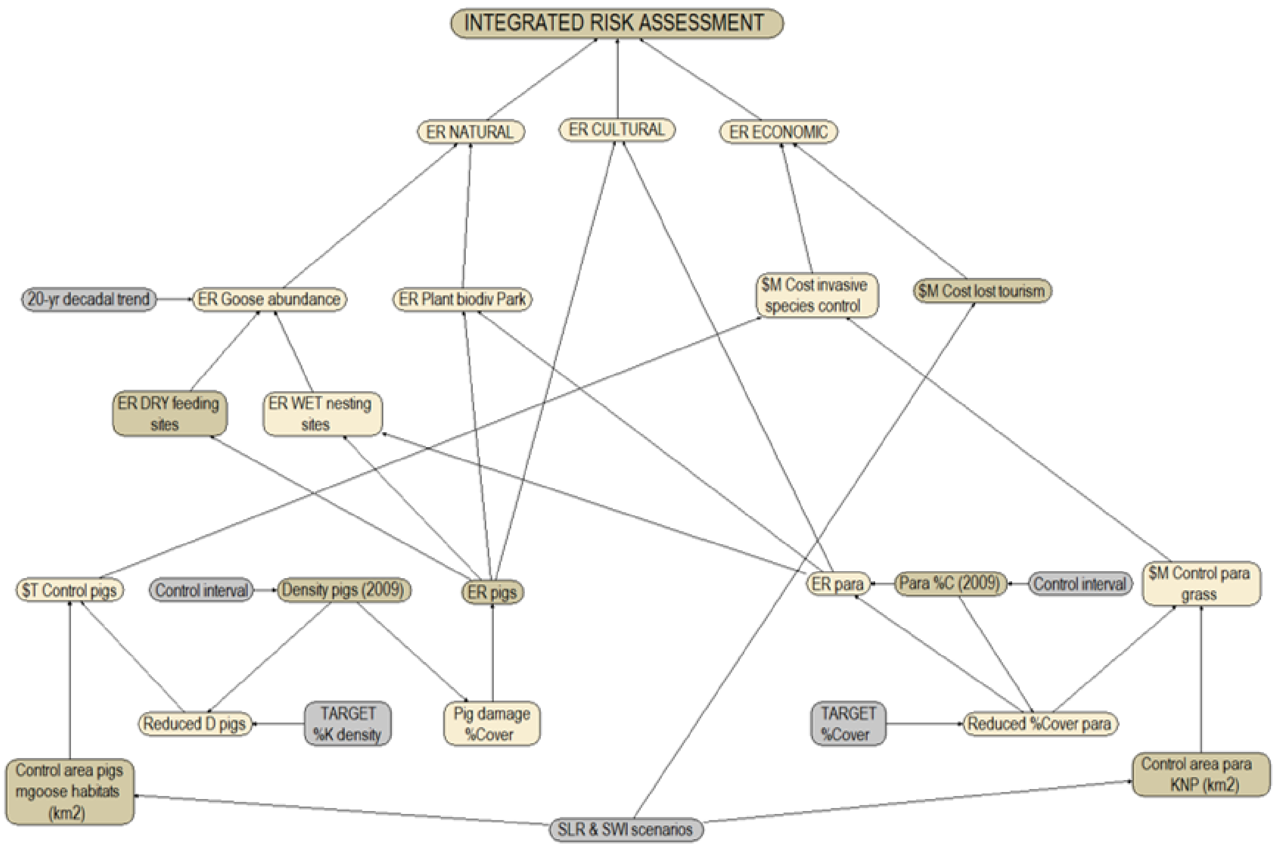

Fig. S5. Conceptual Bayesian belief network (BBN) model for the integrated risk assessment (IRA) of invasive-species and sea level-rise–saltwater-inundation (SLR–SWI) risks to natural, cultural and economic assets on Kakadu National Park (KNP; see BBN in Fig. S6, with management nodes for all invasive species). The IRA combines risks to natural systems (indexed by magpie goose seasonal habitats and here includes plant biodiversity on floodplains) from feral pigs and para grass impacts, and includes an economic-risk node indexed by the combined costs of invasive-species control and potential lost tourism revenue from the reduction of freshwater ecosystems as a result of SLR–SWI for the present-day (2013–2009), 2070 and 2100 time frames.

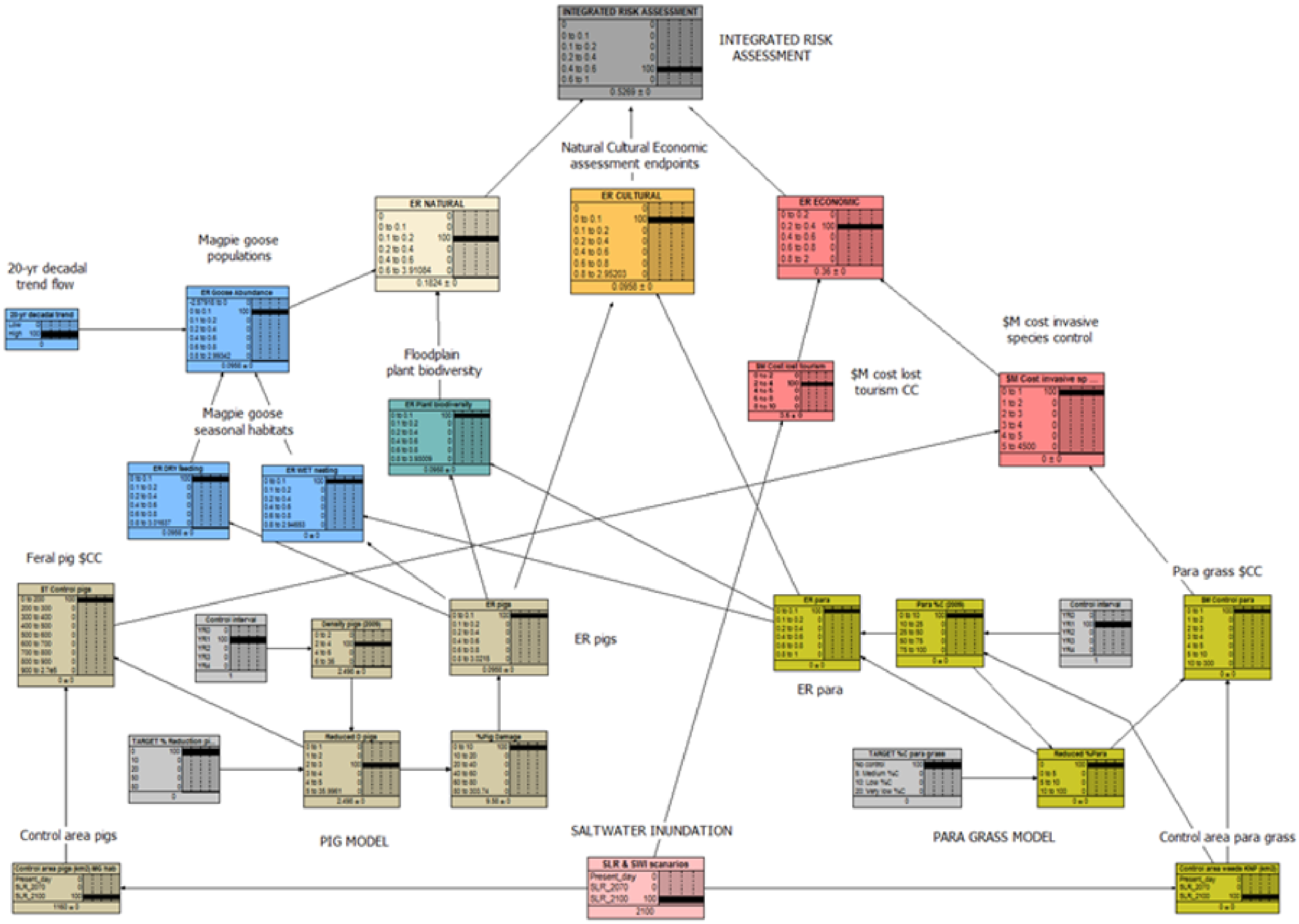

Fig. S6. The integrated risk assessment–Bayesian belief network (IRA–BBN) for the conceptual risk model illustrated in Fig. S5 at the 2100 sea level-rise (SLR) scenario time frame. The risk probabilities for the combined and individual impacts of para grass and pigs to natural, cultural and economic park values, and the overall integrated risk probability, are shown in each node and summarised in Table S4. Management scenarios are set to 'no-control'. Bioeconomic submodel equations are summarised in Table 2 in the paper (and see Figs 6 and 7), and management-control scenarios are summarised in Table S3. Magpie geese are in the 'high'-abundance phase of their decadal cycle (Bayliss and Ligtermoet 2018). Colour codes are as follows: para grass (olive green); SLR–saltwater-inundation (SLR–SWI) scenario (pink); pig (brown); management settings (grey); geese (blue); economic (red); plant biodiversity (blue-green); combined natural values (light brown); cultural values (hunting–fishing sites; orange); and overall integrated risk assessment (IRA; dark grey).

Table S4. Summary of Bayesian belief network (BBN) results for the integrated risk assessment of invasive-species impacts (percentage cover of ground-disturbance damage by pigs and percentage cover of para grass) on magpie goose seasonal habitats and Indigenous hunting and fishing sites (see Fig. 8*a* in the paper and Fig. S6), using the assessment and measurement endpoints summarised in Table 1 in the paper

Assessments were undertaken for the three sea level-rise (SLR) scenario time frames (2009–2013, 2070, 2100) used by Bayliss *et al*. (2018). The 'no state' exist levels resulting from projected SLR–saltwater-inundation (SLR–SWI) extent are highlighted in bold

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Risk variable	Present-day		2070		2100	
	No control	Control	No control	Control	No control	Control
Integrated risk assessment	0.68	0.46	0.73	0.51	0.53	0.37
Risk to natural values	0.55	0.21	0.55	0.21	0.18	0
Risk to cultural values	0.28	0.11	0.28	0.11	0.10	0
Risk to economic values	0	0.25	0.18	0.32	0.36	0.37
Risk to magpie goose numbers	0.35	0.11	0.35	0.11	0.10	0
Risk to wet-season goose habitat	0.28	0.11	0.28	0.11	0	0
Risk to dry-season goose habitat	0.10	0	0.10	0	0.10	0
Risk to floodplain plant biodiversity	0.30	0.11	0.30	0.11	0.30	0
Loss to tourism from climate change-induced SLR (A$ million)	0	0	1.8	1.8	3.6	3.60
Cost of total invasive species control (A$ million)	0	2.5	0	1.43	0	0.08
Cost of para grass control (A$ million)	0	2.3	0	1.31	0	0
Cost of pig control (A$ million)	0	0.18	0	0.12	0	0.08
Ecological risk (ER) from pigs	0.10	0	0.10	0	0.11	0
ER from pigs to goose seasonal habitats	0.10	0	0.10	0	0.10	0
ER from pigs to goose nesting habitat	0.10	0	0.10	0	0.10	0
ER from pigs to goose dry-season habitat	0.10	0	0.10	0	0.10	0
ER from pigs to plant biodiversity	0.10	0	0.10	0	0.10	0
ER from para grass	0.21	0.11	0.21	0.11	**No state**	**No state**
ER from para grass to both goose habitats	0.21	0.11	0.21	0.11	**No state**	**No state**
ER from para grass to goose nesting habitat	0.21	0.11	0.21	0.11	**No state**	**No state**
ER from para grass to goose dry-season habitat	**No state**	**No state**	**No state**	**No sate**	**No state**	**No state**
ER from para grass to plant biodiversity	0.21	0.11	0.21	0.11	**No state**	**No state**
Risk from pigs to cultural values	0.10	0	0.10	0	0.10	0
Risk from para grass to cultural values	0.21	0.11	0.21	0.11	**No state**	**No state**
Pig management target (percentage reduction)	0	80	0	80	0	80
Pigs starting density (D, km^{-2})	2.5	2.5	2.5	2.5	2.5	2.5
Pigs controlled density (number km^{-2})	2.5	0.5	2.5	0.5	2.5	0.5
Percentage cover pig damage controlled	10	0	10	0	10	0
Area of pig control (km^2)	2627	2627	1621	1621	1160	1160
Para grass percentage cover target reduction	0	10	0	10	**No state**	**No state**
Para grass percentage cover start	20.7	20.7	20.7	20.7	**No state**	**No state**
Para grass percentage cover controlled	20.7	10.7	20.7	10.7	**No state**	**No state**
Area of para grass control (km^2)	26.2	26.2	15	15	**No state**	**No state**

S1.8. Assessing structural uncertainty in the Kakadu socio-ecological system (SES) model using qualitative modelling (QM) methods

Qualitative-modelling (QM) methods were used to assess structural uncertainty in the SES model that underpins the integrated risk-assessment (IRA) framework. Although mimosa and feral buffalo now occur only at trace levels in the KNP, they are included in the qualitative SES model examined here (Fig. 1*a* in the paper), so as to capture a moderate-level of ecological system complexity (2 × 2-species interactions). Two alternative SES models were compared, namely (*a*) with (QM1, Fig. S7*a*) and without (QM2, Fig. S7*b*) ecological interactions and feedback (FB) loops associated with threats from four invasive species to floodplain assets (aquatic weeds: mimosa (*pigra*) and para grass (*Urochloa mutica*); feral animals: pigs (*Sus scrofa*) and buffalo (*Bubalus bubalis*)). Assets were cultural (CUL), natural (NAT), economic (ECO) and SES, used as the combined assessment endpoint in the IRA conceptual model (i.e. receiving inputs from NAT, CUL and ECO). QM1 assumes that the impacts (or effects) of threats of invasive species on the three key assets are linear and additive. In contrast, QM2 assumes the following interactions: positive feedbacks between NAT and CUL, and CUL and NAT (i.e. an Indigenous peoples caring-for-country philosophy that is mutually beneficial), and between NAT and CUL to ECO (i.e. Indigenous tourism depends on healthy natural ecosystems); negative feedbacks between all invasive species and all assets, except that a plant–herbivore relationship exists (i.e. with both positive and negative feedbacks) between pig and NAT, reflecting consumption of water chestnut (*Eleocharis dulcis*) bulbs as a food source (see Bayliss and Ligtermoet 2018; Dutra *et al*. 2018). A negative interaction is assumed between mimosa and para grass, where the former outcompetes the latter. Similarly, a negative competitive interaction is assumed between buffalos and pigs.

Bayesian belief networks (BBNs, Fig. S8*a*, *b*) were next developed in Netica (Netica, ver. 4.16, Norsys Software Corporation, Vancouver, BC, Canada, see www.norsy.com, accessed 1 October 2017) to estimate the likelihoods of each of the two competing SES models in Fig. S7 given current knowledge (i.e. with and without ecological FB loops and interactions). The community matrices in Fig. S7 were converted to probabilities using a Maple (ver. 13) program (http://www.maplesoft.com/, accessed 12 January 2017), and incorporated into the conditional probability tables (CPTs) of each BBN variable node, with the following three state levels: increase, no change and decrease (see Dambacher *et al*. 2007*b* for detailed methods on the joint use of QMs and BBNs to evaluate management options for invasive-species control, and Dutra *et al*. 2018 for their Yellow Water case study). The following four 'press' perturbation experiments were conducted simultaneously to represent the current state of invasive-species management on KNP floodplains: mimosa and buffalo are controlled to trace levels and, hence, their state levels are set to 'decrease'; there is no current broad-scale control program for para grass and, hence their state level is set to 'no change'; in contrast, pigs are subjected to a broad-scale control program and, hence, their state level is set to 'decrease'. Fig. S8*a* shows that model QM1 is more likely than model QM2 by a factor of two, given the current state of knowledge embedded in the CPTs (%Pr = 61.2 cf. 31.4), and that all floodplain assets have high probabilities of positively increasing, as reflected in the combined IRA metric (%Pr SES = 78.0). These results basically reflect a simple additive linear IRA model. When QM2 (with ecological FB loops) is selected, counter-intuitive results emerge in that pigs and para grass will both increase only marginally (%Pr = 50.5 and 68.8 respectively), in contrast to their 'pressed'-state levels. The positive increase in the condition of all assets also becomes marginal (%SES Pr = 50.3). Even with known ecological interactions incorporated into the SES model, the results suggest that the simple additive, linear IRA model is a good 'starting point'. Nevertheless, given that the BBN analysis cannot select which model is 'true' (Dambacher *et al*. 2007*b*), the results suggest also that if ecological interactions and FB loops do exist and influence system dynamics, then control programs may produce counter-intuitive results and, potentially, less effective positive outcomes as indexed by assessment-measurement endpoints.

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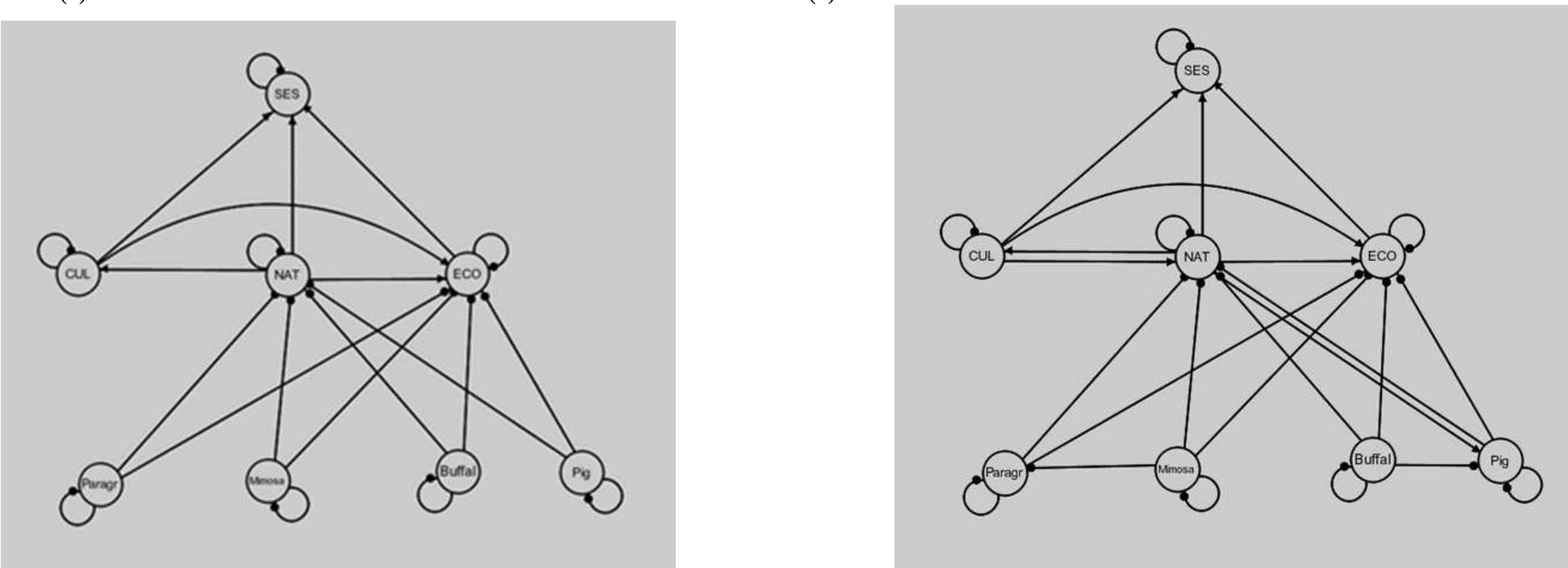
(*a*) (*b*)



(*a*) Matrix Output

	CUL	NAT	ECO	Paragrass	Mimosa	Buffalo	Pig	SES
CUL	-1	1	0	0	0	0	0	0
NAT	0	-1	0	-1	-1	-1	-1	0
ECO	1	1	-1	-1	-1	-1	-1	0
Paragrass	0	0	0	-1	0	0	0	0
Mimosa	0	0	0	0	-1	0	0	0
Buffalo	0	0	0	0	0	-1	0	0
Pig	0	0	0	0	0	0	-1	0
SES	1	1	1	0	0	0	0	-1

1: CUL, 2: NAT, 3: ECO, 4: Paragrass, 5: Mimosa, 6: Buffalo, 7: Pig, 8: SES

[-1,1,0,0,0,0,0,0],[0,-1,0,-1,-1,-1,-1,0],[1,1,-1,-1,-1,-1,-1,0],[0,0,0,-1,0,0,0,0],[0,0,0,0,-1,0,0,0],[0,0,0,0,0,-1,0,0],[0,0,0,0,0,0,-1,0],[1,1,1,0,0,0,0,-1]

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(*b*) Matrix Output

	CUL	NAT	ECO	Paragrass	Mimosa	Buffalo	Pig	SES
CUL	-1	1	0	0	0	0	0	0
NAT	1	-1	0	-1	-1	-1	-1	0
ECO	1	1	-1	-1	-1	-1	-1	0
Paragrass	0	0	0	-1	-1	0	0	0
Mimosa	0	0	0	0	-1	0	0	0
Buffalo	0	0	0	0	0	-1	0	0
Pig	0	1	0	0	0	-1	-1	0
SES	1	1	1	0	0	0	0	-1

1: CUL, 2: NAT, 3: ECO, 4: Paragrass, 5: Mimosa, 6: Buffalo, 7: Pig, 8: SES

[-1,1,0,0,0,0,0,0],[1,-1,0,-1,-1,-1,-1,0],[1,1,-1,-1,-1,-1,-1,0],[0,0,0,-1,-1,0,0,0],[0,0,0,0,-1,0,0,0],[0,0,0,0,0,-1,0,0],[0,1,0,0,0,-1,-1,0],[1,1,1,0,0,0,0,-1]

n:=8:A:=array(1..n,1..n,[[-1,1,0,0,0,0,0,0],[1,-1,0,-1,-1,-1,-1,0],[1,1,-1,-1,-1,-1,-1,0],[0,0,0,-1,-1,0,0,0],[0,0,0,0,-1,0,0,0],[0,0,0,0,0,-1,0,0],[0,1,0,0,0,-1,-1,0],[1,1,1,0,0,0,0,-1]]);

Fig. S7. Qualitative socio-ecological system (SES) model used in the integrated risk assessment (IRA) with two alternative models, namely, (*a*) with (QM1) and (*b*) without (QM2) ecological interactions and feedback loops associated with four invasive-species threats to Kakadu floodplain assets (aquatic weeds: mimosa and para grass; feral animals: pigs and water buffalo). Assets are cultural (CUL), natural (NAT), economic (ECO) and SES of the combined assessment endpoint in the IRA conceptual model (i.e. receiving inputs from NAT, CUL and ECO). All variables have a negative self-effect. Panels below each PowerPlay (http://www.ecoplexity.org/?q=model_computer, accessed 12 January 2017) conceptual system model (sign-directed di-graphs) are the community matrices (see Dambacher *et al*. 2007*b* for detailed methodologies on the joint use of qualitative models and Bayesian belief networks to evaluate management options for invasive species control).

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(*a*) (*b*)

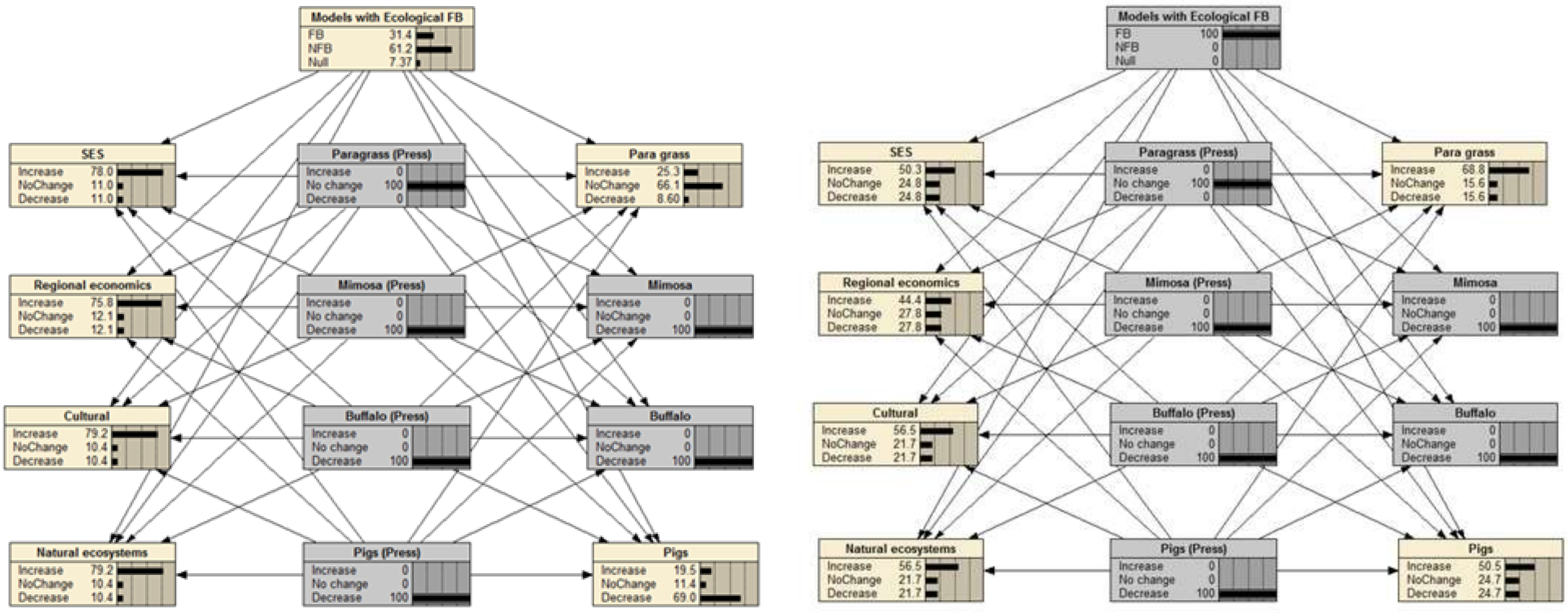

Fig. S8. Bayesian belief network (BBN) representation of the qualitative socio-ecological system (SES) model that underpins the integrated risk assessment (IRA) conceptual model, used to examine the likelihoods of the following two competing models in Fig. S7: (*a*) with (QM1, with feedback loops FB) and (*b*) without (QM2, no feedback loops NFB) ecological interactions and feedback loops associated with four invasive-species (aquatic weeds: mimosa and para grass; feral animals: pigs and water buffalo) threats to natural, cultural and economic floodplain assets. See Dambacher *et al*. (2007*a*, 2007*b*) for detailed methodologies on the joint use of qualitative models and BBNs to evaluate management options for invasive species control.

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S2. Climate change and tourism

Climate change in Kakadu National Park and the tourism sector (visitor survey 2014–2015)

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Note that the results of the visitor survey and choice experiment are currently in preparation for publication. Please contact Dr Innes for any queries (james.innes@csiro.au) or permission to cite.

The Aboriginal (Bininj) community in Kakadu receives income from their land through lease and park-use fees, and through enterprises related to tourism, art and craft and natural-resource management. Through the lease agreement established from 1991 (Kakadu and Jabiluka Aboriginal Land Trusts) and 1996 (Gunlom Aboriginal Land Trust), rent paid to the Kakadu, Jabiluka and Gunlom Aboriginal Land Trusts from the Director of National Parks totals A\$273 702 year^{-1}. This amount is reviewed every 5 years. The Land Trusts also receive 38.8% of park-entrance fees, camping fees, charges, penalties, fees, fines, imposts and amounts received pursuant to the grant of any estate or interest (Director of National Parks 2011). When the park-entrance fee of A\$16.50 was abolished in 2004, compensation was paid to traditional owners to cover the revenue previously received from fees. The park-entry fee was reintroduced in 2010 at a rate of A\$25 for each visitor over 16 years of age. Residents of the Northern Territory are exempt from the fee. Park-entry fees are expected to generate A\$4.5 million in net annual revenue, with A\$1.746 million to be paid to the Aboriginal Land Trusts (Garrett 2008). The net annual revenue in 2016 terms is assumed to be ~A\$10 million, although this estimate does not reflect true regional revenue provided by Kakadu National Park (Tremblay 2010; Straton and Whitten 2009, see below).

Lease fees are unlikely to be affected by climate change. However, the combined impacts of sea-level rise, the intensity of rainfall leading to flooding, damage to infrastructure and disruption to services, and access (in terms of variety and number of areas that can be accessed) may indirectly affect park-use fees, should predicted impacts decrease visitor numbers. Currently, access to areas such as Jim Jim Falls, Twin Falls, Maguk, Gunlom and Koolpin Gorge is limited to the dry-season months of May to November. Four-wheel-drive vehicles are required to access Jim Jim Falls, Twin Falls and Koolpin Gorge, whereas other sites are accessible on unsealed roads by a two-wheel drive. Should the dry season contract or more intense and frequent storms cause road damage, access to these sites may be limited to an even shorter season. Visitor dis-satisfaction may result if tourists are unable to access well known destinations such as Jim Jim Falls, Twin Falls and Gunlom.

Aims of the visitor survey

Kakadu National Park (KNP) faces several threats as a consequence of climate change and characteristic attributes of the park, many of which draw tourists to visit it, are expected to be affected in a range of ways by invasive species (feral animals and weeds), climate change, in particular impending sea-level rise and concomitant increases in saltwater inundation on pristine freshwater wetlands and, by unmanaged fires (see Bayliss *et al*. 2012, 2015, 2018; Setterfield *et al*. 2013; Dutra *et al*. 2015). The survey of park visitors was undertaken to collect data on tourist perceptions of climate change and to identify their priorities for the protection of key attributes of the park into the future. Given that management resources are limited and choices may need to be made, the aim of the survey was to collect previously unavailable information that could be used to better inform and support the management

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process into the future. The initial findings of this survey are presented here and detail the preferences respondents stated for the mitigation of climate-related impacts on KNP.

Survey design and the sampling process

The questionnaire collected demographic information on each respondent and detailed data on their reasons for visiting the park and priorities for maintaining specific attributes. These findings are summarised and discussed below. The questionnaire also contained a choice experiment[A], in the context of a voluntary visitor fee, and collected data on travel costs. Choice-experiment data were collected to assess the extent to which visitors are willing to pay for impact mitigation and whether this varied across specific attributes of the park. Travel-cost data were collected to allow the overall economic value of tourist visits to KNP to be quantified and how this may change as a consequence of climate change. The choice experiment and travel-cost assessments will be the focus of subsequent papers.

Following a pilot phase, the survey was run between September 2014 and August 2015, to cover seasonal differences in the park and its visitors, and the majority of questionnaires were conducted online. To participate, individuals had to have visited the park and be familiar with the attributes being asked about. Respondents were essentially self-selecting and a range of approaches were used to publicise the survey and give individuals the opportunity to participate. This included placing flyers and information sheets at prominent locations in the park major visitor centres[B], support from tour guides, and visits to the park by project staff where flyers were handed to people and the purpose of the work was discussed. The survey was also publicised on social media by CSIRO communications team and to recreational fishers by the Amateur Fishermen's Association of the Northern Territory. Paper versions of the questionnaire were also made available because some respondents preferred this format. In total, 267 complete questionnaires were collected, 85% of which were completed online and 15% on paper.

The attributes considered in the questionnaire were chosen on the basis of sites and activities that experts identified as being most threatened and affected by climate change. These attributes are Aboriginal art sites, freshwater habitats, terrestrial habitats, recreational fishing activities and cost of protection. It is anticipated that, as a consequence of climate change, greater management action would be required to maintain and protect the park from more intense and frequent fires and flooding. Also, terrestrial and freshwater habitats would need protection from saltwater inundation resulting from sea-level rise. Extra management action will be dependent on more funding being available. The explanation provided to respondents on the reasons for protection of the different features is outlined in Table S5.

[A]Choice experiments (CE) present a range of scenarios to individuals to elicit information on the strength of their preferences for alternative attributes of the situation under consideration and how they trade these off against one another. In this case, the context is alternative levels of management intervention and how these may be applied to attributes of the park that visitors come to visit. CE allow welfare estimates (WTP) to be estimated, which is of vital importance in the policy making context, where resource-allocation decisions and the inherent trade-offs associated with these benefit from better understanding of the value to society of specific attributes and policy outcomes.

[B]This included Bowali visitor centre, Warradjan cultural centre, and Yellow Water visitor centre, Jabiru Bakery, BP petrol station in Jabiru and all the major hotels and campsites in Jabiru.

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Questions relevant to the integrated risk-assessment paper

(1) Do tourists have different preferences regarding the protection of different emblematic park features when considering the impacts of future climate change?

(2) Of the park features listed in the survey, where would freshwater ecosystems sit with respect to visitor preference? Is it high on the list (e.g. the Yellow Water waterbird tours)?

(3) What proportion of respondents would still use the park if freshwater ecosystems significantly reduced as a result of sea-level rise; for example, to view rock art or other assets not physically affected by climate change?

(4) What proportion of respondents were willing to pay a climate-change conservation fee, in addition to the entrance fee, for active management of climate-change impacts, and what proportion thought that government needed to pay all future costs of managing climate-change impacts?

Preliminary results

Respondents were asked to rank different features of the park to indicate how important each one was to them when considering alternative levels of management and cost. A summary of their weighted preferences is shown in Fig. S10. Generally, respondents stated that they placed greater importance on protecting the three main features of the park than on the cost of their participation in the climate-change fund; these features are conservation of terrestrial plants and species, conservation of aquatic plants and species, and aboriginal rock-art sites. The weighted preferences of these three features were respectively 25, 24 and 22%, basically showing similar ranked preferences across them.

Aboriginal rock art sites	**Impact.** More frequent and intense fires & floods could make Aboriginal rock art sites less accessible or potentially damage them. Sea level rise could restrict access to some cultural sites on low-lying floodplains. **Action.** Implement more broad scale fire management programs and infrastructures (e.g. levee banks) to protect low-lying floodplain sites.
Aquatic freshwater habitats and their associated plant and animal species	**Impact.** Sea level rise will increase saltwater inundation which will in turn impact freshwater plant and animals . **Action.** Rehabilitate and protect freshwater habitats from saltwater inundation in order to protect plant and animal biodiversity into the future.
Terrestrial habitats and their associated plant and animal species.	**Impact.** An increase in temperature will result in more frequent and intense fires, which will impact on the ecology of terrestrial plants and animals. **Action.** Implement more broad-scale fire management programs on the park including the development of new infrastructure needed to maintain tourist activities and to enhance visitor safety.
Recreational fishing	**Impact.** Recreational catches of freshwater fish and of fish such as barramundi that depend on both freshwater and saltwater habitats for their life cycle (diadromous species) could decline due to loss of freshwater nursery habitats. **Action.** Rehabilitate and protect freshwater fish habitats from saltwater inundation (particularly nursery habitats), in order to maintain stocks of freshwater (e.g. black brim) and diadromous (e.g. barramundi) recreational species.

Fig. S9. Features and potential climate-change impacts and actions.

The cost of the climate-change fund was ranked fourth, with 18% of the weighted responses, followed by the protection of fishing, with only 2% of the weighted responses. The low level of consideration given to fishing is likely to be related to the fact that a low number of respondents in the survey indicated that fishing was their primary reason for visiting the park. Eight visitors, who stated either ‘I don't believe the consequences of climate change are that bad so no need to worry about any of the options' or 'I don't think Kakadu National Park needs further protection' did not provide answers to this component, and so could not be included in the ranked preferences.

The protection of freshwater ecosystems was considered to be important by respondents; however, overall, it was ranked a close second to the protection of terrestrial habitats (Fig. S10). Although respondents placed a greater importance on the protection of the park main features, they also stated that cost was a variable they would consider if they were to participate in a conservation fund. A more detailed understanding of visitors' willingness to pay to protect specific features of the park will be obtained from a detailed analysis of the choice experiment (J. Innes, unpubl. data, 2015).

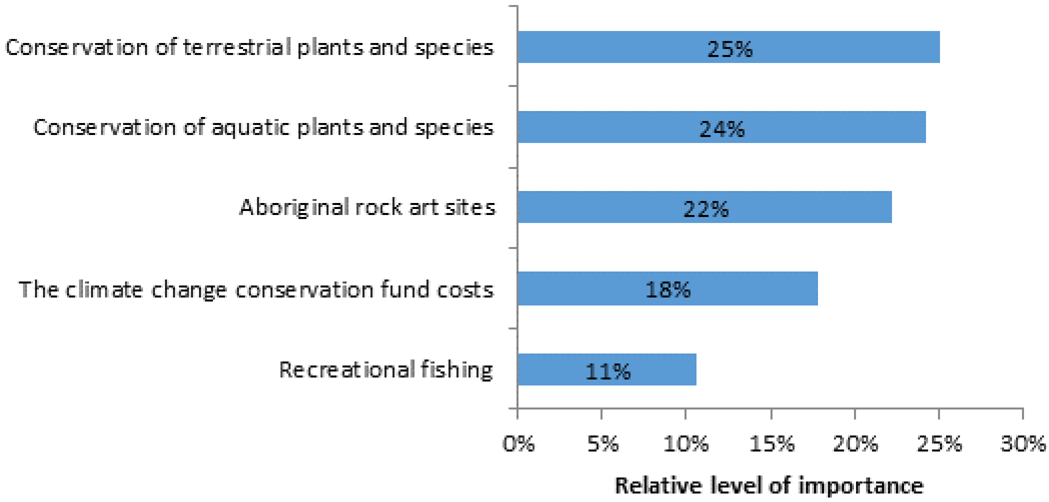

Fig S10. Stated importance of different attributes when considering alternative levels of management and cost.

When a range of alternative levels of management and costs was presented to individuals, 91% (*n* = 243) indicated that they would be willing to pay for at least some additional level of management action directed towards mitigating the impacts of climate change. The remaining 9% of respondents (*n* = 23) indicated that they were unwilling to contribute as much as the minimum amount proposed (A$15 in every year they visited the park). The most commonly stated reason for this was that respondents believed that the Government should be funding mitigation out of its existing budget (*n* = 9). This was followed by respondents believing that Kakadu National Park did not require further protection (*n* = 5), followed by their financial circumstances preventing them from being able to afford it (*n* = 4), the belief that the consequences of climate change are not bad enough to worry about the mitigation options presented (*n* = 4), and that a different fire management strategy is required instead (*n* = 1).

Interestingly, 22% of respondents indicated that they had not paid the park-entry fee on their most recent trip (note that Northern Territory residents and children ≤16 years are exempt from the park-entry fee). Of the individuals that had indicated that they were unwilling to pay for impact mitigation, 29% had not paid the fee, whereas only 21% of the individuals that were willing to fund additional mitigation work had not paid the fee. However, 41% of visitors stated that they would not have gone to the park if the impacts of climate change meant that it was no longer possible for them to do the activities they were planning to undertake.

The data used in Table S6 are from the results of the 2014–2015 visitor survey on Kakadu National Park (J. Innes, unpubl. data, 2015). Estimates of risk probability are for demonstration purposes only in the integrated risk-assessment (IRA) framework presented in the paper. That is, they are not based on real projections. We assumed that annual revenue loss would be reflected in reduced park-entry fees, here arbitrarily set to A$10 million year^{-1} However, this could be much higher if an economic multiplier effect throughout the Kakadu region, and the Northern Territory generally, is applied (Tremblay 2010). For example, Gillespie Economics and BDA Group (2008) estimated that Kakadu and Uluru–Kata Tjuta national parks combined contributed more than A$320 million year^{-1} to regional economies in the Northern Territory. Straton and Whitten (2009) estimated ~A$36 million in 1991, using conventional travel-cost methods and, in contrast, A$647 million by using contingent valuation methods. They, therefore, argued that it is important to identify which environmental impacts the non-market value estimate represents and which it does not. However, notwithstanding the range of estimates, Indigenous tourism is a key component of existing and future tourism opportunities in the Kakadu region, and is recognised as being a major component of the national long-term tourism strategy of this industry sector and of the economic development of Indigenous Australians (Tourism Research Australia 2011).

Table S6. Derivation of the economic risk associated with future large-scale loss of freshwater ecosystems in the Kakadu region as a result of projected climate change-induced sea level-rise (SLR) impacts (e.g. by 2100)

P_{tourism} is the proportion of survey respondents that prioritised each key park landscape attribute for future protection (i.e. excludes responses to the climate change fund question). Adjusted P_{tourism} rescales these values to a maximum of 1.0 and is a relative measure of visitor preference for different landscapes. The estimates are only 'what if'-scenario estimates based on tourist preferences for freshwater aquatic landscapes and their natural and cultural attributes (e.g. the Yellow Water waterbird tours)

Landscape attribute	Relative importance	P_{tourism}	Adjusted P_{tourism}	Million dollars (park entry fee)	Million-dollar cost SLR impacts due to loss of freshwater habitats
Terrestrial	0.25	0.25	0.30	3.0	
Freshwater aquatic	0.24	0.24	0.29	2.9	2.9
Rock art	0.22	0.22	0.27	2.7	
Climate change conservation fund	0.18				
Recreational fishing[A]	0.11	0.11	0.13	1.3	0.67
Total	1.00	0.82	1.00	10.0	3.6

[A]Assumes that 50% of fishers prefer saltwater fishing.

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