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Supplementary Material

Carbon-dioxide-driven increase in foliage projective cover is not the same as increased woody plant density: lessons from an Australian tropical savanna

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Supplementary material for Crowley and Murphy: *Carbon-dioxide-driven increase in projective foliage cover is not the same as elevated carbon sequestration: Lessons from an Australian tropical savanna*

Appendix S1. Persistent Green and fire mapping

Persistent Green (PG) mapping is undertaken every three months by the Department of Environment and Science (2022) as a measure of foliage area. PG is derived from sequential Landsat-5 TM (2001-2013) and Landsat-7 ETM+ (1999 onwards; Armston *et al.* 2009) images after the effects of landform, shadows, clouds, water, and variation in radiance and reflectance are removed using a masking process with an average accuracy of 97-98% (Tindall *et al.* 2014). Fractional green cover is then extracted using an unmixing process with a root mean square error of 9.5% (Scarth *et al.* 2015b). PG is calculated from the green fraction that persists through several sequential Landsat images. Values are stabilized through comparison with imagery two years on either side of the date of interest, creating a two-year lag in PG availability. PG is calibrated using on-ground measurements of vegetation structure collected from more than 1,500 sites across Australia (Scarth *et al.* 2015a). Maps of fires across Northern Australia, derived from MODIS, VIIRS and NOAA satellite imagery, are available through the North Australia Fire Information website at a resolution of 250 m (Charles Darwin University 2021).

PG is available as a single raster for each of four seasons each year: Summer (December to February), Autumn (March to May), Winter (June to August) and Spring (September to November; Fig. S1) using images from a range of dates depending on availability of cloud-free imagery. Fire mapping for carbon accounting in northern Australia uses two seasons: Early Dry Season (EDS; January to July) and Later Dry Season (LDS; August to December (Whitehead *et al.* 2015). Average fire extent on Cape York Peninsula between 2000 and 2018 was lowest in Autumn (0.8 ± 0.2%; Fig. S1). Hence, PG from Autumn (APG) is least affected by fires from the current year (Fig. S1). We therefore APG used to examine any lasting impact of previous-year fires on changes in foliage area. However, this selection weakens the ability of the imagery to capture the impact of variation in wet season rainfall, as approximately one-quarter of annual rainfall occurs in Autumn (Fig. S2).

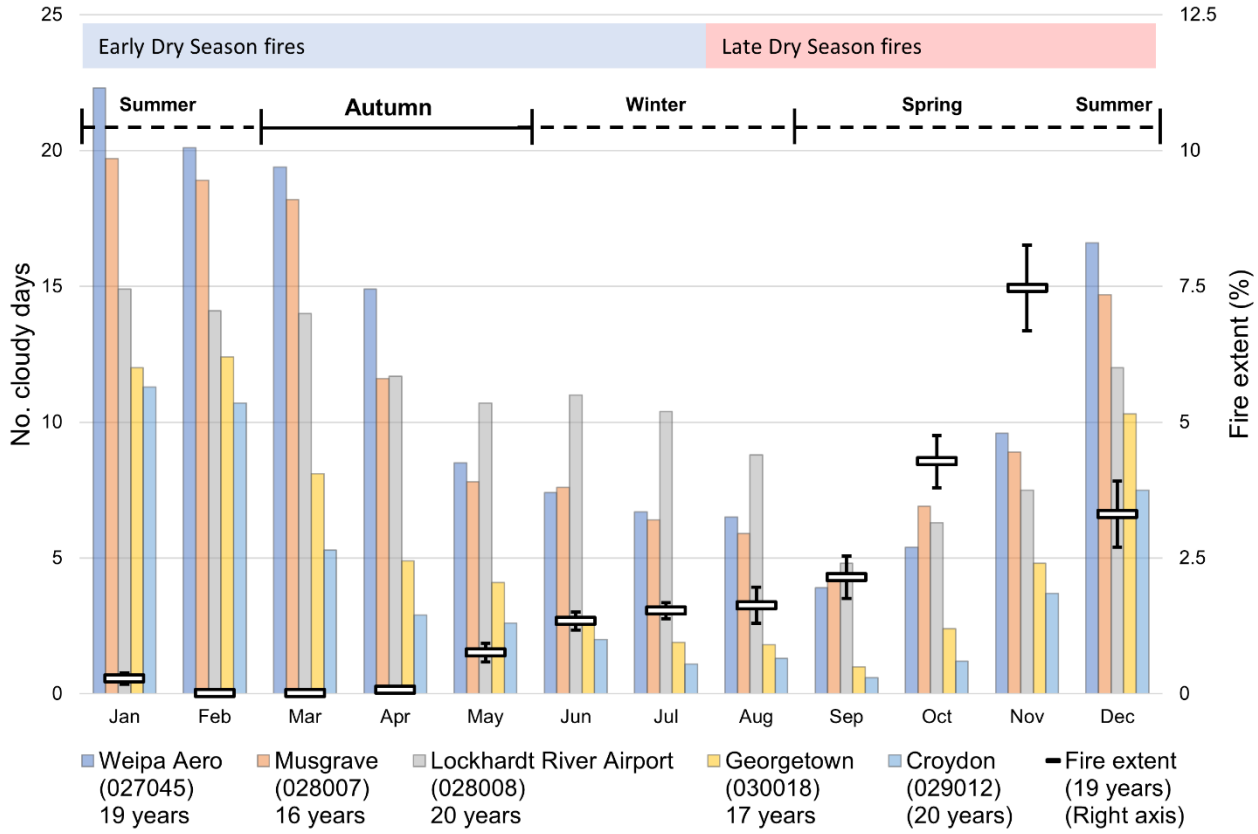

Fig. S1. Frequency of cloudy days (1991-2020) and extent of fire (2000-2018) (mean ± s.e.m.) across Cape York Peninsula.

A cloudy day is when the mean cloud cover at 9 am and 3 pm is at least 75% of the sky.

Sources of data: Cloud cover: (Bureau of Meteorology 2023); Fire extent: Charles Darwin University (2021).

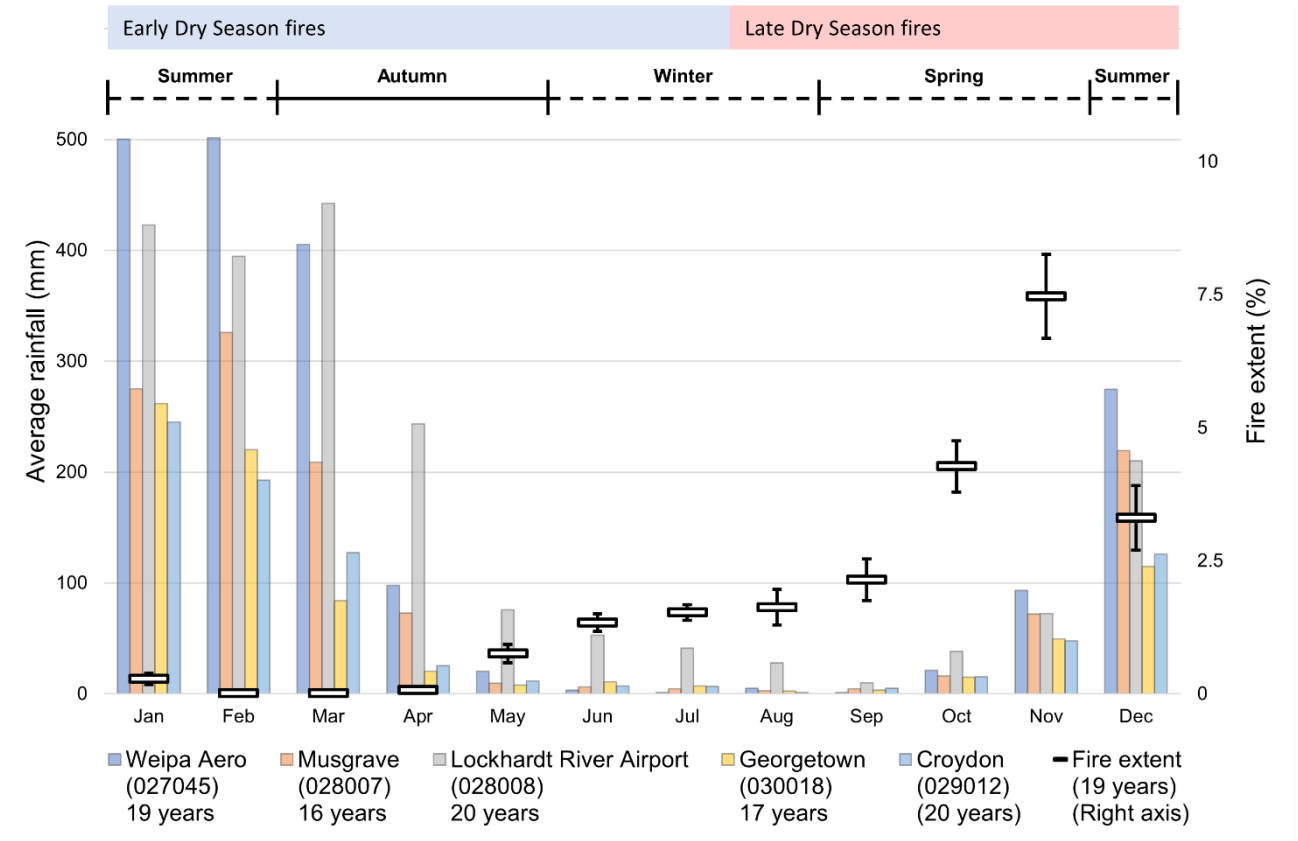

Fig. S2. Rainfall (1991-2020) and extent of fire (200**0**-2018) **(mean ± s.e.m.)** across Cape York Peninsula.

EDS = Early Dry Season; LDS = Late Dry Season.

Source of data: Rainfall: (Bureau of Meteorology 2023); Fire: Department of Environment and Science (2018).

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Appendix S2. Characteristics of the study area

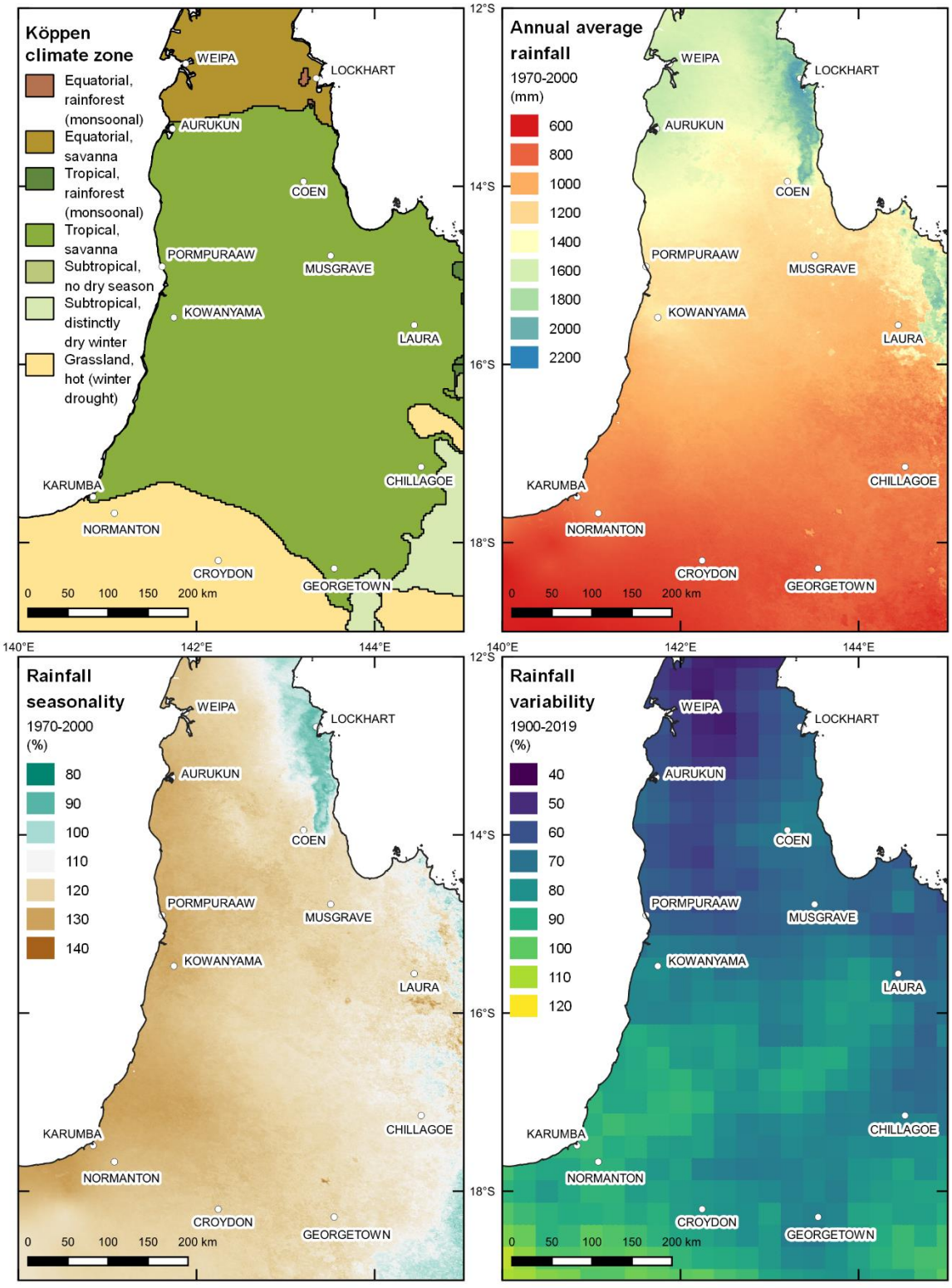

Fig. S3. Climate of the study area.

Sources of data: Köppen climate zones: Bureau of Meteorology (2006) based on Dick (1975); 1961-1990 Average annual rainfall: Bureau of Meteorology (2008); Rainfall seasonality: Fick and Hijmans (2017); and Rainfall variability: Bureau of Meteorology (2021).

Table S1. Classification and extent of vegetation communities assessed in this study.

Name	1:5 million scale Broad Vegetation Group (BVG)[a]	Main study area (%)[b]	Artemis Antbed Nature Refuge (%)[b]
Rainforest	1. Vine forests and thickets	1.62	-
Eucalypt woodland	3. Woodlands to open forests, primarily dominated by Darwin Stringybark, Clarkson's Bloodwood, Hyland's Bloodwood or Ironbarks, often with Melville Island bloodwood or Cooktown Ironwood	45.45	56.4
	6. Eucalypt low open woodlands usually with spinifex understorey	2.22	-
Floodplain forest	4. Open forest and woodlands drainage lines and alluvial plains, primarily dominated by Coolabah/Coolibah, Shiny-leaved and Molloy Box	12.35	3.7
Tea tree woodland	8. Open woodlands on depositional plains, primarily dominated by Broad-leaved Tea Tree, often with other tea tree species, bloodwoods and/or bauhinia. Includes riparian paperbark communities	18.82	26.3
Grassland	13. Tussock grasslands and forblands characterised by wanderrie, wire and panic grasses, Annual Kangaroo Grass, Ribbon Grass, Silky Browntop and Queensland Bluegrass	7.72	9.1
Other communities	2. Wet tall open forest characterised by Red Mahogany, White Mahogany, Pink Bloodwood, Gympie Messmate and Turpentine, or Rose Gum, often with Forest Oak and Stringybark Pine in the subcanopy	0.01	-
	5. Dry woodlands on inland depositional plains, dominated by Shiny-leaved and Molloy Box on Cape York Peninsula and by Gilbert River Box and Silver-leaved Ironbark on the Gulf Plains	3.97	-
	7. Woodlands to open forests dominated by Coast Cypress Pine with ironbarks, bloodwoods and wattles	0.08	-
	10. Lancewood woodlands and open forests other wattle-dominated communities	2.79	-
	11. Mixed species low open woodland to low woodland characterised by Beefwood, Hooker's Bauhinia, Whitewood, Yellow-wood, Cooktown Ironwood, wattles and kapoks	0.82	-
	12. Heath communities characterised by Thryptomene, Liniment Tree or Brown Salwood on Cape York Peninsula, and by Weeping Ghost Gum in the Gulf Plains	1.61	4.4
	14. Spinifex grassland	0.14	-
	15. Seasonal swamps, lakes and lagoons, often fringed with broad-leaved and other tea trees eucalypts, commonly vegetated with Mud Grass, Wild Rice, sedges or rushes	0.65	0.2
	16. Mangroves and tidal saltmarshes	1.75	-

a: Department of Environment and Science (2018a); b: (Department of Environment and Science 2021).

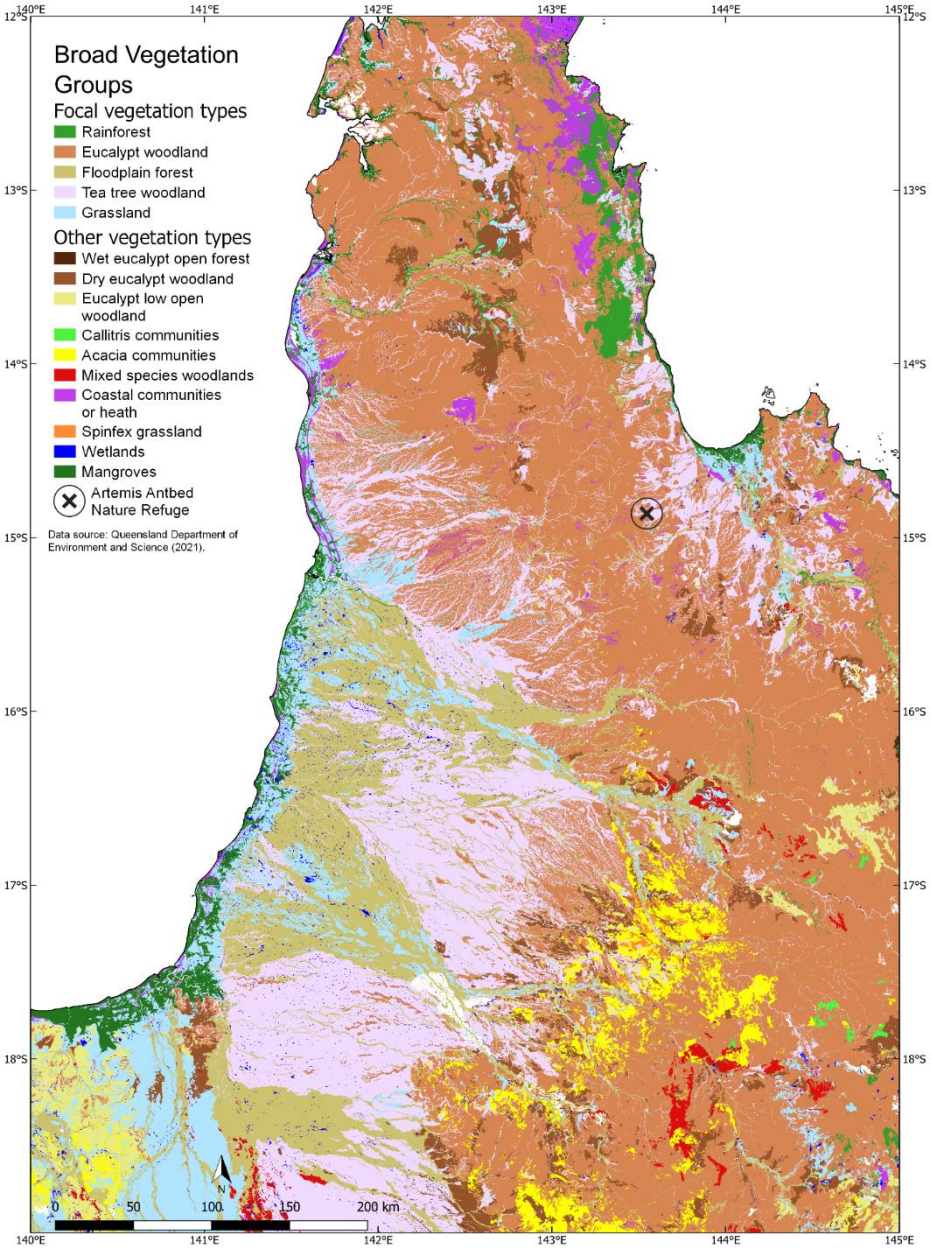

Fig. S4. Vegetation of the study area.

Source of data: Department of Environment and Science (2018a).

Table S2. Grazing and land tenure classes of the study area.

Grazing tenure	Land use/Tenure class	Study area (%)
1	Grazed up until 2018	76.5
0	Aboriginal reserve until 1987 followed by transfer to Aboriginal tenure	7.6
0	Managed for conservation from at least 1990	6.4
0	Managed for conservation from at least 2000	1.1
N/A	Grazed up until 2010	6.1
N/A	Excluded	2.4
	Total area (km^2)	272,885
	Aboriginal land in 2018 (%)	28.7

Sources of data: Balkanu Cape York Aboriginal Corporation (2004); Cape York Land Council (2014); Department of Environment and Science (2020); Department of Natural Resources (2018); Holmes (2011); State of Queensland (1994-2018); L. Kazmeier pers. comm. (2021); and personal knowledge of the authors.

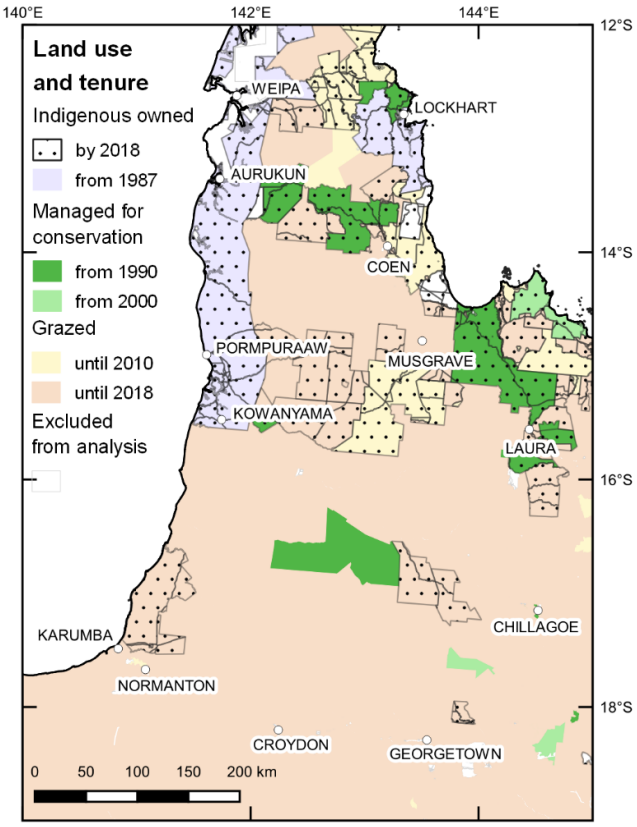

Fig. S5. Land use and tenure classes in the study area.

Sources of data: See Table S2. Disclaimer: This map does not claim to represent Native Title or any other land claims.

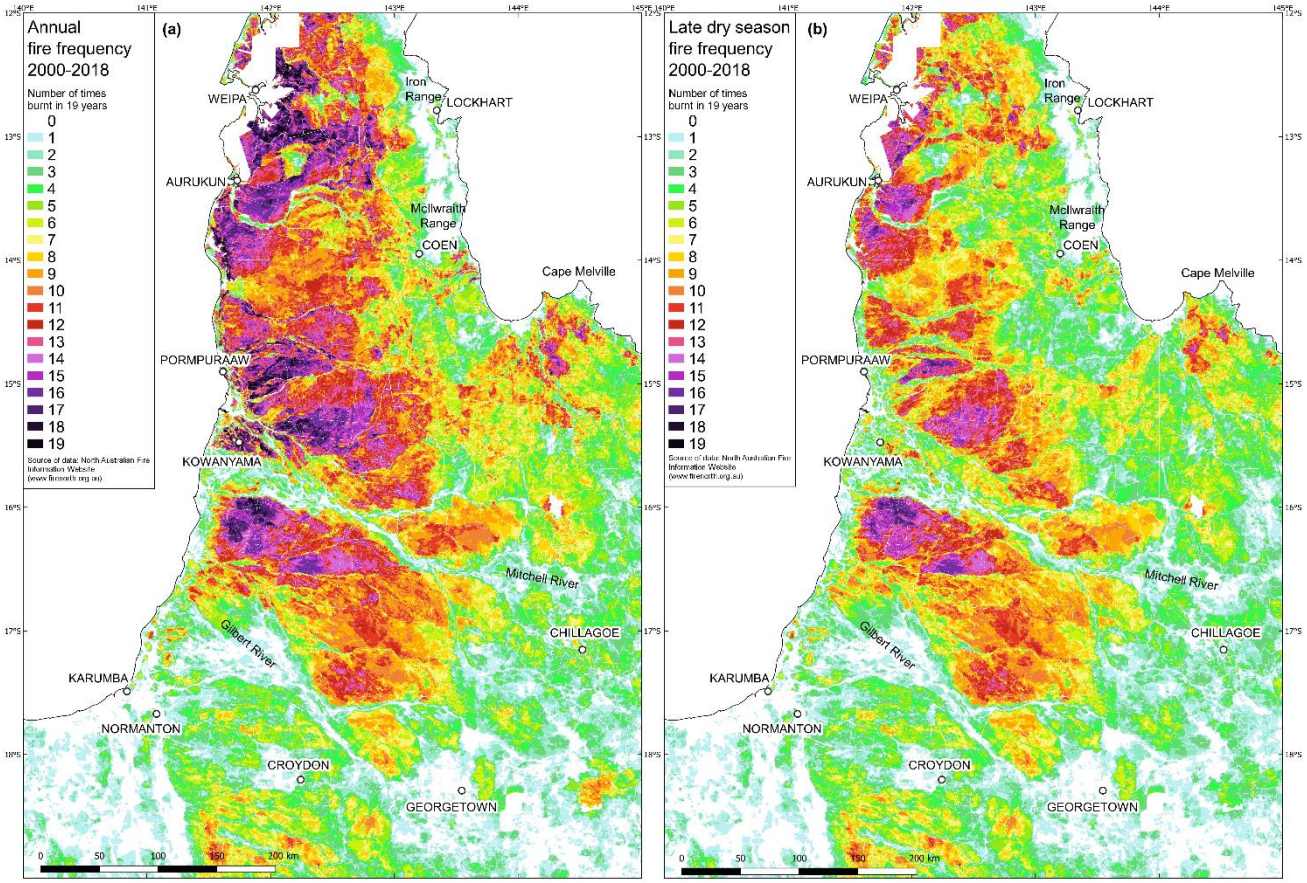

Fig. S6. Fire frequency in the study area over the study period: (a) All fires; and (b) Late Dry Season fires.

Sources of data: North Australian Fire Information website (Charles Darwin University 2021).

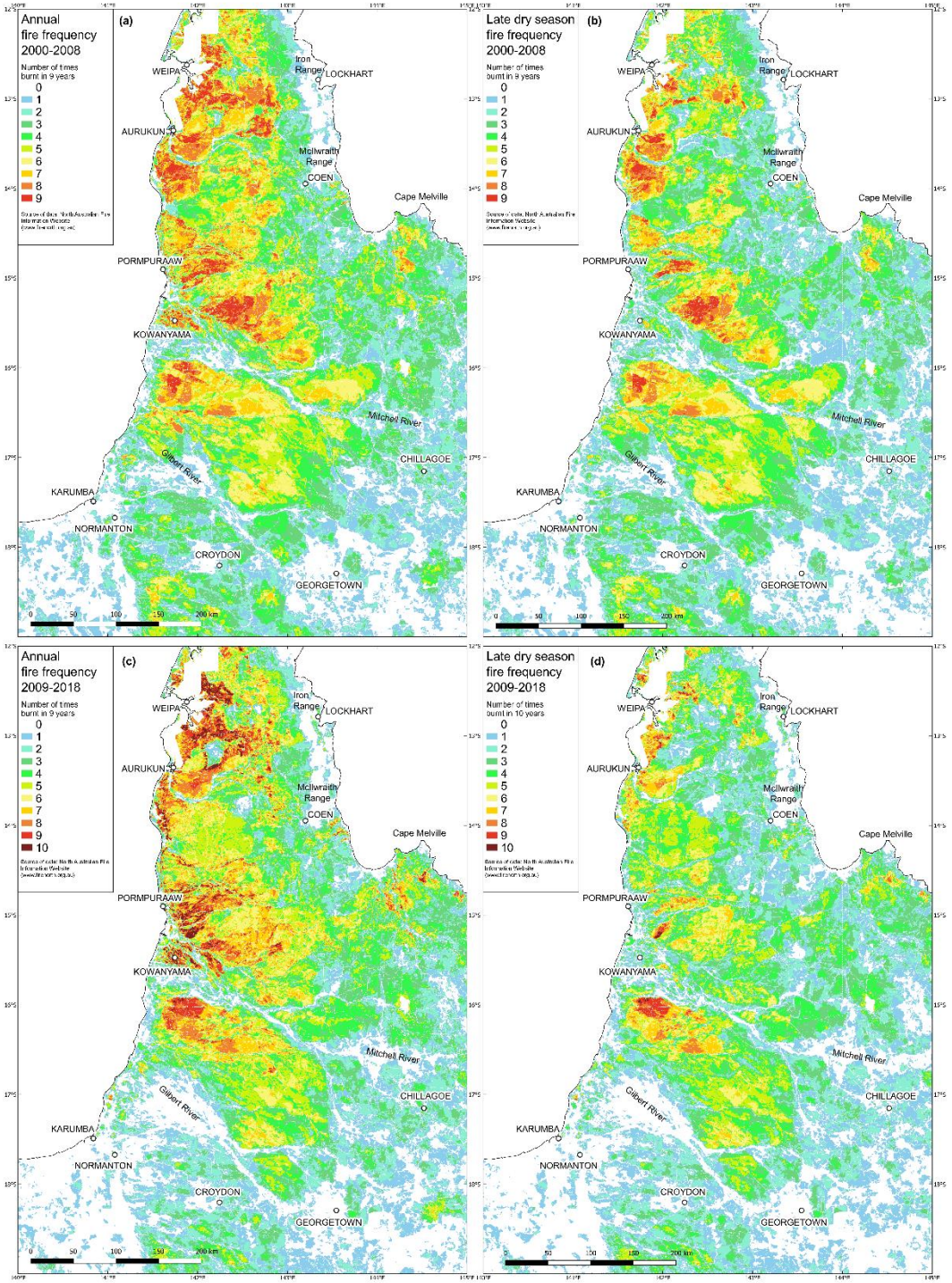

Fig. S7. Fire frequency in the study area for 2000-2008: (a) All fires; and (b) Late Dry Season fires; and for 2009-2018: (c) All fires; and (d) Late Dry Season fires.

Sources of data: North Australian Fire Information website (Charles Darwin University 2021).

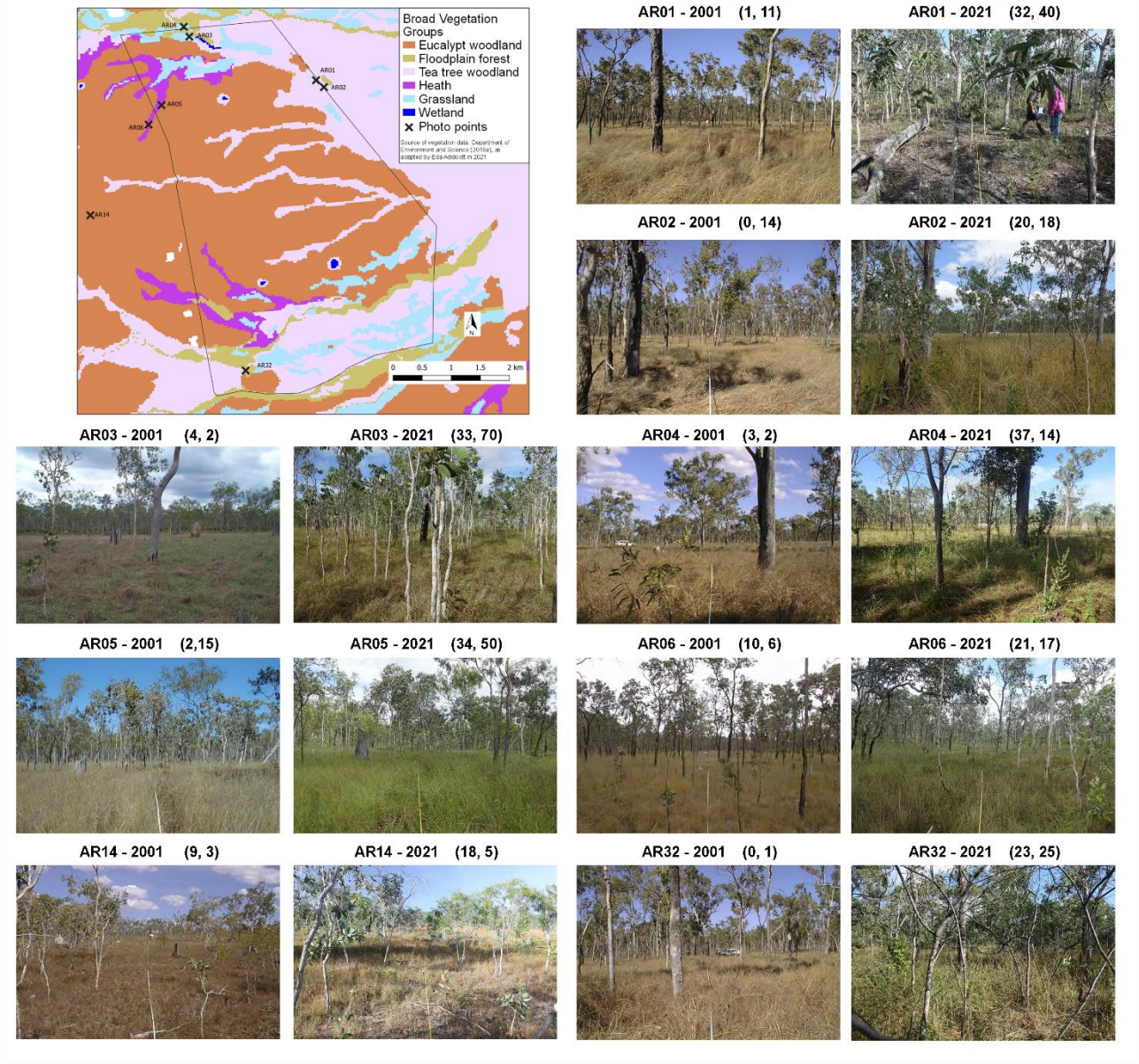

Fig. S8. Vegetation and vegetation change at monitoring plots in and around Artemis Antbed Nature Refuge.

Numbers in brackets indicate number of woody plants (1 – 3 m high, > 3 m high).

Source of vegetation mapping data: (Department of Environment and Science 2018b), as adapted by Eda Addicott in 2021.

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Appendix S3. Data layers used in modelling

Table S3. Data layers used in generalised additive modelling to explain incidence of fire and change in Seasonal Persistent Green. Processing was undertaken in R or QGIS.

Variable	Description and source	File properties	Processing
Sample points	Random sample stratified by vegetation type, excluding points on areas of non-remnant vegetation, or properties under extractive use or for which grazing land tenure had changed between 2001 and 2018	Text (csv) file in EPSG:3577	None
Autumn Persistent Green	Seasonal persistent green 2001-2018 (Department of Environment and Science 2022)	Raster with 30 m pixels in EPSG:3577	None
Vegetation types	1:5 million Broad Vegetation Groups (Department of Environment and Science 2021)	Polygon shapefile at 1:100,000 in EPSG:4283	Rasterised to 30 m resolution in EPSG:3577
Early Dry Season fires	Early Dry Season fire scar mapping (Charles Darwin University 2021)	MODIS-derived, 250 m pixels in EPSG:4283	Disaggregated to 30 m resolution in EPSG:3577
Late Dry Season fires	Late Dry Season fire scar mapping (Charles Darwin University 2021)	MODIS-derived, 250 m pixels in EPSG:4283	Disaggregated to 30 m pixels in EPSG:3577
Annual rainfall	Mean annual rainfall (1961-1990; Bureau of Meteorology 2008)	Raster with 0.025° (~2.5km) pixels in EPSG:4283	Disaggregated to 30 m resolution in EPSG:3577
One-, two- and three-yearly percentage rainfall anomalies	Calculated from 12-monthly (July to June Rainfall anomalies (1986 to 2018) (Bureau of Meteorology order Q- L39D325264	Raster in netCDF format with 0.05° (~5.7 km) pixels in EPSG:3577	Disaggregated to 30 m resolution in EPSG:3577
Grazing land tenure	Property-scale land use map derived from Balkanu Cape York Aboriginal Corporation (2004); Cape York Land Council (2014); Department of Environment and Science (2020); Department of Natural Resources (2018); Holmes (2011); State of Queensland (1994-2018); L. Kazmeier pers. comm. (2021); and personal knowledge of the authors	Polygon shapefile at 1:100,000 resolution in EPSG:3577	Rasterised to 30 m resolution in EPSG:3577

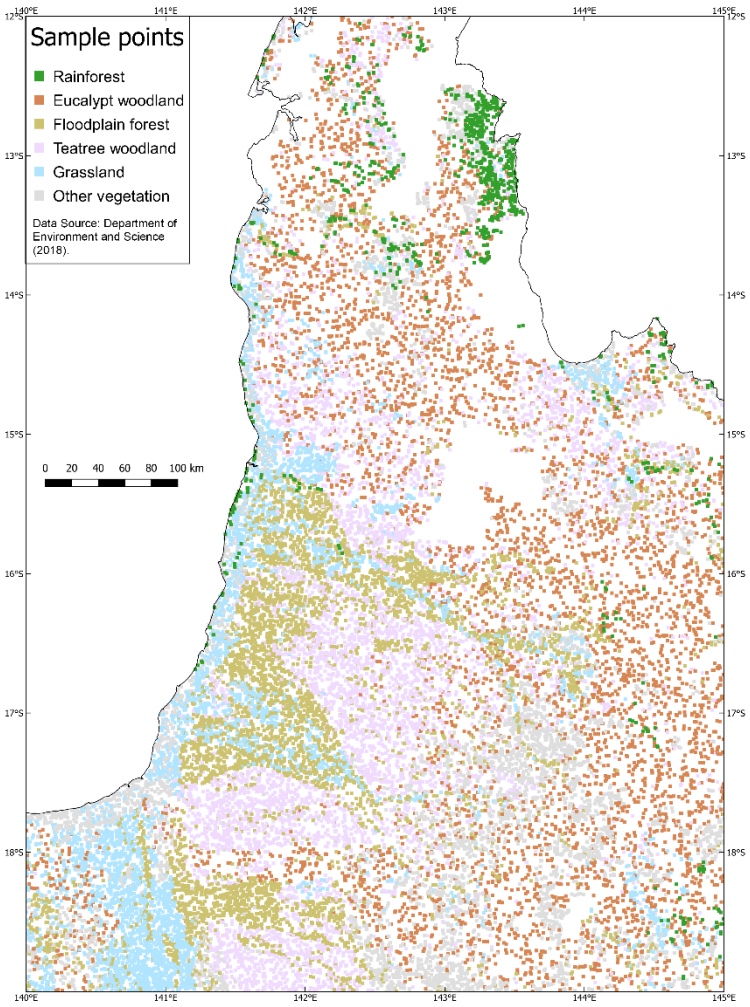

Fig. S9. Sample points used in the modelling, stratified by vegetation type

Source of vegetation data: Department of Environment and Science (2018).

Table S4. Number of sample points used in the modelling, stratified by vegetation type

Vegetation type	Points
Rainforest	959
Eucalypt woodland	5,246
Floodplain forest	5,742
Teatree woodland	5,591
Grassland	4,836
Other vegetation	5,248
Total	**27,622**

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Appendix S4. Variography

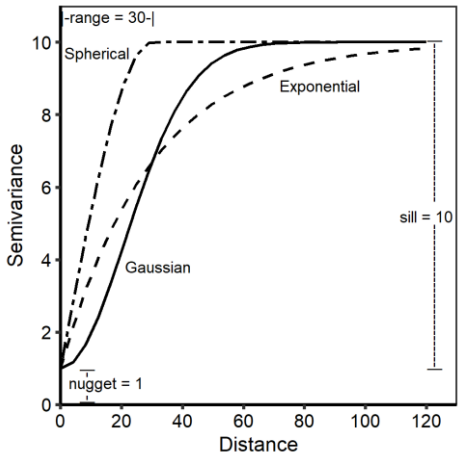

Fig. S10. Model variogram showing the features that reflect vegetation structure as explained in the text.

Table S5. Interpretation of variogram features (after Hamada *et al.* 2019).

Variogram feature	Attribute	Categories	Foliage cover (PG)
Sill	Variation in foliage cover (PG)	High	Varies greatly between absent and closed canopy
		Low	Uniform, whether absent, closed or intermediate
Nugget	Noise: within-pixel variation in foliage cover, not explained by distance	High	High within-canopy (within-pixel) variation
		Low	Low within-canopy (within-pixel) variation
Partial sill	Variation in foliage cover explained by distance or associated with spatial autocorrelation	High	High between-canopy (between pixel) variation
		Low	Low within-canopy (between pixel) variation
Range	Size of dominant patches of canopy cover	High	Large canopy patches interspersed with large canopy gaps
		Low	Small canopy patches interspersed with small canopy gaps
Form	Pattern of canopy features, and variance in their distribution	Gaussian	Variance increases gradually at short distances, then more rapidly towards sill e.g. relatively uniform patches of trees and canopy gaps
		Exponential	Variance initially increases rapidly, then gradually tapers towards sill. e.g. small clumps of trees within an open grassland
		Spherical	Variance increases at a relatively constant rate as distance between points increases only tapering close to the sill. e.g. trees and canopy gaps relatively interspersed

Reference

Hamada, Y, Szoldatits, K, Grippo, M, Hartmann, HM (2019) Remotely sensed spatial structure as an indicator of internal changes of vegetation communities in desert landscapes. *Remote Sensing* **11**, 1495. doi:10.3390/rs11121495

Appendix S5. Modelling of Early Dry Season and Late Dry Season fire occurrence on Cape York Peninsula (2001-2018)

Model inputs

R Package: mgcv; Family: gaussian; Link function: identity

Formula

A. EDS ~ s(Year, Vname, k = 18, bs = "fs") + s(BLY, bs = "re") + s(Grazing, bs = "re") + s(Rain.Avg, bs = "re") + s(RA1, bs = "re") + s(x, y, bs = "re")
B. EDS ~ s(Year, Vname, k = 3, bs = "fs") + s(BLY, bs = "re") + s(Grazing, bs = "re") + s(Rain.Avg, bs = "re") + s(RA1, bs = "re") + s(x, y, bs = "re")
C. LDS ~ s(Year, Vname, k = 18, bs = "fs") + s(EDS, bs = "re") + s(BLY, bs = "re") + s(Grazing, bs = "re") + s(Rain.Avg, bs = "re") + s(RA3, bs = "re") + s(x, y, bs = "re")
D. LDS ~ s(Year, Vname, k = 3, bs = "fs") + s(EDS, bs = "re") + s(BLY, bs = "re") + s(Grazing, bs = "re") + s(Rain.Avg, bs = "re") + s(RA3, bs = "re") + s(x, y, bs = "re")

Key to abbreviations

BLY = previous year fire season (classes: Unburnt, EDS, LDS)

bs = basis type

EDS = Burnt Early Dry Season (current year)

fs = factor smooth

Grazing = Grazing land tenure (Classes: Yes, No)

k = knots (nodes)

LDS =Burnt Late Dry Season (current year)

RA1 = one-year rainfall anomaly (%)

RA3 = three-year rainfall anomaly (%)

Rain.Avg = Average annual rainfall (1961-1990) (mm)

re = random effects

s = smooth function

Vname = Vegetation type (Classes: Rainforest, Eucalypt woodland, Floodplain forest, teatree woodland, Grassland, Other vegetation)

x = Easting

y = Northing

Model outputs

Table S6. Generalized additive models that best explained fire occurrence on Cape York Peninsula (2001-2018).

Parameter	Occurrence of Early Dry Season fire				Occurrence of Late Dry Season fire			
Formula	A		B		C		D	
Model	Best-fit		Maximum smooth		Binomial		Maximum smooth	
Family	Binomial		Binomial		Binomial		Binomial	
Link function	Logit		Logit		Logit		Logit	
Adjusted r^2	0.0922		0.082		0.165		0.137	
Deviance explained (%)	16.6		14.9		16.2		13.8	
k for fixed effects	18		3		18		3	
Variable	**Estimate**	***p***	**Estimate**	***p***	**Estimate**	***p***	**Estimate**	***p***
Intercept	-4.231	0.0000	-4.227	0.0000	-8.687	0.192	-9.566	0.148
	e.d.f.*	***p***	**e.d.f.***	***p***	**e.d.f.***	***p***	**e.d.f.***	***p***
Year interactions (basis type = factor smooth) as fixed effects								
Vegetation	103.7	0.0000	16.68	0.0000	106.0	0.0000	16.94	0.0000
Random effects (basis type = random effects)								
Burnt EDS	-	-	-	-	0.909	0.0000	0.914	0.0000
Burnt last year	2.000	0.0000	2.000	0.0000	1.998	0.0000	1.998	0.0000
Grazing land tenure	0.999	0.0000	0.999	0.0000	0.995	0.0000	0.995	0.0000
Average rainfall	1.000	0.0000	1.000	0.0000	1.000	0.0000	1.000	0.0000
1-year rainfall anomaly	0.993	0.0000	0.002	0.0000	-	-	-	-
3-year rainfall anomaly	-	-	-	-	0.995	0.0000	1.000	0.0000
Location (x, y)	0.995	0.687	0.9916	0.762	0.980	0.976	0.938	0.987
Analysis of deviance tests (X^2)								
Residual	**d.f.**	**Deviance**	**d.f.**	**Deviance**	**d.f.**	**Deviance**	**d.f.**	**Deviance**
	497,082	168,106	497,173	171,606	497,081	445,675	497,171	462,467
d.f.	-90.70				-89.98			
Deviance	-3,499				-16,792			
p	0.0000				0.0000			

* e.d.f. = effective degrees of freedom

Appendix S6. Modelling of Autumn Persistent Green on Cape York Peninsula (2001-2018)

Model input

R Package: mgcv; Family: gaussian; Link function: identity

Formula

A. APG ~ s(Year, Vname, k = 18, bs = "fs")

B. APG ~ s(Year, Vname, k = 18, bs = "fs") + (Vname * Burnt.LY) + (Vname * Grazing) + s(Rain.Avg, bs = "re") + s(RA3, bs = "re") + s(x, y, bs = "re")

Key to abbreviations

APG = Seasonal Persistent Green

bs = basis type

Burnt.LY (Classes: Unburnt, EDS, LDS)

fs = factor smooth

Grazing = Grazing land tenure (Classes: Yes, No)

k = knots (nodes)

RA3 = three-year rainfall anomaly

Rain.Avg = Average annual rainfall (1961-1990)

re = random effects

s = smooth function

Vname = Vegetation type (Classes: Rainforest, Eucalypt woodland, Floodplain forest, teatree woodland, Grassland, Other vegetation)

x = Easting

y = Northing

Model output

Table S7. Best-fit generalised additive model explaining Autumn Persistent Green on Cape York Peninsula (2001-2018).

Parameter	Vegetation trends				Full model			
Formula	A				B			
Family	Binomial				Gaussian			
Link function	Logit				Identity link			
Adjusted r^2	0.376				0.586			
Deviance explained (%)	37.6				58.6			
Parametric coefficients	**Estimate**	**s.e.**	***t***	***p***	**Estimate**	**s.e.**	***t***	***p***
(Intercept)	18.72	5.18	3.221	0.0013	19.63	0.277	70.85	0.0000
Year interactions (basis type = factor smooth) as fixed effects								
Vegetation type								
Eucalypt woodland	-	-	-	-	-27.99	0.220	-127.46	0.0000
Floodplain forest	-	-	-	-	-31.32	0.238	-131.91	0.0000
Teatree woodland	-	-	-	-	-34.89	0.218	-159.91	0.0000
Grassland	-	-	-	-	-46.22	0.227	-203.76	0.0000
Other vegetation	-	-	-	-	-27.56	0.218	-126.32	0.0000
Other fixed effects (basis type = factor smooth)								
Previous-year fire season								
EDS	-	-	-	-	-16.56	0.439	-37.74	0.0000
LDS	-	-	-	-	-12.20	0.286	-42.69	0.0000
Grazing land tenure								
Yes	-	-	-	-	-11.94	0.178	-67.20	0.0000
Vegetation type – fire season interactions								
Eucalypt woodland EDS burnt	-	-	-	-	15.30	0.462	33.10	0.0000
Eucalypt woodland LDS burnt	-	-	-	-	11.92	0.298	40.03	0.0000
Floodplain forest EDS burnt	-	-	-	-	11.27	0.473	23.84	0.0000
Floodplain forest LDS burnt	-	-	-	-	7.543	0.297	25.36	0.0000
Teatree woodland EDS burnt	-	-	-	-	10.80	0.463	23.32	0.0000
Teatree woodland LDS burnt	-	-	-	-	7.813	0.295	26.45	0.0000
Grassland EDS burnt	-	-	-	-	12.92	0.468	27.59	0.0000
Grassland LDS burnt	-	-	-	-	9.449	0.306	30.86	0.0000
Other vegetation EDS burnt	-	-	-	-	10.58	0.481	21.98	0.0000
Other vegetation LDS burnt	-	-	-	-	9.885	0.301	32.84	0.0000
Vegetation type – grazing land tenure interactions								
Eucalypt woodland on Grazing land	-	-	-	-	7.017	0.201	34.97	0.0000
Floodplain forest on Grazing land	-	-	-	-	7.456	0.218	34.14	0.0000
Teatree woodland on Grazing land	-	-	-	-	12.56	0.197	63.75	0.0000
Grassland on Grazing land	-	-	-	-	15.10	0.208	72.71	0.0000
Other vegetation on Grazing land	-	-	-	-	4.17	0.203	20.58	0.0000
Approximate significance of smooth terms								
	Effective d.f.	**Reference d.f.**	***F***	***p***	**Effective d.f.**	**Reference d.f.**	***F***	***p***
s(Year, Vegetation type)	67.02	107	2,798	0.0000	84.54	1	83.54	0.0000
s(Average rainfall)	-	-	-	-	1.000	1	1.001	0.0000
s(three-year rainfall anomaly)	-	-	-	-	0.975	1	0.974	0.0000
s(y,x)	-	-	-	-	1.000	1	1.000	0.7700
Analysis of deviance tests (X^2)								
Residual	**d.f.**		**Deviance**		**d.f.**		**Deviance**	
	497,115		85,735,273		497,074		56,873,165	
d.f.	40.6							
Deviance	28,862,107							
p	0.0000							