10.1071/WF23193
International Journal of Wildland Fire

Supplementary Material

Framework for a savanna burning emissions abatement methodology applicable to fire-prone miombo woodlands in southern Africa

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Supplementary Table S1. Shrub dry weight measurements—

(a) Shrub species sampled in field and assigned Form Type

(b) Mean dry weight of Form Type species per height class

(c) Proportion of dry weight per shrub height class in respective vegetation structure types

(d) Proportion of leaf and woody fractions per shrub height class

(a) Shrub species sampled in field and assigned Form Type

Species	Type	Species	Type	Species	Type
Acacia erioloba	8	*Diospyros batocana*	1	*Parinari curatellifolia*	1
Acacia erubescens	8	*Diospyros chamaethamnus*	1	*Parinari suffrutex*	8
Acacia fleckii	8	*Diospyros kirkii*	1	*Peltophorum africanum*	4
Acacia nigrescens	8	*Diospyros mespiliformis*	1	*Pericopsis angolensis*	4
Acacia sp	8	*Diospyros sp*	1	*Philenoptera nelsii*	6
Afzelia quanzensis	6	*Diospyros whyteana*	1	*Phyllocosmus lemaireanus*	8
Albizia versicolor	4	*Diplorhynchus condylocarpon*	1	*Piliostigma thonningii*	2
Amblygonocarpus andongensis	4	*Euclea divinorum*	1	*Pseudolachnostylis maprouneifolia*	1
Annona sp	1	*Fadogia spp*	8	*Pterocarpus angolensis*	3
Baikiaea plurijuga	4	*Flacourtia indica*	1	*Pterocarpus antunesii*	3
Baphia massaiensis	1	*Fleuggea virosa*	1	*Rhus spp*	8
Bauhinia petersiana	2	*Friesodielsia obovata*	1	*Rhynchosia spp*	8
Brachystegia boehmii	3	*Gardenia imperialis*	7	*Rothmannia englerana*	7
Brachystegia longifolia	3	*Grewia flavescens*	8	*Schinziophyton rautanenii*	8
Brachystegia natallis	3	*Grewia monticola*	1	*Securidaca longepedunculata*	8
Brachystegia spiciformis	6	*Grewia spp*	8	*Solanum sp*	8
Brachystegia spp	3	*Guibourtea coleosperma*	2	*Sphenostylis erecta*	8

Species	Type	Species	Type	Species	Type
Bridelia micrantha	1	*Gymnosporia senegalensis*	8	*Steganotaenia araliacea*	8
Burkea africana	4	*Hymenocardia acida*	8	*Strychnos cocculoides*	8
Colophospermum mopane	2	*Isoberlina angolensis*	6	*Swartzia madagascariensis*	6
Combretum apiculatum	5	*Jasminum sp*	8	*Terminalia brachystemma*	7
Combretum collinum	5	*Julbernardia globifolia*	6	*Terminalia sericea*	7
Combretum eleagnoides	7	*Julbernardia paniculata*	6	*Unknown*	8
Combretum hereroense	5	*Kigelia africana*	6	*Vangueria infausta*	7
Combretum molle	5	*Landolphia kirkii*	8	*Vangueriopsis lanciflora*	7
Combretum mossambicense	7	*Lannea discolor*	6	*Vitex doniana*	8
Combretum sp	5	*Maprounea africana*	1	*Xerompis obvovata*	8
Combretum zeyheri	5	*Monotes africana*	1	*Ximenia americana*	8
Croton gratissimus	8	*Ochna pulchra*	1	*Ximenia caffra*	8
Dalbergia sp	4	*Ochna suffrutex*	8	*Zanha africana*	8
Dalbergiella nyasae	4	*Otoptera burchellii*	8		
Dichrostachys cinerea	8	*Ozoroa spp*	8		

(b) Mean dry weight of Form Type species per height class

Type	Type species	Height class (cm)			
		<50	**50-100**	**100-200**	**>200**
		Mean dry wt (g)			
1	*Baphia massaiensis*	29	214	966	4295
2	*Bauhinia petersiana*	29	432	1860	4943
3	*Brachystegia longifolia*	15	112	651	1617
4	*Burkea africana*	25	147	533	2859
5	*Combretum collinum*	29	251	1044	4696
6	*Julbernardia paniculata*	48	257	461	638
7	*Terminalia sericea*	29	88	1377	3311
8	Average (all spp)	29	214	982	3332

(c) Proportion of dry weight per shrub height class in respective vegetation structure types

Shrub height class (cm)	Proportion shrub dry wt per vegetation structure type (%)			
	Open woodland	***Woodland <1000 mm***	***Woodland >1000 mm***	***Woodland (total)***
<50	0.9	4.2	14.4	7
50-100	6.9	13.6	15.9	14.2
100-200	51.7	43	18.4	36.2
>200	40.5	39.2	51.3	42.6

(d) Proportion of leaf and woody fractions per shrub height class

Fraction	Proportion of fraction per shrub height class (%)			
	<50 cm	***50-100 cm***	***100-200 cm***	***>200 cm***
leaf	60.4	39.9	28.1	20.9
twig and stem	39.6	60.1	71.9	79.1

Supplementary Table S2. Correlation matrix related to Principal Coordinate Analysis of tree floristics data and independent environmental and vegetation structure variables at 160 plot samples

Linear Pearson correlations between environmental variables ($P < 0.001$ for all). Rank-based Spearman correlations showed similar values with $P < 0.001$ for all (data not shown).

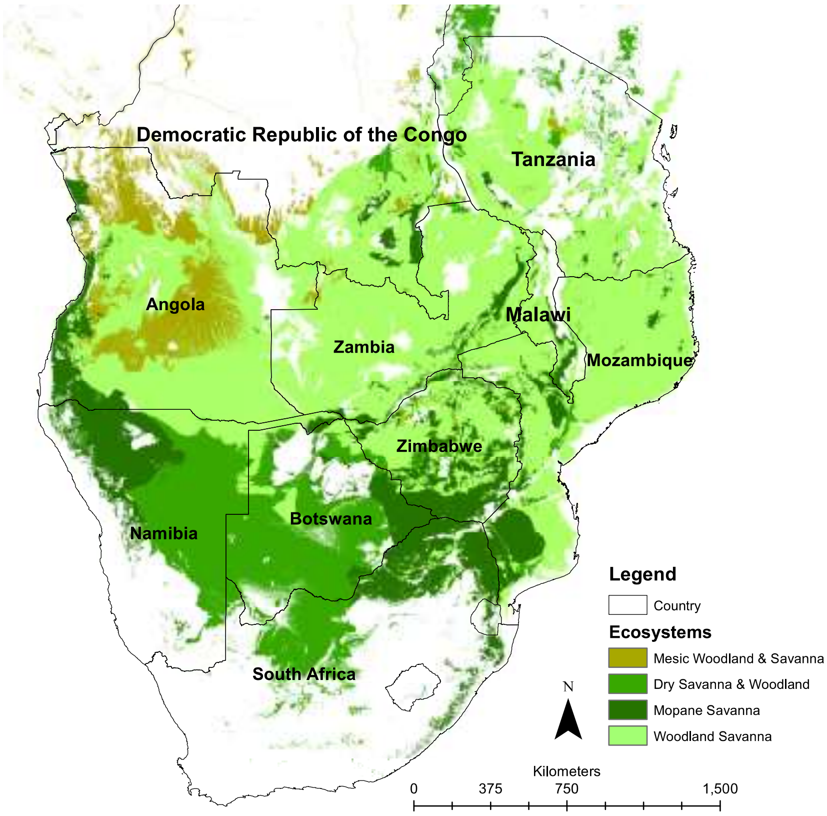
	Rainfall	Live Basal Area	Fire Frequency	Canopy Cover Index
Rainfall	1			
Live Basal Area	0.67	1		
Fire Frequency	-0.46	-0.45	1	
Canopy Cover Index	0.83	0.79	-0.43	1

Supplementary Table S3. Frequency (mean number of stems per plot) of common tree species (occurring at 5+ plots) in three rainfall-vegetation structure classes. Mean plot frequencies >0.5 given in **bold**.

Species	**<1000 mm MAR**		**>1000 mm MAR**
	OWDL	**WDL**	**WDL**
Albizia adianthifolia		0.38	**0.5**
Albizia antunesiana			**0.65**
Albizia versicolor		**0.93**	0.33
Amblygonocarpus andongensis	0.32	0.48	
Anisophyllea boehmii		0.04	**1.67**
Baphia bequaertii			**0.60**
Baphia massaiensis	0.03	**0.65**	0.04
Bauhinia petersiana		0.32	0.02
Brachystegia boehmii		**1.02**	**0.67**
Brachystegia bussei			**3.42**
Brachystegia floribunda		0.37	0.29
Brachystegia longifolia		0.79	**16.42**
Brachystegia spiciformis		**2.27**	**5.08**
Brachystegia utilis			**2.12**
Burkea africana	0.05	**1.79**	**0.92**
Colophospermum mopane		0.33	
Combretum apiculatum		**1.27**	
Combretum collinum	0.08	**1.05**	0.04
Combretum elaeagnoides		0.36	
Combretum hereroense	0.16	0.12	
Combretum molle		0.35	**0.62**
Combretum zeyheri	0.06	**1.10**	0.19
Commiphora angolensis	0.24	0.23	
Dalbergiella nyasae		0.36	**1.29**
Dichrostachys cinerea		**0.56**	0.12
Diospyros batocana		**0.89**	0.02
Diospyros kirkii		0.27	0.42
Diospyros whyteana			**0.56**
Diplorhynchus condylocarpon		**0.85**	**7.44**
Erythrophleum africanum	**0.92**	**1.99**	0.08
Faurea saligna			0.25
Flacourtia indica		0.21	0.06
Friesodielsia obovata		0.37	0.02
Guibourtia coleosperma	0.08	0.25	
Isoberlinia angolensis		0.51	**2.79**
Julbernardia globiflora		0.12	0.21
Julbernardia paniculata		**5.99**	**12.96**

Species	<1000 mm MAR		>1000 mm MAR
	OWDL	WDL	WDL
Marquesia macroura			**0.83**
Monotes africanus			0.48
Ochna pulchra		0.40	0.27
Ochna schweinwfurthiana		0.20	**1.67**
Olax obtusifolia		0.04	0.35
Parinari curatellifolia		0.02	**0.94**
Pericopsis angolensis		0.07	**1.29**
Phyllocosmus lemaireanus			**0.90**
Pseudolachnostylis maprouneifolia	0.08	**1.54**	**2.65**
Psydrax livida			0.29
Pterocarpus angolensis	0.03	0.73	**2.63**
Pterocarpus rotundifolius			0.21
Strychnos cocculoides		0.11	0.21
Strycnos poatorum			0.27
Swartzia madagascariensis		0.32	**1.12**
Syzygium cordatum			0.12
Syzygium guineense			**0.58**
Terminalia brachystemma	0.11	**0.58**	
Terminalia sericea	0.39	**1.37**	0.02
Terminalia stenostachya		0.26	
Uapaca bangweolensis			0.21
Uapaca kirkiana			**1.98**
Uapaca nitida		0.16	0.29
Uapaca sansibarica			**0.79**

Supplementary Fig. S1. Map of southern Africa savanna biome (after Sayre *et al*. 2013), and subsequent Table describing mean proportions of savanna biome burnt by large fires (>250 ha) and in Late Dry Season (LDS), 2001-2019, in respective countries. Fire mapping data derived from Collection 6 MODIS 500m burned area data (after Giglio *et al*., 2018); LDS is defined here as commencing July 1; fire extent mapping for the period 2001-2019 to be consistent with similar data for fewer countries reported in Russell-Smith *et al*. (2021).



Country	Mean proportion of savanna biome burnt, 2001-2019	Mean proportion of savanna biome burnt in LDS, 2001-2019
Angola	23.0	79.5
Botswana	9.0	95.0
Dem. Rep. Congo	30.1	53.5
Malawi	4.8	93.3
Mozambique	26.5	95.8
Namibia	7.0	94.3
South Africa	2.8	84.3
Tanzania	18.3	75.4
Zambia	27.3	86.6
Zimbabwe	8.2	95.9

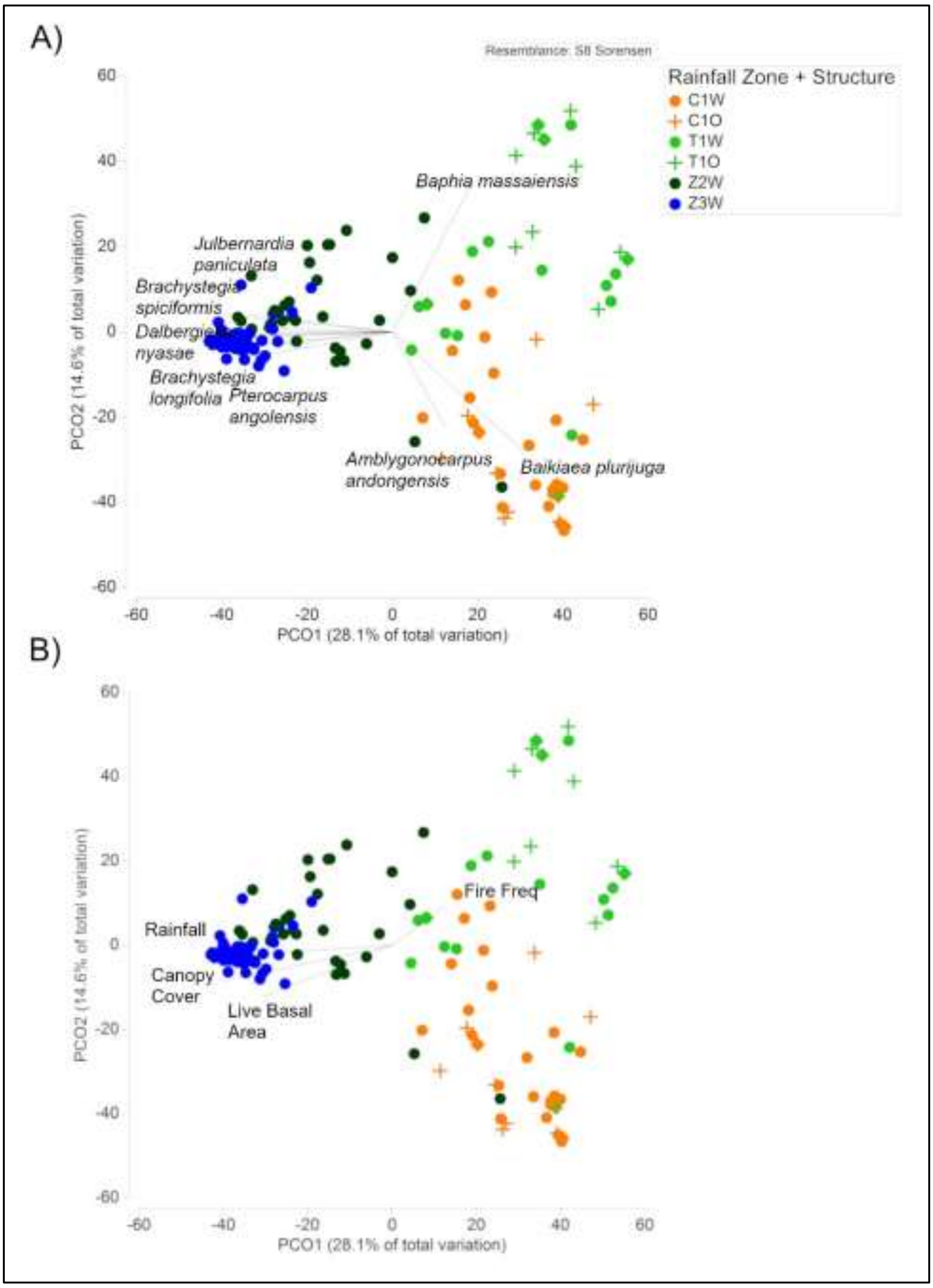
Supplementary Figure S2. Principal Coordinates Analysis (PCO) of plant assemblages based on a Sorensen resemblance matrix of the presence-absence species data. 28.1% of the variation in the data was explained by the first axis and 14.6% by the 2nd axis.

A) PCO with vectors showing the strength and direction of the relationship between the top correlated plant species and the PCO axes (Pearson correlations >0.5). **B)** same PCO with vectors showing the Pearson correlations with the corresponding normalized environmental variables.

Key: Botswana plots (all <1000 mm MAR)—C1W = Chobe site woodland; C1O = Chobe site open woodland;

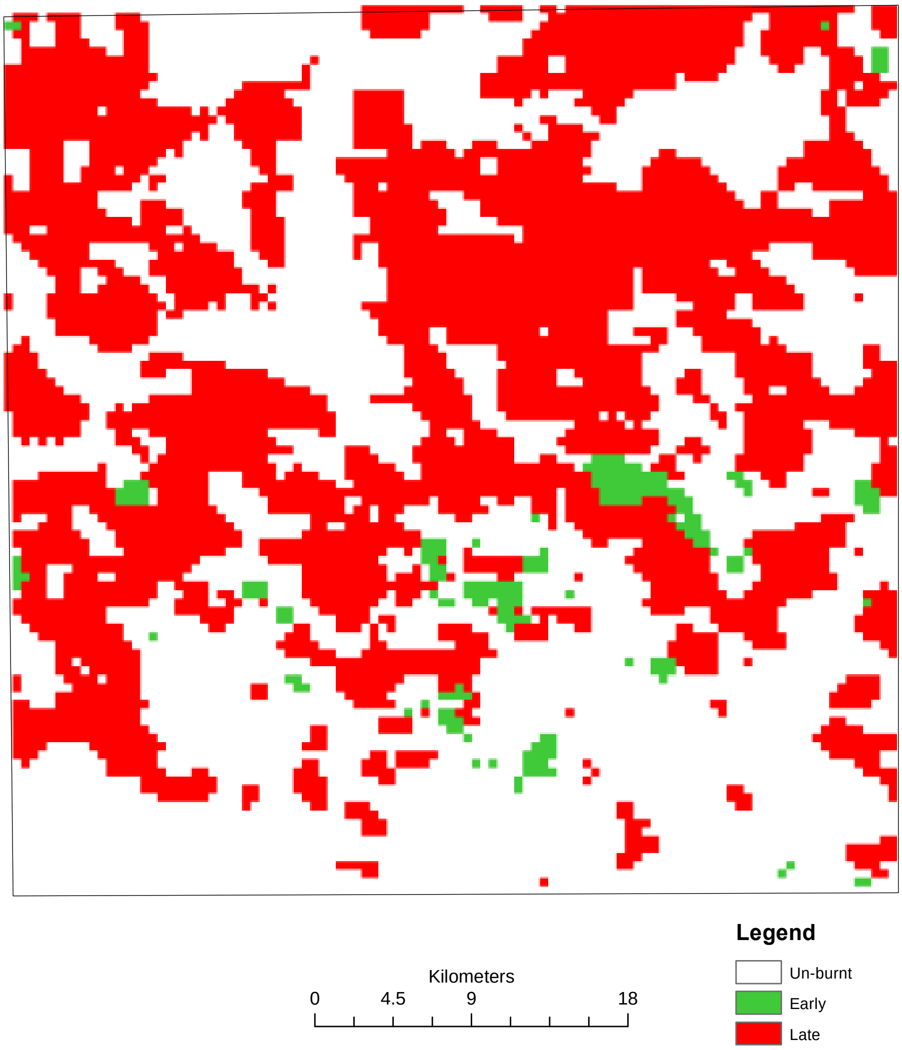
T1W = Tsodilo site woodland; T1O = Tsodilo site open woodland

Zambia plots—Z2W = woodland <1000 mm MAR; Z3W = woodland >1000 mm MAR

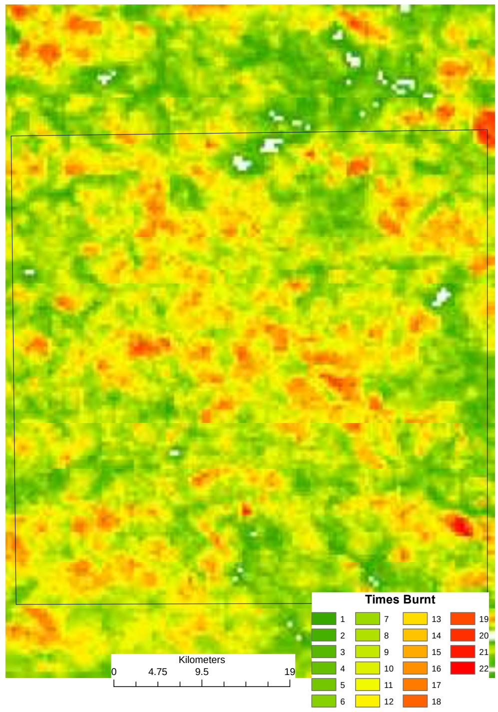


Supplementary Figure S3. Application of fire emissions parameters derived through this study to calculate emissions from a 2716 km^2 example miombo vegetation site, Zambia, based on available automated MODIS 500m fire mapping 2012-2022.

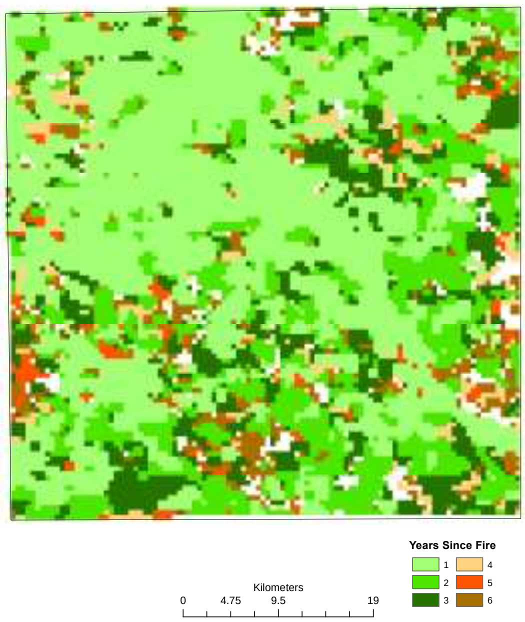
(i) Fire mapping 2022, where early dry season (EDS) fire mapping includes all fires mapped to end of July, and late dry season for the months thereafter. In 2022 a total area of 1222 km^2 (45%) was burnt over the example site, with 54 km^2 (2%) burnt in the EDS, and 1168 km^2 (43%) burnt in the LDS.



(ii) Fire frequency 2012-2022 for the example site, where an annual mean of 85.9 km^2 (3.2%) was burnt in the EDS and 967.4 km^2 (35.6%) was burnt in the LDS



(iii) Time-since last fire (TSF) since 2022, where: TSF 1 yr = 654 km^2, TSF 2 yr =225.5 km^2, TSF 3 yr = 144.3 km^2, TSF 4 yr = 55.8 km^2, TSF 5 yr = 31.8 km^2, TSF 6+ yrs = 57 km^2.



(iv) Look-up-table for fuel accumulation and consumption values, used for calculations in Table (e) following

Accumulation

Fine Fuels

Time since fire	Early Dry Season			Late Dry Season		
	OWDL	**WDL**	**WDH**	**OWDL**	**WDL**	**WDH**
1	2.27	2.16	2.42	2.56	2.4	2.75
2	2.63	2.5	2.75	2.97	2.78	3.14
3	2.87	2.72	2.97	3.24	3.02	3.39
4	3.05	2.88	3.14	3.45	3.21	3.57
5	3.2	3.02	3.27	3.61	3.36	3.73
6	3.33	3.14	3.38	3.76	3.5	3.86

Shrubs

Time since fire	OWDL	WDL	WDH
1	3.37	1.58	1.14
2	3.37	2.25	1.83
3	3.37	2.77	2.42
4	3.37	3.21	2.95
5	3.37	3.6	3.44
6	3.37	3.95	3.89

	OWDL	WDL	WDH
Coarse (CWD)	0.55	0.52	0.39
Heavy (HWF)	0.91	0.99	1.6

Consumption

	EDS	LDS
Patchiness		
OWDL	0.6754	0.8189
WDL	0.6462	0.9552
Fine fuel		
OWDL	0.6594	0.7642
WDL	0.5982	0.7314
CWD		
OWDL	0.1018	0.1923
WDL	0.0577	0.1364
HWF		
OWDL	0.0105	0.2333
WDL	0.0051	0.0973
Shrub		
OWDL	0.049	0.0933
WDL	0.0542	0.1428

(v) Application of emissions calculations for 2022 at example miombo vegetation site, Zambia, based on available fire mapping (Supplementary Figs. 2i,ii,iii) and emissions calculation parameters derived in this this study, where:

fuel consumed = area burnt x season x time since last burnt x patchiness x ((fine fuel accumulation x fine fuel consumption) + (coarse fuel accumulation x fine fuel consumption) + (heavy fuel accumulation x heavy fuel consumption) + (shrub fuel accumulation x shrub fuel consumption))

emissions = **fuel consumed x Emission Factors** (refer Tables (a) – (g) below)

Fuel consumed

fuel consumed (tonnes)	Early	Late
Open Woodland	7107	269065
Woodland Low	5716	269983
Woodland High	6155	297457

Fuel consumed X Carbon Content (Table (a))

t consumed x carbon content (TCC)	Early	Late
Open Woodland	3483	130739
Woodland Low	2485	125380
Woodland High	2796	137663

CH_4 Calculation

TCC x Table (b) x Table (c)

t CH_4 yr-1	Early	Late
Open Woodland	8.82	313.77
Woodland Low	8.28	518.24
Woodland High	9.69	642.43

t CH_4 yr-1 x GWP CH_4 (Table (f))

t CO2-e yr-1 (CH_4)	Early	Late
Open Woodland	300	10668
Woodland Low	282	17620
Woodland High	330	21843

N_2O Calculation

TCC X N:C ratio (Table (d))

t N yr-1	Early	Late
Open Woodland	69.66	2614.78
Woodland Low	37.28	2507.61
Woodland High	39.15	1651.96

t N yr-1 x Table (e) X Table (f)

t N_2O yr-1	Early	Late
Open Woodland	0.66	28.76
Woodland Low	0.26	17.73
Woodland High	0.26	14.02

t N_2O yr-1 x GWP N_2O Table (g)

t CO_2-e yr-1 (N_2O)	Early	Late
Open Woodland	196	8571
Woodland Low	79	5284
Woodland High	79	4177

Summary Emissions

Total GHG Emissions	Early	Late	Total
Open Woodland	495.73	19239.54	19735.26
Woodland Low	360.25	22904.36	23264.61
Woodland High	408.43	26019.94	26428.37

t GHG emissions per km^2	Early	Late
Open Woodland	9.22	16.47
Woodland Low	6.70	19.61
Woodland High	7.60	22.27

Table (a)

Fuel C content	Early	Late
OWDL	0.4901	0.4859
WDL <1000 mm	0.4348	0.4644
WDH >1000 mm	0.4543	0.4628

Table (b)

Elemental to molecular mass (EMM) CH_4 = 16/12

Table (c)

CH_4 EF /100	Early	Late
OWDL	0.0019	0.0018
WDL <1000 mm	0.0025	0.0031
WDH >1000 mm	0.0026	0.0035

Table (d)

Fuel N:C ratio	Early	Late
OWDL	0.02	0.02
WDL <1000 mm	0.015	0.02
WDH >1000 mm	0.014	0.012

Table (e)

Elemental to molecular mass N_2O (EMM) = 44/28

Table (f)

N_2O EF /100	Early	Late
OWDL	0.006	0.007
WDL <1000 mm	0.0045	0.0045
WDH >1000 mm	0.0043	0.0054

Table (g)

Global Warming Potential	
CH_4	34
N_2O	298