

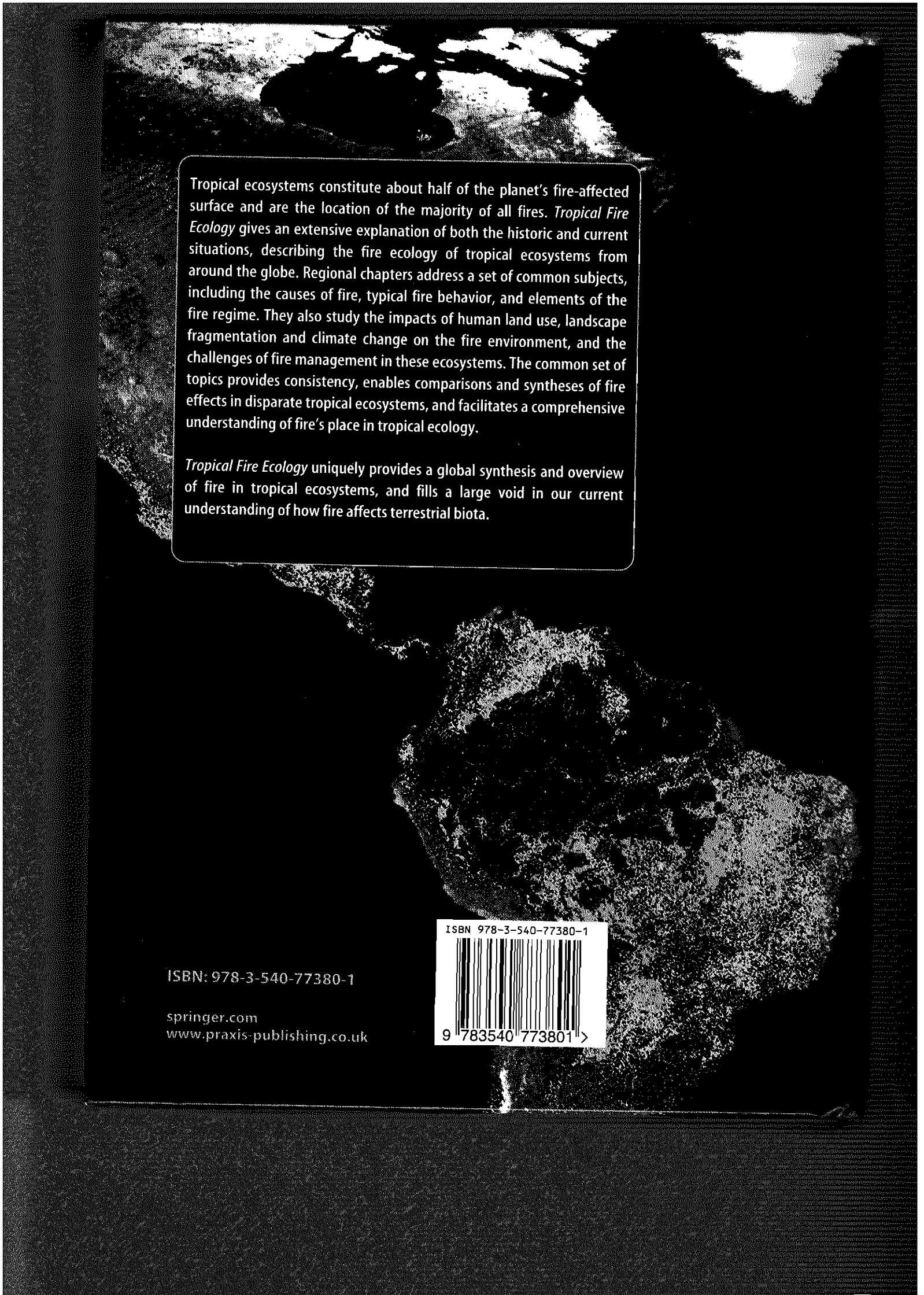
Mark A. Cochrane

TROPICAL FIRE ECOLOGY

Climate Change, Land Use,
and Ecosystem Dynamics

 Springer

PRAXIS



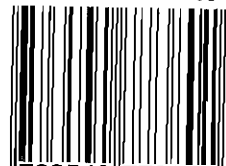
Tropical ecosystems constitute about half of the planet's fire-affected surface and are the location of the majority of all fires. *Tropical Fire Ecology* gives an extensive explanation of both the historic and current situations, describing the fire ecology of tropical ecosystems from around the globe. Regional chapters address a set of common subjects, including the causes of fire, typical fire behavior, and elements of the fire regime. They also study the impacts of human land use, landscape fragmentation and climate change on the fire environment, and the challenges of fire management in these ecosystems. The common set of topics provides consistency, enables comparisons and syntheses of fire effects in disparate tropical ecosystems, and facilitates a comprehensive understanding of fire's place in tropical ecology.

Tropical Fire Ecology uniquely provides a global synthesis and overview of fire in tropical ecosystems, and fills a large void in our current understanding of how fire affects terrestrial biota.

ISBN: 978-3-540-77380-1

springer.com
www.praxis-publishing.co.uk

ISBN 978-3-540-77380-1



9 783540 773801 >

Professor Mark A. Cochrane
South Dakota State University
Brookings
South Dakota
USA

SPRINGER-PRAXIS BOOKS IN ENVIRONMENTAL SCIENCES
SUBJECT ADVISORY EDITOR: John Mason M.B.E., B.Sc., M.Sc., Ph.D.

ISBN 978-3-540-77380-1 Springer Berlin Heidelberg New York

Springer is part of Springer-Science + Business Media (springer.com)

Library of Congress Control Number: 2008943661

Apart from any fair dealing for the purposes of research or private study, or criticism or review, as permitted under the Copyright, Designs and Patents Act 1988, this publication may only be reproduced, stored or transmitted, in any form or by any means, with the prior permission in writing of the publishers, or in the case of reprographic reproduction in accordance with the terms of licences issued by the Copyright Licensing Agency. Enquiries concerning reproduction outside those terms should be sent to the publishers.

© Praxis Publishing Ltd, Chichester, UK, 2009

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Cover design: Jim Wilkie
Project management: OPS, Gt Yarmouth, Norfolk, UK

Printed in Germany on acid-free paper

Contents

Preface	xvii
List of figures	xxi
List of tables	xxvii
List of abbreviations and acronyms	xxix
List of contributors	xxxiii
1 Fire in the tropics	1
1.1 Introduction	1
1.2 Tropical wildfires: situation and impacts	2
1.2.1 Overview	2
1.2.2 Economic impacts	4
1.2.3 Health issues	5
1.2.4 Environmental impacts	7
1.3 Case studies of tropical fires: Mexico and Brazil	10
1.3.1 Mexico	10
1.3.2 Brazil	14
1.4 Implications	17
1.5 Acknowledgments	18
1.6 References	18
2 Fire and fire ecology: Concepts and principles	25
2.1 Fire and combustion	25
2.2 Heat transfer	28
2.2.1 Conduction	28
2.2.2 Convection	29
2.2.3 Radiation	29

2.3	Fuels	31
2.3.1	Fuel composition	31
2.3.2	Fuel loading and arrangement	31
2.3.3	Fuel moisture	33
2.3.4	Total fuels	33
2.3.5	Live fuels	33
2.3.6	Dead fuels	37
2.3.7	Moisture exchange	37
2.3.8	Fuel continuity	38
2.4	Oxygen	39
2.5	Wildland fire	39
2.5.1	Fire types	40
2.5.2	Fire characteristics	41
2.6	Fire ecology	49
2.6.1	Fire regimes	49
2.6.2	Fire regime characteristics	50
2.6.3	Fire regime classification	51
2.6.4	The action of fire in ecosystems	53
2.6.5	Tropical fire ecology	55
2.7	Acknowledgments	55
2.8	References	55
PART I	Global overview of fire in the tropics	63
3	Overview: Global fire regime conditions, threats, and opportunities for fire management in the tropics	65
3.1	Abstract	65
3.2	Introduction	66
3.3	Assessing the World's fire regimes	67
3.4	Fire regime types	68
3.5	The state of the world's tropical fire regimes	69
3.6	Causes of changing fire regimes in the tropics	72
3.6.1	Climate change	72
3.6.2	Agriculture and livestock ranching	73
3.6.3	Rural and urban development	75
3.6.4	Energy production	75
3.6.5	Fire exclusion and suppression	75
3.6.6	Invasive species	76
3.6.7	Plantations	76
3.6.8	Arson	76
3.7	Interactions	77
3.8	Prescribed burning for ecological benefit	77
3.9	Integrated fire management	77
3.10	Conclusions	79
3.11	References	80

PART II Fire in the Australian tropics	85
4 Fire-driven land cover change in Australia and W.D. Jackson's theory of the fire ecology of southwest Tasmania	87
4.1 Abstract	87
4.2 Introduction	88
4.3 The ecology of southwest Tasmania	89
4.3.1 Development of a theory	89
4.3.2 Ecological Drift model	89
4.3.3 Evidence and alternative perspectives	93
4.4 The Ecological Drift model and quantifying fire frequency	94
4.4.1 Methods of quantifying fire frequency	94
4.4.2 Fire frequency in Victorian montane forests	95
4.4.3 Stand age and fire risk	96
4.4.4 Landscape effects on fire frequency	96
4.5 Fire frequency, edaphic feedbacks, and Aboriginal landscape burning in Australian tropical savannas	98
4.5.1 Aboriginal fire regimes: evidence from northern Australia savannas	98
4.5.2 Cessation of Aboriginal burning and the grass-fire cycle	99
4.5.3 Edaphic "inertia" of monsoon rainforest-savanna boundaries	99
4.5.4 Monsoon rainforest boundary dynamics	101
4.5.5 Monsoon rainforests and fire frequency	102
4.6 <i>Acacia aneura</i> shrublands in a <i>Triodia</i> grassland mosaic in central Australia	102
4.7 Ecological drift, changing fire regimes, and fire feedbacks	103
4.8 Conclusion	104
4.9 References	106
5 Fires in Australia's tropical savannas: Interactions with biodiversity, global warming, and exotic biota	113
5.1 Abstract	113
5.2 Introduction	113
5.2.1 The region	114
5.2.2 Fires in the region	117
5.3 Fire behavior, fire weather	118
5.4 Fire regimes	120
5.5 Relationships between fire, woody plants, and grasses	122
5.6 Fire, global warming, and greenhouse gases	124
5.6.1 Predicted changes in climate	124
5.6.2 Management of emissions	125
5.7 Biodiversity and fire regimes	126
5.7.1 Biodiversity, fire, and grazing regimes	126
5.7.2 Biodiversity conservation in reserves	129

5.8	Protection of human life and property	131	
5.9	Discussion and conclusions	132	
5.10	Acknowledgments	133	
5.11	References	133	
6	Aboriginal fire use in Australian tropical savannas: Ecological effects and management lessons	143	
6.1	Abstract	143	
6.2	Introduction	143	
6.3	Stereotypes of seasonality and spatiality	147	
6.4	Aboriginal uses for fire: hunting, vegetation management, and cleaning country	148	
6.4.1	Fire for hunting	148	
6.4.2	Domiculture: management of plant resources	151	
6.4.3	Vegetation management: facilitating life in a tall-grass savanna	153	
6.4.4	A landscape management system	153	
6.5	European settlement and fire regimes	154	
6.5.1	Ecological impact of wildfire regimes	154	
6.5.2	Contemporary Aboriginal fire management	156	
6.6	Conclusion	161	
6.7	References	161	
	PART III Fire in the African tropics	169	
7	Fire ecology and fire politics in Mali and Madagascar	171	
7.1	Abstract	171	
7.2	Introduction	172	
7.3	Biophysical context	174	
7.3.1	Mali and West Africa	174	
7.3.2	Madagascar	176	
7.4	Prehistory	177	
7.4.1	Generalities on prehistoric African fire and issues of vegetation "origin"	177	
7.4.2	West African anthropogenic fire history	180	
7.4.3	Madagascar	181	
7.5	Contemporary fire regimes and impacts	182	
7.5.1	Mali	182	
7.5.2	Madagascar	185	
7.6	Humans and fire in landscape management	187	
7.6.1	Why do Africans burn the land?	187	
7.6.2	Seasonal mosaic burning in Mali	189	
7.6.3	The culture of fire use in Madagascar	196	

31	7.7	Estimating fire impacts	201
32	7.7.1	Climate and hydrology	202
33	7.7.2	Land cover conversion and vegetation change	203
33	7.7.3	Fragmentation and connectivity	204
	7.7.4	Atmospheric and health effects of emissions	205
43	7.8	Fire politics	206
43	7.8.1	Early fire policies	206
43	7.8.2	Fire as a necessary evil: a late colonial softening	208
47	7.8.3	Post-colonial approaches: strong words, weak enforcement	208
	7.8.4	From drought to revenue: fire in 1980s' Mali	209
48	7.8.5	Biodiversity hotspot: fire in 1980s'-1990s' Madagascar	211
48	7.8.6	The 1990s' community devolution movement	212
51	7.8.7	Today	212
	7.8.8	Lessons	213
53	7.9	Conclusion	214
53	7.10	References	215
54			
54			
56			
161			
161	8	Climate change and wildland fires in Mozambique	227
	8.1	Abstract	227
	8.2	Introduction	228
	8.3	Climate, fire, and livelihood linkages	229
169	8.4	Climate conditions: present and future projections	230
	8.4.1	Current climatic conditions	231
171	8.4.2	Future climate change projections	233
171	8.5	Current fire regimes in Mozambique today	234
172	8.5.1	Fire distribution and frequency	235
174	8.5.2	Fire seasonality	236
174	8.6	Underlying causes of wildland fire	236
176	8.6.1	Ecological impacts of fire	237
177	8.6.2	Miombo woodland species	238
	8.6.3	Ecological consequences of fire in the miombo woodland	242
177	8.7	Economic impacts of fire	244
180	8.8	Emissions from biomass burning	246
181	8.8.1	Emissions released directly from fires	247
182	8.8.2	Emissions from land use change and forestry	247
182	8.9	Policy framework and institutional arrangements	248
185	8.9.1	Historical policy and institutional framework	248
187	8.9.2	Current policy and institutional framework	249
187	8.10	Conclusions	251
189	8.11	Acknowledgment	254
196	8.12	References	255

PART IV Fire in the Asian tropics	261
9 Tropical peatland fires in Southeast Asia	263
9.1 Abstract	263
9.2 Introduction	264
9.3 The tropical peatlands of Southeast Asia	265
9.4 Fire history and the causes of fire	266
9.5 Land use change as the driver of contemporary peatland fires ..	269
9.6 Causes of fire: the blame game	270
9.6.1 Role of fire in recent deforestation of tropical peatlands in Borneo	272
9.7 Ecological changes	276
9.7.1 From fire to flood	276
9.7.2 Carbon emissions and fire behavior	279
9.7.3 Tropical peatlands under a changing climate	281
9.8 Future prospects	282
9.9 References	283
10 Fire ecology and management of seasonal evergreen forests in mainland Southeast Asia	289
10.1 Abstract	289
10.2 Introduction	289
10.3 Study area	292
10.4 Fire in seasonal evergreen forest	294
10.5 Why do seasonal evergreen forests burn?	298
10.6 Effect of fire on seasonal evergreen forest	301
10.7 Summary and implications	305
10.8 References	306
11 Fire behavior and fire effects across the forest landscape of continental Southeast Asia	311
11.1 Abstract	311
11.2 Introduction	312
11.3 Causes of fire	314
11.3.1 Climate	314
11.3.2 Fuels	315
11.3.3 Ignition	316
11.4 Fire behavior	316
11.5 Fire severity	320
11.5.1 Fire effects on individual trees	320
11.5.2 Fire effects at the stand scale	322
11.5.3 Fire and tree species abundance	323
11.6 Fire regimes	326
11.7 Fire, landscapes, and land use	328
11.8 Fire and climate	329

12 Forest
ecosy

12.1

12.2

12.3

12.4

12.5

12.6

12.7

12.8

12.9

12.10

12.11

13 Fire and

13.1

13.2

13.3

13

13

13

13

13

13.4

13.5

11.9	Issues for fire management	330
11.10	References	331
12	Forest fire regimes and their ecological effects in seasonally dry tropical ecosystems in the Western Ghats, India	335
12.1	Abstract	335
12.2	Introduction	336
12.3	Humans and fire in the Western Ghats	336
12.3.1	Indigenous communities and fires	337
12.3.2	Agricultural fires in the Western Ghats	337
12.3.3	Fire and forestry	337
12.4	Link between fire regimes and field studies	337
12.5	Background	338
12.5.1	Spatial parameters of fire regimes	338
12.5.2	Vegetation types and forest fires in the Nilgiri landscape	339
12.6	Methods	340
12.6.1	Vegetation map	340
12.6.2	Delineating forest fires in the Nilgiri landscape	340
12.6.3	Forest structure, diversity, fuel loads, and fire frequency	341
12.7	Results	342
12.7.1	Spatial and temporal characteristics of fires in the Nilgiri landscape	342
12.7.2	Fuels, vegetation characteristics, and forest fires	343
12.8	Discussion	349
12.8.1	Climate change and forest fires	350
12.8.2	Forest fires and conservation	350
12.9	Conclusions	351
12.10	Acknowledgments	351
12.11	References	351
13	Fire and land use effects on biodiversity in the southern Sumatran wetlands	355
13.1	Abstract	355
13.2	Introduction	356
13.3	Methods	358
13.3.1	Land cover classification	358
13.3.2	Socio-economic surveys	359
13.3.3	Field ecological surveys	359
13.3.4	Distance and access	359
13.3.5	Fire patterns	359
13.3.6	Vegetation structure and links to environmental/disturbance variables	360
13.3.7	Woody species diversity and composition	360
13.4	Fire history	361
13.5	Land use history	363

13.6	Driving forces behind the fires	365	15
13.7	Biodiversity impacts	367	
13.7.1	Landscape level	367	
13.7.2	Woody species diversity and composition at the patch level	368	
13.7.3	Vegetation structure at the patch level	374	
13.7.4	Further fire susceptibility and regeneration potential	375	
13.8	Discussion	377	
13.8.1	Fire management issues and options for the wetlands of southern Sumatra	379	
13.9	Acknowledgments	381	
13.10	References	382	16
PART V Fire in the South American tropics		387	
14	Fire, land use, land cover dynamics, and climate change in the Brazilian Amazon	389	
14.1	Abstract	389	
14.2	Introduction	390	
14.3	Fire as a tool	391	1
14.4	Fire and land use	392	
14.4.1	Shifting cultivation	392	
14.4.2	Cattle ranching	392	
14.4.3	Industrial agriculture	393	10
14.4.4	Logging	393	
14.4.5	Fire and landscapes	395	10
14.5	Fire behavior	398	10
14.6	Fire severity	400	
14.7	Ecosystem effects	402	
14.8	Fire and climate	406	17
14.8.1	Climate, weather anomalies, and climate change effects	406	17
14.8.2	Land cover change and climate	408	17
14.8.3	Fire and climate	408	17
14.9	Fire modeling	409	17
14.9.1	Fire susceptibility	409	17
14.9.2	Mechanistic model of fire susceptibility	410	
14.9.3	Fuels	413	
14.10	Conclusions	415	
14.10.1	Rehabilitating fire-impacted forests	417	17.
14.11	Acknowledgments	418	17.
14.12	References	418	17.

365	15 Fires in the cerrado, the Brazilian savanna	427
367	15.1 Abstract	427
367	15.2 Introduction	427
	15.3 Fire history and fire frequency	428
368	15.4 Cerrado fires	430
374	15.5 Herbaceous-layer vegetation	433
375	15.6 Woody-layer vegetation	437
377	15.7 Water use and carbon flux	442
	15.8 Final considerations	443
379	15.9 References	444
381	16 The role of fire in the vegetation dynamics of upland savannas of the	
382	Venezuelan Guayana	451
	16.1 Abstract	451
	16.2 Introduction	452
	16.3 Causes and use of fire	453
387	16.4 Study site	454
	16.5 Experimental design	458
	16.6 Fire behavior	460
389	16.7 Effect of fire on savanna plant cover and species composition	465
389	16.7.1 Plant species composition and abundance	466
390	16.7.2 Effect of fire on plant species composition and abundance	469
391	16.8 Effect of fire on savanna biomass	470
392	16.8.1 Biomass dynamics in unburned savanna plots	471
392	16.8.2 Biomass recovery of burned savanna plots	472
392	16.8.3 Biomass recovery and fire frequency	473
393	16.9 Conclusions: Options for fire management in Canaima National	
393	Park	473
395	16.10 Acknowledgments	475
398	16.11 References	476
400	17 Pattern and process: Fire-initiated grass invasion at Amazon transitional	
402	forest edges	481
406	17.1 Abstract	481
406	17.2 Introduction	482
408	17.3 Methods: increasing fire frequency at a forest-pasture edge	483
409	17.4 Results: fire promotes grass invasion	484
409	17.5 Potential mechanisms of fire-initiated vegetation transitions	487
410	17.5.1 Competition-based mechanisms	487
413	17.5.2 Demographic mechanisms	491
415	17.5.3 Grass-fire cycle	494
417	17.6 Conclusions	495
418	17.7 Acknowledgments	496
418	17.8 References	497

PART VI Fire in the Central American tropics	503	
18 Fire in the páramo ecosystems of Central and South America	505	20.8
18.1 Abstract	505	20.9
18.2 Introduction	506	20.10
18.3 The páramos of Central and South America	506	20.11
18.4 Causes of páramo fires	510	20.12
18.5 The "naturalness", fire dependency, and conservation value of neotropical páramos	512	20.13
18.6 Fire behavior	515	
18.7 Fire severity and post-fire vegetation development	516	
18.8 Fire frequency	520	
18.9 Charcoal and pollen evidence of long-term fire history	522	
18.9.1 Records from Costa Rica	522	
18.9.2 Records from Ecuador and northern Peru	524	
18.10 Issues for fire management	527	20.14
18.11 Acknowledgments	531	20.15
18.12 References	531	
PART VII Pan-tropical fire	541	
19 The consequences of fire for the fauna of humid tropical forests	543	21
19.1 Abstract	543	21.1
19.2 Introduction	543	21.2
19.3 Faunal mortality and temporal responses to fire	544	21.3
19.4 Sub-lethal effects	546	21.4
19.5 Fire severity and recurrent fires	546	21.5
19.6 Spatial scale of effects	547	21.6
19.7 Fires and other threats to biodiversity	548	21.7
19.8 Synergistic effects of fire	548	21.8
19.9 Geographical variance in faunal responses to fire	549	21.9
19.10 Fire and the arthropod litter fauna	550	
19.11 Conclusion and research priorities	551	
19.12 References	553	
20 Fire in tropical pine ecosystems	557	
20.1 Abstract	557	
20.2 Introduction	558	
20.3 Fire and life history characteristics and adaptations of tropical pines	561	
20.4 Ecosystem characteristics	569	
20.5 Fire regimes	570	
20.6 Pine stand structure and stand dynamics	574	
20.7 Ecosystem dynamics	579	
		Index . . .

503	20.8 Causes of fire	582
	20.9 Fire behavior and severity	585
505	20.10 Fire, land use, and landscapes	587
505	20.11 Fire, pines, and climate change	589
506	20.12 Issues for fire management	591
506	20.13 Regional example: <i>Pinus hartwegii</i> forests in Mesoamerica	592
510	20.13.1 Background	592
	20.13.2 Fire regime and vegetation dynamics	593
512	20.13.3 Fire behavior and severity	593
515	20.13.4 Understory species response to fire	595
516	20.13.5 Wildlife	596
520	20.13.6 Soils, hydrology, and air quality	596
522	20.13.7 Landscape value	597
522	20.13.8 Other project studies	597
524	20.13.9 Integrated fire management	597
527	20.14 Conclusion	598
531	20.15 References	599
531		
	21 Changing fire regimes in tropical montane cloud forests: a global synthesis	607
	21.1 Abstract	607
541	21.2 Introduction	607
	21.3 MCFs: characteristics, distribution, and disturbance dynamics	609
543	21.4 Paleocological evidence for historical fire regimes in MCFs	610
543	21.5 Modern evidence for changing fire regimes in MCFs	614
543	21.6 Case study: modern patterns of fire activity in MCFs of south-eastern Mexico	617
544	21.7 Conclusions	621
546	21.8 Acknowledgements	622
546	21.9 References	622
547		
548		
548		
549	Index	627
550		
551		
553		
557		
557		
558		
561		
569		
570		
574		
579		

5

Fires in Australia's tropical savannas: Interactions with biodiversity, global warming, and exotic biota

1. Malcolm Gill, Richard J. Williams, and John C.Z. Woinarski

5.1 ABSTRACT

The vast tropical savanna region of northern Australia is generally flat, vegetated by native species and sparsely populated by people. The climate is typified as monsoonal, with contrasting wet and dry seasons. Temporal and spatial patterns of rainfall, cattle grazing, and fires help shape the vegetation of the region. *Eucalyptus* spp. dominate the tree cover while grasses are a feature of woodland understories. Grasses fuel fires which occur mostly in the dry season. Fire regimes (including between-fire interval, fire intensity, and season of occurrence) affect the relationships between the woody and grassy components of the vegetation. Fires, at a given point in the landscape, can occur with mean intervals as short as about two years but mean intervals vary widely across the region. Fire intensity varies seasonally: it can arbitrate between outcomes such as tree survival, shoot survival, or tree death. Introduced grasses, especially gamba grass (*Andropogon gayanus*), can alter fire regimes to the extent that the structure and composition of plant communities is strongly affected. Near major towns and cities, increased fire intensities due to gamba grass increases the fire threat to houses. Fire regimes, whether or not influenced by exotic species, affect land management for broad-scale pastoralism and biodiversity conservation, and influence carbon emissions and storage.

5.2 INTRODUCTION

This chapter describes the pattern and management of fire in the tropical savannas of northern Australia. This region has characteristics shared with strongly seasonal tropical areas elsewhere in the world, but has a distinct ecological context. Fire is a pervasive management issue in the region and the management of fire affects, or is affected by, land use, biodiversity conservation, the maintenance of indigenous

culture, the spread of exotic plants and animals, and global climate change. Across most of the region, fire regimes have changed over the 150 years or so since European settlement.

Reflecting the main arena of research activity, our focus in this chapter is on the central third of the tropical savanna area, locally known as the "Top End" of the Northern Territory (Figure 5.1). However, consideration of the region as a whole is possible for some topics and research in areas outside the Top End are not neglected.

5.2.1 The region

The island continent of Australia is generally flat, hot, and dry, but has great variety in climate, soils, vegetation, and topography. Its northern quarter—an area of 1.9 million km² (Russell-Smith *et al.*, 2003b)—is characterized by a monsoonal (strongly seasonal wet-dry) climate and tropical savanna vegetation. The circumscription and naming of this area has varied: here, the definition based on bioregional boundaries defined in the interim biogeographic regions of Australia (Thackway and Cresswell 1995), and its broad subdivisions ("provinces") are used (Russell-Smith *et al.*, 2003a) and shown in Figure 5.1. The whole area is referred to as northern Australia or the Australian tropical savanna, reflecting local usage.

This region spans parts of three Australian political jurisdictions (Figure 5.1 inset), with variable legislative, land use, and management contexts. Unlike most of the World's other tropical savanna regions, it is sparsely populated by people: excluding a handful of larger towns, the average population density is less than 0.1 person/km² (Woinarski *et al.*, 2007). Australia's tropical savannas are managed by both indigenous people (who own 20% of it) and by relatively recent settlers of predominantly European origin. Cattle-based pastoralism is by far the most widespread land use, extending over about 70% of the savannas (Woinarski *et al.*, 2007); it is more intensive (i.e., with much smaller properties) in the eastern and southeastern parts of the region, compared with the west and northwest. The iconic 2-million-hectare World Heritage Kakadu National Park is found in the savanna region along with a number of other national parks, totaling about 6% of the region's area (Woinarski *et al.*, 2007). There are much smaller areas devoted to military training, horticulture, mining, and other industries (Russell-Smith *et al.*, 2003a).

Climate is a defining feature of the region, but also shows ecologically important variation. Rainfall is strongly seasonal, with a distinct short and hot summer wet season and a long warm dry season (April–November in the Top End); seasonality is least marked in the southeast. Total rainfall varies from >2,000 mm yr⁻¹ in some near-coastal areas to less than 400 mm at the fringe of the vast arid zone of Australia's interior and central west (Gill *et al.*, 1990; Williams *et al.*, 1997a; Russell-Smith *et al.*, 2003a). There is considerable variability in the duration, intensity, and the timing of the onset of the wet season (Ridpath, 1983; Holland, 1986; Cook and Heerdegen, 2001).

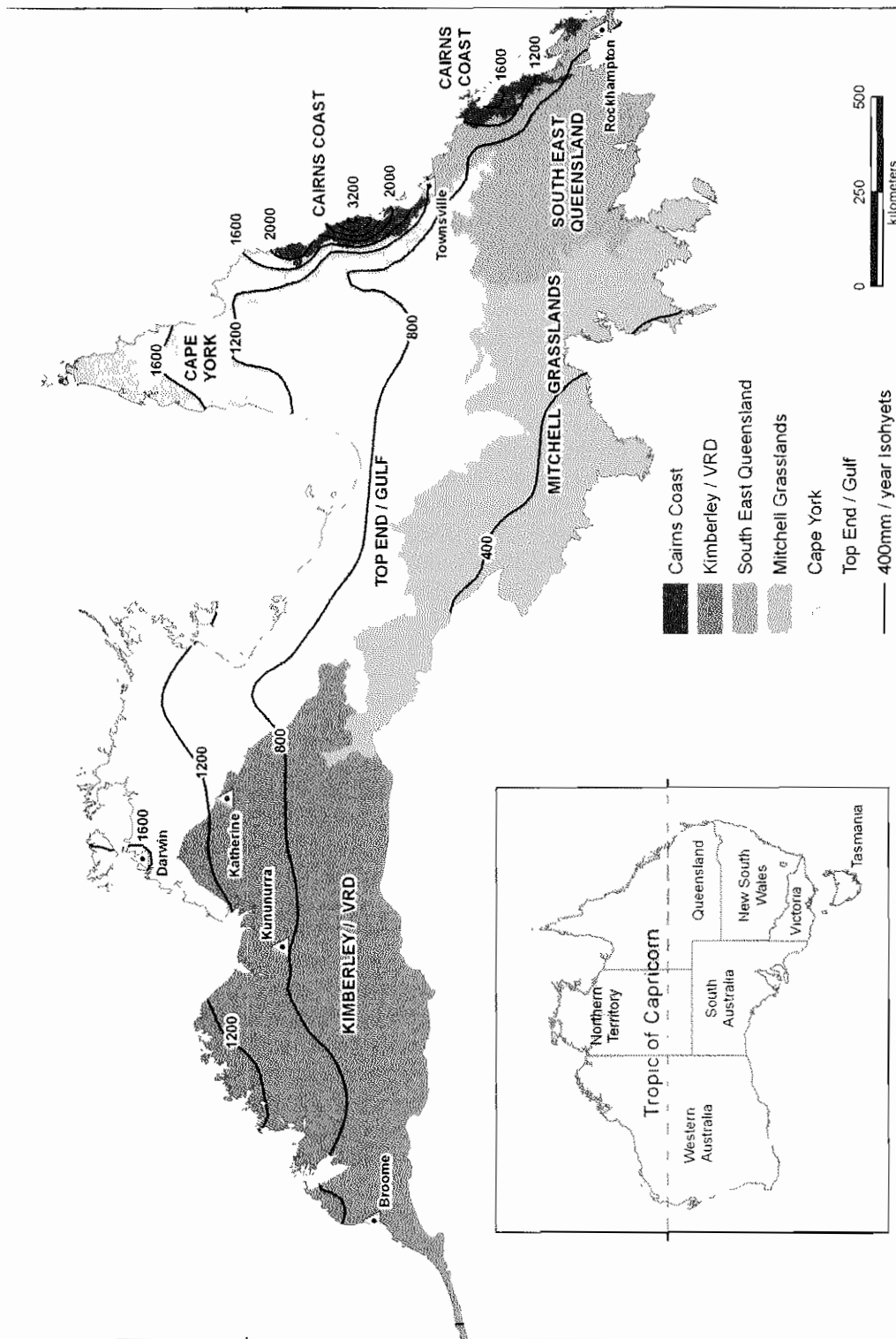


Figure 5.1. Interim provincial regions of Australia's tropical savanna region—in capital letters (courtesy of the Australian Department of Environment and Water Resources, Canberra, ACT, Australia; after Thackway and Cresswell, 1995, see also Russell-Smith *et al.*, 2003a), national context (inset), and rainfall isohyets in millimeters.

The period of change from the dry to the wet season is often characterized by highly localized storm activity, with lightning strikes being a major ignition source for fires. Particularly in the wet season, coastal areas are subjected to frequent destructive cyclones.

The passage of the dry season is marked by increasing depth of drought and the presence of the southeast Trade Winds; it is conveniently subdivided into "early" and "late". May and June are typical early dry-season months in the Top End (R.J. Williams *et al.*, 2003a) and Russell-Smith *et al.* (2003a) defined the early dry season there as the period up until the end of July. The rest of the dry season, August to November, is regarded as the late dry season (Hill *et al.*, 2006). Cook and Heerdegen (2001), with an eye to biological responses, defined a "rainy season" and a "wet season" based on differing probabilities of 10-day dry spells. Seasons could also be defined in terms of ecological indicators (Lewis, 1985). Crowley and Garnett (2000) defined "storm-burns" as those being undertaken soon after the first heavy rains of the wet season.

Native vegetation is extensive across the savanna region and is a highly significant asset for biodiversity conservation (Woinarski *et al.*, 2007). Apart from some parts of Queensland (e.g. see Tassicker *et al.*, 2006), there has been relatively little intensive clearing for agriculture; forestry is rare. As a consequence, the savannas are relatively intact structurally, and "relatively little transformed by modern development" but despite this "the savanna landscapes of Australia are in flux" (Whitehead *et al.*, 2005) with increasing pressure for substantial modification and resource use. Naturalized exotic plants have established and spread in some areas, strongly affecting fire regimes and their outcomes (Douglas and Setterfield, 2005); feral cats, horses, pigs, and donkeys are widespread (Strahan, 1995).

The dominant, savanna, vegetation of northern Australia comprises extensive grasslands, grassy forests, and woodlands, with far smaller areas of other structural types (Fox *et al.*, 2001; Williams *et al.*, 2002; Russell-Smith *et al.*, 2003b), notably including heathlands (mostly on skeletal sandy soils in rugged rocky areas) and closed forest (rainforest), typically occurring as small patches in relatively fire-protected areas or in sites with seasonally persistent water supply, especially along the coastlines and in the immediate hinterland (Russell-Smith *et al.*, 2003a). While these more restricted vegetation types are not strictly tropical savannas, some consideration is given to them here as their ecology, conservation, and management is intimately associated with the savannas that typically surround them.

Forests and woodlands are typically 10 m to 20 m in height, occasionally reaching 30 m (Gillison and Walker, 1981). Tree height and density tend to decrease with decreasing rainfall: for example, along the aridity gradient south from Darwin (Williams *et al.*, 1996). Eucalypts, trees of the genera *Eucalyptus* and *Corymbia*, family Myrtaceae, and especially the *Eucalyptus* subgenera *Blakella* and *Eudesmia* (Gill *et al.*, 1985, p. 29) feature as dominants to a grassy understory. The presence of these eucalypt subgenera in the north contrasts with the predominance of the species-rich subgenera *Monocalyptus* and *Symphyomyrtus* in the southern part of Australia (Gill *et al.*, 1985, p. 29). Other common tree genera include the pantropical *Erythrophleum* and *Terminalia*, the native conifer *Callitris*, and Myrtaceae like

Melaleuca,
Acacia, *Alp*
and *Planch*
Grasse
subdomina
Dicanthium,
(formerly
1992). Kin
(spinifex);
Sarga; the
Dicanthium
(Mitchell
pastures a:
southeast

While
from the t
season bei
Williams e
of the long
from the s
lished data
monsoon j
monthly r
rainfall (S)

Thus t
shortest in
of the gro
the dry sea
length of t
the wet se

5.2.2 Fir

In this se
subsequen
underlie o
ment and
include th
and grass
sions, the
emergent
with a tra

Like
feature of
of the reg

Melaleuca. There is a wide range of other tree and shrub genera present including *Acacia*, *Alphitonia*, *Brachychiton*, *Calytrix*, *Cochlospermum*, *Grevillea*, *Petalostigma*, and *Planchonia*.

Grasses dominate the ground stratum of savannas. Common dominant or subdominant grass genera include *Aristida*, *Astrebla*, *Bothriochloa*, *Chrysopogon*, *Dicanthium*, *Eriachne*, *Heteropogon*, *Imperata*, *Plectrachne*, *Schizachyrium*, *Sarga* (formerly *Sorghum*), *Sporobolus*, *Triodia*, and *Xerochloa* (Tothill and Gillies, 1992). Kimberley/Victoria River province has widespread *Triodia* and *Plectrachne* (spinifex); the western part of the Top End Gulf province is dominated by annual *Sarga*; the eastern Top End Gulf Province has widespread *Aristida*–*Bothriochloa* and *Dicanthium* pastures; the Mitchell Grasslands province has widespread *Astrebla* (Mitchell Grass) (Tothill and Gillies, 1992). *Schizachyrium* and perennial *Sarga* pastures are common in Cape York while *Heteropogon* pastures are common in southeast Queensland (Weston, 1988).

While grass predominates as the understory throughout the savanna region, litter from the trees may be substantial in quantity in some places and times, the late dry season being associated with increased litter fall and litter fuel load (Gill *et al.*, 1996; Williams *et al.*, 1997b). In the wet season the grasses are green but with the approach of the long dry season, grasses start to cure (i.e., shoots die) in a rapid mottled wave from the south to the north and towards the northern coastlines (S. Berry, unpublished data). With the arrival of the early wet-season convective storms, and, later the monsoon proper, a wave of greening up spreads from the north to the south. The monthly raingreen (mostly grass) component of the vegetation follows monthly rainfall (Spessa *et al.*, 2005).

Thus the period in which fuels are predisposed to burn is longest in the south and shortest in the north, although greater than about 4 months in all regions. The length of the growing season may be seen as setting the grassy fuel load while the length of the dry season—the non-growing season (Walker 1981)—may be seen as setting the length of the potential “fire season”. However, fires are also possible in drier parts of the wet season (Williams and Lane, 1999; Crowley and Garnett, 2000).

5.2.2 Fires in the region

In this section, the broad characteristics of fire in this region are described. In subsequent sections, more detailed attention is given to some of the factors that underlie or define these characteristics and we consider in more detail the management and consequences of particular fire regimes. Management considerations include the manner in which fires affect the interrelationships between woody plants and grasses, the interactions between global warming effects and atmospheric emissions, the conservation of biodiversity in pastoral systems and in reserves, and the emergent issue of the protection of human life and property, particularly in districts with a transition from rural to urban.

Like tropical savannas in monsoonal climates elsewhere, fires are a pervasive feature of northern Australia. Fires are frequent and extensive especially in the north of the region; individual fires can cover an area of over a million hectares (Luke and

McArthur, 1978, p. 260); the region has been characterized as "perhaps the most extensive and flammable ecosystem in the world" (Liedloff and Cook, 2007). Fires affect all landscapes and land tenures—pastoral properties, conservation lands, indigenous freehold land, mining leases, and, increasingly, the urban-savanna interface (Dyer *et al.*, 2001; Williams *et al.*, 2002).

Without ignition there is no fire. In the early dry season, all fires are caused by humans while in the late dry season lightning can be a major source of ignition. Early dry-season fires include those deliberately lit with the aim of mitigating the effects (or reducing the likelihood) of intense late dry-season fires, some of which are caused by arson and some by lightning strikes; no systematic data are known regarding causes of fire starts across northern Australia, other than those for central Cape York Peninsula (Crowley and Garnett, 2000). Early dry-season fires typically go out at night but the chances of overnight burning (and hence greater fire extent) increase as the dry season progresses. There are a number of reasons for this including increasingly drier conditions in which fuel is more continuous, fewer dews, and increasing wind speeds (Gill *et al.*, 1996). The control of prescribed fires, then, becomes increasingly problematic as the dry season advances. Hence, particularly in the Top End province (Figure 5.1), early dry-season fires are typified by short-lived human-initiated fires burning grassy fuels in relatively mild weather, whereas late dry-season fires are of generally higher intensity and capable of burning day and night in grass-litter fuels under drier and windier conditions.

5.3 FIRE BEHAVIOR, FIRE WEATHER

"Fire behavior" is represented by a range of attributes varying from the rate of spread of the fire burning with the wind to the rate of the setting of new fires downwind as a result of firebrands arising from the "mother" fire. Besides rates of spread, fire behavior variables include temperature (Weber *et al.*, 1995), intensity (Byram, 1959), duration of burning (flaming and smoldering), and various dimensions of flames (height, length, depth), and flame angles. Fire behavior can also be seen to be the way in which fires interact with tree stems (Tunstall *et al.*, 1976). Rates of spread of fires burning with the wind are the primary object of measurement and prediction. In conjunction with "fuel loading", rates of spread contribute to fire intensity (Byram, 1959) which, in turn, may be correlated with flame dimensions and immediate effects of fires like the scorch height and char height of leaves (Williams *et al.*, 1998). Australian researchers have traditionally adopted an empirical approach to fire prediction (e.g., Cheney *et al.*, 1993), an approach that is particularly advantageous where there are large tracts of similar fire-prone vegetation.

The only formal fire-modeling program conducted in Australia's tropical savanna region has been that of Cheney *et al.* (1993) in the Top End province. These authors examined rate of spread of fire burning with the wind in manipulated and control swards of cured (i.e., with dead shoot systems) *Themeda triandra* and *Eriachne burkittii*. They found that neither the grass species nor the fuel load above about 1 t ha⁻¹ significantly influenced the rate of fire spread, but wind speed and

moisture
predictive
namely c
This north
grassland

Rate:
fire weath
uses the r
GFDI_4,
(McArthur
represent
in a gene
modified
speed, gr
from wid
curing ar
by bushl
least, ind
thereby j
values a
documen
In coast
during t

The
(1998), i
found a
dry-seas
up to 15
more ty
(2007) s
and We
E. tetro

In t
region a
influenc
of G. C
increase
of betw
variety
may be
very ro
annual
dry sea
the lat
deciduo

moisture content were important. Their research formed the basis of a rate-of-spread predictive system that required added input variables for its practical application, namely curing (CSIRO, 1997a; Cheney *et al.*, 1998) and slope (CSIRO, 1997a). This northern Australian spread meter applies to open forest, woodland, and open grassland (CSIRO, 1997b).

Rates of spread of fires burning with the wind on level ground form the basis of fire weather forecasts and fire danger warnings. Australia's Bureau of Meteorology uses the modified McArthur Grassland Fire Danger Index Mark 4 (Purton, 1982), or GFDI_4, for such forecasts and warnings in northern Australia. McArthur's GFDI (McArthur, 1966), and Purton's (1982) modification of it, have a scale of 1 to 100; 100 represents the "worst possible" weather condition. The indices are grouped as ratings in a generally logarithmic fashion with "extreme" being the range from 50 to 100. The modified McArthur GFDI_4 has inputs of temperature, relative humidity, wind speed, grass curing, and fine-fuel load (Purton, 1982). Weather inputs are provided from widely distributed weather stations in the savanna region while estimates of curing and fuel loading (from "very sparse" to "heavy"—Purton, 1982) are provided by bushfire agencies. Across the Northern Territory and northern Queensland at least, indices in the "extreme" range occur (Bureau of Meteorology, pers. commun.), thereby predicting possible extreme rates of spread, but the frequency of "extreme" values and historically peak values have not been reported. Tapper *et al.* (1993) document the synoptic conditions for high fire danger in the Northern Territory. In coastal Darwin, and in its hinterland at Jabiru, the GFDI (McArthur, 1966) rises during the dry season and peaks in September (Gill *et al.*, 1987, 1990).

The effects of individual fires often depend on fire intensity. Williams *et al.* (1998), measuring fire intensity in their plots at Kapalga in the Top End province, found a mean of $2,100 \text{ kW m}^{-1}$ for early dry-season fires and $7,700 \text{ kW m}^{-1}$ for late dry-season fires with a peak intensity of $18,000 \text{ kW m}^{-1}$. In this province, fuel loads up to 13 t ha^{-1} have been measured in native ecosystems but 2 t ha^{-1} to 5 t ha^{-1} are more typical, perhaps due to frequent burning (Williams *et al.*, 1998). Bowman *et al.*'s (2007) study of grass biomass across the northern parts of the Northern Territory and Western Australia found sampled grassy fuel loads in savannas dominated by *E. tetradonta* to vary from 0.1 t ha^{-1} to 5.8 t ha^{-1} .

In Australian savannas, fuel loads are generally higher in the wetter north of the region and lower in the south in accord with trends in annual rainfall, but are also influenced by fuel type and fire history. Williams *et al.* (2002) report unpublished data of G. Cook for an "open-forest savanna" in the Top End in which fuel loads increased rapidly in the first 4 or 5 years after fire to reach a quasi-equilibrium value of between 8 t ha^{-1} and 9 t ha^{-1} . Large local variations may be expected due to the variety of circumstances in which various fuels occur. Locally, distinguishing features may be lowland (e.g., floodplain or swamp) vs. upland (e.g., plateau sites, sometimes very rocky); grass species composition (including the productive exotic grasses, native annuals, and native perennials); and, early vs. late dry season, the fuels in the early dry season being mainly grassy and only partly cured if perennial, whereas those of the late dry season comprise cured grasses supplemented by litter from semi-deciduous eucalypts and other woody species.

Fire behavior models need a weather and landscape context for their use—which may be actual or virtual. In the latter case the fire prediction system of Cheney *et al.* (1998) has been incorporated into a fire effects savanna model called “FLAMES” (Liedloff and Cook, 2007). FLAMES allows for the modeling of fire effects using multiple fires with different properties in different seasons—in short, the fire regime.

5.4 FIRE REGIMES

Fires spread across landscapes forming burnt patches of many magnitudes (Gill *et al.*, 2003). As these patches age, further fires overlay them to various extents thereby diminishing their area. Thus, a time sequence of patch size starting with the frequency distribution of the newest (less than 1-year-old) patches, is transformed into successive frequency distributions of ever older, smaller, patches. In a similar way, frequency distributions of areas with the same between-fire interval can be constructed, the mean area of the patches declining as the interval increases (Gill *et al.*, 2003).

Mean “interval between fires” is the reciprocal of the average proportion of the landscape burnt per year. The interval between fires is an important component of the fire regime along with type of fire, season of fire, and fire intensity (Gill, 1975). Peat fires in *Melaleuca* swamps (Innis, 1994), then, may be contrasted with the more common above-ground fires. Fire intensity varies with diurnal, seasonal topographic and fuel load variations (R.J. Williams *et al.*, 2003a). Seasonal variation in fire occurrence in any one location can be extensive, as has been mentioned above, while variation in interval between fires is also large and is considered below.

Intervals between fires can be determined using a series of yearly maps of burnt areas, the maps often being derived from satellite imagery. Analysis of five years of NOAA-AVHRR satellite imagery across northern Australia suggested that there were two distinct groups of vegetation with respect to the mean proportion burnt per year (Spessa *et al.*, 2005):

- (i) low open woodland, open forest, open woodland, woodland, and low woodland—with 23% to 34% burnt per year; and,
- (ii) open heathland and closed [or “rain”] forest—the remaining two vegetation types—with 8.1% and 8.5% burnt per year, respectively.

These proportions translate to mean intervals between fires of 4.4 to 2.9 years for the first group and 12.3 and 11.8 years for the second. A statistical model examining the proportion burnt in relation to “raingreen” and “evergreen” components of the vegetation suggested that the proportions burnt per year can be greater than 0.54 per year (a mean interval of approximately 2 years).

Using a similar 5-year set of NOAA-AVHRR data, Spessa *et al.* (2005) and Russell-Smith *et al.* (2003a) examined a wider area—the entire tropical savanna region (Figure 5.1)—and estimated the average percentage of burnt area according

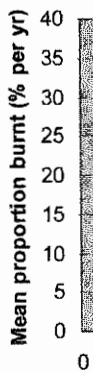


Figure 5
mean an
and Rus
savanna
the mea
Russell-
1,750 mi

to rain
are plo
suggest
val bet
are spa
also de
only a
gloss o
vast are
ing and
topogr

At
about
propor
Centra
was bi
2005).
bioregi
For 12
the rat
season
propoi
season
t al.,

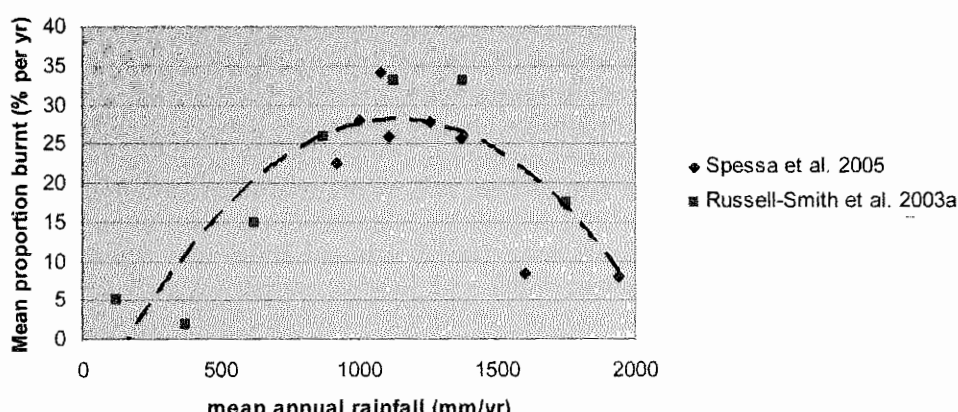


Figure 5.2. Mean NOAA-AVHRR proportion burned per year as a function of interpolated mean annual rainfall (based on five years of data only): combined results of Spessa *et al.* (2005) and Russell-Smith *et al.* (2003a) for the “wet-dry tropics” and the more extensive “tropical savannas”, respectively for an almost identical period. The baseline for Spessa *et al.*, (2005) was the mean annual rainfall for vegetation types (including closed forest—rainforest); that of Russell-Smith *et al.* (2003a) for rainfall classes, the top class (>1,500 mm) being taken as 1,750 mm yr⁻¹. The trend line is a quadratic function.

to rainfall category rather than mean rainfall for vegetation categories. The results are plotted in Figure 5.2 with a trendline for the combined data. The trendline suggests that the mean proportion burnt is greatest—and, therefore, the mean interval between fires is least—when mean annual rainfall is about 1,100 mm. These data are spatially averaged so cannot be expected to reflect local circumstances; they are also derived for areas of various size and for a short period, and they may provide only a coarse index of the actual extent of land cover being burned. They necessarily gloss over the effects of other variables like topography and land use. Across the vast area of northern Australia, there is substantial variability in the seasonal patterning and extent of fire, associated largely with differences in land use and intensity, topography, and climate.

At the regional scale of their study, Russell-Smith *et al.* (2003a) calculated that about 77% of the savanna region that burned did so in the late dry season. This proportion can be very variable. For example, while more than 50% of Pine Creek, Central Arnhem, and Daly Basin bioregions (all in the Top End province, Figure 5.1) was burnt by late dry-season fires in four years of a nine-year study period (1997–2005), this was the case for only one (North Kimberley) of the remaining 19 bioregions that comprise the tropical savanna region (G. Crowley, pers. commun.). For 12 of these bioregions, the mean rate was less than 25%, and for five bioregions the rate was less than or equal to 1% (G. Crowley, pers. commun.). There are various reasons for this variability, one of which is that there can be a tradeoff between the proportion of landscape burning in the early dry season with that in the late dry season (as in lowland Kakadu National Park during the 15-year study period of Gill *et al.*, 2000).

The seasonality of fires affects the scale of patterning of burnt areas. For sandstone heath vegetation, Price *et al.* (2003) found that individual early dry-season fires burnt, on average, 64% of the vegetation within their perimeter, whereas this proportion averaged 84% for fires in the late dry season. Similarly, R.J. Williams *et al.* (2003a) reported that the burned percentage of their transects in experiments in mesic savanna increased from zero to over 90% as fire intensities rose up to, then above, $2,000 \text{ kW m}^{-1}$.

Local studies of fire regimes have been conducted across the region using historical accounts (e.g., Stanton, 1992) and Landsat imagery (e.g., Gill *et al.*, 2000; references in Russell-Smith *et al.*, 2003a; Felderhof and Gillieson, 2006), for example. These studies are more appropriate to guiding fire management (Felderhof and Gillieson, 2006) than the region-wide studies but the latter provide an overview not possible from local studies. The foci of local studies have usually been on between-fire interval and season.

Fire regimes have changed in the last 150 years or so (e.g., Stanton, 1992; Russell-Smith *et al.*, 2003a) in association with the general replacement of indigenous land management by pastoralism, changes in human dispersion, changed fuel conditions, and the spread of exotic invasive grasses. Global warming can be expected to produce further changes and attempts to reduce emissions of greenhouse gases such as those from fires (see below): thus, with frequent fires and a vast area, increasing attention is being paid to the greenhouse gas implications of management (Gill *et al.*, 1990; Russell-Smith *et al.*, 2007). Like other savannas of the world, those in northern Australia generate the majority of such emissions that result from biomass burning in the continent (Meyer, 2004; Russell-Smith *et al.*, 2007).

A living legacy of changes in fire regimes can be found in landscapes in the form of increased tree and shrub density. The relationships between woody plants, grasses, and fires is important in relation to the cattle industry, biodiversity conservation, and global warming.

5.5 RELATIONSHIPS BETWEEN FIRE, WOODY PLANTS, AND GRASSES

As with tropical savannas throughout the world (Scholes and Archer, 1977), in northern Australia the tree-grass relationship is driven primarily by rainfall (Liedloff and Cook, 2007) and soil type; the general lack of trees on the Mitchell Grass (*Astrebla*) grasslands can be attributed to the clay soils there (Figure 5.1; Thackway and Cresswell, 1995). However, in this section, emphasis is placed on the dynamics of woody plants locally and the impact of fire regimes, a secondary driver of the grass-tree balance. Where woody plants become more abundant, the grass component of the community can be expected to diminish.

Tree survival in a fire is a function of fire intensity, the height of the tree, and its bud-protective mechanisms (Gill, 1995). In the Top End, the study of the effect of fires on trees has largely been directed towards the ubiquitous eucalypts (Williams *et al.*, 1999) and the sporadically distributed conifer *Callitris intratropica*. Seedlings and

saplings of
crowns are
canopy-st
regenerati
have led to
and Russe
the arriva

Eucaly
often reco
Williams
intensity a
rate; smal
land, P.R
frequent
frequent
by contin

Woo
become a
p. 36)—i
Starr, 19
Burrows
et al., 19
ivity an
them (St
Crowley
partial v
woody r
Lovett,

The
across th
regimes.
concent
exceptic
and Fa
exceptic
(1999).

Bowm

Gr.
genera
of usin
Smith,
there is
then do
are sup
variety

saplings of *Callitris* are readily killed by fire, and adults may be readily killed if the crowns are completely scorched (browned). If scorched trees of *Callitris* have no canopy-stored seed then local extinction can occur as this seed is the only source of regeneration; the species is an obligate seeder (Yates and Russell-Smith, 2003). Fires have led to the depletion of *Callitris* in various parts of northern Australia (e.g., Yates and Russell-Smith, 2003), probably because of changes in fire regimes associated with the arrival of Europeans (Bowman and Panton, 1993).

Eucalypt trees behave quite differently from *Callitris* in the face of fire. They often recover after crown-scorching fires and even after above-ground stem death. Williams *et al.* (1999) found stem death to increase quite markedly with increasing intensity and whole tree death to increase in the same manner but at a much reduced rate; smaller and larger tree stems were the most affected in their model. In Queensland, P.R. Williams *et al.* (2003) found that eucalypt saplings were suppressed by frequent fire (<4-year interval). In the simulations of Liedloff and Cook (2007), frequent fire, in the early or late dry season, affected the size distribution of stems by continually removing recruits and killing larger stems.

Woody plant thickening (typically an increase in the density of woody stems) has become an issue on pastoral properties across the savannas (Crowley *et al.*, 2004, p. 36)—including parts of the Kimberley (Craig, 1997), the Top End (McGuffog and Starr, 1997; Dyer and Stafford Smith, 2003), central Queensland (Landsberg, 1997; Burrows *et al.*, 2002), Gulf country (Grice, 2006) and Cape York Peninsula (Neldner *et al.*, 1997; Crowley and Garnett, 1998). This may be detrimental to pastoral productivity and lead to decline of grassland ecosystems and the biota that depend upon them (Stanton, 1992; Neldner *et al.*, 1997; Crowley and Garnett, 1998; Crowley, 2001; Crowley *et al.*, 2004), but conversely may benefit bird species diversity following partial vegetation clearance (Tassicker *et al.*, 2006) and can increase carbon storage in woody material, thereby benefiting users of a carbon-trading scheme (Ockwell and Lovett, 2005).

The complex dynamic of the tree-grass relationship is influenced differentially across the region by variations within grazing (Sharp and Whittaker, 2003) and fire regimes, by climatic variation and more globally by changes in greenhouse gas concentrations (Bond *et al.*, 2003). Periods of above-average rainfall may trigger exceptional episodes of woody plant recruitment (Crowley, 1995, p. 13; Fensham and Fairfax, 2003), while extended periods of below-average rainfall may trigger exceptional rates of tree mortality across broad areas (Fensham and Holman, 1999). With very low fire frequency or fire exclusion, woody thickening can occur (Bowman *et al.*, 1988; Crowley and Garnett, 1998; Russell-Smith *et al.*, 2003c).

Grass is a major fuel of the savanna but also the major food of cattle (generally *Bos indicus*) on pastoral properties. The pastoralist is faced with a choice of using grass for cattle or grass for fire (Liedloff *et al.*, 2001; Dyer and Stafford Smith, 2003) but the choice can be pre-empted by an unplanned fire. Without fire, there is the chance of an increasing density of native or exotic woody plants which then deplete pastures. With fire, pastures are temporarily removed but woody plants are suppressed; this is a simplistic characterization of the situation as fires have a variety of advantages to the pastoralist as well as disadvantages (Leigh and Noble,

1981; Dyer and Stafford-Smith, 2003). The management key here is the choice of the appropriate fire regime for various parts of a pastoral property for different purposes using fires of different intensities, times of year, and intervals (Leigh and Noble, 1981; Liedloff *et al.*, 2001; Dyer and Stafford Smith, 2003; Crowley *et al.*, 2004, pp. 18–20).

The interactions between rainfall, livestock grazing, and fire regimes as they affect temporal aspects of woody plant–grass relationships is a theme that extends beyond savannas. Multiple stable states are possible according to the models of Janssen *et al.* (2004) who applied them to sheep country in New South Wales, Australia. These authors showed the importance of rainfall variability to their results, an outcome also emphasized by Liedloff and Cook (2007) who concluded, for tree density across a rainfall gradient: “While fire is an important factor in northern Australia, the model indicates its effects on tree populations at a sub-continental scale are secondary to the impact of rainfall variability.”

Changing climates and vegetation, along with land use intensification, may cause shifts in carbon stocks and fluxes. Cattle grazing and its intensification may have increasing importance given the methane content of emissions from ruminants (Blaxter and Clapperton, 1965; Howden and Reyenga, 1999), while the creation of a market for carbon “has the potential to drive land use away from fire-assisted pastoralism toward sustainable forestry and environmental conservation” in northern Australia (Ockwell and Lovett, 2005). Thus, the management of greenhouse gases and biodiversity conservation in Australian savannas can be considered to be a cross-tenure issue of increasing importance.

5.6 FIRE, GLOBAL WARMING, AND GREENHOUSE GASES

5.6.1 Predicted changes in climate

Rising concentrations of greenhouse gases such as CO_2 , CO , CH_4 , N_2O , and NO_x in the atmosphere (greenhouse gas emissions) cause increased planetary warming and other atmospheric changes which, in turn, affect nearly all aspects of life on Earth (IPCC, 2007). Predictions of changes in climate as a result of human-mediated emissions in the decades ahead can be made by using global climate models assuming various emission scenarios and by extrapolating current trends.

The regional climate of northern Australia has changed since the beginning of the 20th century (http://www.bom.gov.au/cgi-bin/silo/reg/cli_chg/trendmaps.cgi), and further changes are predicted as a consequence of global climate change (Pearce *et al.*, 2007). Since about 1950, northwestern Australia has become wetter by about 5 mm per year, but there have been declines in rainfall over much of the drier inland savannas of the Northern Territory and Queensland. Mean annual temperature has been generally rising in the same period but not so in the Kimberley region of Western Australia. Pan evaporation has generally declined over much of the savanna biome since 1970 and this has considerable significance for fire behavior as it appears to be due to a reduction in wind speed (Roderick *et al.*, 2007).

With changes in global warming, the number of fires is either nil or will show a southeast and spring of an increase in fires.

Predicted most global but the inclusion of

Climate the savanna use, grass (Andropogon)

5.6.2

Management of woody

In the late 20th century, in the north and central regions, more sequestration

A the Kimberley death camp Coolidge north Will by re source

With due caveats for imprecision and regional variation, predicted climate changes for northern Australia by 2030, as a consequence of greenhouse gas-induced global warming, are for an increase in temperature of about 1°C and an increase in the number of days on which temperatures exceed 35°C in major centers like Darwin, Broome, and Cairns (Pearce *et al.*, 2007). Predicted changes in annual rainfall are either nil or show small decreases of about 1% to 3%. Other changes predicted by Pearce *et al.* (2007) are that evapotranspiration will increase and relative humidity will show little change or record a small decrease. Predictions with respect to the southeast Trade Winds, which predominate during the dry season (southern winter and spring), are either for no change or increases of 2% to 5%. There is a likelihood of an increase in incidence of severe cyclones (Pearce *et al.*, 2007). Lightning ignition of fires may increase (Goldammer and Price, 1998).

Predictions made by extrapolating current climatic trends and those made by most global climate models are presently inconsistent for parts of northern Australia but the situation may be resolved for the northwest, at least for rainfall, by the inclusion of Asian aerosols in the models (Rotsteyn *et al.*, 2007).

Climate change alone may or may not cause major changes to the fire regime of the savannas but rising human populations, patterns of human ignitions of fires, land use, grazing intensification, and the spread of exotic plants such as gamba grass (*Andropogon gayanus*) (Rossiter *et al.*, 2003), are likely to do so.

5.6.2 Management of emissions

Managing savannas for carbon raises a number of questions. How best can we manage grass—use it as fuel for fires, or for cattle fodder, or just let it decompose (Gill *et al.*, 1990)? Would some forms of management allow grass to be replaced by woody vegetation which maximizes carbon storage and offsets emissions?

In the Top End (Figure 5.1) and some other parts of northern Australia, fires in the late dry season may be extensive and of high intensity, resulting in widespread consumption of fuel and the potential death of trees (Williams *et al.*, 1999). In comparison, fires in the early dry season may be of relatively low intensity and consume less fuel. Greater tree death means less carbon sequestration and more carbon in the atmosphere; alternatively, tree thickening creates a gain in sequestration.

A short-term perspective on losses and gains through burning is apparent from the Kapalga experiments (Andersen *et al.*, 2003b) in the Top End province where tree death from high-intensity fires increased the net emissions per fire by 15–44 times compared with the emissions from the burning of fine fuels by low-intensity fire (Cook, 2003). Similarly, estimates using a number of methods, suggest that the widespread *Eucalyptus miniata*–*E. tetradonta* savannas of higher rainfall areas of northern Australia are a carbon sink, even when burnt by early dry-season fires (Williams *et al.*, 2004; Beringer *et al.*, 2007). Sequestration capacity can be decreased by repeated late dry-season fires and, under these circumstances, fires can be a net source of carbon to the atmosphere (Cook *et al.*, 2005).

With due caveats for imprecision and regional variation, predicted climate changes for northern Australia by 2030, as a consequence of greenhouse gas-induced global warming, are for an increase in temperature of about 1°C and an increase in the number of days on which temperatures exceed 35°C in major centers like Darwin, Broome, and Cairns (Pearce *et al.*, 2007). Predicted changes in annual rainfall are either nil or show small decreases of about 1% to 3%. Other changes predicted by Pearce *et al.* (2007) are that evapotranspiration will increase and relative humidity will show little change or record a small decrease. Predictions with respect to the southeast Trade Winds, which predominate during the dry season (southern winter and spring), are either for no change or increases of 2% to 5%. There is a likelihood of an increase in incidence of severe cyclones (Pearce *et al.*, 2007). Lightning ignition of fires may increase (Goldammer and Price, 1998).

Predictions made by extrapolating current climatic trends and those made by most global climate models are presently inconsistent for parts of northern Australia but the situation may be resolved for the northwest, at least for rainfall, by the inclusion of Asian aerosols in the models (Rotstayn *et al.*, 2007).

Climate change alone may or may not cause major changes to the fire regime of the savannas but rising human populations, patterns of human ignitions of fires, land use, grazing intensification, and the spread of exotic plants such as gamba grass (*Andropogon gayanus*) (Rossiter *et al.*, 2003), are likely to do so.

5.6.2 Management of emissions

Managing savannas for carbon raises a number of questions. How best can we manage grass—use it as fuel for fires, or for cattle fodder, or just let it decompose (Cull *et al.*, 1990)? Would some forms of management allow grass to be replaced by woody vegetation which maximizes carbon storage and offsets emissions?

In the Top End (Figure 5.1) and some other parts of northern Australia, fires in the late dry season may be extensive and of high intensity, resulting in widespread consumption of fuel and the potential death of trees (Williams *et al.*, 1999). In comparison, fires in the early dry season may be of relatively low intensity and consume less fuel. Greater tree death means less carbon sequestration and more carbon in the atmosphere; alternatively, tree thickening creates a gain in sequestration.

A short-term perspective on losses and gains through burning is apparent from the Kapalga experiments (Andersen *et al.*, 2003b) in the Top End province where tree death from high-intensity fires increased the net emissions per fire by 15–44 times compared with the emissions from the burning of fine fuels by low-intensity fire (Cook, 2003). Similarly, estimates using a number of methods, suggest that the widespread *Eucalyptus miniata*–*E. tetradonta* savannas of higher rainfall areas of northern Australia are a carbon sink, even when burnt by early dry-season fires (Williams *et al.*, 2004; Beringer *et al.*, 2007). Sequestration capacity can be decreased by repeated late dry-season fires and, under these circumstances, fires can be a net source of carbon to the atmosphere (Cook *et al.*, 2005).

If cattle consumed the grass, fire-caused emissions might be depleted due to fuel reduction and lower fire intensities. However, northern Australia's 14 million head of cattle (Petherick, 2005) emit copious quantities of methane (e.g., Blaxter and Clapperton, 1965; Howden and Reyenga, 1999; NGGIC, 2005), which has a greenhouse gas effect much more potent than carbon dioxide (Hansen *et al.*, 2007). With less grass and more trees, and therefore more carbon sequestration (Williams *et al.*, 2004), there may be fewer cattle, and fewer cattle—in general terms only—may mean less income for pastoralists.

Cattle properties have benefited from the introduction of productive exotic grasses but the escape and naturalization of such grasses has raised the potential for the loss of tree-stored carbon and increased emissions from burning, particularly with gamba grass. On pastoral properties gamba grass fuels may be reduced by grazing but on properties devoted to other land uses reduction by grazing does not occur. Gamba grass can reach 4 m in height and have a standing biomass of up to 17 t/ha—which is up to seven times that of the local grasses (Rossiter *et al.*, 2003). Unpublished data show fuel loads can reach 30 t/ha (N. Rossiter, pers. commun.). Measurements suggest that this exotic grass has the potential to raise the fire intensity to at least eight times that of fires in native grasses in the early dry season (Rossiter *et al.*, 2003). Invasion of this grass initiates the grass–fire cycle in which fires are more intense, thereby decreasing tree canopy cover and increasing the grass to tree ratio until grass dominates the system (see Rossiter *et al.*, 2003). Thus, reducing the extent of gamba grass will bring greenhouse gas abatement benefits.

Given the complex interactions between grazing, fire, and greenhouse accounting, especially with respect to methane, further investigation of interactions between pasture production, grazing, fires, and tree demographics is urgently needed for this region; a cue may be taken from Moorc *et al.* (2001) who simulated burning and grazing effects on a semi-arid rangeland, but outside the region of interest; the system could be managed as a source (with livestock grazing) or a sink (especially without grazing or burning) for emissions.

5.7 BIODIVERSITY AND FIRE REGIMES

The effects of fire regimes on indigenous biodiversity may be seen in two contexts: in non-park landscapes generally (where fire regimes interact with cattle-grazing regimes); and, in the conservation-reserve context. In Section 5.7.1, examples of the interaction of plant and animal species and grazing and fire regimes are described. In Section 5.7.2, some examples of responses of biodiversity to fire regimes in conservation reserves are considered.

5.7.1 Biodiversity, fire, and grazing regimes

In concert with the gradual transitions of dominant grass species across the longitudinal expanse of the northern Australian savannas, there is a muted change

in native anir associated wi north coast t

There are changes in th the area abou are concentra granivorous mammals. A species for at regimes and thereby affec

The graz have as its co ticular speci between feed regime affect grazing regir Suijdendorp that pastoral but that sur interactions that favored *Macropus ro*

In easter areas by *Ha* groves and and is repla thout live remeda an

The stro art, to fire. out 60 ye Queensland.

years le stitute a this area.

on the p eared, a decline i red fin

terstories Frankli

alent ac e repor

in native animal species (Woinarski, 1992). The most notable directional trends are associated with the rainfall gradient (and tree density) from relatively high on the north coast to relatively low in the inland south (Woinarski *et al.*, 1999a).

There are clear indications that there have been, and continue to be, substantial changes in the faunal biodiversity of northern Australia since European settlement of the area about 150 years ago. Unsurprisingly—given that fire and pastoral impacts are concentrated particularly in the grass layer—change appears most pronounced in granivorous (seed-eating) birds and in the assemblage of small native terrestrial mammals. Animal species that have particular dependencies on one or a few grass species for at least part of the year have been particularly prone to decline. Both fire regimes and grazing regimes affect the species composition of the grass layer and thereby affect the native animals that depend on them.

The grazing regime may be defined in parallel with the fire regime (Gill, 1975) and have as its component variables the type of herbivore (e.g., grazer/browser or particular species), the season of feeding, the intensity of feeding, and the intervals between feeding at points on the ground (Gill, 2008). To the extent that the grazing regime affects the fuel, and thus fire behavior, there is an interaction between the grazing regime and the fire regime. In a semi-arid fringe area of northern Australia, Suijddorp (1981) studied the interactions of grazing by sheep and fire. He found that pastorally inspired winter burning had a detrimental effect on *Triodia* pastures but that summer burning with deferred grazing was best for them. There were interactions between the effects of fire and grazing regimes on vegetation composition that favored sheep on the one hand and native herbivores (in this case euros, *Macropus robustus*) on the other.

In eastern Queensland, *Themeda*-dominated pastures have been replaced in many areas by *Heteropogon*-dominated pastures (Shaw and Bisset, 1955; Shaw, 1957; Groves and Williams, 1981; Crowley and Garnett, 1998). *Themeda* is palatable, and is replaced by *Heteropogon contortus* under heavy grazing. However, even without livestock grazing, Walker *et al.* (1983) found that the proportions of *Themeda* and *Heteropogon* varied in response to the season of burning.

The strongest evidence of broad-scale changes in native fauna due, at least in part, to fire and grazing comes from the detailed reporting of bird observations over about 60 years by Barnard (1925, 1934) at a single pastoral property in central Queensland, with a further assessment of the bird fauna at that location about 60 years later (Woinarski and Catterall, 2004). Together these observations constitute a chronicle spanning about 120 years since the introduction of pastoralism to this area. Of 192 bird species with adequate information, 18 species disappeared from the property over this period, a further 68 species declined, 13 species increased, and 11 species were new colonists. The species that suffered local loss or decline included many that favored dense grassy understories, and some that favored fine-scale vegetation mosaics including both open and relatively dense understories.

Franklin (1999) provided evidence for the above pattern of change to be prevalent across northern Australia by means of an analysis of historical changes in the reporting rates of granivorous bird species. Over the historical span of his study

(150 years), he found declines in 12 of the 49 species considered and increases in three species. One species was "probably extinct" while two species were considered to be "critically endangered". Declines were most marked in locations exposed to the longest history of, and most intensive, pastoralism, and in environments with little topographic relief (Franklin *et al.*, 2005).

A strong role for grazing and, interrelatedly, fire, in structuring faunal communities of the tropical savannas of northern Australia has been demonstrated in a range of experimental (e.g., Woinarski and Ash, 2002) and correlative studies (e.g., Kutt and Woinarski, 2007). In experimental studies with no pastoral factor, long-term imposition of different fire regimes produced substantial divergence in fauna (Woinarski, 1990; Woinarski *et al.*, 1999b, 2004; Pardon *et al.*, 2003; Corbett *et al.*, 2003; Andersen *et al.*, 2006), typically with the most notable polarization in faunal communities being between long-unburnt treatments and those burnt frequently by intense late dry-season fires.

Research on individual fauna species has revealed much of the important detail that underpins community-based responses to fire regimes, and demonstrates that there may be highly idiosyncratic—but ecologically pivotal—relationships between individual animal species and components of fire regimes. For example, the ecology and persistence of some animal species may be linked irrevocably with one grass species, or a small subset of such species. The endangered golden-shouldered parrot (*Psephotus chrysopterygius*) of Cape York Peninsula is one such case (Crowley *et al.*, 2004). For part of the year (the early wet season), the principal seeds available in the landscape for this granivorous bird are those from cockatoo grass (*Alloteropsis semialata*). Grazing and uprooting by cattle and pigs, respectively, reduced the seed production of this grass species (Crowley and Garnett, 2001; Crowley *et al.*, 2004). Where pastoral managers have lit fires after early storms at the start of the wet season, seed production may be delayed by a month. Thus, where this "storm burning" is practiced patchily, there can be a landscape-wide expansion in the temporal availability of these seeds, and hence a direct benefit to the parrots (Crowley and Garnett, 2001; Crowley *et al.*, 2004). Similar circumstances have been reported for other declining granivorous birds (Woinarski *et al.*, 2005). While the seasonal timing of burning may influence the timing of seed production, the overall abundance of cockatoo grass may also be affected by fire interval as shown by its substantial increase following five years of fire exclusion at Kapalga (Top End province) (R.J. Williams *et al.*, 2003b) and in the absence of grazing by livestock.

Other animal species may be keyed into the spatial patterning of fire events. The threatened partridge pigeon (*Geophaps smithii*), a ground-dwelling granivore, requires both unburnt areas (for providing shelter from predators for its rudimentary ground nests) and burnt areas (to enhance access to the fallen seeds on which it feeds) (Fraser *et al.*, 2003); and, its survival and reproductive output will be maximized where these are both available simultaneously within its territory—that is, where fires are of relatively low intensity and provide a fine-scale (1 ha to 10 ha) mosaic of burnt and unburnt patches. A similar preference for heterogeneity has been demonstrated and modeled for the iconic frilled lizard (*Chlamydosaurus kingii*), where survival is typically low in unburnt areas (because dense grasses reduce foraging ability) and in

the period s
lizards) (Gr

5.7.2 Biodi

The savann
conservation
they includ
Purnululu N

Two m
National Pa
Munmarlar
sketch the f
introduced

Over th
annual burn
of the Top
meanwhile,
Smith *et al*
precluded th
supported i
over (Woi

The K
actively b
e woodla
e regime
annual Sarg
is in the
et used b
ontrol of

In the
ement c
ie relati
ected by
e affect
ction c
burnt re
ected a
imizing
ageme
ion m
obly bo
ed than
experi

period soon after intense late-season fires (when the fires themselves may kill birds) (Griffiths and Christian, 1996).

5.7.2 Biodiversity conservation in reserves

The savanna region of northern Australia contains many areas set aside for nature conservation. These areas have regional, national, and international significance as they include World Heritage Areas like Kakadu National Park (Top End) and Uluru National Park (Kimberley).

Two major experimental programs have been conducted in, or near, Kakadu National Park (Top End): the Kapalga experiment (Andersen *et al.*, 2003b) and the Munmarlary experiment (Bowman *et al.*, 1988; Russell-Smith *et al.*, 2003c). Here we sketch the findings of these studies, introduce fire-related concerns associated with introduced species, and note the effects of fire regimes.

Over the two to three decades of the Munmarlary experiments, metronomic annual burning maintained the dominance of annual *Sarga*—a major fuel species in the Top End—while, in the absence of fire, annuals, including *Sarga*, declined; meanwhile, the perennial grass *Eriachne trisetata*, and shrub cover, increased (Russell-Smith *et al.*, 2003c). The small size of plots in the Munmarlary experiment (1 ha) precluded their general utility for the study of faunal responses, but the unburnt plots supported more bird species associated with a relatively dense woody understory (Woinarski, 1990).

The Kapalga experiment was larger in spatial scale, but conducted over a relatively brief period (5 years) (Andersen *et al.*, 2003b). In the ground stratum of the woodlands there, plant species composition was not affected by variation in the fire regime but was strongly correlated with wet-season rainfall and the cover of the annual *Sarga* (R.J. Williams *et al.*, 2003b). Annual *Sarga* can be locally eliminated by fires in the early wet season, soon after its germination (Williams and Lane, 1999), a fact used by managers to reduce fuel loads in strategic areas, thus assisting with the control of late dry-season fires.

In the Kapalga experiment, small mammals in general increased in the unburnt treatment compared with both early dry-season and late dry-season fire treatments while relatively few species of frogs (1 of 11), lizards (5 of 16), or birds (5 of 25) were affected by experimental treatment (Corbett *et al.*, 2003). Those animal species that were affected by fire treatment did so in a variety of ways such as by population reduction or increase under late dry-season treatment, or reduction or increase in unburnt relative to fire treatments (Corbett *et al.*, 2003). Such variation is to be expected and highlights the importance of: (i) conserving the species rather than maximizing populations; and, (ii) varying fire regimes within limits appropriate to management aims (Gill, 2008). Some species, such as the northern brown bandicoot (*Isodon macrourus*), a small fossorial marsupial, decreased under all fire treatments, possibly because it is reliant on a mosaic of burnt and unburnt patches that is finer scaled than that produced in the 15 km² to 20 km² landscapes of the fire treatments in this experiment (Pardon *et al.*, 2003).

At Boggy Plains, a wetland in Kakadu National Park, the native grass *Hymenachne acutigluma* proliferated when populations of feral Asian water buffalo (*Bubalus bubalis*) were removed (Robinson and Whitehead, 2003). In a program to restore pre-buffalo assemblages of plant and animal species to the wetland, low-intensity fires were ignited twice within a short period in the late dry season (CSIRO, 2005; Davidson, 2005). This caused a marked change in plant species composition in the wetland, from the *Hymenachne*-dominated one to one with a variety of native plant species including red lily (*Nelumbo* sp.) and other water lilies, wild rice (*Oryza meridionalis*), and water chestnut (*Eleocharis dulcis*) (CSIRO, 2005; Davidson, 2005).

A number of vigorous grasses have been introduced into northern Australia to increase the productivity of pastures for cattle; besides gamba grass (mentioned above), these include para grass (*Urochloa mutica*), and mission grasses (*Pennisetum* spp.). Para grass has spread to wetlands near Kakadu National Park on the Mary River (Ferdinands *et al.*, 2005). This species can completely exclude all species of native vascular plants, including the native wild rice and native birds. Ferdinands *et al.* (2005) point out that wild rice is a critical resource for the magpie goose (*Anseranas semipalmata*), the most characteristic bird species of floodplain areas, because it produces "large and abundant carbohydrate and protein-rich seeds" which are a preferred food source for their newly hatched young.

Individual species form communities which vary in structure according to the stature and density of the constituent plants. Fire regimes affect both the structure and the composition of savanna communities as noted above but, embedded within these communities, are closed forests (rainforests) with apparently different responses. These embedded communities (often in particular and limited topographic or other positions that provide some shelter from fire) have substantial conservation value, especially in national parks. In parts of the savanna that now have frequent intense fire, these communities, such as monsoon rainforests and heathlands, may be shrinking (Russell-Smith and Bowman, 1992). Conversely, there is recent evidence of widespread expansion of at least some rainforest types (a spatial counterpart to the vegetation thickening described above). While there are substrate limitations to expansion, "low fire disturbance" and favorable moisture conditions (Russell-Smith *et al.*, 2004a, b) and/or changes in greenhouse gases (Banfai and Bowman, 2006) may be implicated. However, the impacts of fire regimes on the rainforest boundary are complex (Williams, 2000) but dramatically altered when invasion by highly flammable *Lantana camara* occurs as it has in north Queensland (Fensham *et al.*, 1994).

Scientists working in savanna conservation reserves highlight the need for adaptive management (Andersen *et al.*, 2003a; Russell-Smith *et al.*, 2003c). Russell-Smith *et al.* (2003c) suggest further that adaptive management involving collaborative partnerships between managers and scientists is desirable; they question the value of experimental studies using deterministic fire regimes because fire regimes "vary idiosyncratically over multiple time and spatial scales." Such variation for between-fire intervals is reflected in the randomness of fire occurrence at a point in the landscape as in Kakadu National Park (Gill *et al.*, 2000). Incorporating randomness as a formal treatment in experimental programs constitutes a major challenge.

5.8 PRO

Until very low risk t restricted to manage of habita various cu that fire generally,

Atten about 701 of rocky woodland are severa orchards cattle are farming c natural w

In 19: dry seas "extreme" of 35 km/ Bureau of or more a of the Bu may trave Winds fre breeze ex

With suppressio occurred. occurring fire notec firefighter and the v

Fuel: grass earl up as th concomit: leaves bel

The info manage Lamb and

5.8 PROTECTION OF HUMAN LIFE AND PROPERTY

Until very recently, fires in northern Australia have been regarded as posing a very low risk to human life and infrastructure; hence, the management of fire has been restricted largely to pastoralists who want to maintain good habitat for their animals, to managers of conservation lands who attempt to use fire to maintain an optimal mix of habitats for biodiversity, and to indigenous people who use fire according to various cultural imperatives. The spread of vigorous exotic pasture grasses has meant that fire is becoming a problem for the society of northern Australians more generally, even the suburban or semi-suburban householder.

Attention in this section is focused on the area around the village of Batchelor, about 70 km south-southeast of Darwin, in the Top End province. The area consists of rocky hills and sometimes extensive flats all covered with shrubby or grassy woodland. Relatively small holdings (0.5 ha) are a feature of the landscape, and there are several villages in the area, but holdings may be as large as 6,000 ha. Mango orchards are sometimes established where there are deeper soils: Asian buffalo or cattle are raised on some properties while other properties are undeveloped as far as farming or horticulture is concerned: the latter properties retain the appearance of natural woodland although houses and other buildings have been erected in clearings.

In 1980 gamba grass was introduced into the area as a pasture grass.¹ In the late dry season, peaking in this area in August–September, fire weather can reach “extreme” on the McArthur Mark 4 grassland meter: Trade Winds may reach speeds of 35 km/hr. with gusts 50% higher (Northern Territory Branch, Commonwealth Bureau of Meteorology, pers. commun.). Air temperature in the shade may be 37°C or more at 3 PM while relative humidity can drop to 20% (Northern Territory Branch of the Bureau of Meteorology, pers. commun.). In the evening a strong sea breeze may travel through the area from the northwest—as opposed to the daytime Trade Winds from the southeast—thereby complicating fire control: the duration of the sea breeze extends as the dry season progresses.

With extreme weather and high fuel loads due to gamba grass (see above), fire suppression is sometimes impossible and losses of buildings including a house have occurred. Flame heights of up to 15 meters have been observed with spot fires occurring up to 1 km ahead of the fire front, and a maximum rate of spread of a fire noted as being 5 km in 25 minutes, in 2004. These fires are dangerous for firefighters and residents alike. Filters on vehicles are readily clogged in thick smoke and the vehicles then disabled, rendering their occupants in peril.

Fuel managers aim to establish buffer areas for fire spread by burning the gamba grass early in the dry season. Fire suppression capacity at prescribed fires is ramped up as the dry season progresses because the chances of fire escape increase concomitantly. The first prescribed fire occurs while the plants are carrying dead leaves below the mostly green foliage: a follow-up fire in the same season may be

¹ The information in this section, unless otherwise noted, was supplied by the regional management officer of NT Bushfires, John Whatley, and his informed team—especially Sue Lamb and Lee Humphris.

needed to burn regrowth or the dead fuel created by the first fire. Heavy grazing, early dry-season cutting and harvesting, and protracted use of herbicides may reduce grassy fuel loads to low levels. Gamba grass may burn at any time of the year, weather permitting; however, fire spread in the wet season may be more likely if fuel has accumulated over at least a 2-year period.

In this area, gamba grass is spreading rapidly. At the same time, the human population and numbers of dwellings in the area is growing. Few people are aware of the seriousness of the fire issue because it is a relatively new one and people moving into the area may come from areas without this grass. Dense stands of the grass occur in the vicinity of the city of Darwin and its satellite Palmerston in the Northern Territory and also in Queensland. Further serious consequences of fires in gamba grass seem inevitable.

With large fuel loads and intense fires, the smoke volume arising exacerbates an already high smoke load in the regional atmosphere during the dry season, the adverse air quality increasing hospital admissions for asthma sufferers (Johnston *et al.*, 2002).

5.9 DISCUSSION AND CONCLUSIONS

Fire regimes, and the environments they interact with, vary spatially at different scales. Fire interval, season of occurrence, and fire intensity all vary in ecologically significant ways in northern Australia. Peat fires may have local significance. Fire patchiness can be important at the event level—such as in the grazing–burning interaction on grasses—but the effects of patch size distributions of land with specific between-fire intervals and times since fire, as shown by Gill *et al.* (2003), has not been explored; landscape dynamics of fire-prone environments may be better understood when the dynamics of patches with different between-fire intervals (and other components of the fire regime) are also understood.

Fire regimes have changed over the course of the last century, and continue to change. This change has led to some significant environmental change, including, in some places, woody plant thickening but, in other places, decline of woody species like *Callitris intratropica*. With increasing intensification of the cattle industry, global warming, and further spread of exotic plants, perhaps even more rapid change is to be expected. These changes will affect the species composition of pastures and vegetation generally and, in turn, affect populations of dependent fauna. There is an obvious challenge to conservation managers as a result.

With the uncertainties of the future, the continuance and increasing the resolution and verification of fire mapping (Pereira, 2003) is essential. Enhancement of the monitoring of fires by remote sensing of fire intensity within and between events, or routine recording of the distribution of char and scorch heights in woody vegetation is possible but universally overlooked to date.

Fire is one of several key event-based drivers of ecosystems across northern Australia. If we are to have an understanding of management issues such as global warming, cattle husbandry (rather than “hunting”—Lewis, 1985), conservation of a

distinctive
integrate kn
Achieving s
knowledge s

5.10 ACKN

The senior a
of northern
Fire and E
Peninsula D
land Parks a
Cooperative
collaboration
for providin
geographic l
(2003a) was

5.11 REFE

- Andersen, A.
conserva
in *Tropic*
- Andersen, A.]
Experim
- Andersen, A.
commun
successio
- Banfai, D.S. &
sion in K
- Barnard, C.A.
Queensl
- Barnard, H.C.
native bi
- Berninger, J.,
their im
- 13, 990
- axter, K.L.
ruminan
- nd, W.J.,
CO₂ and
- 9, 973–9
- wman, D
and H.C
coloniza

instinctive biodiversity and human health and safety, we need to improve and integrate knowledge of fire regimes, herbivory, climate and resource economics. Achieving such understanding remains a challenge despite the many gains in knowledge so briefly summarized in this chapter.

5.10 ACKNOWLEDGMENTS

The senior author is grateful for assistance to work in parts of the vast savanna region in northern Australia over the past 20 years. Support came from NT Bushfires, the Fire and Emergency Services Authority of Western Australia, the Cape York Peninsula Development Association, CSIRO Sustainable Ecosystems, and Queensland Parks and Wildlife Service. R.J.W. and J.C.Z.W. thank the Tropical Savannas Cooperative Research Centre for support and providing many opportunities for collaboration. We are very grateful to Dr. Gay Crowley and an anonymous referee for providing insightful comments on an earlier draft, and helping us over our geographic biases. Permission to publish Figure 5.1 based on Russell-Smith *et al.* (2003a) was provided by the *International Journal of Wildland Fire*.

5.11 REFERENCES

- Andersen, A.N., G.D. Cook, and R.J. Williams (2003a) Synthesis: Fire ecology and adaptive conservation management. In A.N. Andersen, G.D. Cook, and R.J. Williams (Eds.), *Fire in Tropical Savannas: the Kapalga Experiment*. Springer-Verlag, New York.
- Andersen, A.N., G.D. Cook, and R.J. Williams (2003b) *Fire in Tropical Savannas: The Kapalga Experiment*, Ecological Studies 169. Springer-Verlag, New York.
- Andersen, A.N., Hertog T., and Woinarski J.C.Z. (2006) Long-term fire exclusion and ant community structure in an Australian tropical savanna: Congruence with vegetation succession. *Journal of Biogeography*, **33**, 823–832.
- Attai, D.S. and D.M.J.S. Bowman (2006) Forty years of lowland monsoon rainforest expansion in Kakadu National park, Northern Australia. *Biological Conservation*, **131**, 553–565.
- Chard, C.A. (1925) A review of the bird life on Coomooboolaroo Station. Duaringa district, Queensland, during the past fifty years. *Emu*, **24**, 252–265.
- Chard, H.G. (1934) Observations on the disappearance and probable cause of many of our native birds in central Queensland. *Queensland Naturalist*, February 1934. 3–7.
- Conger, J., L.B. Hutley, N.J. Tapper, and L.A. Cernusak (2007) Savanna fires and their impact on net ecosystem productivity in North Australia. *Global Change Biology*, **13**, 990–1004.
- Crother, K.L. and J.L. Clapperton (1965) Prediction of the amount of methane produced by ruminants. *British Journal of Nutrition*, **19**, 511–522.
- Edwards, W.J., G.F. Midgley, and F.I. Woodward (2003) The importance of low atmospheric CO₂ and fire in promoting the spread of grasslands and savanna. *Global Change Biology*, **9**, 973–982.
- Edwards, D.M.J.S. and W.J. Panton (1993) Decline of *Callitris intratropica* R.T. Baker and H.G. Smith in the Northern Territory: Implications for pre- and post-European colonization fire regimes. *Journal of Biogeography*, **20**, 373–381.

- Bowman, D.M.J.S., B.A. Wilson, and R.J. Hooper (1988) Response of *Eucalyptus* forest and woodland to four fire regimes at Munmarlary, Northern Territory, Australia. *Journal of Ecology*, **76**, 215–232.
- Bowman, D.M.J.S., D.C. Franklin, O.F. Price, and B.W. Brook (2007) Land management affects grass biomass in the *Eucalyptus tetrodonta* savannas of monsoonal Australia. *Austral Ecology*, **32**, 446–452.
- Burrows, W.H., B.K. Henry, P.V. Back, M.B. Hoffmann, L.J. Tait, E.R. Anderson, N. Menke, T. Danaher, J.O. Carter, and G.M. McKeon (2002) Growth and carbon stock change in eucalypt woodlands in northeast Australia: Ecological and greenhouse sink implications. *Global Change Biology*, **8**, 769–784.
- Byram, G.M. (1959) Combustion of forest fuels. In K.P. Davis (Ed.), *Forest Fires: Control and Use*. McGraw Hill, New York.
- Cheney, N.P., J.S. Gould, and W.R. Catchpole (1993) The influence of fuel, weather and fire shape variables on fire spread in grasslands. *International Journal of Wildland Fire*, **3**, 31–44.
- Cheney, N.P., J.S. Gould, and W.R. Catchpole (1998) Prediction of fire spread in grasslands. *International Journal of Wildland Fire*, **8**, 1–13.
- Cook, G.D. (2003) Fuel dynamics, nutrients and atmospheric chemistry. In A.N. Andersen, G.D. Cook, and R.J. Williams (Eds.), *Fire in Tropical Savannas: The Kapalga Experiment*. Springer-Verlag, New York.
- Cook, G.D. and R.G. Heerdegen (2001) Spatial variation in the duration of the rainy season in monsoonal Australia. *International Journal of Climatology*, **21**, 1723–1732.
- Cook, G.D., A.C. Liedloff, R.W. Eager, X. Chen, R.J. Williams, A.P. O'Grady, and L.B. Hutley (2005) The estimation of carbon budgets of frequently burnt tree stands in savannas of northern Australia using allometric analysis and isotopic discrimination. *Australian Journal of Botany*, **53**, 621–630.
- Corbett, L.K., A.N. Andersen, and W.J. Muller (2003) Terrestrial vertebrates. In A.N. Andersen, G.D. Cook, and R.J. Williams (Eds.), *Fire in Tropical Savannas: The Kapalga Experiment*. Springer-Verlag, New York.
- Craig, A. (1997) Fire management issues in Kimberley pastoral lands. In *Bushfire '97 Proceedings: Parks Australia North*, Darwin, pp. 227–232.
- Crowley, G.M. (1995) *Fire on Cape York Peninsula: Cape York Peninsula Land Use Strategy*. The State of Queensland/The Commonwealth of Australia, Brisbane/Canberra.
- Crowley, G.M. (2001) Grasslands of Cape York Peninsula: A fire-dependent habitat. In R. Dyer, P. Jacklyn, I. Partridge, J. Russell-Smith, and R. Williams (Eds.), *Savanna Burning: Understanding and Using Fire in Northern Australia Tropical Savannas*. Tropical Savannas Cooperative Research Centre, Darwin.
- Crowley, G.M. and S.T. Garnett (1998) Vegetation change in the grasslands and grassy woodlands of east-central Cape York Peninsula, Australia. *Pacific Conservation Biology*, **4**, 132–148.
- Crowley, G. and S. Garnett (2000) Changing fire management in the pastoral lands of Cape York Peninsula: 1623 to 1996. *Australian Geographical Studies*, **38**, 10–26.
- Crowley, G.M. and S.T. Garnett (2001) Growth, seed production and effect of defoliation in an early flowering perennial grass, *Alloteropsis semialata* (Poaceae), on Cape York Peninsula, Australia. *Australian Journal of Botany*, **49**, 735–743.
- Crowley, G., S. Garnett, and S. Shephard (2004) *Management Guidelines for Golden-shouldered Parrot Conservation*. Queensland Parks & Wildlife Service, Brisbane.
- CSIRO (1997a) *CSIRO Grassland Fire Spread Meter*. Styrox Pty Ltd., Warriewood, New South Wales.

- CSIRO (1997b) *CSIRO Fire Spread Meter for Northern Australia*. Styrox Pty Ltd., Warriewood, New South Wales.
- CSIRO (2005) *Aboriginal Wetland Burning in Kakadu*. CSIRO Publishing, Melbourne.
- Davidson, S. (2005) Cultural burning revives a Kakadu wetland. *ECOS*, **125**, 14–16.
- Douglas, M.M. and S.A. Setterfield (2005) Impacts of exotic tropical grasses: Lessons from gamba grass in the Northern Territory. In *Eighth Queensland Weed Symposium, Brisbane*, pp. 69–73.
- Dwyer, R. and M. Stafford Smith (2003) Ecological and economic assessment of prescribed burning impacts in semi-arid pastoral lands of northern Australia. *International Journal of Wildland Fire*, **12**, 403–413.
- Dwyer, R., P. Jacklyn, I. Partridge, J. Russell-Smith, and R.J. Williams (2001) *Savanna Burning: Understanding and Using Fire in Northern Australia*. Tropical Savannas Cooperative Research Centre, Darwin.
- Elderhof, L. and D. Gillieson (2006) Comparison of fire patterns and fire frequency in two tropical savanna bioregions. *Austral Ecology*, **31**, 736–746.
- Ensham, R.J. and R.J. Fairfax (2003) Assessing woody vegetation cover change in north-west Australian savanna using aerial photography. *International Journal of Wildland Fire*, **12**, 359–367.
- Ensham, R.J. and J.E. Holman (1999) Temporal and spatial patterns in drought-related tree dieback in Australian savanna. *Journal of Applied Ecology*, **36**, 1035–1050.
- Ensham, R.J., R.J. Fairfax, and R.J. Cannell (1994) The invasion of *Lantana camara* L. in Forty Mile Scrub National Park, north Queensland. *Australian Journal of Ecology*, **19**, 297–305.
- Ferdinands, K., K. Beggs, and P. Whitehead (2005) Biodiversity and invasive grass species: Multiple use or monoculture. *Wildlife Research*, **32**, 447–457.
- Fraser, I.D., V.J. Neldner, G.W. Wilson, P.J. Bannink, B.A. Wilson, P.S. Brocklehurst, M.J. Clark, K.J.M. Dickinson, J.S. Beard, A.J.M. Hopkins *et al.* (2001) *The Vegetation of the Australian Tropical Savannas* (1:2,000,000 scale map in 3 sheets). Queensland Herbarium, Environmental Protection Agency, Brisbane and the Cooperative Research Centre for the Sustainable Development of Tropical Savannas, Darwin.
- Franklin, D.C. (1999) Evidence of disarray amongst granivorous bird assemblages in the savannas of northern Australia, a region of sparse human settlement. *Biological Conservation*, **90**, 53–68.
- Franklin, D.C., P.J. Whitehead, G. Pardon, J. Matthews, P. McMahon, and D. McIntyre (2005) Geographic patterns and correlates of the decline of granivorous birds in northern Australia. *Wildlife Research*, **32**, 399–408.
- Fraser, F., V. Lawson, S. Morrison, P. Christopherson, S. McGregor, and M. Rawlinson (2003) Fire management experiment for the declining partridge pigeon, Kakadu National Park. *Ecological Management and Restoration*, **4**, 93–101.
- Gill, A.M. (1975) Fire and the Australian flora: A review. *Australian Forestry*, **38**, 4–25.
- Gill, A.M. (1995) Stems and fires. In B. Gartner (Ed.), *Plant Stems, Physiology and Functional Morphology*. Academic Press, San Diego. pp. 323–342.
- Gill, A.M. (2008) *Underpinnings of Fire Management for the Conservation of Biodiversity in Reserves*, Fire and Adaptive Management Series, Report 73. Victorian Department of Sustainability and Environment, Melbourne.
- Gill, A.M., L. Belbin, and G.M. Chippendale (1985) *Phytogeography of Eucalyptus in Australia*. Australian Government Publishing Service, Canberra.

- Gill, A.M., E.W. Pook, and P.H.R. Moore (1987) Measuring fire properties for ecological effects at Kakadu National Park. Unpublished Report. Australian National Parks & Wildlife Service, Canberra.
- Gill, A.M., J.R.L. Hoare, and N.P. Cheney (1990) Fires and their effects in the wet-dry tropics of Australia. In J.G. Goldammer (Ed.), *Fire in the Tropical Biota*, Ecological Studies 84. Springer-Verlag, Berlin.
- Gill, A.M., P.H.R. Moore, and R.J. Williams (1996) Fire weather in the wet-dry tropics of world heritage Kakadu National Park, Australia. *Australian Journal of Ecology*, **21**, 302–308.
- Gill, A.M., P.G. Ryan, P.H.R. Moore, and M. Gibson (2000) Fire regimes of world heritage Kakadu National Park, Australia. *Austral Ecology*, **25**, 616–625.
- Gill, A.M., G. Allan, and C. Yates (2003) Fire-created patchiness in Australian savannas. *International Journal of Wildland Fire*, **12**, 323–331.
- Gillison, A.N. and J. Walker (1981) Woodlands. In R.H. Groves (Ed.), *Australian Vegetation*. Cambridge University Press, Cambridge, U.K.
- Goldammer, J.G. and C. Price (1998) Potential impacts of climate change on fire regimes in the tropics based on MAGICC and a GISS GCM-derived lightning model. *Climatic Change*, **39**, 273–296.
- Grice, A.C. (2006) *Developing, Implementing and Evaluating Fire Management of Woody Vegetation in the Gulf Region*. Final Report for Project NBP 319. Meat & Livestock Australia, Sydney.
- Griffiths, A.D. and K.A. Christian (1996) The effects of fire on the frillneck lizard (*Chlamydosaurus kingii*) in northern Australia. *Australian Journal of Ecology*, **21**, 386–398.
- Groves, R.H. and O.B. Williams (1981) Natural grasslands. In R.H. Groves (Ed.), *Australian Vegetation*. Cambridge University Press, Cambridge, U.K.
- Hansen, J., M. Sato, P. Kharecha, G. Russell, D.W. Lea, and M. Siddall (2007) Climate change and trace gases. *Philosophical Transactions of the Royal Society A*, **365**, 1925–1954.
- Hill, M.J., S.H. Roxburgh, J.O. Carter, and D.J. Barrett (2006) Development of a synthetic record of fire probability and proportion of late fires from simulated growth of ground stratum and annual rainfall in the Australian tropical savanna zone. *Environmental Modelling and Software*, **21**, 1214–1229.
- Holland, G.J. (1986) Interannual variability of the Australian Summer Monsoon at Darwin: 1952–82. *Monthly Weather Review*, **114**, 594–604.
- Howden, S.M. and P.J. Reyenga (1999) Methane emissions from Australian livestock: Implications of the Kyoto Protocol. *Australian Journal of Agricultural Research*, **50**, 1285–1291.
- Innis, G.J. (1994) Fire management—in the wake of two centuries of mismanagement in conservation reserves of tropical Australia. In K.R. McDonald and A.R. Batt (Eds.), *Proceedings of a Workshop on Fire Management on Conservation Reserves in Tropical Australia*. Queensland Department of Environment & Heritage, Brisbane.
- IPCC (2007) *Climate Change 2007: The Physical Science Basis*, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.
- Janssen, M.A., J.M. Anderies, and B.H. Walker (2004) Robust strategies for managing rangelands with multiple stable attractors. *Journal of Environmental Economics and Management*, **47**, 140–162.
- Johnston, F.H., A.M. Kavanagh, D.M.J.S. Bowman, and R.K. Scott (2002) Exposure to bushfire smoke and asthma: An ecological study. *The Medical Journal of Australia*, **176**, 535–538.

- Kutt, A.S. and J.C.Z. Woinarski (2007) Vegetation and the vertebrate fauna assemblage pattern in response to grazing and fire in a tropical savanna woodland in north-eastern Australia. *Journal of Tropical Ecology*, **23**, 95-106.
- Landsberg, R.G. (1997) The use of fire as a management tool in the semi-arid tropics: A producer's perspective. In *Bushfire '97 Proceedings: Parks Australia North*, Darwin.
- Leigh, J.H. and J.C. Noble (1981) The role of fire in the management of rangelands in Australia. In A.M. Gill, R.H. Groves, and I.R. Noble (Eds.), *Fire and the Australian Biota*. Australian Academy of Science, Canberra.
- Lewis, H.T. (1985) Burning the "Top End": Kangaroos and cattle. In J.R. Ford (Ed.), *Fire Ecology and Management of Western Australian Ecosystems*. Western Australian Institute of Technology, Perth.
- Liedloff, A.C. and G.D. Cook (2007) Modelling the effects of rainfall variability and fire on tree populations in an Australian tropical savanna with the FLAMES simulation model. *Ecological Modelling*, **201**, 269-282.
- Liedloff, A.C., M.B. Coughenour, J.A. Ludwig, and R. Dyer (2001) Modelling the tradeoff between fire and grazing in a tropical savanna landscape, northern Australia. *Environment International*, **27**, 173-180.
- Luke, R.H. and A.G. McArthur (1978) *Bushfires in Australia*. Australian Government Publishing Service, Canberra.
- McArthur, A.G. (1966) *Weather and Grassland Fire Behaviour*, Leaflet 100. Australian Forestry & Timber Bureau, Canberra.
- McGuffog, T. and T. Starr (1997) Fire management in northern Australia: the Top End trilecta. In *Bushfire '97 Proceedings: Parks Australia North*, Darwin.
- Meyer, C.P. (2004) *Establishing a Consistent Time-series of Greenhouse Gas Emission Estimates from Savanna Burning in Australia*, Report C/0958. Australian Greenhouse Office, Canberra.
- Moore, J.L., S.M. Howden, G.M. McKeon, J.O. Carter, and J.C. Scanlan (2001) The dynamics of grazed woodlands in southwest Queensland, Australia and their effect on greenhouse gas emissions. *Environment International*, **27**, 147-153.
- Neldner, V.J., R.J. Fensham, J.R. Clarkson, and J.P. Stanton (1997) The natural grasslands of Cape York Peninsula, Australia: Description, distribution and conservation status. *Biological Conservation*, **81**, 121-136.
- NGGIC (2005) *National Greenhouse Gas Inventory 2005*. National Greenhouse Gas Inventory Committee, Canberra, p. 29.
- Ockwell, D. and J.C. Lovett (2005) Fire-assisted pastoralism vs. sustainable forestry: The implications of missing markets for carbon in determining optimal land use in the wet-dry tropics of Australia. *Journal of Environmental Management*, **75**, 1-9.
- Pardon, L.G., B.W. Brook, A.D. Griffiths, and B.W. Braithwaite (2003) Determinants of survival for the northern brown bandicoot under a landscape-scale fire experiment. *Journal of Animal Ecology*, **72**, 106-115.
- Pearce, K., P. Holper, M. Hopkins, W. Bouma, P. Whetton, K. Hennessy, and S. Power (2007) *Climate Change in Australia*, Technical Report 2007. CSIRO/Bureau of Meteorology, Melbourne. Available at <http://www.climatechangeinaustralia.gov.au/documents/resources/>
- Pereira, J.M. (2003) Remote sensing of burned areas in tropical savannas. *International Journal of Wildland Fire*, **12**, 259-270.
- Petherick, J.C. (2005) Animal welfare issues associated with extensive livestock production: The northern Australian beef cattle industry. *Applied Animal Behaviour Science*, **92**, 211-234.

- Price, O., J. Russell-Smith, and A. Edwards (2003) Fine-scale patchiness of different fire intensities in sandstone heath in northern Australia. *International Journal of Wildland Fire*, **12**, 227–236.
- Purton, C.M. (1982) *Equations for the McArthur Mark 4 Grassland Fire Danger Meteorological Note 147*. Australian Bureau of Meteorology, Adelaide.
- Ridpath, M.G. (1983) Ecology of the wet dry tropics: How different? *Proceedings of the Ecological Society of Australia*, **13**, 3–20.
- Robinson, C.J. and P. Whitehead (2003) Cross-cultural management of pest animal damage: A case study of feral buffalo control in Australia's Kakadu National Park. *Environmental Management*, **32**, 445–458.
- Roderick, M.L., L.D. Rotstayn, G.D. Farquhar, and M.T. Hobbins (2007) On the attribution of changing pan evaporation. *Geophysical Research Letters*, **34**, L17403. doi: 10.1029/2007GL031166.
- Rossiter, N.A., S.A. Setterfield, M.M. Douglas, and L.B. Hutley (2003) Testing the grass-fire cycle: Alien grass invasion in the tropical savannas of northern Australia. *Diversity and Distributions*, **9**, 169–176.
- Rotstayn, L.D., W. Cai, M.R. Dix, G.D. Farquhar, Y. Feng, P. Ginoux, M. Herzog, A. Ito, J.E. Penner, M.L. Roderick, and M. Wang (2007) Have Australian rainfall and cloudiness increased due to the remote effects of Asian anthropogenic aerosols? *Journal of Geophysical Research*, **112**, D009202. doi: 10.1029/2006JD007712.
- Russell-Smith, J. and D.M.J.S. Bowman (1992) Conservation of monsoon rainforest isolates in the Northern Territory, Australia. *Biological Conservation*, **59**, 51–63.
- Russell-Smith, J., C. Yates, A. Edwards, G.E. Allan, G.D. Cook, P. Cooke, R. Craig, B. Heat, and R. Smith (2003a) Contemporary fire regimes of northern Australia, 1997–2001: Change since Aboriginal occupancy, challenges for sustainable management. *International Journal of Wildland Fire*, **12**, 283–297.
- Russell-Smith, J., P.J. Whitehead, R.J. Williams, and M. Flannigan (2003b) Fire and savanna landscapes in northern Australia: Regional lessons and global challenges. *International Journal of Wildland Fire*, **12**, v–ix.
- Russell-Smith, J., P.J. Whitehead, G.D. Cook, and J.D. Hoare (2003c) Response of *Eucalyptus*-dominated savanna to frequent fires: Lessons from Munmarlary, 1973–1996. *Ecological Monographs*, **73**, 349–375.
- Russell-Smith, J., P.J. Stanton, P.J. Whitehead, and A. Edwards (2004a) Rain forest invasion of eucalypt-dominated woodland savanna, Iron Range, north-eastern Australia. I. Successional processes. *Journal of Biogeography*, **31**, 1293–1303.
- Russell-Smith, J., P.J. Stanton, A.C. Edwards, and P.J. Whitehead (2004b) Rain forest invasion of eucalypt-dominated woodland savanna, Iron Range, north-eastern Australia. II. Rates of landscape change. *Journal of Biogeography*, **31**, 1305–1316.
- Russell-Smith, J., C.P. Yates, P.J. Whitehead, R. Smith, R. Craig, G.E. Allan, R. Thackway, I. Frakes, S. Cridland, M.C.P. Meyer *et al.* (2007) Bushfires "down under": Patterns and implications of contemporary Australian landscape burning. *International Journal of Wildland Fire*, **16**, 361–377.
- Scholes, R.J. and S.R. Archer (1977) Tree-grass interactions in savannas. *Annual Review of Ecology and Systematics*, **28**, 517–544.
- Sharp, B.R. and R.J. Whittaker (2003) The irreversible cattle-driven transformation of seasonally flooded Australian savanna. *Journal of Biogeography*, **30**, 783–802.
- Shaw, N.H. (1957) Bunch spear grass dominance in burnt pastures in south-eastern Queensland. *Australian Journal of Agricultural Research*, **8**, 325–334.

- Shaw, N.H. and W.J. Bisset (1955) Characteristics of a bunch spear grass (*Heteropogon contortus* (L.) Beauv.) pasture grazed by cattle in subtropical Queensland. *Australian Journal of Agricultural Research*, **6**, 539-552.
- Spessa, A., B. McBeth, and C. Prentice (2005) Relationships among fire frequency, rainfall and vegetation patterns in the wet-dry tropics of northern Australia: An analysis based on NOAA-AVHRR data. *Global Ecology and Biogeography*, **14**, 439-454.
- Stanton, J.P. (1992) J. P. Thomson oration: The neglected lands: Recent changes in the ecosystem of Cape York Peninsula and the challenge of their management. *Queensland Geographical Journal*, **7**, 1-18.
- Strahan, R. (1995) *The Mammals of Australia*. Revised Edition. New Holland Publishers, Sydney.
- Suijddorp, H. (1981) Responses of the hummock grasslands of northwestern Australia to fire. In A.M. Gill, R.H. Groves, and I.R. Noble (Eds.), *Fire and the Australian Biota*. Australian Academy of Science, Canberra.
- Tapper, N.J., G. Garden, J. Gill, and J. Feron (1993) The climatology and meteorology of high fire danger in the Northern Territory. *Rangeland Journal*, **15**, 339-351.
- Tassicker, A.L., A.S. Kutt, E. Vanderduys, and S. Mangru (2006) The effects of vegetation structure on the birds in a tropical savanna woodland in north-eastern Australia. *The Rangeland Journal*, **28**, 139-152.
- Thackway, R. and I.D. Cresswell (1995) *An Interim Biogeographic Regionalisation for Australia*, Version 4.0. Australian Nature Conservation Agency, Canberra.
- Tothill, J.C. and C. Gillies (1992) *The Pasture Lands of Northern Australia*, Occasional Publication No. 5. Tropical Grassland Society of Australia, St. Lucia, Queensland.
- Tunstall, B.R., J. Walker, and A.M. Gill (1976) Temperature distribution around synthetic trees during grass fires. *Forest Science*, **22**, 269-276.
- Walker, J. (1981) Fuel dynamics in Australian vegetation. In A.M. Gill, R.H. Groves, and I.R. Noble (Eds.), *Fire and the Australian Biota*. Australian Academy of Science, Canberra.
- Walker, J., K. Malafant, and J. Edwards (1983) The effects of fire on a *Themeda-Heteropogon* grassland near Rockhampton. *Proceedings of the Second Queensland Fire Workshop, Gympie, July 2003*.
- Weber, R.O., A.M. Gill, P.R.A. Lyons, and G.N. Mercer (1995) Time dependence of temperature above wildland fires. *CALM Science Supplement*, **4**, 17-22.
- Weston, E.J. (1988) Native pasture communities. In W.H. Burrows, J.C. Scanlan, and M.T. Rutherford (Eds.), *Native Pastures in Queensland: The Resources and Their Management*. Queensland Department of Primary Industries, Brisbane.
- Whitehead, P.J., J. Russell-Smith, and J.C.Z. Woinarski (2005) Fire, landscape heterogeneity and wildlife management in Australia's tropical savannas: Introduction and overview. *Wildlife Research*, **32**, 369-375.
- Williams, P.R. (2000) Fire-stimulated rainforest seedling recruitment and vegetative regeneration in a densely grassed wet sclerophyll forest of north-eastern Australia. *Australian Journal of Botany*, **48**, 651-658.
- Williams, P.R., R.A. Congdon, A.C. Grice, and P.J. Clarke (2003) Effect of fire regime on plant abundance in a tropical eucalypt savanna of north-eastern Australia. *Austral Ecology*, **28**, 327-338.
- Williams, R.J. and A. Lane (1999) Wet season burning as a fuel management tool in wet-dry tropical savannas: Applications at Ranger Mine, Northern Territory, Australia. In D. Eldridge and D. Freudenberger (Eds.), *People and Rangelands: Proceedings Sixth*

- International Rangelands Congress*. International Rangelands Congress Incorporated, Townsville, Queensland.
- Williams, R.J., G.A. Duff, D.M.J.S. Bowman, and G.D. Cook (1996) Variation in the composition and structure of tropical savannas as a function of rainfall and soil texture along a large-scale climatic gradient in the Northern Territory, Australia. *Journal of Biogeography*, **23**, 747–756.
- Williams, R.J., G.D. Cook, J.L. Ludwig, and D. Tongway (1997a) Torch, trees, teeth and tussocks: Disturbance in the tropical savannas of the Northern Territory (Australia). In N. Klomp and I. Lunt (Eds.), *Frontiers in Ecology: Building the Links*. Elsevier, Oxford, U.K.
- Williams, R.J., B.A. Myers, W.J. Muller, G.A. Duff, and D. Eamus (1997b) Leaf phenology of woody species in a northern Australian tropical savanna. *Ecology*, **78**, 2542–2558.
- Williams, R.J., A.M. Gill, and P.H.R. Moore (1998) Behaviour of fires in a tropical savanna at Kapalga, Kakadu National Park, northern Australia. *International Journal of Wildland Fire*, **8**, 227–239.
- Williams, R.J., G.D. Cook, A.M. Gill, and P.H.R. Moore (1999) Fire regime, fire intensity and tree survival in a tropical savanna in northern Australia. *Australian Journal of Ecology*, **24**, 50–59.
- Williams, R.J., A.D. Griffiths, and G.E. Allan (2002) Fire regimes and biodiversity of the savannas of northern Australia. In R.A. Bradstock, J.E. Williams, and A.M. Gill (Eds.), *Flammable Australia: The Fire Regimes and Biodiversity of a Continent*. Cambridge University Press, Cambridge, U.K.
- Williams, R.J., A.M. Gill, and P.H.R. Moore (2003a) Fire behaviour. In A.N. Andersen, G.D. Cook, and R.J. Williams (Eds.), *Fire in Tropical Savannas: The Kapalga Experiment*. Springer-Verlag, New York.
- Williams, R.J., W.J. Muller, C-H. Wahren, S.A. Setterfield, and J. Cusack (2003b) Vegetation. In A.N. Andersen, G.D. Cook, and R.J. Williams (Eds.), *Fire in Tropical Savannas: The Kapalga Experiment*. Springer-Verlag, New York.
- Williams, R.J., L.B. Hutley, G.D. Cook, J. Russell-Smith, A. Edwards, and X. Chen (2004) Assessing the carbon sequestration potential of mesic savannas in the Northern Territory, Australia: Approaches, uncertainties and potential impacts of fire. *Functional Plant Biology*, **31**, 415–422.
- Woinarski, J.C.Z. (1990) Effects of fire on bird communities of tropical woodlands and open forests in northern Australia. *Australian Journal of Ecology*, **15**, 1–22.
- Woinarski, J.C.Z. (1992) Biogeography and conservation of reptiles, mammals and birds across north-western Australia: An inventory and base for planning an ecological reserve system. *Wildlife Research*, **19**, 665–705.
- Woinarski, J.C.Z. and A.J. Ash (2002) Responses of vertebrates to pastoralism, military land use and landscape position in an Australian tropical savanna. *Austral Ecology*, **27**, 311–323.
- Woinarski, J.C.Z. and C.P. Catterall (2004) Historical changes in the bird fauna at Coomoo-boolaroo, northeastern Australia, from the early years of pastoral settlement (1873) to 1999. *Biological Conservation*, **116**, 379–401.
- Woinarski, J.C.Z., A. Fisher, and D. Milne (1999a) Distribution patterns of vertebrates in relation to an extensive rainfall gradient and soil variation in the tropical savannas of the Northern Territory, Australia. *Journal of Tropical Ecology*, **15**, 381–398.
- Woinarski, J.C.Z., C. Brock, A. Fisher, D. Milne, and B. Oliver (1999b) Response of birds and reptiles to fire regimes on pastoral land in the Victoria River District, Northern Territory. *The Rangeland Journal*, **21**, 24–38.

Woinarski.
fauna
Austr:
Woinarski.
bound
32, 37
Woinarski.
Natur:
Yates, C.
exampl
Wildlu

- Woinarski, J.C.Z., J. Risler, and L. Kean (2004) The response of vegetation and vertebrate fauna to 23 years of fire exclusion in a tropical *Eucalyptus* open forest, Northern Territory, Australia. *Austral Ecology*, **29**, 156–176.
- Woinarski, J.C.Z., R.J. Williams, O. Price, and B. Rankmore (2005) Landscapes without boundaries: Wildlife and their environments in northern Australia. *Wildlife Research*, **32**, 377–388.
- Woinarski, J., B. Mackey, H. Nix, and B. Traill (2007) *The Nature of Northern Australia: Natural Values, Ecological Processes and Future Prospects*. ANU e-press, Canberra.
- Yates, C. and J. Russell-Smith (2003) Fire regimes and vegetation sensitivity analysis: An example from Bradshaw Station, monsoonal northern Australia. *International Journal of Wildland Fire*, **12**, 349–358.

Contributors

Felipe Salvo Aires

Departamento de Ecologia, Universidade de Brasília, 70.910-900, Brasília, D.F., Brazil

Ane A.C. Alencar

School of Forest Resources and Conservation, University of Florida, Gainesville, FL 32611, U.S.A. and Amazon Environmental Research Institute (IPAM), Belem, PA, Brazil
aalencar@ufl.edu; mailto:ane@ipam.org.br

Heidi Asbjornsen

Department of Natural Resource Ecology & Management, Iowa State University, Ames, IA 50010, U.S.A.
hasbjorn@iastate.edu

Patrick J. Baker

School of Biological Sciences, Monash University, VIC 3800, Australia
patrick.baker@sci.monash.edu.au

Jennifer K. Balch

School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511, U.S.A.
jennifer.balch@yale.edu

Jos Barlow

Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, U.K.
jos.barlow@lancaster.ac.uk

Bibiana Bilbao

Universidad Simón Bolívar, Departamento de Estudios Ambientales, Universidad Simón Bolívar, Apartado 89000, Caracas 1080, Venezuela
bibiana.bilbao@gmail.com

David M.J.S. Bowman

School of Plant Science, University of Tasmania, Hobart, TAS 7001, Australia
David.Bowman@utas.edu.au

Meilanie Buitenzorgy

Department of Resources and Environmental Economics, Faculty of Economics and Management, Bogor Agricultural University (IPB), Kamper Kampus IPB Darmaga Bogor 16680, Indonesia
meilanie.buitenzorgy@ipb.ac.id

Sarayudh Bunyavejchewin

Research Office, National Parks, Wildlife, and Plant Conservation Department, Bangkok, Thailand

Unna Chokkalingam

Jalan Taman Cilandak VI - C4 Cilandak, Jakarta 12430, Indonesia
u.chokkalingam@gmail.com

Mark A. Cochrane

Geographic Information Science Center of Excellence (GIScCE), South Dakota State University, Brookings, SD 57007, U.S.A. and Instituto do Homem e Meio Ambiente na Amazônia (IMAZON), Belém, PA Brazil
mark.cochrane@sdstate.edu

Carla Cristina Dinis Cuambe

Ministry of Agriculture: National Directorate of Land and Forestry: Department of Natural Resources Inventory, Maputo, Mozambique
Carlacuambe@hotmail.com

Lisa M. Curran

Yale School of Forestry & Environmental Studies, New Haven, CT 06517, U.S.A.
lisa.curran@yale.edu

Philip Dearden

Department of Geography, University of Victoria, Victoria V8W3P5, Canada

Maria Dolores Delgado-Cartay

Universidad Simón Bolívar, Departamento de Estudios Ambientales, Universidad Simón Bolívar, Caracas 1080, Venezuela. Present address: Institut für Physische Geographie, Universität Frankfurt, Altenhoferallee, 160438 Frankfurt a.M., Germany

A. Malcolm Gill

CSIRO Plant Industry, Canberra, ACT 2601, Australia; Fenner School of Environment and Society, The Australian National University, Canberra, ACT 0200, Australia; and, Bushfire CRC, East Melbourne, VIC 3002, Australia
malcolm.gill@csiro.au

Anja A. Hoffmann

Current address: P.O. Box 202, Phuti Crescent 2628, Gaborone, Botswana
aahoffmann@email.de

Sally P.

Department
shorn@utl

Agata H.

Department

Laura A.

Department
ljohnson_u

Maarten

The Natural
 Geography

Narendra

Natural Resources
nkodanda@

Christian

School of
 Melbourne
Christian.K

Iwan Kurr

Riap Indor
IKurniawan

Dominick

Universidad
dkweshu@u

Andreas L.

Department
 Tokyo, Kas
 GmbH, 816

Paul Laris

Department
 U.S.A.
plaris@csull

Alejandra I.

Universidad
 Bolívar, Car

Suwido Lim

CIMTROP,

Sally P. Horn

Department of Geography, The University of Tennessee, Knoxville, TN 37996, U.S.A.
shorn@utk.edu

Agata Hoscilo

Department of Geography, University of Leicester, University Road, Leicester LE1 7RH, U.K.

Laura A. Johnson

Department of Geography, University of Victoria, Victoria, BC, Canada
ljohnson_uvic@hotmail.com

Maarten Kappelle

The Nature Conservancy, Mesoamerican and Caribbean Science Program, Department of Geography, The University of Tennessee, Knoxville, TN 37996, U.S.A.

Narendran Kodandapani

Natural Resources Program, Grays Harbor College, Aberdeen, WA 98520, U.S.A.
nkodanda@ghc.edu

Christian Kull

School of Geography and Environmental Science, Monash University - Clayton Campus, Melbourne, VIC 3800, Australia
Christian.Kull@arts.monash.edu.au

Iwan Kurniawan

Riap Indonesia, Gunung Batu, Bogor, 16118 Indonesia
IKurniawan@riapindo.net

Dominick Kwesha

Universidade Católica de Moçambique (UCM), Beira - Moçambique
dkwesha@ucm.ac.mz; dkwesha2001@yahoo.co.uk

Andreas Langner

Department of International Studies, Graduate School of Frontier Sciences, The University of Tokyo, Kashiwanoha, Kashiwa-shi, Chiba, 277-8563, Japan and Remote Sensing Solutions GmbH, 81667 Munich, Germany

Paul Laris

Department of Geography, California State University Long Beach, Long Beach, CA 90840, U.S.A.
plaris@csulb.edu

Alejandra Leal

Universidad Simón Bolívar, Departamento de Estudios Ambientales, Universidad Simón Bolívar, Caracas 1080, Venezuela

Suwido Limin

CIMTROP, University of Palangkraya, Palangkraya, Central Kalimantan, Indonesia

Carlos Méndez

Universidad Simón Bolívar, Departamento de Estudios Ambientales, Universidad Simón Bolívar, Caracas 1080, Venezuela

Helois Sinátora Miranda

Departamento de Ecologia, Universidade de Brasília, 70.910-900, Brasília, D.F., Brazil
hmiranda@unb.br

Brett P. Murphy

School of Plant Science, The University of Tasmania, Hobart, TAS 7001, Australia

Ronald L. Myers

Global Fire Team, The Nature Conservancy, Tallahassee, FL, U.S.A.
rmyers@TNC.ORG

Daniel C. Nepstad

Woods Hole Research Center, Falmouth, MA 02450, U.S.A and Instituto de Pesquisa Ambiental da Amazônia, Belém, Brazil

Walter Nascimento Neto

Departamento de Ecologia, Universidade de Brasília, 70.910-900, Brasília, D.F., Brazil

María Manta Nolasco

Forestry Faculty, Universidad Nacional Agraria La Molina, Lima 12, Peru
mmanta@lamolina.edu.pe

Susan Page

Department of Geography, University of Leicester, Leicester LE1 7RH, U.K.
sep5@le.ac.uk

Jo-Ellen Parry

International Institute for Sustainable Development, Climate Change and Energy International Institute for Sustainable Development, Winnipeg, Manitoba, Canada R3B 0Y4
jparry@iisd.ca

Rizki Pandu Permana

Faculty of GeoSciences, Utrecht University, Utrecht, the Netherlands
r.permana@geo.uu.nl

Jack Rieley

School of Geography, University of Nottingham, University Park, Nottingham NG7 2RD, U.K.

Dante Arturo Rodríguez-Trejo

División de Ciencias Forestales, Universidad Autónoma Chapingo, Chapingo, Estado de México, C.P. 56230, Mexico

Kevin C. Ryan

USDA Forest Service, Fire Sciences Laboratory, Missoula, MT 59808, U.S.A.
kryan@fs.fed.us

Margarete I
Departament

Ayn Shlisky
Prineville Dis
Ayn_Shlisky@

Florian Sieg
Remote Sens
at the Ludwi

Juliana M.
Museu Parae

R. Sukumar
Center for Ec
rsuku@ces.iis

Robiyanto I
Faculty of Ag
Indonesia

Suyanto
World Agrof
Indonesia
suyanto@cgi

Kevin Tanse
Department

Tom Vigilar
Current addr
tom.vigilar@

Bart Wickel
National Cor
Pedregal, Tla
Conservation
bart.wickel@

Richard J. V
CSIRO Susta
dick.williams@

John C.Z. V
Northern Ter
NT 0831. Au
john.woinarsk

Sam W. Wo
School of Pla

Margarete Naomi Sato

Departamento de Ecologia. Universidade de Brasília, 70.910-900. Brasília, D.F., Brazil

Ayn Shlisky

Prineville District, Bureau of Land Management, Prineville, OR 97754, U.S.A.

Ayn_Shlisky@blm.gov

Florian Siegert

Remote Sensing Solutions GmbH, Wörthstr. 49, 81667 Munich, Germany and GeoBio Center at the Ludwig-Maximilians-University, 82152 Planegg-Martinsried, Germany

Juliana M. Silveira

Museu Paraense Emilio Goeldi, Belém, Brazil

R. Sukumar

Center for Ecological Sciences, Indian Institute of Science, Bangalore 560 012, India.

rsuku@ces.iisc.ernet.in

Robiyanto Hendro Susanto

Faculty of Agriculture, Sriwijaya University, Kampus Indralaya OKI 30661, South Sumatra, Indonesia

Suyanto

World Agroforestry Centre, Southeast Asia Regional Office, Sindang Barang, Bogor 16601, Indonesia

suyanto@cgiar.org

Kevin Tansey

Department of Geography, University of Leicester, Leicester LE1 7RH, U.K.

Tom Vigilante

Current address: PO Box 1442, Derby, WA 6728, Australia

tom.vigilante@klc.org.au

Bart Wickel

National Commission for Knowledge and Use of Biodiversity (CONABIO), Parques del Pedregal, Tlalpan, 14010, Mexico City, Mexico and current address: World Wildlife Fund, Conservation Science Program, Washington, D.C. 20037, U.S.A.

bart.wickel@wwfusa.org

Richard J. Williams

CSIRO Sustainable Ecosystems, Winnellie, NT 0821, Australia

dick.williams@csiro.au

John C.Z. Woinarski

Northern Territory Department of Natural Resources Environment and the Arts, Palmerston, NT 0831, Australia

john.woinarski@nt.gov.au

Sam W. Wood

School of Plant Science, University of Tasmania, Hobart, TAS 7001, Australia

Washington Zhakata

University of Zimbabwe/ National Coordinator, Climate Change Office, Ministry of Environment and Tourism, Harare, Zimbabwe

climate@ecoweb.co.zw; washingtonzhakata@hotmail.com

1

Fire Mark

1.1 IN

Why the
boreal e
the mor
wildfires
States. I
implicat
ecosyste
of the co
why wri

The
more fir
Cancer :
rainfore:
surface o
the vast
tropical
of dollar
several o
ecosystem
addresse
significan