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Introduction

The chapters in this introductory section provide an overview of the grassland biome and how ecologists collect (or should collect) data needed to address the threat of climate change. In the first chapter (Gibson and Newman), we set the stage for the rest of the book by summarising the unique aspects of grasslands compared with other biomes, the changes already observed, and those predicted to occur in response to anthropogenic climate change. We also discuss grasslands in the context of climate change policy and note some of the challenges in complying with mitigation mandates and recommendations. Two methodology chapters follow and review the ways in which ecologists collect the data necessary to study climate change. Some of the methods are general and applicable to biomes across the globe, while others are specific or adapted for grasslands. Regardless, we are trying to project forward from current data and trends into the future, despite the admonition that you may remember from basic statistics not to extrapolate beyond the bounds of your data. Hence, the use of models. The first of the two methodology chapters is by Hager and Newman (Chapter 2), who use a systematic review to address issues related to experimental design and how to collect appropriate field data to adequately detect grassland change in response to climate change. In particular, they discuss some of the issues related to ensuring that experiments are appropriately designed to have sufficient statistical power. Adequate statistical power is necessary to allow experiments to detect what may be subtle effects. The detection and incorporation of these subtle effects into models allow us to predict impacts that may only be evident over timeframes longer than the typical ecological experiment (and the duration of funding). The second methodology chapter by Henebry (Chapter 3) asks how successful we are in remotely detecting grassland change in response to the changing global climate. The most appropriate new technology is reviewed, especially with respect to detecting change at different spatial and temporal scales of resolution. Five aspects of change analysis in grasslands are emphasised: change detection, change quantification, change assessment, change attribution, and change projection.

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CHAPTER ONE

Grasslands and climate change: an overview

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1.1 Introduction

Grassland covers 31–43 percent of the Earth's terrestrial habitats offering a variety of critical ecosystem services including carbon storage, food, forage, and biofuels, and opportunities for tourism and recreation. In addition, grasslands are a unique repository of biodiversity. Some 792 million people live in grasslands worldwide (1). Despite their importance, grasslands are an endangered biome, threatened through land-use change, agricultural intensification, suppression of fire, and abandonment, and now anthropogenic climate change (ACC) leading to warming, changed patterns of precipitation, and other effects. The aim of this book is to bring together an international team of researchers to review the scientific knowledge of the effects of ACC on world grasslands. In doing so, we can better predict the future of this important biome and understand how anthropogenic effects can be mitigated as this ecosystem both diminishes in extent and is altered in response to climate change.

In this introductory chapter, the unique aspects and the importance of grasslands compared with other biomes are first defined, followed by a summary of the effects of climate change on grasslands worldwide. Broadly, the main threats to grasslands will be summarised along with the opportunities that grasslands provide for ecological research.

1.2 Grassland extent and distribution

Estimates of grassland extent vary depending upon the definition of grassland that is adopted and the methodology used. It is surprisingly difficult to define a grassland and a variety of grassland definitions have been proposed (see table 1.1 in (2)). For example, the International Forage Grazing Terminology Committee (3) defines **native or natural grassland** as a 'natural ecosystem dominated by indigenous or naturally occurring grasses and other herbaceous species used mainly for grazing by livestock and wildlife', in contrast to **savannas** which are considered as grassland 'characterized by precipitation between 375 and 1500 mm year^{-1}' . . . 'variable proportions of trees or large shrubs', and 'often a transitional vegetation type between grassland and forestland', and **shrublands** as 'land on which the vegetation is dominated by low-growing woody plants'. In developing a map of world grassland types, Dixon et al. (4) define grassland as 'with at least 10% vegetation cover, dominated or co-dominated by graminoid and forb growth forms, and where the trees form a single-layer canopy with either less than 10% cover and 5 m height (temperate) or less than 40% cover and 8 m height (tropical)' (4).

Notwithstanding vagaries in definition, grasslands occur historically over 31–43 percent of the Earth's land surface, on every continent except Antarctica (although there are native and non-native grass populations expanding on Antarctic islands in response to anthropogenic activities and regional warming (5,6)), with a global extent ranging 41–56 $\times$ 10^6 km^2 (7). Eleven countries each have more than 1 million km^2 of grassland (in order these are: Australia, Russian Federation, China, USA, Canada, Kazakhstan, Brazil, Argentina, Mongolia, Sudan, and Angola). In an assessment of seven proposed anthropogenic biomes, grassland, including rangeland, had the most extensive land cover occupying 39.7 $\times$ 10^6 km^2 (30.4 percent). Across all anthropogenic biomes, pasture in remote rangelands was the most extensive single land cover type (9.5 $\times$ 10^6 km^2, 7.3 percent) (8). It is important to recognise that many grasslands are not 'natural' but are wholly or partly anthropogenic in origin, e.g. many of the 'improved grasslands', seeded leys, or pastures of Europe. Regardless of origin, these grasslands are an important part of the global grassland biome and are likely to change in composition and extent in response to climate change. The International Vegetation Classification (IVC) recognised 49 taxonomically and spatially distinct historical and current grassland formations and divisions (4). Below upper-level physiognomic formations, the lower levels of grassland divisions were characterised by floristics. Eleven IVC grassland divisions individually covered more than 1.0 $\times$ 10^6 km^2 with the North Sahel Semi-Desert Scrub and Grassland of Africa being the most extensive (Table 1.1). It is notable that the major continental land masses are all represented on the listing in Table 1.1, i.e, Africa, Eurasia, North and South America, and Australia.

1.3 Grassland goods and services

Grasslands have many important goods and services including: food, forage, biofuels, tourism, recreation, wildlife habitat, and ecosystem services such as: storm water management, soil conservation, soil carbon storage, aquifer recharge, soil water conservation during drought, improved soil physical and chemical properties. All of these goods and services are threatened by

Table 1.1 *International Vegetation Classification (IVC) of dominant grassland divisions with land area more than 1.0 × 10^6 km^2. Compiled from data in Dixon et al. (4).*

IVC division	Area (10^6 km^2)
North Sahel Semi-Desert Scrub and Grassland	3.04
Great Plains Grassland & Shrubland	2.98
Eastern Eurasian Cool Semi-Desert Scrub & Grassland	2.85
Central Asian Alpine Scrub, Forb Meadow & Grassland	2.80
Australian Tropical Savanna	2.15
Eastern Eurasian Grassland & Shrubland	2.11
Brazilian-Parana Lowland Shrubland, Grassland & Savanna	2.04
West-Central African Mesic Woodland and Savanna	1.84
Eastern Africa Xeric Scrub and Grassland	1.70
Sudano Sahelian Dry Savanna	1.63
Western Eurasian Cool Semi-Desert Scrub & Grassland	1.35

climate change ((2), and see Lavorel, Chapter 8). With up to 90 percent of grassland biomass belowground, soil carbon levels are high in grasslands compared with other ecosystems (estimated at 650–810 Gt C worldwide, (1)). As a current sink for terrestrial carbon, the changes in response to climate change are uncertain, but of concern (9). Grasslands have an important role in global food security, providing ruminant milk and meat production that is under threat from climate change as productivity changes and plant species' adaptation is uncertain and variable (10). As noted in this book, and elsewhere (11), ecological research is important in meeting this challenge of maintaining global food security in the face of climate change.

1.4 Climate change as a threat to grassland

Anthropogenic climate change is a growing threat to grasslands worldwide and encompasses local and regional changes in temperature (generally, warming), precipitation (often drought, including intensification of weather extremes), and snow cover, and increasing concentrations of atmospheric CO_2, CH_4, and N_2O and nitrogen deposition ((12), and see Jones, Chapter 4). Global temperature is projected to increase from 1 to 6°C depending upon the scenario and climate model used, with temperatures in grasslands predicted to rise 1–1.5°C with considerable regional variation (13). These changes in global climate have been occurring since the onset of the Industrial Revolution and were predicted as far back as the early 1800s by German naturalist Alexander von Humboldt (14).

For example, significant changes in climate have been recorded in the southern plains region of the USA since 2000 with record droughts in the tallgrass prairie areas of Texas, Oklahoma, and Kansas in 2011 (15). The 2014

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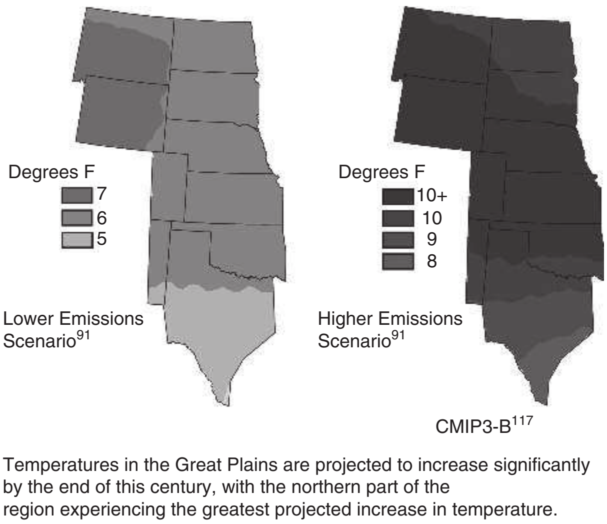

Figure 1.1. Projected summer temperature increase in the US Great Plains by 2080–2099 according to two IPCC emissions scenarios. This region corresponds closely to the historical extent of the tallgrass prairie. (Reproduced with permission by Cambridge University Press from Karl et al., 2009 (19).) (A black and white version of this figure will appear in some formats. For the colour version, please refer to the plate section.)

National Climate Assessment of the US Global Change Research Program (16) projects temperatures in this region to rise 2.8–5.5˚C by 2080–2099 (Figure 1.1) with high maximum temperature days (35–38˚C) becoming more frequent in the summer, especially in the southern part of the region. These increases in heat will lead to increases in surface water losses, heat stress, a longer growing season by up to 24 days, and more overwintering insect populations. Winter and spring precipitation will increase in northern states as will the number of days with heavy precipitation, and days with winter snow events. More intense droughts are projected to increase fire frequency and desertification. Ecologically, species will have difficulty migrating as climate variability and change alters habitats in the increasingly fragmented landscape. There are already shifts in species phenology occurring in response to climate change (17), and it is expected that native species abundance will decline as non-natives increase. Increasing atmospheric CO_2 will somewhat offset the drying from warming, but nutritional quality of the forage may decrease (18), leading to reduced weight gain in herbivores. O'Mara (10) poignantly asked the question, 'Can grasslands simultaneously produce extra food, cope with climate change and mitigate greenhouse gas emissions?'

Projected climate change in other grassland regions across the globe are similar to those projected for the US Great Plains. For example, rangelands in

Australia are similarly predicted to show increases in average temperature in all seasons, with more hot days and fewer frosts, decreased winter rainfall in the southern rangelands, and an increased intensity of extreme rainfall events (20). In South African grasslands, projected climatic changes are variable, but summer rainfall is projected to increase, but with a delayed onset, and is projected to lead to a decrease in range extent of native species and widespread species loss throughout the century (Figure 1.2) (21). In Europe, 13.2 percent of the land area is under 'permanent grassland' and climate change is predicted to lead to warmer temperatures, increased summer drought, and more frequent heatwaves, floods, droughts, and wildfires, although changes are expected to be region-specific and vary among agro-climatic zones (22). As a result, grassland production is predicted to increase in northern and north-western Europe, but decrease in southern Europe; phenology will be advanced in many plant species (but not all); and changes in species composition will occur. While enhanced production may be beneficial from an agronomic perspective, in some regions traditional grassland areas are projected to become unsuitable for grassland production without irrigation and become threatened by more profitable cropping systems. For example, in Europe, some climate scenarios project a decrease in grassland areas by as much as 50 percent, necessitating policy development to anticipate future use of this land (e.g. continued urban expansion, recreational land, or forested land use) (23).

In addition to climate change, grassland habitats are under threat worldwide due to fragmentation, habitat loss, land-use change, invasive species, agricultural intensification, and species loss through 'improvement'. Many grasslands are overgrazed and already suffer from problems of soil erosion and weed encroachment that are now being exacerbated by the effects of climate change. These altered climatic patterns are leading to altered productivity patterns, shifts in balance among functional groups (especially dominance of C_3 versus C_4 grasses), and transient or permanent regime change ((15,25), and see Fraser, Chapter 5 and Lavorel, Chapter 8).

Research into the effects of climate change is increasing across the board in all scientific disciplines including in grassland ecology. A systematic Boolean search of Web of Science™ on 7 June 2017 retrieved 4963 papers with only 12 papers on ecological research on climate change in grasslands (broadly defined) in 1992 rising to 669 in 2016; an exponential increase in research output over a 24-year period (Figure 1.3). The largest number of articles was published by authors based in the USA (40.7 percent) followed by China (18.7 percent), Germany (10.9 percent), Australia (8.8 percent), and England (8.3 percent), with 119 other countries making up the remainder. These articles were published in 324 different journals with the largest number (380 articles, 7.6 percent) in the journal *Global Change Biology*. Other important sources included the journals *Plant and Soil* (113, 2.3 percent), *Ecology* (112, 2.3 percent),

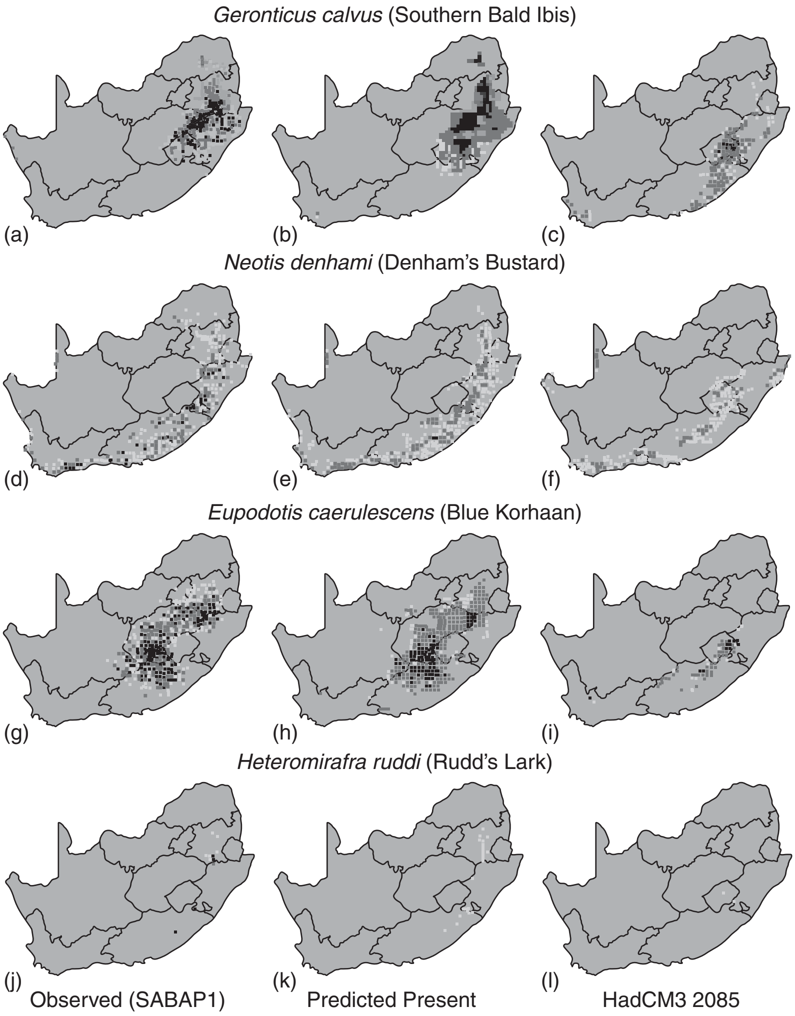

Figure 1.2. Present recorded and predicted, and a projected potential future, ranges and reporting rates for four grassland bird species of conservation concern in South African grassland. (a–c) *Geronticus calvus* (southern bald ibis); (d–f) *Neotis denhami* (Denham's bustard); (g–i) *Eupodotis caerulescens* (blue korhaan); (j–l) *Heteromirafra ruddi* (Rudd's lark); (a,d,g, j) Recorded distribution and reporting rates; (b,e,h,k) Predicted present distribution and reporting rates; (c,f,i,l) Distribution and reporting rates projected for the HadCM3 2085 climate scenario (24). (Shading indicates relative reporting rate for each species, darker shades indicating higher values.) (A black and white version of this figure will appear in some formats. For the colour version, please refer to the plate section.)

Reproduced with permission from Huntley and Barnard 2012 (21).

Agriculture Ecosystems and Environment (110, 2.2 percent), *Climatic Change* (109, 2.2 percent), *Agricultural and Forest Meteorology* (109, 2.2 percent), with the other 318 journals each publishing less than 2 percent of the articles. Such research is

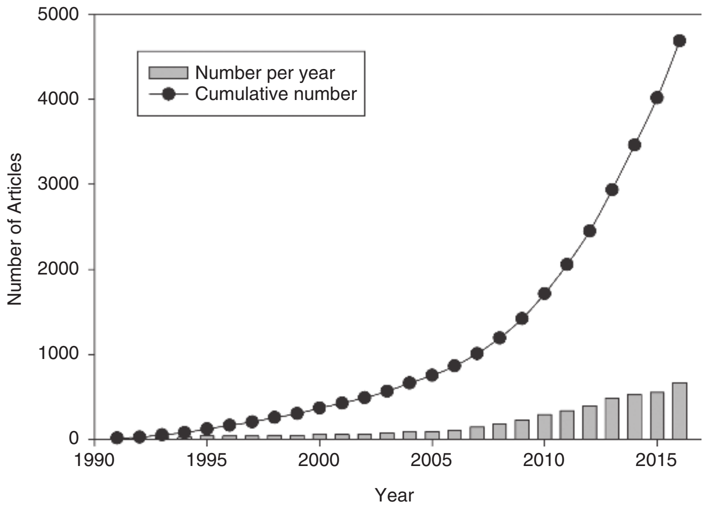

Figure 1.3. Number of articles published per year, and cumulative number, on grassland ecology and climate change since 1990. Data extracted from a systematic review using the Thompson–Reuters Web of Science database using the following terms: (old field OR savanna* OR steppe* OR grassland* OR prairie OR tallgrass* OR shortgrass* OR veld*) AND (climate change OR global warming OR climatic change) refined to include only articles, reviews, or book chapters in ecology, environmental science, plant science, biodiversity and conservation, agronomy, remote sensing, and evolutionary biology journals. As of 7 June 2017 the search revealed 4963 records (280 records from 2017 are not plotted here).

often inter- or transdisciplinary involving teams of researchers from different disciplinary backgrounds. This type of collaborative research brings challenges related to project management and coordination, engagement, and knowledge integration (26). Moreover, successful facilitation of interdisciplinary climate change research requires development of new global, regional, and sectorial scenarios to enable assessment of the range of future climates and their effects on, in this case, grassland systems and their interaction with social, economic and environmental components ((27), and see Dove, Chapter 16). Ecologists can take an important lead in developing new scientific and conceptual frameworks that can be translated into the development of sustainable mitigation and adaption policies (11). For example, the Great Plains Systems and Climate Change Report (28) shows how socio-ecological research can be brought together to assess the effects of climate change on the United States Great Plains region in order to develop future projections and identify research needs.

1.5 Grasslands and climate change policy

As discussed earlier in this chapter and throughout this book, grasslands are both threatened by climate change, contribute greenhouse gases (GHGs: N_2O

from soils, CH_4 from livestock, and CO_2 from fire) to climate change, and act as a carbon sink to mitigate increases in atmospheric CO_2. Nevertheless, despite the clear need to consider grasslands in climate change policy, grasslands are not explicitly mentioned in the most recent international climate change treaty, the Paris Agreement (http://unfccc.int/paris_agreement/items/9485.php). As part of the United Nations Framework Convention on Climate Change (UNFCCC), the Paris Agreement focuses on encouraging signatory countries around the world to voluntarily keep rising global temperatures to below 2˚C above pre-industrial levels. Of 197 Parties (countries), 157 ratified the Paris Agreement on 5 October 2016 providing broad international support. On a land-use basis, the UNFCCC focuses on forest ecosystems through recommendations of Land Use, Land-Use Change and Forestry (LULUCF: subsequently renamed Agriculture, Forestry and Other Land Uses: AFOLU) activities to increase removal of atmospheric GHGs, decrease emissions, and increase forest biomass and soil carbon stocks to mitigate climate change (http://unfccc.int/land_use_and_climate_change/lulucf/items/1084.php).
Under the framework of Article 3.4 of the earlier 1998 Kyoto Protocol (KP) of the UNFCCC, signatories voluntarily committed to reporting CO_2 emissions and AFOLU activities through Reducing Emissions from Deforestation and Forest Degradation (REDD) mechanisms to promote sequestration of CO_2 in soils and living biomass (29). However, inclusion of grasslands in KP AFOLU activities has lagged behind that proposed for forests. Nevertheless, a number of activities have been proposed to mitigate GHG emissions to improve rangeland health (Table 1.2) ((30,31), and see Bradford et al., Chapter 17). Uptake of these voluntary activities varies among signatories; for example, the expansion of sown biodiverse, legume-rich pastures has been promoted in Portugal to increase soil organic matter and carbon sequestration in low-productivity grasslands (32). There are many challenges to complying with Article 3.4. Australia, for example, has a large area of grassland (Table 1.1) and high levels of native and feral animals make managed reductions in grazing intensity to reduce GHG emissions problematic. Also, windstorms, floods, and wildfires lead to continental-wide movements and loss of carbon, and landowner rewards systems for reduced income from sustaining higher C stocks, and the costs involved in measuring and verifying C stocks, are challenges that need addressing (33). In Latin America, research has been undertaken to assess the efficacy of C sequestration in restoring degraded deforested areas to well-managed pastures and silvopastoral systems (34). Under these schemes, the Clean Development Mechanism (CDM) of the KP could provide payments to participating low-income rural farmers practising sustainable C storage land-use systems (35). A similar scheme of incentivising local farmers to adopt sustainable silvopastoral land-use systems through CDM payments is being explored in high-altitude grasslands of Nepal (36). However, a constraint with