Encyclopedia of Global Environmental Change

Proofing Instructions

Enclosed you should find:

- a proof of your article
- a list of proofreading symbols

queries to author ☐ are also enclosed ☒ there are none

About your text

Please check the proof of your article, **taking care to answer all outstanding queries** (these will be highlighted by the typesetter with a marginal mark).

Authors are advised that changes to the text other than corrections of errors introduced after manuscript submission or changes required by answering a specific query or by completing 'in press' references must be avoided at this stage. Such alterations may be charged back to the author.

All amendments should be made clearly and legibly. You must not send a new electronic version of your article as a way of indicating the corrections you have made. If you do, this will severely delay your article.

Please note that the Editors/Publisher may have made alterations to the text of your article not only to improve presentation but also to achieve consistency of style throughout the Encyclopedia.

Authors should also note that the original wording of article titles may have been changed. In some instances this may have been done to achieve consistency of style but more crucially it may have been done to ensure that the article appears in the most suitable position within the alphabetic structure of the Encyclopedia. **In order to avoid reordering the entire Encyclopedia, please refrain from amending article titles.**

About your artwork

Please mark all corrections to figures on the proofs enclosed. Note that your line figures may have been redrawn to establish consistency of style and notation and will therefore require careful checking.

All corrections must be marked on the proof. **Please refrain from supplying replacement artwork at this stage.** However, if this is absolutely necessary you must supply a reproduction-quality hard copy and, if possible, an electronic file.

If you are supplying replacement artwork, you must send this to the production office along with your corrected proofs (i.e. you must use option 3 overleaf).

CONTINUED ON PAGE TWO

Your unique reference number is

GB268-

Frequently asked questions

Is anybody else reading my proofs?
As first-named (or corresponding author) proofs have been sent to you alone, not to your co-authors. This is the only opportunity you will have to check proofs of your article. However, the proofs have also been sent to a professional proofreader, who will read the proofs against the manuscript, and to your volume editor and the editor-in-chief.

What is the most common mistake made when correcting proofs?
Being unclear or ambiguous. Remember that your corrections may be obvious to you but not necessarily to the person who is applying these corrections to the master proof. Take particular care to specify exactly what changes are required and to write proper names clearly. Please use the symbols shown on the enclosed document, *Proofreading Marks.* This will help us take in your corrections accurately and quickly.

Is this how my article will appear in the Encyclopedia?
Your article has been proofed as a single article beginning at the top of a page. When articles are run together to form the Encyclopedia they may actually start at different positions, halfway down a column for example, not necessarily at the head of a column. While this proof does indicate the relative positions of figures and their citations for example, it need not be checked for detailed page make up.

When will I receive proofs of the other articles I have contributed to the Encyclopedia?
If you have contributed other articles to the Encyclopedia, proofs of these articles will be sent to you separately. Articles are being proofed in the order that they were received at the typesetter.

How to return your corrections

Please send corrections to the production office by return. If you have no corrections to make please e-mail confirmation of this fact to the production office (p.warshell@deerpark.ie).

There are **three** methods of returning corrections to the production office. (Important: **please do not send your corrections by more than one method** – doing so will delay your article)

1 By email to p.warshell@deerpark.ie

Use this method if you have simple changes; these must be described clearly and unambiguously (e.g. by specifying page, column and line numbers). In the subject line of the e-mail header please quote your unique reference number (G) and your surname.

All corrections must be sent in a single e-mail, which will be acknowledged.

OR...

2 By fax to +353 61 361323

Use this method if you have too many corrections to describe in a single e-mail or if they cannot *easily* be described. Please take extra care to write your corrections clearly. We will contact you if the fax is unclear, otherwise we will only acknowledge receipt of the fax if specifically asked to do so.

OR...

3 By returning a corrected proof to the address below

You must use this method for complicated changes or if replacement artwork has to be supplied. If you are returning corrections by this method please make a copy of the corrected proof and retain it for reference in any further correspondence concerning your article before publication. **Mark all changes in red ink.**

Patricia Warshell
Deerpark Publishing Services Ltd.
Kincora Hall
Shannon Town Centre
Shannon, Co. Clare
Ireland

How wil I know that my corrections have been received?

We will contact you if it appears that you have not returned your corrections or if anything seems unclear. All e-mailed corrections will be acknowledged.

When will the Encyclopedia be publlshed?

Publication is planned for September 2001. Information will be available on the EGEC website (http://www.wiley.co.uk/ egec/), which also contains information on the contents and editors of the encyclopedia.

What about offprints?

Printed offprints will not be available for this encyclopedia. However, your article will be available as an individual PDF file, which can be supplied to you at no charge; this is known as a 'digital offprint'. Digital offprints will be paginated as page 1 to page *n*, where *n* represents the final page of the offprint. The offprint will not follow the pagination of the Encyclopedia. This file will not be available until November 2001. If you want to order a digital offprint you should contact the EGEC Co-ordinator, Louise Portsmouth (lportsmo@wiley.co.uk).

Who do I talk to about contracts/payments and marketing issues?

Please address any questions you have on these subjects to Louise Portsmouth (lportsmo@wiley.co.uk). Important: if you have not yet returned your signed contract, you should return it now to Louise Portsmouth at John Wiley.

How can I contact the production office?

Any queries should be addressed by e-mail if possible (see option 1 opposite). Please quote your unique reference number and give your surname in the subject line of the e-mail. You can also make contact by phone (+353 61 361211) or by fax (+353 61 361323). Please call only between the hours of 8:30 am and 5:30 pm (GMT) Monday to Friday.

 paruelo@ifeva.edu.ar

Temperate Grasslands

José M Paruelo
Universidad de Buenos Aires, Buenos Aires, Argentina

Temperate grasslands have been the biome most affected by one of the main dimensions of the global change: land cover modification. The replacement of grasslands by agricultural fields have local, regional, and global consequences, including loss of soil fertility, soil erosion, reduction of biological diversity, hydrological changes, climate alteration and modification of atmospheric composition. Field and laboratory experiments are beginning to show a positive response, both in total biomass production and water use efficiency for the dominant species of temperate grasslands to the increase of atmospheric carbon dioxide (CO_2). Simulation analyses indicated that climate change by itself increased net primary production in most of the grassland regions of the world and reduced soil carbon stocks everywhere. The combined effect of climate change and elevated CO_2 increased net primary production in all the sites studied and reduced carbon losses by half.

Temperate grasslands are an important biome in Eurasia (Paleartic realm, 7.5×10^6 km^2), North America (Neartic realm, 2.7×10^6 km^2) and southern South America (Neotropical realm, 1.1×10^6 km^2), also occupying small areas in Africa, Australia and New Zealand. At least three physiognomic types are considered grasslands in temperate regions: meadows, prairies, and steppes. Species of the Poaceae family are dominant or co-dominant in these physiognomic types. Grasslands occur in between forest and deserts. The boundaries among these biomes are not clear, and transitional areas develop among them, scattered trees or shrubs are then a common feature in grassland areas. The relative importance of the woody components in grassland is often the consequence of the disturbance regime.

Grasslands played an important role in human history because the centers of origin of the most important cultivated plants (wheat, barley, peas, etc.) and livestock (goats, sheep, cattle) are located in them. Humans dramatically modified grassland areas and the sub-humid portion of this biome has been almost completely transformed by agriculture.

GENERAL CHARACTERISTICS OF TEMPERATE GRASSLANDS

Climate and Soils

Grasslands occur over a broad range of temperatures. Mean annual temperature (MAT) of grassland areas range between $-3\,^{\circ}$C in the Mongolian and Russian steppes and $20\,^{\circ}$C in the tallgrass prairies of Texas (USA) and the desert grasslands of Northern Mexico. A large proportion of grasslands have a continental climate, showing much larger seasonal temperature differences than areas under maritime influence. The range of mean annual precipitation (MAP) where grasslands can be found varies from 150–1500 mm.

Grasslands are not evenly distributed in the climatic space defined by the ranges of MAT and MAP presented above. Grasses are not dominant where temperatures are high and precipitation low (close to the $20\,^{\circ}$C and 150 mm corner). At this extreme, grasslands become replaced by shrublands or deserts. At the coldest and wettest extreme, forests are the dominant biome. The distribution of grasslands in the climatic space is related to the magnitude of the water deficit. Grasslands show a ratio of mean annual precipitation and potential evapotranspiration (PET) lower than 1. The MAP/PET ratio is close to 0.3 for dry steppes and to 0.6 for sub-humid prairies.

Grassland soils are among the most productive under agricultural use. High productivity derives mainly from the high content of organic matter. Mollisols is the dominant soil order in this biome.

Biotic Characteristics and their Environmental Controls

An important structural characteristic of temperate grassland is that most of the carbon is stored below ground, in soil organic matter and plant roots. This large accumulation of carbon results from low decomposition rates relative to net primary production. The total amount of soil organic carbon decreases with MAT and increases with MAP (Burke *et al.*, 1989). Fine textured soils retain more organic matter than coarse textured soils (Burke *et al.*, 1989).

Despite the dominance of just one family, Poacea, grasslands show marked differences in species composition. Over continental scales, a structural comparison of grasslands based on species composition is precluded by the differences in floras among the different biogeographical realms. Such comparison is possible, though, at the plant functional level (PFT). Five main PFTs can be identified in grassland areas: C_3 grasses, C_4 grasses, shrubs, forbs and succulents. The first three account for most of the biomass and show a clear pattern across environmental gradients. The relative abundance of C_4 grasses increases with MAP, MAT, and the proportion of precipitation falling in summer. C_3 grasses are more abundant as MAT decreases and in areas with a high proportion of precipitation falling in winter. The relative abundance of shrubs increases in dry areas with most of the precipitation falling in winter.

Above-ground net primary production (ANPP) is a key attribute of grassland ecosystems and the main entrance of energy to the ecosystem. Characterization of the climatic controls of ANPP is essential to understand the impact of global changes on this biome. A positive, linear relationship between ANPP and MAP has been documented for many grasslands around the world (McNaughton *et al.*, 1993). The slope of the relationship between ANPP and MAP in grassland ecosystems ranges between 0.48 and $0.64\,\mathrm{g\,C\,m^{-2}\,mm^{-1}}$. Epstein *et al.*, (1997) showed a negative relationship between ANPP and MAT when MAP was held constant. Soil texture, through its effect on soil water holding capacity, also showed a significant relationship with ANPP (Sala *et al.*, 1988; Epstein *et al.*, 1997). Below-ground net primary production is equivalent or slightly greater than ANPP. Annual net primary production (below and above-ground) may vary then, from less than $100\,\mathrm{g\,m^{-2}}$ in a semi-arid shortgrass steppe to almost $1000\,\mathrm{g\,m^{-2}}$ in a tallgrass prairie (Paruelo *et al.*, 1999). Compared to other biomes, grasslands' above-ground biomass is low. Shrublands may have 10 times more biomass than grasslands and evergreen forest up to 100 times more (Chapin, 1993). Differences in ANPP among biomes, however, are not so extreme as in the case of biomass (Chapin, 1993). As a consequence, the ratio ANPP/biomass is higher in grasslands than in any other biome.

McNaughton *et al.* (1993) showed that biomass and consumption of wild herbivores were positively and exponentially related to ANPP. The exponential form of these relationships suggests that the proportion of the ANPP consumed by herbivores increased with ANPP. The efficiency of energy transfer between trophic levels (animal production/net primary production) is higher in grasslands than in forests.

The disturbance regime affects carbon gains in grasslands. Fire reduces ANPP in the driest portion of a precipitation gradient (Oesterheld *et al.*, 1999). In subhumid grasslands fire generally increases ANPP, except in dry years (Knapp *et al.*, 1998). In these grasslands, fire removes large amounts of above-ground dead material, increasing light and soil nutrient availability (Knapp and Seastedt, 1986). In dry years this effect is less important than the reduction in evapotranspiration promoted by the detritus layer (Knapp *et al.*, 1998). Grazing may increase or reduce ANPP depending on the evolutionary history of grazing, MAP, and levels of consumption (Milchunas and Lauenroth, 1993). Over a broad range of grasslands, Oesterheld *et al.* (1999) found that, on average, grazing by large vertebrates slightly reduced ANPP.

Grassland biogeochemistry is largely controlled by precipitation, temperature and soil texture. Decomposition rates are more affected than ANPP by temperature. Given the same amount of precipitation, the consequence of the effect of temperature on decomposition is a higher accumulation of organic carbon in cold than in warm areas. Species composition, through litter quality, has a significant influence on decomposition rates and nutrient immobilization.

THE IMPACT OF GLOBAL CHANGE ON TEMPERATE GRASSLANDS

Land Use

Land cover changes associated with agriculture and grazing by domestic herbivores have had an enormous impact on the structure and functioning of grasslands. Agricultural practices have reduced soil carbon stocks by 35% in the US Central Grasslands during the last 50 years (Burke *et al.*, 1989). Based on carbon isotopic analyses, Wilson (1978) estimated that pioneer agriculture (1860–1890) in temperate areas of Australia, New Zealand, North and South America contributed one and a half times the amount of carbon dioxide (CO_2) produced by all the fossil fuels burnt before 1950. This reduction of soil carbon stocks results from an increase in decomposition rates due to plowing and a reduction of carbon inputs to the soil due to the low below-ground biomass of annual crops and to exports of above-ground biomass.

Land use pattern has a critical influence on mesoscale atmospheric processes, and hence on local climate (Pielke *et al.*, 1997). Mosier *et al.* (1991) reported significant changes in trace gas fluxes associated with cultivation of a semi-arid grassland: agriculture increases the release of methane (CH_4) and nitrous oxide (N_2O), two greenhouse gases. These additions of CO_2 and other trace gases to the atmosphere may represent significant feedbacks to global climate change.

It is not clear to what extent agricultural practices modify total carbon gains. In the Pampas of Argentina, agriculture may increase or decrease above-ground net primary production relative to the native grasslands depending the environmental conditions (Figure 1). The difference in primary production between grasslands and wheat fields was higher in the wettest portion of the Pampas. In warm areas, grasslands were more productive than wheat fields. The opposite happened in the coolest part of the region.

Total carbon gains should be lower for agricultural fields than for native grasslands because below-ground production is one order of magnitude lower for crops than for grasslands. Landuse may modify not only total carbon gains but also the seasonal dynamics of leaf area index and intercepted radiation. Figure 2 show the idealized course of the fraction of radiation intercepted by the canopy for different land covers. Curves were drawn from data provided by spectral indices derived from meteorological satellites (Advanced Very High Resolution Radiometer – National Oceanographic and Atmospheric Agency (NOAA/AVHRR)). Land use modifies both the intra annual range of the fraction of intercepted radiation and the timing of maximum interception. These phenological changes modify the partitioning between latent and sensible heat and, consequently, they may affect the dynamics of the boundary layer of the atmosphere.

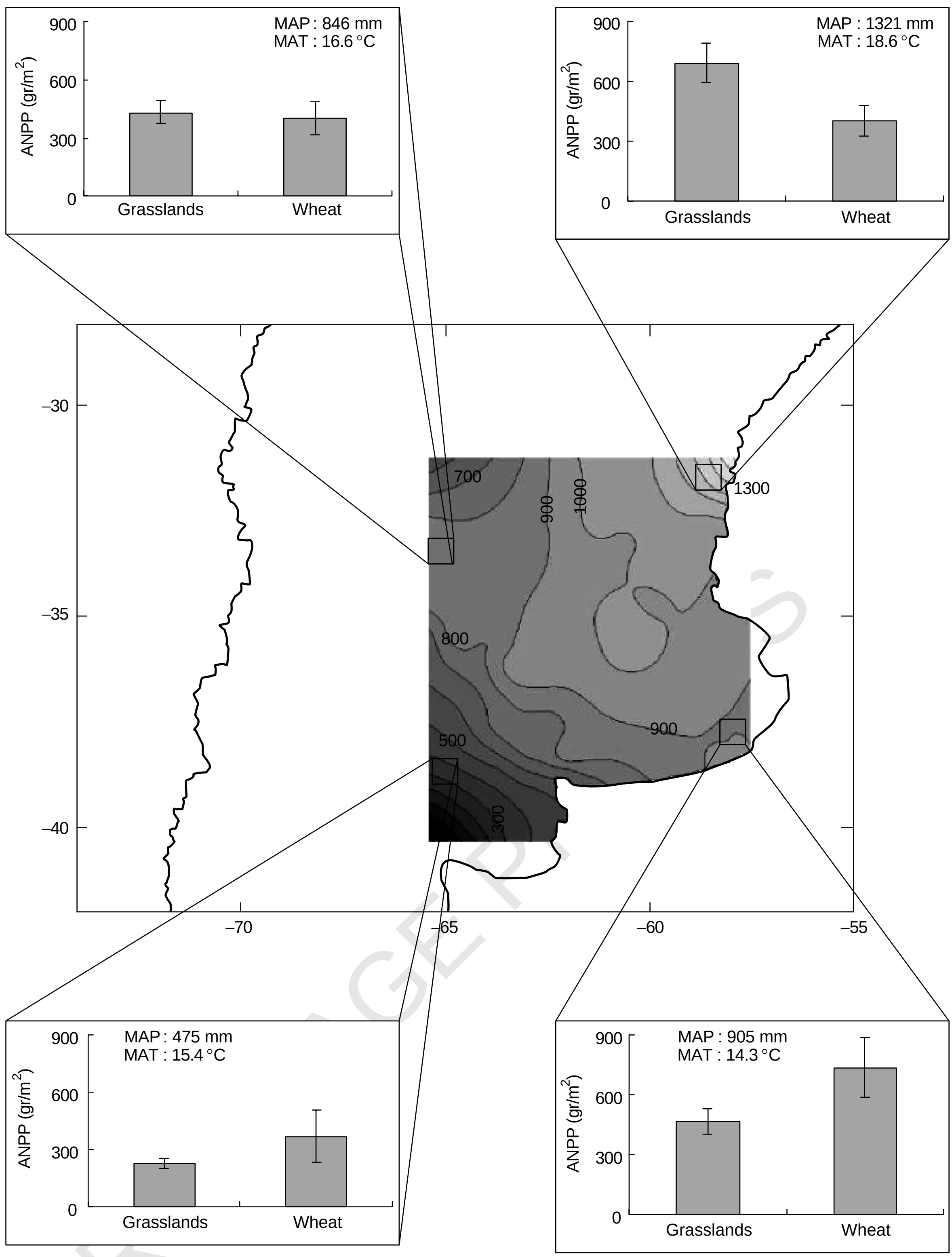

Figure 1 ANPP for wheat and grasslands sites located in the climatic extremes of the Pampa grasslands of Argentina. For wheat fields ANPP was estimated from grain yields (Argentine agricultural census) and harvest index. Wheat ANPPs are the average of 10 years. Small bars showed the temporal standard deviation. Grassland ANPPs are the average of estimates derived from four different models for the relationship ANPP–MAP (Sala *et al.*, 1988; McNaughton *et al.*, 1993; Paruelo *et al.*, 1999 (two models)). Small bars corresponded to the standard deviation of the estimates derived from the different models. Isopleths correspond to mean annual precipitation.

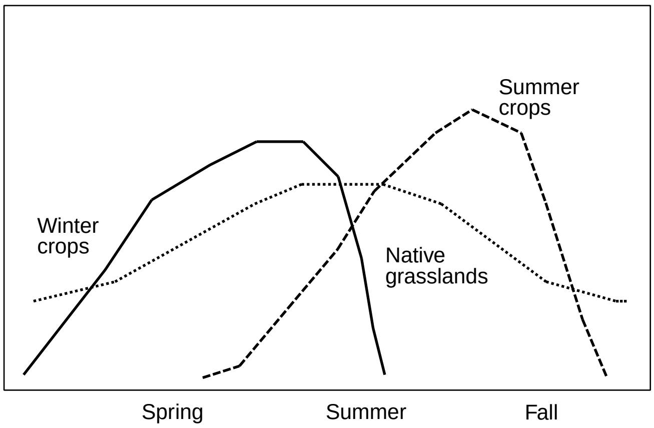

Figure 2 Seasonal dynamics of the fraction of radiation intercepted by the canopy from three land cover categories in the Argentine Pampas. Intercepted radiation is an estimator of ANPP. Curves were derived from normalized difference vegetation index data from NOAA/AVHRR satellites.

Land use has increased the rate of species extinction not only by replacing natural ecosystems, but also by changing the disturbance regime. Leach and Givnish (1996) showed that 8–60% of the original plant species of remnant prairie sites were lost after 50 years due to landscape fragmentation or fire suppression. Changes in species diversity and composition have direct effects on the functioning of grasslands, affecting their productivity and stability.

The introduction of domestic herbivores promotes structural and functional changes in grasslands. A common effect of overgrazing in grasslands is shrub encroachment (Archer, 1994). The increase in shrub cover in grass steppes of Patagonia due to overgrazing (León and Aguiar, 1985) altered water dynamics, increased albedo, reduced primary production and herbivore biomass (Aguiar *et al.*, 1996). Bryant *et al.* (1990) and Nasrallah *et al.* (1994) reported changes in surface temperature associated with overgrazing in southwestern USA.

Atmospheric Composition

Early experiments and photosynthetic theory suggested a differential response of C_3 and C_4 grasses to changes in atmospheric concentration of CO_2. C_3 and C_4 plants differ in their metabolic pathways of CO_2 fixation. In C_3 plants the first product of the photosynthetic CO_2 fixation is a phosphorylated three-carbon compound. In C_4 plants the first product is a four-carbon acid. C_3 and C_4 plants differ also in their leaf anatomy. Two different groups of photosynthetic cells are found in C_4 plants: mesophyllic and bundle sheaths cells. The latest are surrounding the leaf vascular bundles and separate them from the mesophyllic cells. C_4 grasses present a CO_2 concentration mechanism in the bundle sheath cells that increases the effective concentration of CO_2 at the carboxylation site. Such a CO_2 pumping mechanism would saturate photosynthesis at current CO_2 levels. Therefore, it has been suggested that this plant functional group would not show a significant growth response to increases in atmospheric CO_2 concentrations. However, a meta-analysis by Wand *et al.* (1999) indicates that the response of wild C_3 and C_4 grasses to elevated CO_2 concentrations was surprisingly similar.

At the leaf level, an increase in atmospheric CO_2 reduces stomatal conductance and increases net photosynthesis. A consequence of these changes is an increase in water use efficiency (WUE). Specific leaf area and nitrogen concentration are, in general, lower under elevated CO_2 concentrations. At the individual level these changes result in an increase in both above and below-ground biomass and in the number of tillers (Wand *et al.*, 1999). The mentioned analysis showed an overall increase in total biomass of 44% in C_3 species and of 33% in C_4 species.

Studies using open top chambers allow one to explore changes at the population, community, and ecosystem level. These changes result not only from the effect of elevated CO_2 on plant production but also from major changes in soil water dynamics associated with changes in water use efficiency. Jackson *et al.* (1994) working in Mediterranean grasslands in California showed increases in density, seed production, and survival of the dominant grass *Avena barbata* under elevated CO_2. Changes in phenology associated with a delayed senescence have been reported in C_4 tallgrasses (Owensby *et al.*, 1997). In the tallgrass prairie of eastern Kansas (USA) an eight year long open top chamber experiment provided no evidence for a replacement of the dominant C_4 grasses by C_3 grasses or forbs under elevated CO_2 concentrations (Owensby *et al.*, 1993). In these grasslands the balance between C_3 and C_4 grasses seems to be more sensitive to the main disturbances (fire and grazing) than to CO_2 concentration. Elevated CO_2 decreased dominance in sub-humid temperate grasslands (Potvin and Vasseur, 1997). Potvin and Vasseur (1997) showed a higher effect of elevated CO_2 on early successional species growth, which prevented the dominance of late successional ones.

Combining field data and simulation models, Jackson *et al.* (1998) showed that the direct effect of CO_2 on water use efficiency and total biomass production on Mediterranean grasslands affected water dynamics at the ecosystem level. Under elevated CO_2, plant transpiration was lower. Low transpiration at the beginning of the growing season increased soil water content and deep percolation. Studies based both on field experiments and on model simulations suggest that the observed increase in WUE at the ecosystem level would compensate for increases in potential evapotranspiration associated with climatic changes driven by greenhouse gases. Biogeochemistry models (BIOME-BGC, Century and Terrestrial Ecosystem Model) simulated net primary production responses to doubled atmospheric CO_2 for grasslands that range from 1–20% increase.

Climate

Changes in climate are difficult to isolate from changes in CO_2 concentrations. Climate modifications not linked to the increase of greenhouse gases may occur, however, as a result of land use changes (Nasrallah *et al.*, 1994; Pielke *et al.*, 1997). General circulation models simulate changes in temperature in temperate grasslands ranging between $+2.3$ and $+6.2$ for a doubled CO_2 scenario (Houghton *et al.*, 1992). Changes in mean annual precipitation may range from -2.6% up to 17.5%, depending on the GCM and type of grassland considered. For the Central Grasslands of USA, an increase of 1 $^\circ$ Celsius in mean annual temperature represents an increase in potential evapotranspiration of 50 mm.

Two main approaches have been used to explore the effect of climate on grasslands: warming experiments and simulation exercises using climate change scenarios. Experimentally heated plots in montane meadows showed significant differences in the timing and magnitude of net carbon fluxes (Saleska *et al.*, 1999). The reduction of primary production resulted from a combined effect of a reduction in soil moisture and a shift in plant community composition. Alward *et al.* (1999) showed that the observed increase in nocturnal minimum temperatures in a semi-arid steppe was correlated with a reduction in the net primary production of the dominant grass species, and with increased abundance and production of exotic species and C_3 forbs.

Model simulations indicated that climate change, by itself, increased net primary production in most of the grassland regions of the world and reduced soil carbon stocks everywhere. The combined effect of climate change and elevated CO_2 increased net primary production in all the sites studied and reduced carbon losses by half (Parton *et al.*, 1995).

REFERENCES

Aguiar, M R, Paruelo, J M, Sala, O E, and Lauenroth, W K (1996) Ecosystem Consequences of Plant Functional Types Changes in a Semiarid Grassland, *J. Vegetation Sci.*, **7**, 381–390.

Alward, R, Detling, J, and Milchunas, D (1999) Grassland Vegetation Changes and Nocturnal Global Warming, *Science*, **283**, 229–231.

Burke, I C, Yonker, C M, Parton, W J, Cole, C V, Flach, K and Schimel, D S (1989) Texture, Climate, and Cultivation Effects on Soil Organic Content in US Grassland Soils, *Soil Sci. Soc. Am. J.*, **53**, 800–805.

Chapin, F S (1993) Functional Role of Growth forms in Ecosystem and Global Processes, in *Scaling Physiological Processes*, eds J R Ehleringer and C B Field, Academic Press, San Diego, CA, 287–312.

Epstein, H E, Lauenroth, W K, and Burke, I C (1997) Effects of Temperature and Soil Texture on ANPP in the US Great Plains, *Ecology*, **78**, 2628–2631.

Jackson, R B, Sala, O E, Paruelo, J M, and Mooney, H A (1998) Ecosystem Water Fluxes for Two Grasslands in Elevated CO_2: a Modeling Analysis, *Oecologia*, **113**, 537–546.

Jackson, R B, Sala, O E, Field, C B, and Mooney, H A (1994) CO_2 Alters Water use, Carbon Gain, and Yield from the Dominant Species in a Natural Grassland, *Oecologia*, **98**, 257–262.

Knapp, A K, Conard, S L, and Blair, J M (1998) Determinants of Soil CO_2 Flux From a Sub-humid Grassland: Effect of Fire and Fire History, *Ecol. Appl.*, **8**, 760–770.

Knapp, A K, and Seastedt, T R (1986) Detritus Accumulation Limits Productivity of Tallgrass Prairie, *Bioscience*, **36**, 662–668.

Leach, M K, and Givnish, T J (1996) Ecological Determinants of Species Loss in Remnant Prairies, *Science*, **273**, 1555–1558.

McNaughton, S J, Sala, O E, and Oesterheld, M (1993) Comparative Ecology of African and South American Arid to Subhumid Ecosystems, in *Biological Relationships between Africa and South America*, ed P Goldbaltt, Yale University Press, New Haven, CT, 548–567.

Milchunas, D G, and Lauenroth, W K (1993) Quantitative Effects of Grazing on Vegetation and Soils Over a Global Range of Environments, *Ecol. Monogr.*, **63**, 327–366.

Mosier, A, Schimel, D, Valentine, D, Bronson, K, and Parton, W (1991) Methane and Nitrous Oxide Fluxes in Native, Fertilized and Cultivated Grasslands, *Nature*, **350**, 330–332.

Nasrallah, H A, and Balling, R C (1994) The Effect of Overgrazing on Historical Temperature Trends, *Agri. Forest Meteorol.*, **71**, 425–430.

Oesterheld, M, Loreti, J, Semmartin, M, and Paruelo, J M, (1999) Grazing, Fire, and Climate Effects on Primary Productivity of Grasslands and Savannas, in *Ecosystems of Disturbed Ground*, ed L R Walker, Elsevier Science, Oxford.

Owensby, C E, Coyne, P I, Ham, J M, Auen, L M, and Knapp, A K (1993) Biomass Production in a Tallgrass Prairie Ecosystem Exposed to Ambient and Elevated CO_2, *Ecol. Appl.*, **3**, 644–653.

Owensby, C E, Ham, J M, Knapp, A K, and Bremer, D (1997) Water Vapor Fluxes and their Impact Under Elevated CO_2 in a C_4- Tallgrass Prairie, *Global Change Biol.*, **3**, 189–195.

Parton, W J, Scurlock, J M O, Ojima, D S, Schimel, D S, and Hall, D O (1995) Impact of Climate Change on Grassland Production and Soil Carbon Worldwide, *Global Change Biol.*, **1**, 13–22.

Paruelo, J M, Lauenroth, W K, Burke, I C, and Sala, O E (1999) Grassland Precipitation use Efficiency Varies Across a Resource Gradient, *Ecosystems*, **2**, 64–68.

Pielke, R A, Lee, T J, Copeland, J H, Eastman, J L, Ziegler, C L, and Finley, C A (1997) Use of USGS-provided Data to Improve Weather and Climate Simulations, *Ecol. Appl.*, **7**, 3–21.

Potvin, C, and Vasseur, L (1997) Long-term CO_2 Enrichment of a Pasture Community: Species Richness, Dominance, and Succession, *Ecology*, **78**, 666–677.

Sala, O E, Parton, W J, Joyce, L A, and Lauenroth, W K (1988) Primary Production of the Central Grassland Region of the United States, *Ecology*, **69**, 40–45.

Saleska, S R, Harte, J, and Torn, M S (1999) The Effect of Experimental Ecosystem Warming on CO_2 Fluxes in a Montane Meadow, *Global Change Biol.*, **5**, 125–141.

Walter, H (1939) Grassland, Savanne und Busch der arideren Teile Afrikas in Ihrer Okologischen Bedingtheit, *Jb. Wiss Bot.*, **87**, 750–860.

Wand, S, Midgley, G, and Jones, M (1999) Responses of Wild C_4 and C_3 Grass (Poaceae) Species to Elevated Atmospheric CO_2 Concentration: a Meta-analytic Test of Current Theories and Perceptions, *Global Change Biol.*, **5**, 723–741.

Wilson, A T (1978) Pioneer Agriculture Explosion and CO_2 Levels in the Atmosphere, *Nature*, **273**, 40–41.