Global Atmospheric Change and Its Effect on Managed Grassland Systems

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Global atmospheric change and its effect on managed grassland systems

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Key points

1. Increasing atmospheric CO_2 concentration and a trend to warmer mean temperatures are the most reliable aspects of global atmospheric change. Projections of the extent of climate change and the frequency of extreme weather conditions remain uncertain.
2. Research has considerably reduced the uncertainty about effects of global atmospheric change on physiology of plants, productivity and species composition of plant communities.
3. Other factors (e.g. nutrient availability, soil type) and long-term adaptation of the ecosystem (e.g. nutrient cycling and sequestration) influence the response of plant communities to global atmospheric change. Generalisation is not possible with respect to the response of different pasture and rangeland systems.
4. In temperate grasslands with regular fertilisation and defoliation, the effects of elevated CO_2 may be smaller than those of climate and/or management. Adaptations in management can help to mitigate effects of global atmospheric change.

Keywords: elevated atmospheric CO_2, climate change, grassland systems, species, yield

Introduction

Global atmospheric change consists of (i) an increase of the main greenhouse gases - carbon dioxide (CO_2,), methane (CH_4,), and nitrous oxide (N_2O); and (ii) transient changes in temperature, precipitation and other climatic elements over the coming decades and centuries. Using general circulation models, global projections of the earth's climate have been developed for a set of emission scenarios related to a range of assumptions regarding future socio-economic development (IPCC, 2001). The increase in atmospheric CO_2 concentration is the most reliable aspect of global atmospheric change. The projections of climate change carry with them a range of uncertainty, but they consistently show a warming trend in most regions. At smaller scales, and for changes other than temperature e.g. rainfall, and the frequency of extreme weather events, uncertainties in the projections increase. However, a discussion of uncertainties of climate projections is outside the scope of this paper.

The objective of this paper is to review current knowledge on the nature and direction of global atmospheric change, and the potential impact of this change on managed grassland ecosystems in terms of herbage production, herbage composition and animal production. Management approaches to counteract effects of atmospheric change will also be considered.

The response to atmospheric change of individual plants grown in controlled conditions with ample nutrient supply was elucidated in the 1990s, and in the last decade a great deal has been learned about the response of plant communities under natural field conditions. It has become clear, that long-term adaptation processes in the soil are important for the response of the plant communities to atmospheric change. The most important gaps in knowledge still existing concern: (i) the response of low-input plant communities in non-temperate climate zones, (ii) the effects of soil type and management on the response of plant communities to atmospheric change and (iii) the consequences for animal performance. These gaps restrict our ability to make generalisations about different climatic zones and grassland types, and the whole soil-plant-animal system including socio-economic aspects.

Projection of global change

Atmospheric CO_2 concentration

The average increase of atmospheric CO_2 concentration has been about 1.5 ppm (0.4%) per year over the past two decades. The IPCC in its 3rd assessment report (IPCC, 2001), projects CO_2 concentration may rise up to between 540 and 970 ppm by 2100 (depending on future global socio-economic development and associated emission patterns).

Temperature

Annual mean surface air temperature is expected to increase by 1.4 to 5.8 C by 2100 - with distinct regional differences (depending on emission scenario and climate model assumptions) (IPCC, 2001). Nearly all land areas warm more rapidly than the global average. Maximum warming is expected to occur in the high latitudes of the northern hemisphere and minimum warming in the southern ocean region (Figure 1).

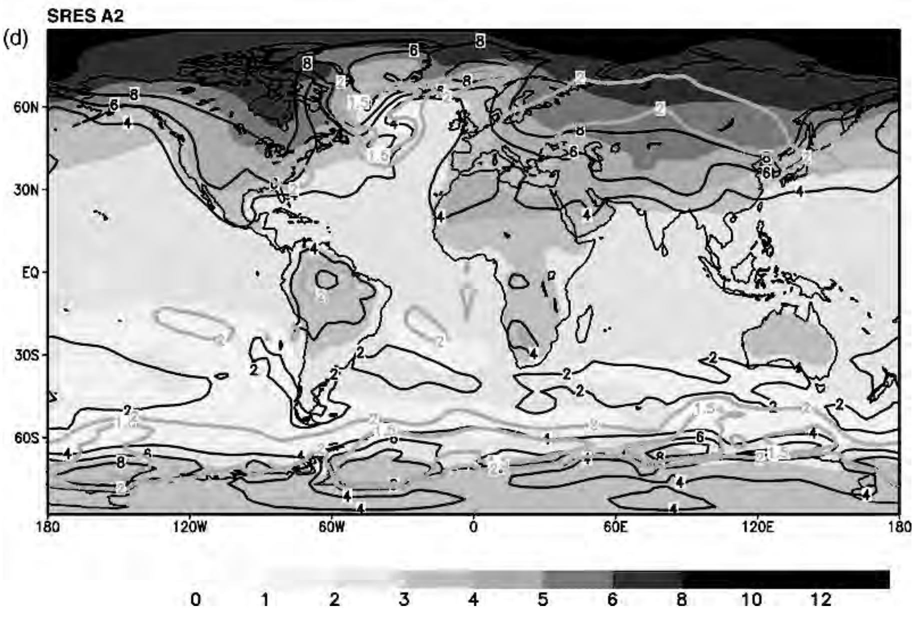

Figure 1 The annual mean change of temperature (grey shading and digits), its multi-model ensemble range (black isolines and digits) and the ensemble mean divided by its standard deviation (grey isolines) (Unit: °C) for the SRES scenario A2 (Period 2071 to 2100 relative to period 1961 to 1990) (IPCC, 2001)

Grasslands will have no major role in regions with the strongest predicted warming; in contrast, those areas that experience warming of 2-5 °C will continue to sustain grassland ecosystems; e.g. for Ireland, warming of 2-3 °C is projected (Figure 1, grey shading) with a range of 4 °C between models (Figure 1, black isoline). Increased inter-annual variability may also be a significant aspect of climate change, which will have high ecological significance. Using a regional climate model, Schär *et al.* (2004) predicted that year-to-year temperature variability for central Europe would increase by up to 100% by 2071-2100. This would lead to more frequent heat waves and droughts during the growing season.

Precipitation

All climate models indicate that average precipitation will increase, although in some regions reductions are likely (IPCC, 2001). A reduction in precipitation may be due to changes in synoptic scale features (e.g. changes in storm track characteristics) and/or local feedback processes (e.g. between soil moisture and precipitation). These changes in annual precipitation are associated with a shift in the seasonal distribution, e.g. in many parts of Europe it is anticipated that winter precipitation will increase and summer precipitation decline (Haylock & Goodess, 2004; Schär *et al.*, 2004).

The magnitude of regional precipitation change varies considerably amongst models, with typical ranges between 0 to 50% where the direction of change is indicated, and around -30 to +30% where it is not. Larger ranges are projected in some regions (e.g. -30 to +60% in southern Africa for the summer) (IPCC, 2001), but this occurs mainly in regions of low seasonal precipitation where the implied range in absolute terms would not be large.

Effects of elevated CO_2 on grassland vegetation

Physiological effects

The physiological effects of elevated CO_2 are well known. Drake *et al.* (1997) reviewed 60 studies where plants were grown separately under controlled conditions with ample nutrient supply, and reported an average increase in leaf photosynthesis of 58% when grown at approximately double the pre-industrial concentration of CO_2. These increases in photosynthesis translate into increased dry matter production of about 30% (Newton, 1991). However, when plants are grown in communities in the field, competition and limiting growth resources can restrict the plant's response to elevated CO_2. These differences have prompted researchers to design experimental systems that more effectively simulate natural conditions. The most advanced systems for this work use a technology called Free Air Carbon Dioxide Enrichment (FACE), which does not require any enclosures and, so does not alter the microclimate of the experimental area. Examples from two of these systems (one in Switzerland (Swiss FACE) and one in New Zealand (NZ FACE)) will be used in this review.

Total yield of swards

Under field conditions Ainsworth *et al.* (2003), confirmed the strong increase in leaf photosynthesis in response to elevated CO_2. However yield response is much weaker; allocation of assimilates to non-harvested plant parts being increased relative to controlled conditions (Hebeisen *et al.*, 1997; Suter *et al.*, 2002). Results from the grassland ecosystems of the 'GCTE (Global Change and Terrestrial Ecosystems) pastures and rangelands core research project network' showed that the stimulatory effect of elevated CO_2 on sward productivity was only 15% (Figure 2A). This response was independent of the above-ground productivity of the ecosystem (Campbell *et al.*, 2000; Figure 2A) and was similar to the effects reported by Mooney *et al.* (1999). In the GCTE network most of the sites are improved pastures under humid and cool/temperate climates; information on grasslands in other climatic zones is much more sparse.

Inter- and intraspecific differences in yield response

Much of the world's grasslands are characterised by swards that are botanically diverse. Thus, the response of individual functional groups and species within the sward are of interest, as changes in these components can alter nutrient cycling, the quality of the diet presented to animals and the maintenance of biodiversity. Significant differences in the yield response to elevated CO_2 are consistently found between legumes and C3 grasses. In the first six years of the Swiss FACE experiment, the yield response to elevated CO_2 of *Lolium perenne* (perennial ryegrass) ranged from -11 to +25%, compared to +10 to + 49% for *Trifolium repens* (white clover) when grown in pure swards (Hebeisen *et al.*, 1997; Daepp *et al.*, 2000). These differences were confirmed in separate studies for other legume and grass species (Lüscher *et al.*, 2004). Both, the New Zealand and the Swiss FACE experiments revealed that forbs showed a stronger response to elevated CO_2 than grasses (Lüscher *et al.*, 1998; Allard *et al.*, 2003).

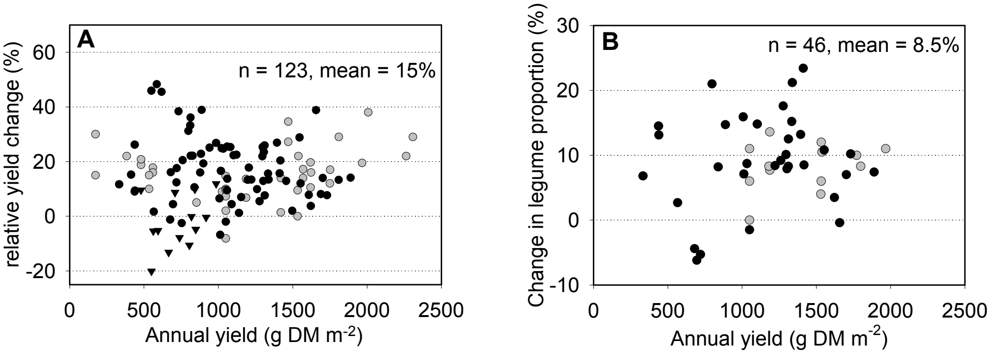

Figure 2 Effect of elevated CO_2 on (A) total production of harvestable biomass in grassland ecosystems, and (B) proportion of legumes in relation to the annual yield. Black symbols: NZ and Swiss FACE experiments; grey symbols: other experiments of the 'GCTE pasture and rangelands core research project network'; ▼ = pure grass swards at low N fertilisation; ● = all other swards (mixed swards or pure grass swards with high N fertilisation). Newton *et al.* (1994; 1995); Ross *et al.* (1995; 1996); Casella *et al.* (1996); Soussana *et al.* (1996); Clark *et al.* (1997); Schenk *et al.* (1997); Owensby *et al.* (1999); Campbell *et al.* (2000).

Changes in species composition

Interspecific differences in the yield response to elevated CO_2 were accentuated in bi-species mixtures of the Swiss FACE experiment compared to pure swards (Hebeisen *et al.*, 1997), indicating changes in competition between species. In the first 6 years the mean yield response to elevated CO_2 of *T. repens* averaged over all management treatments increased from 25% in pure stands to 874% in the mixture. Significant increases in both annual and perennial legume content at elevated CO_2 have also been measured in the NZ FACE experiment (Edwards *et al*., 2001; Ross *et al*., 2004) (Figure 2b).

CO_2 response depends on nutrient availability

Limitations to nutrient availability can limit the sward's response to elevated CO_2. This is evident from comparing the response of *L. perenne* to elevated CO_2, under limiting N fertilisation, where there was a 3% reduction in yield (Figure 2a); this compares to a 25% increase in yield when luxury levels of N-fertiliser were applied (Daepp *et al*., 2001). Since mineral N in the soil was a major limiting factor in this system, the crucial advantage of legumes is their access to non-limiting atmospheric N through symbiotic N_2 fixation (Zanetti *et al*., 1996; 1997). Non N-fixing mutants of *Medicago sativa* (Lucerne) consequently loose this advantage in response to elevated CO_2 (Lüscher *et al*., 2000). Similarly, phosphorus (P)-limitation of *T. repens* has been shown to significantly reduce its response to elevated CO_2 in a growth room experiment (Almeida *et al*., 1999) and with micro swards from calcareous grassland (Stöcklin *et al*., 1998).

Nutrient cycling and long-term adaptation

Since grasslands cover about 20% of the land surface of the earth, potential changes in the cycling and storage of C and N in grassland soils at elevated CO_2, is of importance to future trends in soil fertility and to C sequestration.

Changes in the pools of C and N in the soil are determined by the amount and quality of material returned to the soil through rhizodeposition, via litter or animals. Only small increases in aboveground litter inputs have been found in response to elevated CO_2, but there is evidence for increased rates of input from roots (Loiseau & Soussana, 1999; Allard *et al*., 2004a,b).

Changes in soil microbial populations (structure and/or size) may also play a part in the long-term adaptation of decomposition to elevated CO_2 (Sowerby *et al*., 2000; Montealegre *et al*., 2000; 2002). These responses may in the long run increase plant available N at elevated CO2 (Schneider *et al*., 2004), but this outcome is not inevitable as it depends upon rates of N fertilisation. In lower N status systems, there is some evidence for a decrease in plant available N at high levels of CO_2 (Gill *et al*., 2002). In low N systems, adaptation of C and N pools and thus N-availability to elevated CO_2 is expected to require much longer time periods (100 years) (Cannell & Thornley, 1998).

Several temperate grassland experiments have shown an increase in coarse particulate organic matter under monocultures (Loiseau & Soussana, 1999) and mixed swards (Allard *et al*., 2004b; Gill *et al*., 2002) at elevated CO_2. This can be interpreted as the first stage of incorporation of organic matter into older, finer and more recalcitrant pools, and may imply a greater sink capacity for atmospheric CO_2, but could also represent a more rapid approach to a similar C storage capacity (Hassink, 1997; Van Kessel *et al*., 2000a,b). Potential interactions with increased temperature and changes in rainfall require further study (Thornley & Cannell, 1997), as do the dynamics of non-temperate grasslands.

Effects of climate change on grassland vegetation

Physiological effects

Direct effects of increasing temperature (T) can occur though stimulation of light-saturated photosynthetic rate (A_{max}) up to an optimum (T_{opt}), which is relevant for species growing at suboptimal temperatures. At supra-optimal temperatures, A_{max} declines mainly as a result of increased photorespiration. Thus, without an effect of increased CO_2 on T_{opt}, an increase by 2-3 ^{o}C by 2050 would reduce A_{max} in many C3 species, compared to C4 species. At the canopy level, increased photosynthesis at higher *T* may be counteracted by a reduction in green leaf area index (LAI) (Casella & Soussana, 1997; Long *et al*., 2004).

At higher *T*, the start of the growing season is shifted, and plants develop faster. The growing season is usually limited to the period with daily mean *T* above a threshold of 5 ^{o}C. A survey of experimental data worldwide suggested that a mild warming generally increases grassland productivity, with the strongest positive response in currently colder regions (Rustad *et al*., 2001). In cut and grazed grasslands, there may be a requirement to harvest additional cuts during the season, or extension of the grazing season. Earlier simulations using two climate scenarios suggested reduced production in the cold desert Steppes (-20-30% by 2100), but confirmed increased production (~10%) in the humid temperate ecoregion, and small positive effects in Mediterranean grasslands, and the dry and humid savannas (Ojima *et al*., 1996).

Effects of temperature on plant communities

Since increasing *T* affects individual species or functional types differently, species shifts in frequency and cover can be expected. When transplanting turf and soil from cooler to warmer sites, Bruelheide (2003) found after seven years, that the community had changed into a different plant association. Using a multiple regression model established from observations in regions of north to Southwest Europe, Duckworth *et al*. (2000) concluded that *T*+2 ^{o}C caused only minor shifts. Alpine vegetation was found to have a natural inertia and could tolerate a 1-2 °C warming, but was prone to profound changes at *T*+3 ^{o}C or higher (Theurillat & Guisan, 2001).

Warming may affect the seasonal growth patterns of C3 and C4 species differently. Winslow *et al*. (2003) found that the location-specific temperatures used to delineate the start and end of the growing season of C3 and C4 plants was a more important determinant of final biomass than the photosynthetic response to *T*. All other factors being equal, C4 plants tend to be favoured over C3 plants in warm humid climates, the reverse being the case in cool climates. Epstein *et al*. (2002) in response to climate change scenarios, suggest that the relative abundance of C4 grasses in temperate grasslands will increase throughout most regions of North and South America. In New Zealand, C4 species are favoured over C3 species where there is likely to be exposure to events with extreme heating events (White *et al*., 2000; 2001). This is an example of how increased inter-annual climatic variability, and the frequency of extreme events, are expected to suppress C3 competitive dominance and promote the invasion of C4 species.

The indirect effects of increased *T* can operate through altered nutrient cycling. If mineralisation under non-limiting soil moisture is stimulated by increased soil CO_2 efflux and net N mineralisation rates (Rustad *et al*., 2001), this will lead to higher levels of available soil nutrients and N (Loiseau & Soussana, 1999). However, Kandeler *et al*. (1998) found that the effects of warming on microbial communities and processes are minimal in soils of low nutrient availability.

Effects of altered precipitation

Altered rainfall patterns, storm intensity and more frequent droughts may cause severe perturbations in grasslands. Productivity and plant composition in rangelands are highly correlated with precipitation (Knapp & Smith, 2001). Lack of precipitation operates through reductions in available soil moisture, which is further accentuated by increased evapotranspiration due to higher net radiation and *T* (Jasper *et al.*, 2004). Due to the influence of texture on soil hydrology, effects of increased or decreased precipitation on plant productivity and decomposition vary with the proportion of sand and clay content (Epstein *et al.*, 1997) and may result in distinct patterns of change across landscapes (Riedo *et al.*, 2001).

Simulations for Switzerland using an ensemble of downscaled IPCC climate scenarios, projected significant decreases in average soil moisture towards the end of this century (Jasper *et al.*, 2004). This would reduce aboveground net primary productivity in intensively managed grasslands. Increased variability in rainfall may cause even more severe soil moisture limitation and reduced root growth, as observed in subdominant warm-season C4 grasses in native Great Plain grasslands (Fay *et al.*, 2003). In grasslands of northern Ontario comprised of *Trifolium hybridum*, *T. pratense* and *Phleum pratense*, a reduction in the number of precipitation events, while not altering the total rainfall, reduced productivity because of lower average soil moisture, as compared to a treatment with more evenly distributed precipitation (Laporte *et al.*, 2002).

Reduced soil moisture may also cause adjustments in species composition in permanent, less intensive grasslands. Observations along a climatic gradient in the Hungarian Plain showed how species with Continental and sub-Mediterranean distribution increase with increasing aridity (Kovacs-Lang *et al.*, 2000). Shifts in grass-forb relationships in response to weather variability are well documented. In C4 dominated tallgrass prairies, C3 forbs generally have an advantage over grasses during drought (Briggs & Knapp, 1995), because they respond less to variation in seasonal and inter-annual rainfall (Briggs & Knapp, 2001).

Effect of shifts in climate variability on succession

Climate variability and change is likely to affect succession. As evidenced for limestone grasslands in the UK, the more fertile, early successional grasslands are most responsive (Grime *et al.*, 2000). In calcareous grassland, warmer winters with increased summer droughts increased the amount of plant litter and delayed succession and gap formation, which favour colonisation by annuals (Sternberg *et al.*, 1999). Under wetter summertime conditions, sward closure by perennial grasses inhibited establishment of later successional species. Gap re-colonisation by annuals with a persistent seed bank was observed in sown grasslands after the severe drought in 1995 in Oxfordshire, UK. Hence, effects on gap formation and species invasion during extreme summer droughts could be a major aspect of future climatic conditions, and would make the maintenance of a desired species mixture more problematic.

Interactive effects of climate change and elevated CO_2

Photosynthesis

Rising *T* increases the stimulation of leaf photosynthesis by elevated CO_2 mainly because photorespiration strongly increases with *T* at ambient CO_2, but is strongly reduced at elevated CO_2. Whereas at 10 °C, doubling the CO_2 increased the light-saturated photosynthesis (A_{max}) by only 4%, it increased by 35% at 30 °C (Drake *et al.*, 1997). As a result, the optimum temperature of A_{max} increased with increasing CO_2 by several degrees. The maximum *T* at which photosynthesis is still positive also increased.

Water use efficiency and soil moisture

Plants growing at elevated CO_2 partially close their stomata, thus reducing stomatal conductivity (g_s) and leaf transpiration (Field *et al.*, 1995). The responses of species can differ, but on average, g_s is reduced by 20% at elevated CO_2 (Drake *et al.*, 1997). As this reduction does not reduce the rate of photosynthesis below that at ambient CO_2, and as the rate of transpiration decreases, then plants fix carbon using less water i.e. they have higher water use efficiency at elevated CO_2. This increase in water use efficiency also occurs in C4 species, and is sometimes greater than in C3 species (Drake *et al.*, 1997) providing a mechanism for positive responses of C4 species to elevated CO_2, particularly in conditions of low soil moisture (Owensby *et al.*, 1997).

Through its effect on plant water relations, elevated CO_2 can reduce soil water depletion in different native and semi-native temperate and Mediterranean grasslands, with the extent, timing and duration of this effect depending on ecosystem, year, and species (Morgan *et al.*, 2004). Based on a comprehensive assessment, the authors consider that this indirect effect of elevated CO_2 might even dominate the biomass and plant community responses of drier ecosystems, provided that their plant canopy has a high degree of coupling to the atmosphere. This could counteract expected increases in evapotranspiration due to increased temperature. In Mediterranean annual grassland warming alone increased forb production and abundance, but did not strongly affect diversity or grass response. The largest change (+50% forbs) after 3 years was found in response to the combination of warming, elevated CO_2 and increased precipitation (Zavaleta *et al.*, 2003). In Swiss calcareous grassland, Niklaus & Körner (2004) found over 6 years a significant negative correlation between the amount of precipitation during 6 weeks prior to harvest, and the relative CO_2 stimulation of biomass. Such a direct link demonstrates that future reductions in summer precipitation and higher potential evapotranspiration (PET) could increase the relative CO_2-stimulation of productivity in precipitation-sensitive grasslands. In other words, increased water use efficiency under elevated CO_2 may compensate for reduced summer precipitation and increased PET.

Effects of atmospheric change on nutritive value of herbage

Elevated CO_2 may alter the nutritive composition of animal diets directly through altering the chemical composition of individual plants, or indirectly through changes in botanical composition. A reduced concentration of N in plants and therefore a lower crude protein content is a frequently observed response to elevated CO_2 (Campbell *et al.*, 2000). In both, the Swiss and NZ FACE experiments there were significant reductions in the N content of *L. perenne* (-18% and -19%, respectively). However in *L. perenne*, the concentration of N under elevated CO_2 observed in pure stands, was considerably lower than that found in a bi-species mixture with *T. repens* (Zanetti *et al*., 1997; Hartwig *et al*., 2000). Furthermore, under elevated CO_2 the proportion of N-rich *T. repens* (40 mg N/g DM) increased in the mixture at the expense of the N-poor *L. perenne* (24 mg N/g DM when grown in monoculture). The same form of compensation was measured under grazing in the NZ FACE (Allard *et al*., 2003).

Animal requirements for crude protein (CP) from pasture range from 7 to 8% for animals at maintenance, up to 24% for the highest producing dairy cows. Average values in the NZ FACE over 7 years were 15% CP with little difference between treatments. Clearly in conditions of very low N status the reduction in CP may put a system into a sub-maintenance level for animal performance. Such systems exist in more extensive rangeland situations where elevated CO_2 may reduce protein levels below 6% (Owensby *et al*., 1993; 1996).

Under elevated CO_2, the concentration of carbohydrates in the leaves of *L. perenne* increased (Fischer *et al*., 1997). However, the proportion of digestible organic matter and the concentration of net energy in *T. repens* (Frehner *et al*., 1997) and *L. perenne* (Hebeisen, unpublished) monocultures were not affected by elevated CO_2. This is consistent with results from the NZ FACE where the digestibility of seven species covering C3 and C4 grasses, forbs and legumes was unaltered by CO_2 (Allard *et al*., 2003). However, changes in botanical composition towards a higher content of the more digestible legumes resulted in a significantly higher digestibility of the herbage on offer. It must be remembered that comprehensive animal performance trials have yet to be carried out.

Less information is available on the effects of climate change on forage quality. Various traits such as digestibility, protein and energy content may all be influenced differently by climate change (Seligman & Sinclair, 1995). Extremely dry summers could increase lignification in some species, but also lead to changes in plant composition with more drought resistant species becoming more dominant. In grass-clover mixtures, the clover fraction increased in a drier and warmer year by up to 80%, presumably because of lower drought sensitivity of N_2 fixation relative to the uptake of mineral N in the grasses (Hebeisen *et al*., 1997; Figure 3, year 2). Also, species composition change is likely to be important in altering grassland production and its value for grazing livestock, especially in drier rangelands with woody shrub invasion (Campbell *et al*., 2000). If increasing temperatures result in increased proportions of C4 species in pastures, then a further reduction in forage quality is likely (Barbehenn *et al*., 2004).

Potential for adaptation of management to climate change and elevated CO_2

It would seem from the above that atmospheric change could alter the quantity and quality of forage available to animals. The most predictable change in the environment - an increase in atmospheric concentration of CO_2, is likely to result in greater production of herbage with a lower protein content; where systems include legumes then an increase in the legume content is likely (Figure 2b), with beneficial effects on the availability of dietary components such as protein, water soluble carbohydrates and N-inputs to the system. Moderate increases in temperature will in general increase productivity. The effects of an increase in temperature together with an increase in CO_2 on sward composition have not been tested in a factorial field experiment. However, from the parallel seasonal fluctuations of temperature and clover proportion (Figure 3) it becomes evident, that warming and elevated CO_2 both increase clover proportion.

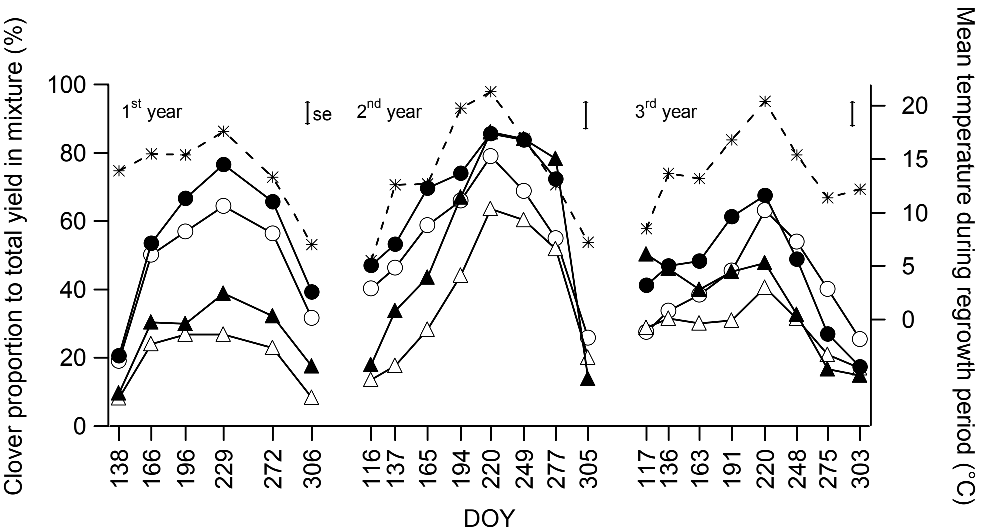

Figure 3 Yield proportion (%) of *Trifolium repens* in bi-species mixtures with *Lolium perenne* during the first three years of the Swiss FACE experiment. Swards were exposed to ambient (350 ppm; white) and elevated (600 ppm; black) CO_2 concentration under low (•=140 kg/ha per annum) and high (▲=560 kg/ha per annum) N fertilisation. Bars = standard error of mean; * = mean daily temperature; DOY = day of the year.

In intensively managed systems, the capacity of management to change herbage quality and quantity is substantial. In addition, there is strong evidence for interactions between management options and climate change drivers such as elevated CO_2 and temperature. For example, the response of grass species to CO_2 can be controlled by the level of N fertiliser input (Daepp *et al.*, 2001; Figure 2a) and the response of legume species by the level of P input (Stöcklin *et al.*, 1998; Almeida *et al.*, 1999).

CO_2-induced changes in the botanical composition of a sward can be modified by management decisions such as the choice of cutting or grazing (Newton *et al.*, 2005), or the frequency of cutting (Hebeisen *et al.*, 1997; Teyssonneyre *et al.*, 2002) and the level of N fertilisation (Figure 3). Large differences in the proportion of *T. repens* (14 vs. 57%) between extreme management regimes (infrequent defoliation combined with high N fertilisation; frequent defoliation combined with low N) were observed during the first three years of the Swiss FACE experiment. These management effects were much stronger than the effect of elevated CO_2 (increase of *T. repens* proportion from 21% to 33%). This and the strong seasonal variation in clover proportion (Figure 3) demonstrate that effects of elevated CO_2 may be smaller than those of climate and/or management. Adaptations in management can thus help to mitigate effects of global atmospheric change.

In sown grassland, there is also the potential to select plant cultivars that will take advantage of the changed environment (Lüscher *et al.*, 1998; Baker 2004; Ziska *et al.*, 2004; Wright *et al.*, 2005) although this aspect of mitigation has received little attention. Consequently, where management flexibility is possible, land managers are in a strong position to buffer the negative effects of climate change and to capitalise on the positive effects. In more extensive situations where the systems are operating close to thresholds of sustainability, management options are fewer and consequently these systems remain vulnerable to global change. A better definition of likely changes is a research priority.

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