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A synthesis of recent global change research on pasture and rangeland production: reduced uncertainties and their management implications

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Abstract

There is significant uncertainty about the effects of global change on the vegetation and animal productivity of pasture and rangeland ecosystems. This paper presents a synthesis of progress made between 1994 and 1999 in the Global Change and Terrestrial Ecosystems (GCTE) Pastures and Rangelands Core Research Project 1 (CRP1) network, a world-wide network of 83 full-time equivalent researchers established in different pasture and rangelands systems to reduce these uncertainties. The network focuses on key processes controlling forage and animal production at a paddock/landscape scale, in order to improve the ability to model animal production. To date, the network has resulted in a considerable reduction in the uncertainties about the effects of elevated CO_2 on growth, and to a lesser extent composition and forage quality, of intensive pastures in cool, wet climatic zones. However, knowledge of other grazed ecosystems and processes is more limited. The greatest confidence is in predicting implications for vegetation production, with lesser confidence in implications for vegetation composition, animal production and adaptation options. Overall, the stimulatory effect of double ambient CO_2 on grassland production averages about +17% in ecosystem-based experiments. This is less than previous estimates. Individual system responses to elevated CO_2 can vary widely and are predicted to be higher in moisture-limited and warm-season grassland systems. Species composition change is likely to be an important mechanism altering grassland production and its value for grazing livestock, especially in drier rangelands with woody shrub invasion. On average, the legume content of productive grass–legume swards is increased by +10% due to CO_2 enrichment. Leaf nitrogen reductions due to elevated CO_2 are often observed but are generally modest compared with effects of other management factors. New data collection efforts should be focused in areas of the world which are most sensitive to food security issues and most subject to global change, in particular humid semi-arid margins and subtropical grasslands. There remains no good basis for extrapolating findings between different pasture and rangeland systems. This synthesis indicates that greater focus is required on the linkages between the biophysical, social and economic factors that will influence future changes in pasture and rangeland ecosystems and their implications for food security.

Keywords: Climate change; Management; Pastures; Rangelands; Sensitive regions; Synthesis

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1. Introduction

Global change science aims to reduce uncertainties for people who are making decisions for the future. For pastures and rangelands, there are two main groups of decision makers seeking information on global change. One group includes managers, farmers, ranchers, and agribusiness, seeking to make decisions about management of their businesses and the deployment of technology. The other group comprises regional, national or international policy makers seeking to develop an appropriate, evidence-based legislative and regulatory environment.

These decision makers face two main challenges: (i) considerable uncertainties surrounding the fundamental changes in climate and the consequent effects of these changes on pastures and rangelands, and (ii) the need to make decisions affecting a wide diversity of systems, when often there is only data available from one or a small suite of these ecosystems. An appropriate conceptual framework for the integration and extrapolation of results is required to unite the results from individual studies.

The GCTE Pastures and Rangelands network was established in 1994 to address both these issues across a wide range of pasture and rangeland ecosystems. The objective of the network is: *To predict the effects of global change on vegetation production and composition and animal productivity in pasture and rangeland ecosystems at a paddock and landscape scale*.

This research is conducted against a background of two opposing pressures. On one hand are researchers who focus on the detailed effects of changes in atmosphere and climate and caution against extrapolation before this understanding is robust (e.g., Huebert, 1999). On the other hand there are the users of this information, who must make decisions for the future whether research results are available or not. Therefore there must be ongoing evaluation of when research has provided sufficient understanding of certain aspects to contribute usefully to decision making. This is also the point at which the research effort may need to be redirected into new questions where a more limiting degree of uncertainty remains.

The two pressures are examined here by undertaking a synthesis describing progress in the GCTE Pastures and Rangelands network between 1994 and 1999. The first part of the synthesis examines the progress towards reducing uncertainties, especially related to the effects of elevated atmospheric CO_2 and climate, enabling better understanding of effects of global change on pasture growth processes and compositional change. The second part examines the extent to which this reduction in uncertainty and integration of results over the past 5 years allows some grassland management implications to be identified for end-users.

2. The synthesis framework

The network was originally formulated in a framework that presumed that soil moisture, temperature, soil fertility and land use were the dominant functional axes along which the vast diversity of pasture and rangeland ecosystems could be best distinguished.

There are currently 15 studies in the network (Table 1), encompassing 83 full-time equivalent researchers world-wide. The network has resulted in over 165 publications (two-thirds of these dealing with elevated CO_2) and this synthesis refers to key publications from this portfolio. The contributing studies are summarised against the predominant classifications of temperature and soil moisture in Fig. 1. As can be seen, the current network coverage of different temperature/moisture combinations is still rather limited. The greatest replication of sites is for improved pastures with relatively intensive inputs.

This synthesis considers trends in terms of: (i) the temperature/moisture plane (although in many cases the current coverage of the network restricts the generalisations that can be drawn), and also (ii) above-ground productivity. Within the present set of contributing projects, net annual above-ground primary dry mass (DM) productivity is generally below 5000 kg DM/ha per year where there are only extensive land use inputs (Table 1). There is also a subset of replicated studies primarily in temperate grass/clover based systems which receive higher management inputs (particularly through added fertiliser) and achieve annual above-ground productivities in the range 5000–20 000 kg DM/ha per year.

Projects contributing to this network focused on key elements controlling forage and animal production at a paddock/landscape scale, in order to improve the ability to model animal production.

Table 1
Projects contributing to the GCTE Pastures and Rangelands CRP1 network

Description	Key species	Latitude	Longitude	Above-ground productivity (kg DM/ha per year)	Forage quality	Fertiliser	Fire	Stocking	Clearing
1 Grassland, Europe	*Lolium perenne*, *Holcus lanatus*, *Anthoxanthum odoratum*, *Festuca rubra*	43–45°N	4–19°E	4770–6000	Moderate–poor	No	No	1 cow or horse/ha (May–September); or 1 annual grazing or cut 12 sheep/ha	
2 Grassland, Switzerland	C_3 perennial grasses	47°N	7–9°E	6500–12 000		45–125 kg/ha		3 large animals/ha	
3 Pasture, Switzerland	*L. perenne*, *Trifolium repens*, *L. multiflorum*	47°N	8°E	12 000–14 000	High	Farmyard manure, supplemented with P and mineral N	No		Original forest cleared
4 Pasture, Germany	*L. perenne*, *T. repens*	52°N	26°E	8000–12 000					
5 Loess grassland, Hungary	*F. rupicola*, *Dactylis glomerata*, *Salvia nemorosa*	47°N	19°E	7000–10 000	High	No	No	Cut once or twice per year and/or frequently grazed	
6 Pasture, France	*L. perenne*, *H. lanatus*, *F. arundinacea*, *T. repens*	45°N	2°E	4000–14 000		Moderate to high	No		
7a Temperate pastures, Australia	*Phalaris aquatica*, *T. subterraneum*	35°S	149°E	5000–10 000		Superphosphate	No		
7b Temperate grassland, Australia	*Danthonia richardonii*	35°S	149°E	500–4000					
8 Pasture, New Zealand	*L. perenne*, *T. repens*, *T. subterraneum*, *Agrostis capillaris*, *Poa pratensis*, *Paspalum dilatatum*	35–40°S	174–175°E	6000–8000	Medium	None–maintenance N, P, K	No	12 sheep/ha	Cleared last century
9 Northern Australian savanna grasslands	*Themeda triandra*, *Cenchrus*, *Heteropogon contortus*, Indian couch, *Bothriocloa*, *Arisitda*; C_4 mainly (C_3 in winter)			500–3000		Mostly no	Mostly yes, 1:10–1:2	0.03–0.25 ha^{-1}	Some clearing on better soils
10 Tropical savanna woodland, Australia	*H. contortus*, *Bothriochloa ewartiana*	20°S	146°E	2000	Wet season: 1.0–1.5% N, 60% DMD; dry season: 0.5–0.8% N, 45% DMD	No fertiliser applied	1 year in 10 (historically 1 year in 3)	0.05–0.25 AE (450 kg/ha)	Only about 10% of region cleared

Table 1 (*Continued*)

Description	Key species	Latitude	Longitude	Above-ground productivity (kg DM/ha per year)	Forage quality	Fertiliser	Fire	Stocking	Clearing
11 Subtropical savanna, Australia	Eucalypt trees, C_4 grasses			2500	Poor		Extensive	0.05 ha^{-1}	Some
12 Semi-arid grassland, Inner Mongolia	*Leymus chinensis*, *Stipa grandis*	43–44°N	116–117°E	1200–2600	1.0–1.9% N	No fertiliser applied	Incidental in winter and spring	1 sheep unit/ha	
13 Short grass steppe, Central Great Plains, USA	*Bouteloua gracilis*, *Buchloe dactyloides*	32–41°N	100°W	500–3000		No fertiliser applied	Not important since European settlement	1 steer/20 ha (4 acres per animal unit month)	More than 50% in natural vegetation
14 Tallgrass prairie, Kansas, USA	*Andropogon gerardii*, *Sorghastrum nutans*, *P. pratensis*	39°N	96°W	3950	High in early season, poor in late season	No fertiliser applied	Annually in most of this grassland	1.4 ha per steer for a 5-month growing season	No
15 Semi-arid savannas, Sahel	*Ctenium elegans*, *Zornia glochidiata*, *Andropogon gayanus*, *Guiera senegalensis*	130°N	20°E	500–2500	Wet season: 1–2.5% N, DMD>55%; dry season: 0.3–0.8% N, 40% DMD	No	Incidental	7–12 TLU/km^2	Fast expansion of cropped lands >2% per year since 1950s

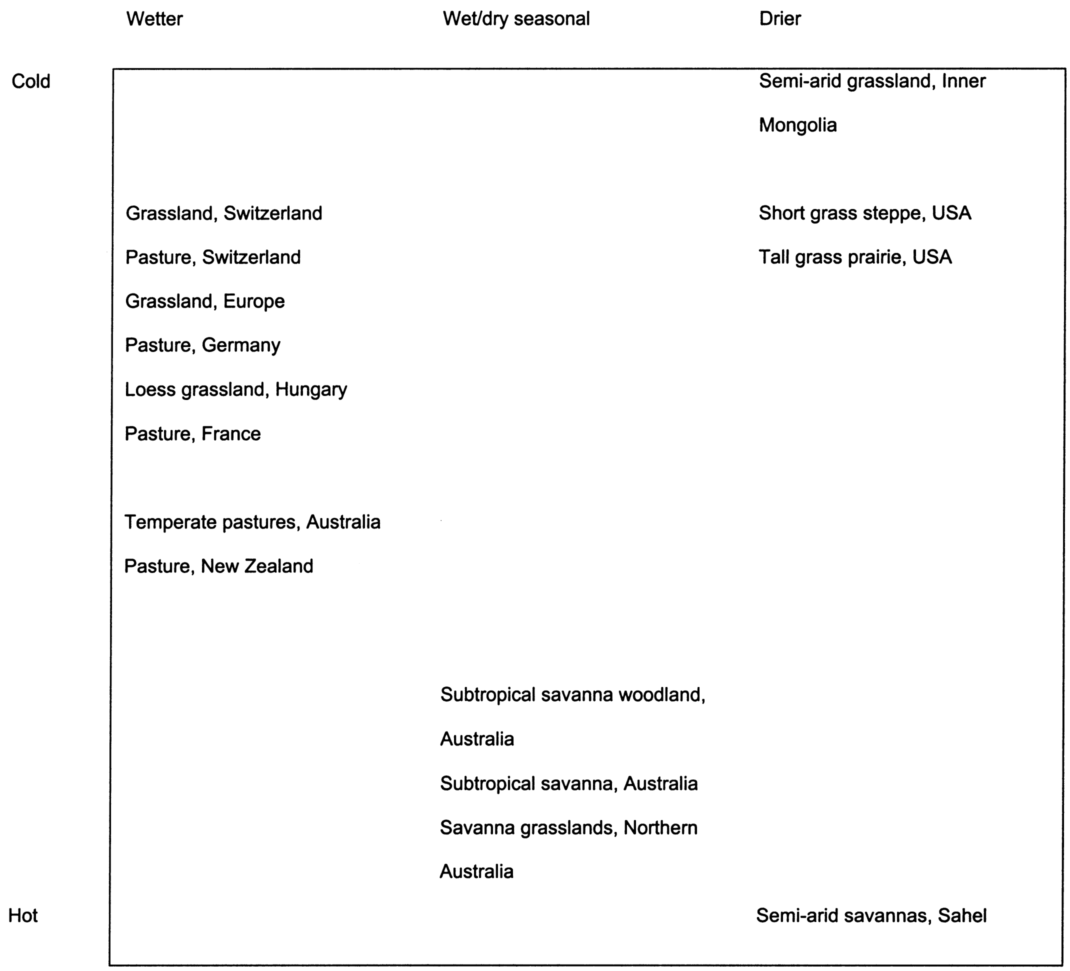

Fig. 1. Projects contributing to the GCTE Pastures and Rangelands network classified according to temperature and rainfall conditions at the study site.

3. Reduced uncertainties in the science

3.1. Vegetation growth processes and CO_2

3.1.1. Average effect

At the time of establishing the network there was major emphasis on the uncertainties surrounding the implications of rising CO_2 for pasture productivity. A key achievement in the network to date has been to reduce uncertainty about the implications of rising CO_2 for pasture and rangeland production and growth.

Overall, grasslands are likely to be less affected by CO_2 than was predicted in the original estimates, which were based largely on knowledge of photosynthetic responses. The stimulatory effect of double ambient CO_2 on grassland above-ground ecosystem production averages about +17% (Fig. 2a) in ecosystem-based experiments, although responses for particular systems and seasonal conditions can vary widely (e.g., Newton et al., 1994; Casella et al., 1996; Hunt et al., 1996; Clark et al., 1997; Hebeisen et al., 1997; Owensby et al., 1999). This figure is about half that expected from consideration of the photosynthetic response to CO_2 alone. A recent analysis conducted by Mooney et al. (1999) similarly indicated an increase in above-ground biomass of 14–16%.

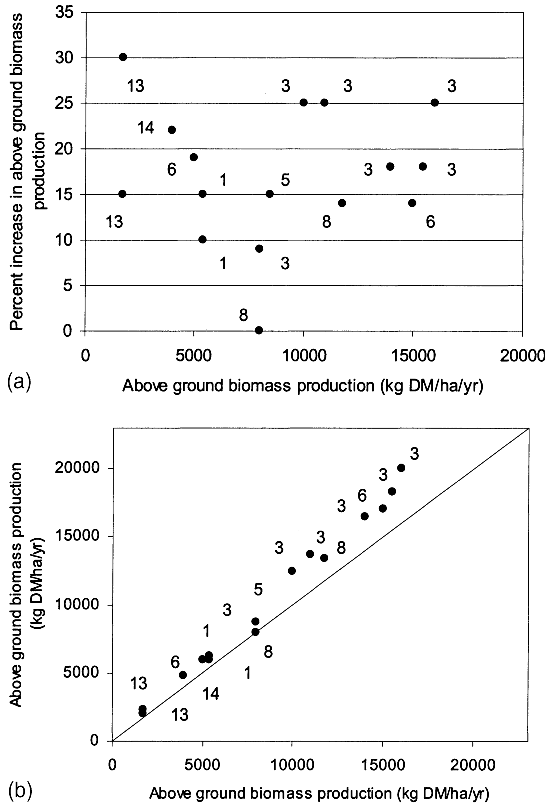

Fig. 2. Effect of doubled ambient CO_2 on above-ground biomass production plotted against above-ground biomass production at the current CO_2 concentration for different pasture and rangeland systems: (a) percentage effect; (b) absolute effect. Numbers refer to studies listed in Table 1: (1) M. Jones, unpublished; (3) Hebeisen et al. (1997); (5) Tuba et al. (1998); (6) Casella et al. (1996); (8) Newton et al. (1994), Clark et al. (1997); (13) J. Morgan, unpublished; (14) Owensby et al. (1999).

3.1.2. Seasonal and site variation

The relative effect of double ambient CO_2 on vegetation production ranges from 0 to 30% (Fig. 2a), but the variation in response is not related consistently to other experimental treatments. Depending on the site, variation may be related to temperatures (e.g., Coughenour and Chen, 1997), nitrogen inputs (e.g., Hebeisen et al., 1997; Casella et al., 1996; Lutze and Gifford, 1998), defoliation intervals (e.g., Hebeisen et al., 1997) and water availability (e.g., Owensby et al., 1997, 1999). This order of magnitude of variation is comparable to commonly encountered field-experiment measurement errors of around 10–15%. The relative effect of elevated CO_2 does not vary systematically with above-ground biomass production, so in absolute terms the effect due to elevated CO_2 is greater in the more productive systems (Fig. 2b).

3.1.3. Long-term resource availability

There is a coupling between the stimulatory effect of CO_2 on growth and accompanying *long-term* changes in soil carbon, nitrogen and water availability resulting from elevated CO_2 (Lutze and Gifford, 1998; Cannell and Thornley, 1998; Williams et al., 2000; Campbell and Hunt, 2000; Ross et al., 2000). Therefore prediction of long-term effects on production using models must take account of changes in these components of the grassland system. The Hurley pasture model predicts soil N pools increasing at high CO_2, resulting in increased mineralisation, N uptake and yield (Cannell and Thornley, 1998), but this increase is predicted to be very slow in less-fertile systems. Increased carbon and nitrogen input as a result of elevated CO_2 may act as a feedback mechanism, thus equilibrating the carbon:nitrogen ratio of the whole ecosystem (Soussana and Hartwig, 1996; Zanetti et al., 1997).

From the foregoing, it is concluded that the effects of CO_2 on the productivity of temperate grass and clover based pastures are now well documented relative to the understanding of effects on production of subtropical and arid systems. Further effort should be directed at understanding these latter systems.

3.2. Vegetation growth processes and other climatic factors

3.2.1. Water limitation

The effects of interactions between elevated CO_2 and climate change on vegetation growth have been less intensively experimentally studied within the network. This is partly because substantial uncertainties remain about the likely magnitude and direction of regional changes in climate, and particularly changes in climatic extremes. The broad effects of climate on production are generally well documented for many systems, but the effects of incidences of extreme events on grassland ecosystems and interactions of climatic factors are less well understood, especially under intensive stocking systems.

Theoretical, growth chamber and ecosystem studies indicate a greater response to CO_2 is often observed in dry years (Owensby et al., 1999). For water-limited systems, elevated CO_2 can result in greater water availability for longer in the growing season, especially if there is not an increase in leaf transpiration surface per unit of ground area (see Campbell et al., 1997; Owensby et al., 1997; Field et al., 1997). These experiments suggest that the hydrological consequences of elevated CO_2 in water-limited systems can be as significant as the direct CO_2 fertilisation effect on photosynthesis. However, there remains uncertainty about how well current experimental designs mimic the actual coupling between atmosphere and vegetation (McLeod and Long, 1999).

3.2.2. Temperature

From the limited analyses that have been conducted to date in relation to temperature, it appears that warmer temperatures will increase the CO_2 response in warm-season grassland systems such as short grass steppe and tall grass prairie (Coughenour and Chen, 1997; J. Morgan, unpublished data). However, in temperate grasslands, a 3–4°C increase in temperature may either counterbalance the effect of CO_2 on productivity (Jones and Jongen, 1996; Lilley et al., 1997), or else reduce productivity in summer but increase it in early spring and late autumn (Casella et al., 1996). In the latter case, a supplemental 3°C elevation in temperature with elevated CO_2 mitigated changes in the soil N cycle, without diminishing the sequestration of below-ground carbon (Casella and Soussana, 1997). This was due apparently to a reduction in soil water content, which partly counterbalanced the positive effect of an increased air temperature on soil organic matter decomposition.

Reductions in temperate sward production at increased temperature may reflect the limited temperature response range of the existing species. In future, composition change such as an increased invasion of C_4 species into temperate regions could mean a greater response to temperature in these systems (see Section 3.3.2).

3.2.3. UV-B radiation

There has been little emphasis in the network on effects of UV-B radiation. Generally, elevated UV-B is expected to have little effect on primary production of grasslands (Norton et al., 1999). The exception may be legume-based grasslands (Campbell et al., 2000), where limited available evidence suggests that UV-B radiation may counterbalance some of the stimulatory effects of CO_2 on legumes (Campbell and Hunt, 2000).

3.3. Vegetation compositional change

3.3.1. Elevated CO_2

Changes in the composition of pasture and rangelands are anticipated to be significant (Polley et al., 2000). This aspect of change resulting from elevated CO_2 or changes in climate is not currently handled well by available models.

The existing experimental results indicate that species composition change is likely to be an important mechanism altering grassland production and its value for grazing livestock. This change is particularly important in drier rangelands (Polley et al., 2000). For example, elevated CO_2 and reductions in water availability are predicted to increase woodland thickening, woody shrub invasion and grass suppression, with negative implications for nutritive value (Stafford Smith et al., 1995; Polley et al., 2000). Polley et al. (1999) show that shrub seedling establishment is promoted at high CO_2 levels through lower water use by the sward leading to longer persistence of soil moisture and higher seedling survival.

3.3.2. C_3 *vs.* C_4 *types*

Available experimental evidence and modelling (e.g., Howden et al., 1999b) indicates that the predicted lesser advantage of elevated CO_2 for C_4 species relative to C_3 species is not necessarily realised in ecosystems. Growth of C_4 species is about as responsive to CO_2 concentration as are C_3 species when water supply restricts growth, as is usual in grasslands containing C_4 species (Samarakoon and Gifford, 1996). Additionally, in water-limited systems, a greater availability of soil moisture later in the growing season due to elevated CO_2 may favour the C_4 species (Owensby et al., 1999). Warmer temperatures, and an increase in the frequency of warm temperature events, are expected to increase the potential for invasion of several warm, temperate grasslands by subtropical C_4 species (Campbell et al., 1996; White et al., 2000). This effect may be linked to high utilisation levels by grazing animals.

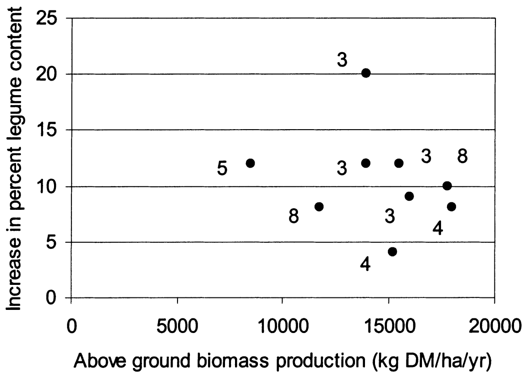

Fig. 3. Effect of doubled ambient CO_2 on legume content plotted against above-ground biomass production at the current CO_2 concentration for different pasture and rangeland systems. Numbers refer to studies listed in Table 1: (3) Hebeisen et al. (1997); (4) Schenk et al. (1997); (5) Tuba et al., unpublished; (8) Newton et al. (1994), Clark et al. (1997).

3.3.3. Legumes

In intensive systems too, there is usually an observed increase in the legume content of these mixed grass–legume swards due to CO_2 enrichment (Fig. 3). This increase averages around +10% across a range of above-ground biomass production between 8500 and 18 000 kg DM/ha per year. The increase in the proportion of legume varies depending on both the nitrogen fertilisation and defoliation regimes imposed (Hebeisen et al., 1997), so that the variation in Fig. 3 is not explained by single factors.

3.4. Forage supply and quality

3.4.1. Forage supply

An increase in forage supply is expected to result from increases in atmospheric CO_2, with the greatest absolute increase in the more productive, intensively managed systems. Reductions in forage supply are anticipated where a region become drier or temperatures become supra-optimal. Conversely, increases in forage supply are predicted if rainfall and temperature favour increased production. Other factors may constrain absolute changes. Riedo et al. (1999) found a greater relative increase in productivity at high altitudes, but a greater absolute increase on better soils at lower altitudes in alpine valleys.

3.4.2. Leaf nitrogen content

Investigations of CO_2 effects on forage quality have frequently (but not always, e.g., Gifford et al., 2000) shown a reduction in leaf nitrogen concentration (Fig. 4) and increase in non-structural carbohydrates concentration as a result of doubled ambient CO_2 enrichment (e.g., Owensby et al., 1993; Soussana et al., 1996; Manderscheid et al., 1997; Jones et al., 1996; Zanetti et al., 1996, 1997; Schenk et al., 1997; Nádas et al., 1997; LeCain and Morgan, 1998). Elevated CO_2 induced changes in the composition of cell walls (ADF, NDF and lignin) are usually small, at least in C_3 forage grasses (Soussana and Loiseau, 1997). The range of nitrogen concentration is largest (Fig. 4) in

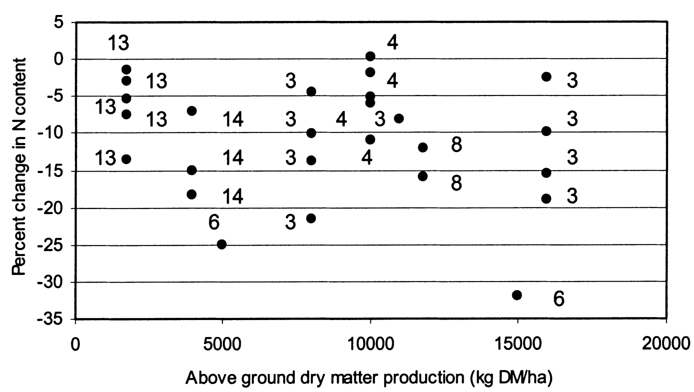

Fig. 4. Effect of doubled ambient CO_2 expressed as percent change in leaf nitrogen content of forage of different pasture and rangeland systems. Numbers refer to studies listed in Table 1: (3) Zanetti et al. (1996, 1997); (4) Schenk et al. (1997), Manderscheid et al. (1997); (6) Soussana et al. (1996), Soussana and Hartwig (1996); (8) H. Clark, unpublished; (13) LeCain and Morgan (1998); (14) Owensby et al. (1993).

relation to the treatments applied at each site, indicating, once again, that the effects of CO_2 are modest compared with those of other management factors.

3.5. Animal utilisation and efficiency of production

Most of the research efforts have been directed at understanding the effects of global change on plants and vegetation, with only a very minor effort to date being made on analysing implications for animals (e.g., Hanson et al., 1993). This imbalance must be addressed in future. For example, modelling work by Howden et al. (1999a) suggests that the frequency of heat stress days will increase markedly in tropical zones resulting in potential reductions in animal productivity requiring a variety of adaptations including breeding programmes and husbandry practices such as the provision of shade.

3.6. Integrated pasture–animal models

Generally the implications of these changes in forage supply and quality have not been taken through to the effect on the animal in experimental studies. Most modelling has only considered changes in forage supply. An exception is the analysis of effects of doubled CO_2 where diet samples collected from oesophageal fistulated sheep were used to predict a 10–15% decrease in steer gain during a 5-month grazing period (Owensby et al., 1996).

An increasingly synthetic view is beginning to develop through models in USA (e.g., Hanson et al., 1993), Australia (e.g., Hall et al., 1998; Howden et al., 1999c; Stafford Smith et al., 1999) and Europe (e.g., Riedo et al., 1998, 1999). A common message from these is that the economic effects of elevated CO_2 are unlikely to be greater than those caused by many other biophysical and management factors. They may provide a valuable systematic increase in forage supply, but this is not always so significant in terms of economic outputs once other limiting factors in the system (whether biophysical, market or institutional) are taken into account (see Section 4.1.1).

Comparisons of potential land use changes using models are also important in assessing impacts of CO_2 and climate change. An analysis at one site (Howden et al., 1999d) showed that under doubled CO_2 without climate changes, the relative productivity of wheat compared with grazing may increase by around 20%, suggesting expansion of wheat is possible. However, if warmer temperatures occur as well, there may be a 20% reduction in the ratio of wheat against cattle liveweight gain but little change against grass production. Livestock production could expand at the expense of wheat, although heat stress effects on cattle were not taken into account, and these could lead to lower animal productivities than indicated (Howden et al., 1999a).

In general, results are indicating that analyses of the whole production system are required to identify which components are most poorly known. For effective prediction of climate change effects, sufficient precision is only required for those processes having major impacts on livestock production and key ecosystem processes.

3.7. Summary of uncertainty

To summarise, the greatest confidence is in predicting implications for forage production, with lesser confidence in implications for tissue composition, pasture composition, animal production and adaptation options (Fig. 5). These latter areas are, of course, those that are of greatest importance to end-users. Also, there is greatest confidence in predicting these outcomes for intensive pastures in cooler, wetter portions of the temperature moisture plane. There is much lesser confidence in predictions for the drier and wet/dry seasonal portions of this plane (Fig. 1).

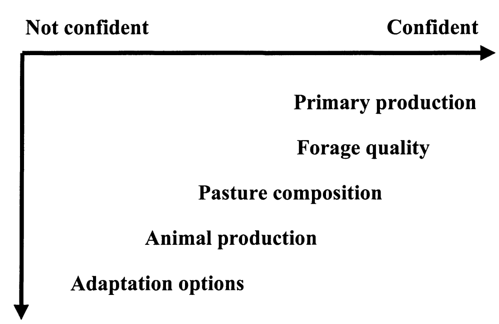

Fig. 5. Generalised degree of confidence in different areas of study; note that the *y*-axis might be said to correspond to an increasing degree of immediate relevance to end-users.

4. Implications for management

4.1. Whole systems

This component of the Pastures and Rangelands network was mainly focused on the paddock and landscape scale, such that the main direct users of results are likely to be land managers. Subsequent work under the network is identifying the key end-user needs in different regions. Such information is essential before it is possible to link the quantitative experimental results discussed above with a qualitative understanding of management activities. Given these links, then system-level analysis of management responses is needed. This is an essential step, since the interpretation of experimental findings can be simplistic if not placed in the whole-system context. The following examples illustrate that management implications and adaptation options must be assessed in the context of the whole system, not by dealing with individual factors in isolation. However, these assessments are in a rudimentary stage at present.

4.1.1. Example: cattle liveweight gain

A recent sensitivity analysis for a subtropical grazing system (Campbell et al., 1997) indicated that a 10% increase in transpiration and radiation use efficiency due to elevated CO_2 would result in about a 5% increase in mean annual pasture growth. This produced a 3% increase in mean annual liveweight gains in cattle (ignoring changes in diet quality), but a somewhat larger gain in economic output. Most of the increases came about through reducing the variability of production between years, not from the direct increase in production itself.

4.1.2. Example: carbon storage

Howden et al. (1999e) simulated the effects of CO_2 and climate change on a semi-arid woodland in Australia, showing that carbon stores would increase by 7–17% with doubled CO_2 in this system as expected, but only in the absence of fire. Thus radical management changes, involving the exclusion of both grazing and fire, were needed to obtain substantial carbon sequestration benefits. This would be unlikely to happen in practice. Similarly, Hall et al. (1998) showed that the dynamic feedback of management across the whole of Queensland, Australia, could alter the expected impacts of climate change on grazing production at this regional scale.

4.1.3. Example: vegetation change

Walker et al. (1999) found in large pot experiments that defoliation (to simulate grazing) substantially reduced the biomass gains resulting from improved water use efficiency in response to elevated CO_2. Because plants were growing poorly under defoliation, they could not take advantage of the extra water available and the slight stimulatory effect on photosynthesis was not enough to overcome the loss of photosynthetic area due to defoliation. In actual ecosystems, the effect of selective defoliation under elevated CO_2 could be to accelerate vegetation change that is occurring in response to grazing.

4.2. Stocking rate decisions

Given the above uncertainties, only preliminary conclusions can be drawn from the individual responses described above for on-farm decisions. Stocking rate strategies are driven by the overall pasture productivity, through the forage supply and composition, and its variability over time, which may alter average stocking rates or drive the need to buy and sell.

Overall, the changes in forage supply in the absence of compositional changes would seem to be modest. In most systems, CO_2 related changes are likely to balance out any negative climate change effects in the medium term, and sometimes enhance production significantly (e.g., Hall et al., 1998; Stafford Smith et al., 1999).

These effects are very subject to the exact nature of climate change in different regions, with forage supply generally being reduced by increases in temperature in many systems not limited by cold temperatures (but see by contrast Riedo et al., 1998, 1999, for cold-limited systems). In general, the 0–30% (average 17%, Fig. 1) net likely increases in forage production are modest compared with the range of uncertainties in predicting the future climate. However, they raise some opportunities in production-limited systems.

In some water or temperature limited systems, the combination of temperature and rainfall changes with the effect of CO_2 on improved water use efficiency may reduce the severity of water deficits during dry periods. In these cases, climate variability impacts on forage supply will be offset.

In warmer, dry areas and where rainfall changes do not compensate for temperature increases, or where seasonality of rainfall shifts unfavourably, there is the likelihood of increased drought problems. These will be of great concern to grazing managers, since it is often the extreme events that drive enterprises out of business, or subsistence people into famine.

There may also be direct changes in climate extremes due to climate change, but these are poorly understood at present.

4.3. Pasture and animal husbandry

On-farm management interventions relate mainly to managing either the pasture or the animals themselves. In the long term, changes in plant composition have the potential to be at least as significant as the previous effects. Temperature changes alone are predicted to increase the invasion of C_3 temperate pastures by C_4 subtropical species (Campbell et al., 1996). Differential responses to CO_2 may be assisting clover and other legumes to outperform grasses in temperate grasslands. Grazing selection, responding to changes in forage quality, has the potential to alter nutrient limited systems, although this may be by stabilising the status quo in terms of C_4 grasses.

Many of these effects are already subjected to management and do not pose radically new problems for management, but rather require an extension of existing effort. For example, additional cutting could control undesirable plants on high fertility loess soils in Hungary; adjusted grazing pressure and the use of fire could maintain tree/grass balances in north Australian savannas; small additions of nutrients could assist grasses to compete with legumes in altered European grasslands. These extra-management inputs come at a cost, however, and will stress enterprises that are already marginal. Also, difficulties will arise in situations where global change exaggerates those botanical composition changes that cannot be adequately controlled currently by manipulating management such as grazing or fire.

In the absence of substantial plant compositional change, forage quality for herbivores will decline in systems where feed conversion efficiency is limited by protein, and will be unchanged or increase in systems where it is limited by carbohydrate. The former will be especially true in subtropical to tropical grasslands, whilst the latter will generally apply in temperate natural and introduced pastures. There will be interzones where the balance will be hard to predict, although there remain some questions hanging over long-term soil nitrogen processes in all cases.

Supplementation technology can potentially offset decreases in forage quality, but this may be expensive or impractical. This will make existing marginal grazing lands in the subtropics and tropics more marginal, whether they are commercial or subsistence systems, although the latter may have opportunities to use dung and other recycled fertiliser more efficiently. It should have little effect on temperate energy limited systems, where there is some opportunity to increase stocking rates. However, in regions such as Europe where production is already capped by regulations, it may result in the need for less grazing land and further abandonment.

4.4. Adaptation

Adaptation to change can be reactive or proactive (Gifford et al., 1996), and can occur at different points through the value-adding chain. Reactive adaptation will tend to maintain the current industries as change occurs. Examples will be the increased use of supplements to offset reduced forage quality in subtropical rangelands, changes in stocking rates in response to productivity changes in many pastures, and management of weeds and other pasture composition changes where appropriate. In some situations, the cost of technologies for handling these changes will not be tenable, and adjustment to land use will be inevitable. For subsistence land users with no alternative but to cope with the vagaries of production, this may require a closer integration of cropping and grazing cycles. In commercial systems, there will simply be abandonment of grazing.

The option of seeking proactive adaptation options is more exciting and forward looking. Rather than simply seeking to maintain current targets for food supply, in some cases there will be real opportunities to set new production targets in line with the increasing world food demand. To achieve this, managers could, e.g., seek cultivars that retain the benefits of CO_2 responses but are more drought-tolerant, although

Luscher et al. (1996) found no intra-specific genetic variation in direct response to CO_2. Similarly, high flavonoid contents could be selected for in white clover leaves to breed higher tolerance to UV-B radiation (Campbell et al., 2000). Some examples exist of linking system management to climate change through seasonal forecasting and other strategies (e.g., McKeon et al., 1993). Proactive adaptation could extend further towards modifying animal husbandry to influence food product quality and other adaptations to add value and quality to the final food product. To date, climate change research has not extended this far down the pastoral food value chain.

5. Meeting future food and environmental security needs

Land use is changing locally around the world in response to local food production expectations, regardless of climatic and atmospheric change. There is a major division in trends in this regard between developed countries where there is a stable demand, increasing productivity per unit area and often a declining area of production, and less developed countries where increasing population is continuing to increase the demands for production (Polley et al., 2000). In the developed nations, the result is an increased emphasis on environmental protection, on niche markets and value-added products, and on policies to deal with land abandonment. In less developed areas, there is an increasing emphasis on commodity production, conversion of forests to pastures and rangelands, of rangelands to croplands, and of increasing intensity of production in pastures. Some of these areas (e.g., the Sahel) are also subjected to immediate obstacles related to poverty (poor production assets, insecure land tenure, poor capacity to increase inputs, education and health) and the opportunities for development are different. A qualitative analysis coupled with the quantitative results described earlier can help to answer the question of how well different regions will be able to deal with the effects of global change (Fig. 6).

The sensitivity of different regions to meeting their production targets for food supply in the future

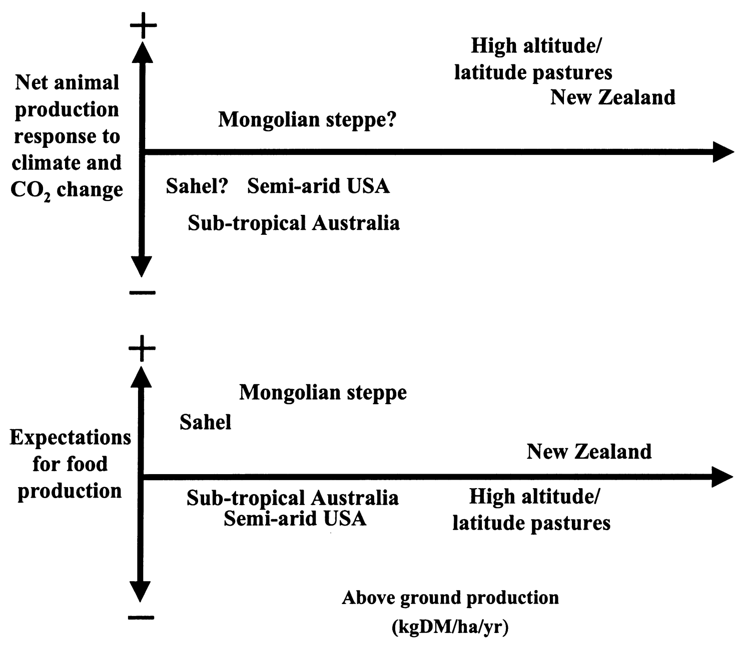

Fig. 6. Approximate estimates of likely responses to climate and atmospheric change and needs under population and land use change for some different pasture and rangeland systems around the world. Problem areas are where + signs in the lower diagram are not matched by + signs in the upper diagram.

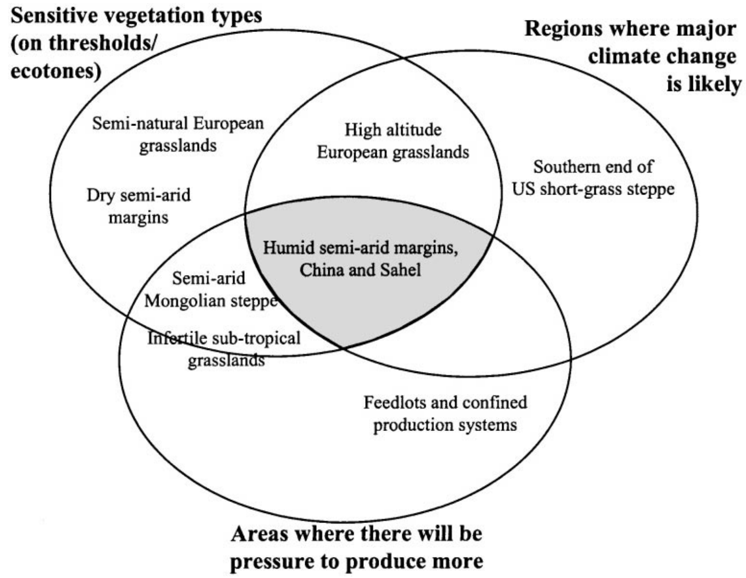

Fig. 7. Three aspects of sensitivity in systems, and the intersections where critical change is most likely to happen, with some examples of placement of different regions and systems studied by this network.

whilst coping with climate and atmospheric change thus depends a complex mix of factors. Systems can be intrinsically sensitive, such as ecotones, where small changes in external conditions take the system over a threshold. Such systems are naturally subject to change. There are also regions where substantial changes in climate are predicted. Sensitivity can also be attributed to regions where food supplies are likely to be more-or-less limiting in the region. Fig. 7 illustrates an analysis where different grassland regions in this network have been qualitatively assigned to positions within ellipsoids representing these three aspects of sensitivity. Humid semi-arid margins of China and the Sahel are located where these three different facets of sensitivity coincide, and it is therefore predicted that these are likely to be particularly sensitive regions within the network.

6. Implications for science

6.1. Looking back

Although the GCTE Pastures and Rangelands network was formed 5 years ago (and in some cases the research originated over a decade ago) half of the research teams in the network still feel that it is premature to extrapolate their results to implications for management and adaptation. Over one-third of teams identify long-term acclimation of systems, compositional changes, and the effects on below-ground processes (especially soil N-fixation) as being critical outstanding uncertainties. That results from a wide range of experiments to date appear to agree well with predictions from the Hurley Pasture Model is encouraging. However, this model forecasts that it would take up to 50–100 years for equilibrium to be reached in infertile soils (Thornley and Cannell, 1997) following stabilisation of atmospheric CO_2 concentrations and climate. Experiments clearly cannot be continued for that long before providing input to management, and that is why results must be incorporated into models to develop predictions ahead of actual changes.

If these results are to have implications for end-users, then one may ask how the end-users will become better informed of these implications. Most emphasis on transfer of results from the network to date has been on transfer to other scientists rather than to producers in pasture and rangeland farming systems. However, some successful examples are now emerging of consultation and transfer of results to this latter group, e.g., in Swiss grasslands, USA short grass prairie and Australian rangelands. Still, relatively few examples exist where farmers or agribusinesses have responded strongly to research findings to date. This is not surprising, given that the predicted changes in cash flows will occur in several decades rather than now. However, these current efforts provide a valuable message for extension: getting today's management systems to be responsive to change is often pre-adapting them for future change as well.

6.2. Filling remaining gaps

The GCTE Pastures and Rangelands network identifies significant scientific uncertainty remaining about:

- Long-term implications of changes in CO_2 and climate for productivity.
- Vegetation compositional change, especially for rangeland regions.
- Effects of extreme events.
- Interactions with pests and diseases.
- Animal production responses.
- Integrated impacts on whole production systems.
- Analyses of options for proactive adaptation along the whole food production value chain.
- Interactions between various global change drivers.

A major future challenge will be to create links between global change scientists, traditional agricultural scientists, some of the new technologies (such as bioengineering) and social scientists/adult learning experts in order to address the opportunities for proactive adaptation. The challenge is to unite the understanding of the global change scientist with the plant breeding, pasture management and animal production knowledge of traditional agriculturalists. This should aim to better understand how management could adjust at appropriate points in the food value chain to cope with current uncertainties and be prepared for future changes. The next goal should be to combine this understanding with the skills arising in the new industries to capture the opportunities in safe and acceptable ways that perhaps involve combining vegetation and livestock attributes and processing technologies to meet conditions that they have not experienced in their evolutionary history.

The new knowledge technologies will combine ecosystem science, biotechnology, agronomy and integrated system modelling to meet food security needs. There is a wide diversity of new thinking, including novel ways of delivering fertilisers, structuring farming to enhance biodiversity conservation, managing international markets to provide subsistence herders with a livelihood, and integrated approaches to pests and diseases. Such changes require a significant adjustment in thinking on the part of all those scientific groupings, as well as strong interactions with end-users to help set priorities and intended outcomes.

7. Conclusions

1. Experimental data now exist to considerably reduce the uncertainties about the effects of elevated CO_2 on intensive pastures in cool, wet climatic zones. Further progress is still needed, however, concerning the interactive effects of elevated CO_2 and climate change on the species dynamics and soil nutrients, especially in grazed pastures.
2. Knowledge of other grazed ecosystems and of the effects of some other climate change variables is more limited. However, this knowledge may not now be particularly limiting except in the most sensitive regions of the world. This means that:
   - In the more intensive pastures, an iteration of integrative modelling and sensitivity analysis, directed at the questions being raised by end-users, is now warranted to define future research direction.
   - Additional new experimental data collection efforts for pastures and rangelands should be focused in ecosystems which are most sensitive to food security issues and most subject to global change, in particular humid semi-arid margins and subtropical grasslands.
3. There remains no good basis for extrapolation of findings between different pasture and rangeland systems, because past work has been disproportionately in intensive systems, and an appropriate functional classification of systems is currently lacking (see Campbell et al., 1999; Campbell and Stafford Smith, 1999). As a consequence:
   - Future data collection should focus on the poorly represented, less intensive systems.
   - A functional classification of rangelands and pastures must be developed.

The concepts, methods and models elaborated in the temperate pastures should be developed in relation to extensive grasslands and rangelands.

4. There is an increasing recognition of the need to link the results to their implications for land manager and policy end-users, which requires:
   - Greater development of regional end-user partnerships to identify the critical relevant issues for different regions.
   - Adaptation research to broaden its considerations to incorporate the whole value-adding production chain.
   - A greater emphasis in future work on integrative modelling of the linkages between the biophysical, social and economic factors which will influence future changes in pasture and rangelands ecosystems and their implications for food security in this large proportion of the world.

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