Dynamics of mulga woodlands in south-west Queensland: global change impacts and adaptation.

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Abstract: The possibility of trading greenhouse gas emission permits as a result of the Kyoto Protocol has spurred interest in developing land-based sinks for greenhouse gases. Extensive grazing lands which have the potential to develop substantial woody biomass are one obvious candidate for such activities. However, any such activity needs to take into account the possible impacts on existing grazing and the possible impacts of continuing CO_2 buildup in the atmosphere and resultant climate change. We use simulation models to investigate these issues in south-west Queensland. These simulations suggest that this system can be managed to act as either a net source or a net sink of greenhouse gases under current climate and CO_2 and under a range of global change scenarios. The key component in determining source or sink status is the management of the woody mulga. Excluding both burning and grazing is the most effective means of permanently increasing carbon stores and hence reducing net emissions. There are combinations of management regimes such as excluding fire with light grazing which, on average, allow productive grazing but transient carbon storage. The effects of increased CO_2 on ecosystem carbon stores were unexpected. Carbon stores increased (7-17%) with doubling of CO_2 only in those simulations where burning did not occur, but decreased when burnt. This occurred because the substantial increases in grass growth with doubling of CO_2 (34 to 56%) enabled more fires, killing off the establishing cohorts needed to ensure continued carbon accumulation. On average doubling CO_2 increased grass growth by 44%, this is identical with mean literature values suggesting that this result may be applicable in other ecosystems where fire has a similar function. A sensitivity analysis of the CO_2 response of mulga showed only minor impacts. We discuss additional uncertainties and shortcomings.

Introduction

Increases in the density of shrubs and trees (woody weeds) in grasslands in semi-arid Australia is currently a major threat to sustainable agricultural production due to the reductions in grass growth and hence livestock performance that occur (eg Burrows *et al.* 1990). However, whilst these invasions reduce grass production and hence wool cuts, they can also result in substantial increases in carbon stores which may become a new source of income for these regions in the eventuality that carbon emission trading arises from the Kyoto Protocol. This may require adaptation of grazing and burning regimes in these regions depending on the management goals. A further complication is that the dynamics of woody weed invasions may themselves be changed by increases in atmospheric CO_2 levels and by possible changes in climate. We investigate responses of the mulga (*Acacia aneura*) woodland ecosystems in south-west Queensland under scenarios of CO_2 and climate change in the context of adaptation for differing management goals. We use an existing model of the dynamics of these woodlands (Moore *et al.* 1997) adapted to simulate responses to varying atmospheric CO_2 levels.

Methods

The model of Moore *et al.* (1997) is an extension of GRASP (McKeon *et al.* 1990). GRASP is a model simulating the above-ground yield of a sward dominated by perennial native grasses. GRASP includes a four layer soil water balance and a plant growth model which calculates the processes of run-off, infiltration, drainage, soil evaporation, tree and grass transpiration, pasture growth, consumption and decay, nitrogen uptake, pasture management effects (i.e. stocking rate and pasture burning) and plant density (i.e. perennial grass basal cover). GRASP calculates pasture growth as a function of grass transpiration, radiation interception, temperature, VPD, nitrogen availability and regrowth potential. Evaluation, calibration and validation of the model are described in Day *et al.* (1997).

The density of trees in GRASP, however, is set by the user within each simulation. The model of Moore *et al.* (1997) adds modules which simulate the population dynamics and growth of mulga in response to changes in environment and management (stocking rate, burning, tree clearing). It also has an emissions module which tracks the flow of carbon and other emissions through the plant and animal components of the ecosystem although it doesn't currently model the soil carbon components. We have modified this model to simulate responses to high atmospheric CO_2 concentrations within both the grass sward and the mulga components.

The general impacts of increased CO_2 on C_3 grasses are understood in terms of photosynthetic and stomatal responses and changes in nitrogen nutrition (eg Wand *et al.* 1999). Mulga lands in good condition have a large component of C_3 grasses and we assume for these simulations that they dominate the sward, acknowledging that many pastures have substantial C_4 components. The CO_2 response of the grass component was modified following Howden (1999a,b) by changing the transpiration efficiency, radiation use efficiency and nitrogen efficiency of the grasses. In contrast, the responses of woody plants to increased CO_2 appear to be more variable than the C_3 grass responses with the meta-analysis by Curtis *et al.* (1998) showing relatively consistent photosynthetic responses (averaging +16% for woody plants in nutrient-stressed conditions) but quite variable stomatal conductance responses (mean -11% but not significant). We thus have used two sensitivity scenarios which vary the response of mulga to high CO_2. These are a low response where daily transpiration per unit tree basal area decreases by 11% but where the water-use efficiency increases proportionately, and a high response where transpiration per unit basal area decreases as before but there is an additional increase in water-use efficiency of 16%.

We apply this model to a range of feasible global change scenarios which reflect the different uncertainties. Increases in atmospheric CO_2 concentration are highly likely due to existing economic and population development pathways and energy and landuse patterns. In the mid-range IPCC scenarios, atmospheric CO_2 concentrations are likely to double to about 700ppm around the year 2100 (Houghton *et al.* 1996). Consequent increases in global temperature are consistently forecast whilst changes in rainfall at regional level have considerable uncertainty. We thus construct a cascading hierarchy of scenarios (Table 1). The temperature and rainfall changes in the Hot, Wet and Dry scenarios are implemented by using the historical climate record for Charleville for the period 1885-1995 but adding 3°C equally to maximum, minimum and dewpoint temperature (Hennessy *et al.* 1999), whilst rainfall changes are implemented as ± 10% multipliers on daily rainfall (Howden 1999a). To ensure consistency between all files, pan evaporation was recalculated using a regression derived from the period 1980 to 1995 when the Class A pan measurements were most reliable (Eq'n 1). VP and VPD were recalculated for the scenarios with changing temperature using the equations in McKeon *et al.* (1998).

Table 1: Changes in carbon dioxide levels, temperature and rainfall for each global change scenario

Scenario	**CO2 (ppm)**	**Temperature (°C)**	**Rainfall (%)**
Baseline	350	0	0
CO_2	700	0	0
Hot	700	+3	0
Wet	700	+3	+10
Dry	700	+3	-10

$$E_{pan} = -1.338 + (0.177 * Rad) + (0.238 * VPD)$$

$$r^2 = 0.920 \qquad \textit{Eq'n 1}$$

The simulations were run using the site data and parameterisations from Moore *et al.* (1997). The initial mulga cohort was altered to give a more even age distribution (200stems/ha each at 0.25m and 1m height, 50 stems/ha at 2m, 30 stems/ha at 5m and 5 stems/ha at 10m) and a total basal area of 0.475m^2/ha. Treatments were a factorial combination of grazing by fire with two grazing treatments [ungrazed (U) and grazed (G) with sheep stocking rate set for 20% utilisation based on pasture availability at 1 June: McKeon *et al.* 1990] and three fire treatments [never burnt (N), burnt every 6 years (F) and burnt annually (A). Burning occurs at the end of the dry season, if a threshold biomass of 1000kg DM/ha is present]. These treatments were simulated for both the global change and baseline scenarios. All scenarios apart from the Baseline were simulated with both the Low and High CO_2 response by the mulga.

Data are generally presented as means of the 110 year simulation. Net emissions are expressed in terms of carbon-dioxide equivalent emissions (CO_2-e) by using Global Warming Potentials to adjust for the different radiative forcing and lifetimes of gases such as methane and nitrous oxide (Houghton *et al.* 1996). The difference between final and inital carbon stores was calculated to give the change in carbon store over the simulation.

Results

There was a substantial trade-off between wool production and net emissions with four clusters of results being dominated by grazing and burning treatment (Fig 1). Variations in global change scenario and/or mulga CO_2 response had lesser impacts than the management. The substantial variation of results within a treatment suggests that there are feasible global change scenarios which result in both high wool production and low net emissions/high average carbon store.

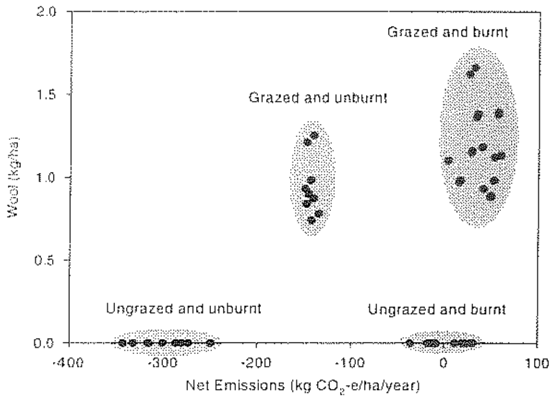

Figure 1: Wool production (kg/ha) and net emissions (kg CO_2-e/ha/year) for all treatments and scenarios.

Doubling CO_2 and climate change increased average net emissions for all treatments except UN with GN remaining similar to the Baseline simulation (Table 2). Average net emissions were negative (ie a sink) for GN (-140kg CO_2-e/ha/year) and not influenced much by global change scenario. The sink size was doubled in the UN treatments (-250 for the Dry scenario to -340 kg CO_2-e/ha/year for the Wet scenario). Climate change in addition to CO_2 increase had minor effects on net emissions for UA, UF, GA and GF treatments. All changes in net emissions were closely linked to differences in average carbon store with decreases in average carbon store from the Baseline simulations for all treatments except UN with marginal changes in GN depending on the climate change scenario. However, carbon store trajectories differed significantly between treatments (Fig. 2) with some treatments (UA, GA) having a carbon store at the end of the 110 year simulation less than that at the start. Only the UN treatments showed continuing carbon storage at the end of the simulation (Table 2) with significant variation with scenario in the increase in storage from +17000 kgC/ha (Dry) to +21000 kgC/ha (Wet). The GN treatments also maintained carbon storage for a long period into the simulation.

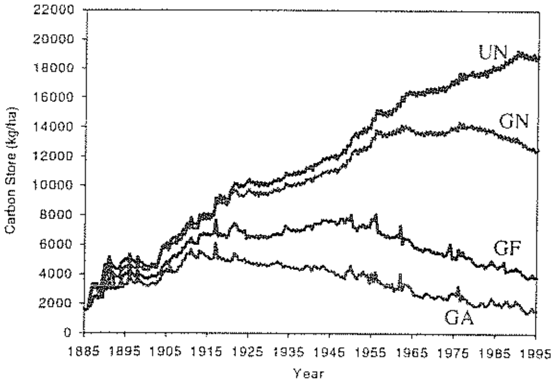

Figure 2: Wool production (kg/ha) and net emissions (kg CO_2-e/ha/year) for selected treatments under the Baseline scenario.

Grass growth was substantially stimulated by the doubling of CO_2 (mean 44%) with the response being mediated by both grazing/burning treatment and the response of the mulga to CO_2 (Table 3). The grass response was least in the treatments that were never burnt (+34 to +40%) and greatest in those frequently burnt (+47 to +56%). High mulga CO_2 response decreased the grass CO_2 response from 40 to 34% in the UN treatment. There was no effect in some treatments (UA and GA).

Table 3: Response (% change from baseline) of grass production to CO_2 under the different management scenarios

Treatment	Grass Response	
	Low	High
Ungrazed – Annual	43	42
Ungrazed – 6 yearly	56	53
Ungrazed – Never	40	34
Grazed – Annual	44	44
Grazed – 6 yearly	50	47
Grazed – Never	39	35

The number of burning events (Table 2) in the Baseline simulations were 10 (GF), 23 (GA), 11 (UF) and 33 (UA). Doubling CO_2 increased these markedly (14, 43, 17 and 51 respectively). The Hot and the Dry climate change scenarios reduced the number of fire events but they always remained above baseline values.

Wool production varied by 30% for the Baseline scenario with values of 1.18, 1.1 and 0.9 kg/ha/year for the GA, GF and GN treatments (Table 2). Doubling of CO_2 increased production markedly especially for the GF(50%) and GN (38%) treatments. However, when climate change was simulated in conjunction with CO_2 increase, wool production was reduced in all scenarios sometimes to below the Baseline values (eg 30% reduction in the Dry scenario of GA).

Table 2: Average net emissions, average carbon store, change in carbon store, average wool production, number

of burns and grass production for each management treatment and global change scenario.

Treatment	Average Net Emissions (kg CO_2-e /ha/yr)	Average C Store (kg/ha)	Change in C Store (kg/ha)	Wool (kg/ha/yr)	Burns (no.)	Grass Growth (kg DM/ha)
Ungrazed - Annual Burn (UA)						
Baseline	11	3436	294	0	33	758
CO2	30/29	2854/2939	-525/-446	0	51/51	1086/1078
Hot	30/29	2555/2669	-644/-539	0	53/53	1068/1054
Wet	31/29	2735/2858	-504/-396	0	55/56	1163/1157
Dry	22/19	2726/2836	-336/-111	0	44/44	919/909
Ungrazed – Burnt every 6 years (UF)						
Baseline	-36	5913	3285	0	11	622
CO2	-12/-18	5405/5697	2138/2536	0	17/17	971/949
Hot	-13/-18	5891/6132	2228/2503	0	15/15	901/886
Wet	-13/-18	5672/5871	2289/2603	0	17/17	1028/1013
Dry	-9/-13	5488/5775	1798/2102	0	15/15	808/789
Ungrazed - Never Burnt (UN)						
Baseline	-273	11726	17314	0	0	428
CO2	-300/-332	12947/13807	19176/21074	0	0	601/574
Hot	-286/-316	12434/13255	18303/20097	0	0	583/556
Wet	-315/-343	13347/14101	20084/21758	0	0	626/602
Dry	-249/-280	11258/12117	16021/17857	0	0	544/518
Grazed - Annual Burn (GA)						
Baseline	39	3586	-56	1.18	23	719
CO2	56/56	2939/3003	-677/-685	1.39/1.38	43/44	1038/1032
Hot	53/52	2658/2741	-618/-614	0.99/0.98	45/46	1022/1016
Wet	59/52	2698/2788	-830/-315	1.13/1.12	51/48	1133/1150
Dry	49/49	2693/2765	-649/-648	0.89/0.88	39/39	891/886
Grazed - Burnt every 6 years (GF)						
Baseline	3	5721	2233	1.1	10	588
CO2	31/25	5450/5778	1427/1805	1.66/1.62	15/13	885/864
Hot	28/28	5489/5644	1466/1508	1.16/1.15	14/14	848/839
Wet	34/33	5604/5820	1391/1472	1.38/1.36	15/15	946/941
Dry	16/14	5452/5619	1909/1988	0.98/0.97	11/11	731/721
Grazed - Never Burnt (GN)						
Baseline	-146	10079	10912	0.9	0	435
CO2	-141/-148	10820/11278	11247/11626	1.25/1.21	0	605/587
Hot	-141/-148	10543/10998	11157/11541	0.87/0.84	0	588/571
Wet	-144/-150	11068/11468	11499/11830	0.98/0.93	0	639/622
Dry	-135/-143	9863/10357	10618/11033	0.78/0.74	0	537/519

The differences between the two CO_2 responses for the mulga component was small for the average carbon store, average net emissions and the other variables (eg wool production, burning events).

Discussion

These simulations suggest that this system can be managed to act as either a net source or a net sink of greenhouse gases under current climate and CO_2 and under a range of global change scenarios. The key component in determining source or sink status is the management of the woody mulga. Excluding both burning and grazing is the most effective means of increasing carbon stores and hence reducing net emissions although we note that permanent exclusion of fire is probably not a practical option. Under a zero-grazing scenario, this land would no longer be used for agricultural production. If grazing is undertaken with various fire management regimes, there remains a significant trade-off between wool production and increasing carbon stores although there are combinations of management regimes such as excluding fire with light grazing which, on average can provide both. However, it was only in the simulations where no fires or grazing occurred that there a continuing increment of carbon throughout the 110 year simulation. Under other management regimes, initial increases in carbon stores are followed by reductions as the initial mulga cohorts die out. The model is of course a simplification of real management practices and there are opportunities which generally exclude grazing but use the mulga and the associated chenopods as drought reserve (eg Lauder and Freudenberger 1999) which could make multiple uses feasible.

The issue of whether carbon sequestration is an alternative landuse to grazing is currently hotly debated. The purchase cost of land, maintenance costs (eg firebreaks and fencing), income foregone, security of store, the costs, accuracy and precision of monitoring and verification, transaction costs and other possible associated benefits and costs (eg biodiversity) all need to be addressed. The low cost of land and current low returns from wool production from the rangelands in south-west Queensland suggests that this region may be suitable to develop a mosaic of landuses which incorporates carbon storage as one goal provided that some of the above cost issues can be addressed (eg reduce monitoring costs). The simulations in Moore *et al.* (1997) using this model suggest that both the dynamics of storage and total carbon storage are influenced by the initial mulga stand structure. This needs further investigation as it may have an influence on the viability of carbon storage as a landuse.

The effects of increases in CO_2 on ecosystem carbon stores were unexpected. Mean growth responses from the literature for doubling of CO_2 are 44% for C_3 grasses (Wand *et al.* 1999) and 16% for woody species in nutrient stressed conditions (Curtis and Wang 1998). In these simulations when ungrazed and unburnt, this resulted in a 10-17% increase in mean carbon storage with the variation due to the different mulga CO_2 responses investigated. This is consistent with the physiological potential of 16%. When grazed but still unburnt, this changed to 7-11% increase in mean carbon store: considerably lower than the potential. However, under all treatments in which burning occurred, doubling CO_2 resulted in a smaller mean carbon store and less carbon stored over the simulation. This occurred because the substantial increases in grass growth with doubling of CO_2 (34 to 56%) enabled more fire events to occur and this affected the mulga populations, killing off the establishing cohorts needed to ensure continued carbon accumulation. The mean effect of increased CO_2 on grass growth across all treatments is 44%. This is identical with the mean effect of doubling CO_2 for C_3 grasses found in the meta-analysis of Wand *et al.* (1999) suggesting that this result may be applicable in other ecosystems where fire has a similar function.

The effect of changing the CO_2 response of the mulga had surprisingly little impact on the emissions dynamics or other aspects of the ecosystems simulated such as fire frequency or wool production. The high mulga CO_2 response slightly reduced the grass CO_2 response by increasing competition. Further investigation of the response of woody plants under increased CO_2 is needed as we have not explored the full array of possible responses. For example, a scenario with no change in water use from stomatal conductance change but a growth increase due photosynthetic response would result in increased competition with grasses.

There remain, however, several sources of uncertainty in these analyses apart from those we explored by using scenarios. For example, the potential burning frequency of 23% when grazed (baseline GA treatment) appears more frequent than seen on actual properties. This difference probably reflects maximum possible fire frequency with biological constraints as opposed to current cultural practice. The frequently burnt scenario (every 6 years) is probably more representative of current pasture management in the region with 10 burning events in the historical record. Burning frequency is very sensitive to woody plant density. In a study of the effects of *Eremophilla gilesi* on potential fire frequency at Charleville, Carter and Johnston (1986) showed that with grazing at 20% utilisation an increase in *E. gilesii* canopy cover from 7.5% to 10% reduced the frequency of 1000kg yields from 36% to 12%. When average grass fuel load is close to the threshold required for fire one could expect high model sensitivity. The ungrazed/annual burn treatment gave results consistent with those of Johnston and Carter (1986). In the simulations, we also retain domestic stock on the paddock at all times whereas graziers may spell their paddocks occasionally. Mulga is very sensitive to grazing (eg Brown 1985) and these spelling periods appear to be vital in allowing the saplings to grow to a height where they are no longer susceptible to grazing and burning. For these reasons, these simulations cannot be considered to provide a hindcast trajectory of mulga spread even though as discussed in Moore *et al.* (1997), they simulate the correct gross response observed in various management regimes. In addition, different plant communities are likely to provide very different interactions between grazing and fire management, particularly those with unpalatable shrub species. Further studies are needed on such systems.

We do not simulate changes in soil carbon which may be important under some treatments and scenarios. These lands were likely to have been burnt very regularly as part of aboriginal land management practices resulting in the possibility of a relatively large pool of elemental carbon ('charcoal'). This pool can be as large as 30% of the total soil carbon pool (Skjemstad *et al.* 1996). Removal of burning from the system as simulated in some of these treatments could result in long-term reduction in the 'charcoal' pool which may offset part of the increase in biomass carbon store. The global change scenarios could also alter both carbon inputs through increasing growth and carbon outputs through increasing decomposition rates with increased temperature and, in some scenarios, increased soil moisture. The balance between these factors needs evaluating through a model such as CENTURY (Parton *et al.* 1988).

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References

Brown, R.F., The growth and survival of young mulga (*Acacia aneura* F. Muell) trees under different levels of grazing. *Aust. Rangel. J.* 7, 143-48, 1985.

Burrows, W.H., J.O. Carter, J.C. Scanlan and E.R. Anderson, Management of savannas for livestock production in north-east Australia: contrasts across the tree-grass continuum. *J. Biogeogr.*, 17, 503-512, 1990.

Carter, J.O. and P.J. Johnston, Modelling expected frequencies of fuel loads for fire at Charleville in Western Queensland. In: Proceedings Third Queensland Fire Research Workshop, Gatton, 53-67, 1986.

Curtis, P.S., and X. Wang, A meta-analysis of elevated CO_2 effects on woody plant mass, and physiology, *Oecologia*, 113(3), 299-313, 1998.

Day, K.A., G.M. McKeon and J.O. Carter, Evaluating the risk of pasture and land degradation in native pastures in Queensland. Final Project Report for RIRDC project DAQ124A, 1997.

Hennessy, K.J., P.H. Whetton, J.J. Katzfey, J.L. McGregor, R.N. Jones, C.M. Page and K.C. Nguyen, *Fine Resolution Climate Change Scenarios for New South Wales. Annual Report 1997-98.* CSIRO Atmospheric Research, 1998.

Howden, S.M., G.M. McKeon, L. Walker, J.O. Carter, J.P Conroy, K.A. Day, W.B. Hall, A.J. Ash and O. Ghannoum, Global change impacts on native pastures in south-east Queensland, Australia, *Environmental Modelling and Software*, 14, 307-316, 1999a.

Howden, S.M., G.M. McKeon, J.O. Carter and A. Beswick, Potential global change impacts on C_3-C_4 grass distribution in eastern Australian rangelands. In Proceedings of the VI International Rangeland Congress, , pp 41-43, Townsville, Australia, 1999b.

Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K.M. Maskell (eds*)*, *Climate Change 1995. The Science of Climate Change*, IPCC 1996.

Johnston, P.J. and J.O. Carter, The role of fire in production systems in western Queensland: a simulation approach. In: Proceedings Third Queensland Fire Workshop, Gatton, 161-172, 1986.

Lauder, A. and D. Freudenburger, Sustaining a grazing enterprise in south-western Queensland, Australia, In Proceedings of the VI International Rangeland Congress, pp 1037-1039, Townsville, Australia, 1999.

McKeon, G.M., K.A. Day, S.M. Howden, J.J. Mott, D.M. Orr, W.J. Scattini, E.J. Weston, Northern Australian savannas: management for pastoral production, *J. Biogeogr.*, 17,355-72, 1990.

McKeon, G.M., W.B. Hall, S.J. Crimp, S.M. Howden, R.C. Stone, D.A. Jones, Climate change in Queensland's grazing lands. I. Approaches and climatic trends, *Rangel. J.* 20, 151-176, 1998.

Moore, J. L., S.M. Howden, G.M. McKeon, J.O. Carter and J.C. Scanlan, A method to evaluate greenhouse gas emissions from sheep grazed rangelands in south west Queensland. In *Modsim'97 International Congress on Modelling and Simulation Proc*, pp. 137-142. December 8-11, Hobart. Modelling and Simulation Society of Australia, Canberra. 1997.

Parton, W.J., J.W.B. Stewart and C.V. Cole, Dynamics of C,N,P and S in grassland soils: a model. *Biogeochemistry*, 5, 109-131, 1988.

Skjemstad J.O., P. Clarke, J.A. Taylor, J.M. Oades and S.G. McClure, The chemistry and nature of protected carbon in soil. *Aust. J. Soil Res.*, 34, 251-71, 1996.

Wand, S.J.E., G.F. Midgley, M.H. Jones and P.S. Curtis, Response 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, 1999.