INVITED

Modelling the Impacts of Climate Change and Degradation on Semi-arid Landscape Systems

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SUMMARY

For the semi-arid regions of eastern Australia climate change models are predicting that winter rainfall may decrease while summer rainfall may increase, the latter in amount and the intensity. Expected impacts of these changing rainfall patterns include shifts in the balance between shrubs, C3 grasses and C4 grasses within these semi-arid landscapes caused by altered physical and ecological processes which control the way scarce water and nutrient resources are conserved and utilised. In some grazing areas these processes have already been altered by land degradation. A landscape model has been used to simulate the level of annual net plant production from a semi-arid landscape system for scenarios of the impacts of climate change and land degradation. Our simulation results clearly indicate that with land degradation increases runoff and decreases plant production, whereas climate change had only minor impacts. Thus, the impacts of land degradation are expected to be more severe than those expected for changes in climate, at least for semi-arid landscapes in Australia.

INTRODUCTION

Of all the continents Australia has the highest recorded year-to-year variability in rainfall. This variability is strongly related to the El Nino Southern Oscillation (ENSO) phenomenon. Global climate modellers have used ENSO to predict rainfall likelihood in various regions of Australia [1]. These predictions help pastoralists and farmers minimise their economic risks and reduce their ecological impacts on the land [2]. Risks and potential impacts are greatest in the drought-prone arid and semi-arid regions of Australia, which cover about 5.5 million sq. km or about 75% of its total land area [3]. Except for the most arid sandy desert regions, these areas are used extensively as rangelands for grazing sheep and cattle [4].

The ability to predict rainfall likelihood for much of semi-arid Australia has greatly improved through the development of software packages such as "Australian Rainman" [5]. Users of the package, be they pastoralists, farmers or other land managers, can incorporate the latest estimates of the Southern Oscillation Index (SOI) to obtain the probability of rainfall in the coming season for their region. This helps to minimise the risk of making an inappropriate management decision. For example, if the long-term forecast is for no rain, keeping too many stock on the land during a drought which can cause severe land degradation -- stock can be sold or agisted early enough to avoid this damage. Such forecasts are vital to pastoralists who must manage the expected consumption of forage production by stock and other herbivores such as kangaroos [6].

Australian rainfall and hence vegetation responds strongly to ENSO, and is also likely to respond strongly to longer-term changes in climate [7]. For semi-arid eastern Australia, global climate change modellers predict that over the next thirty years that these rangelands could experience higher temperatures, lower winter rainfall and higher summer rainfall, the latter occurring in fewer but more intense storms. One aim of this modelling study was to simulate the likely impacts of such a climate change scenario on vegetation composition and annual net primary production (NPP) for the semi-arid rangelands of eastern Australia.

The vegetation of Australia has undergone many changes under the impacts of humans, particularly since its settlement by Europeans [8]. It is estimated that some one-half million sq. km (about 8%) of Australia's rangelands have undergone 'severe' desertification, that is, areas currently in 'poor' range condition and showing signs of severe soil erosion such as gullies [9]. Semi-arid landscapes with these forms of degradation have less ability to conserve resources than similar but undegraded landscapes [10]. Another aim of this study was to simulate the impacts of land degradation on NPP, and to compare these impacts with those for climate change.

SEMI-ARID LANDSCAPES

Many semi-arid landscapes in Australia, and around the world, are patchy, runoff-runon systems. For example, in eastern Australia groves of mulga trees (*Acacia aneura*) are interspersed with open, grassy intergroves [11, 12]. Patchiness also occurs at smaller scales, for example, as log mounds-intermounds, or as grass clumps-interclumps. Schematically, in a top-view, these semi-arid landscapes appear as a number of discrete units or patches dispersed across flat, gentle slopes of usually less than 1% (Fig. 1). Patches are separated by open areas (interpatch). Runoff from rainfall flows down the slope unless it is 'filtered' or captured by a patch. Runoff not captured by the landscape unit is termed runout.

Landscape patchiness functions to optimise plant production by concentrating and conserving limited water and nutrient resources [13]. This optimisation is based on the theory that arid and semi-arid lands function as source-sink or runoff-runon systems [14]. This theory predicts that in arid and semi-arid environments with limited resources, NPP will be higher if resources are concentrated into patches and not uniformly dispersed over the landscape.

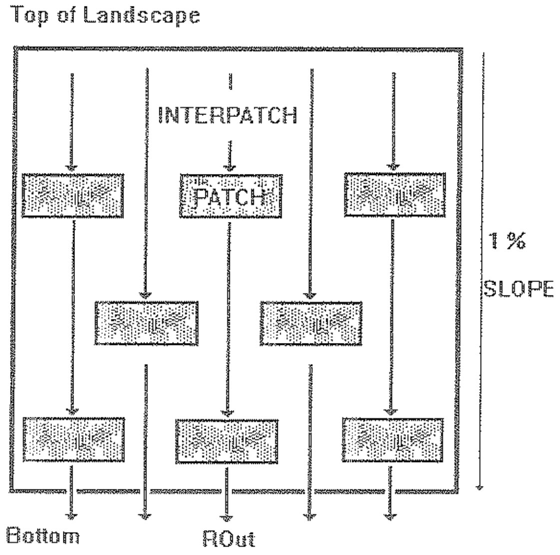

Fig. 1. A schematic, top-view diagram of a typical semi-arid landscape in eastern Australia, with patches separated by open interpatch areas [12].

Our landscape studies, and others around the world, have demonstrated that patchiness is maintained by physical processes such as surface winds and surface water flows which redistribute resources into patches, for example, runoff goes to recharge soil water, litter to soil organic carbon and runoff sediments to soil nutrient pools [11]. Biological and chemical processes help to maintain patches, for example, plants within a patch utilise water and nutrients for growth and then these resources recycle back to the patch through death and decay.

LANDSCAPE SIMULATION MODEL

A 'flow-filter' simulation model was developed to quantify how runoff flows down, and possibly out of a landscape [13]. If the amount and intensity of rainfall (R) exceeds the water infiltration rate (IR) or water storage capacity (SC) of the soil within the interpatch area then runoff (ROff) occurs (Fig. 2). This ROff can run out (ROut) of the system or be captured by patches. If the IR and SC of the patch is exceeded then ROut occurs from the patch. The total ROut from a landscape following a rainfall event at time (t) is also a function of the slope (S), total area of patch (AP) and area of interpatch (AI):

$$\mathrm{ROut}_t = f(\mathrm{R,IR,SC,S,AP,AI})_t$$

Annual net plant production (NPP) for the landscape system was estimated by using another, but linked simulation model. This SEESAW model is designed to simulate the ecology and economics of semi-arid woodlands, and has been briefly described elsewhere [13, 15]. A submodel within SEESAW computes NPP through time (t) as a function of plant available moisture (PAM) and available nutrients (AN) and temperature (TEMP):

$$\mathrm{NPP}_t = f(\mathrm{PAM,AN,TEMP})_t$$

PAM is estimated by a submodel, called WATDYN, which computes soil water balance dynamics [16].

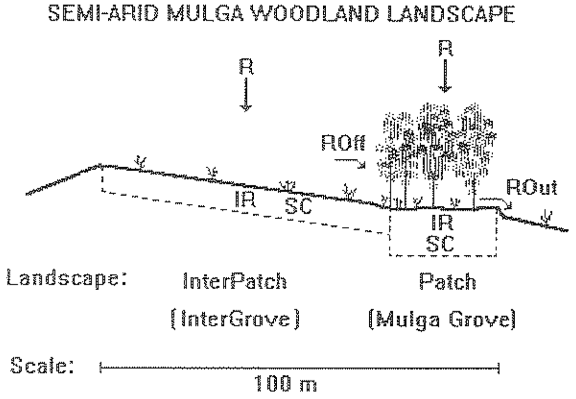

Fig. 2. A cross section of a typical semi-arid mulga woodland landscape of eastern Australia depicting the flow of resources following rainfall events (R) with runoff (ROff) occurring when the amount and intensity of rainfall exceeds the infiltration rate (IR) or the water storage capacity (SC) of the soil. Resources not captured by the patches run out (ROut) of the landscape system. Note that soils within patches are deeper, hence have a greater SC, and also have a higher IR [13].

NPP was computed for four plant guilds or functional groups: ephemerals (forbs and grasses), C3 grasses, C4 grasses, and shrubs. Processes of plant growth, senescence death, decay and consumption are incorporated into these computations. Given initial or starting biomass values for leaf, stem and root components, yearly or annual NPP was computed using a weekly time-step for patch and interpatch areas. The WATDYN submodel computes water dynamics on a daily time-step by rainfall event within each rainy day.

The rainfall and temperature data used as inputs to 'drive' the simulations was based on a 31.5 yr record from mid-year 1962 through 1994 collected from a Class A weather station at Cobar, New South Wales, located in the heart of the semi-arid woodlands of eastern Australia.

SIMULATION SCENARIOS

For the simulations we used a semi-arid landscape system of fixed size, shape and patch structure (Fig. 1). We assumed a rectangular area of 1 ha (10000 m^2) with a uniform slope (S) of 1% and with patches occupying 30% of the area and dispersed regularly over the area. Three scenarios were simulated: (1) an undegraded or natural semi-arid landscape, (2) a similar but degraded landscape, and (3) a natural landscape being impacted by climate change. Undegraded semi-arid woodland landscapes in eastern Australia typically have mulga tree groves occupying about 30% of the surface area [12].

Parameter sets for each of the three scenarios included differences in rainfall inputs, soil infiltration rates (IR) and soil water storage capacities (SC) which are dependent on soil depth (Table 1). The parameter values for the natural and degraded landscape systems are based on actual field measurements in the semi-arid woodlands of eastern Australia [17]. The climate change scenario included a two degree centigrade rise in average annual temperature, a 10% drop in mean winter rainfall and a 10% rise in mean summer rainfall. Summer rains occurred in fewer, but more intense events.

Table 1
Parameter values for three scenarios used to simulate the impacts of climate change and land degradation on semi-arid landscape systems in eastern Australia.

Environmental & Landscape Characteristics	Landscape System		
	Natural System	Degraded System	Climate Change
Precipitation Cobar, NSW	Actual 1962-94	Actual 1962-94	+10% S* -10% W
IR (mm/hr)			
Patch	60	30	60
Interpatch	10	5	10
Soil Depth (cm)			
Patch	100	75	100
Interpatch	45	30	45

* S = summer (Dec-Feb); W = winter (Jun-Aug)

RESULTS

On average, over the 31.5 year simulation the natural landscape system had a NPP of about 330 kg/ha/yr (Fig. 3). Because the degraded landscape lost a greater amount of rainfall as ROut of the system, its NPP averaged only about 160 kg/ha/yr. The impact of a changed climate was to increase NPP, relative to the natural system, to about 425 kg/ha/yr.

Compared to a natural semi-arid landscape system in eastern Australia, one subjected to the impacts of climate change is likely to experience a shift in plant species composition (Fig. 4). C4 grasses significantly increased their NPP under climate change while other guilds changed little compared to the natural system. C4 grasses significantly declined when subjected to degradation as did other guilds, except for shrubs which only declined slightly.

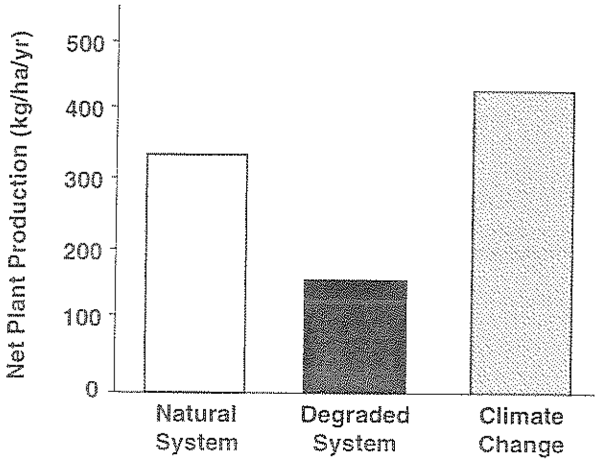

Fig. 3. Average annual net plant production over a 31.5 year period (mid-1962-1994) for a semi-arid landscape system for three scenarios: natural, degraded and climate change.

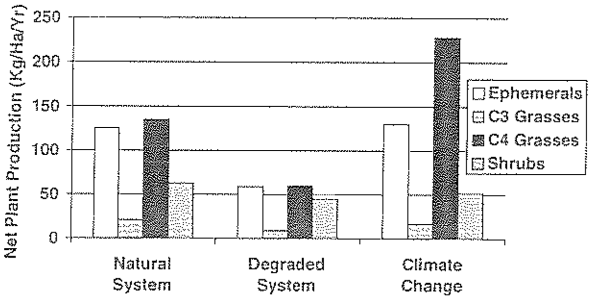

Fig. 4. Annual net plant production for four plant guilds averaged over a 31.5 year period (mid-1962-1994) for a semi-arid landscape system and three scenarios: natural, degraded and climate change.

DISCUSSION

These modelling results strongly suggest that the likely impacts of land degradation are far greater than any impacts expected from climate change, at least in the semi-arid regions of eastern Australia. When resources such as water and nutrients, which are already very limited in supply in these landscapes, are lost from the system due to degradation, significant declines in plant production can be expected, particularly for forbs and grasses, perhaps less so for shrubs and trees. Land degradation often leads to a loss of landscape patches [18], hence a decline in the capacity of the system to capture resources.

The increase in C4 grasses predicted by this simulation study for the climate change scenario might be expected from a knowledge of the adaptive responses of plants with the C4 photosynthetic pathway [19, 20]. Compared to plants with the C3 pathway, the C4 pathway gives plants a higher rate of photosynthesis for a given CO_2 level when conditions are warm but dry and light intensities are high. Thus a scenario of warmer temperatures with greater summer rainfall favours the C4 grasses relative to the C3 grasses and forbs.

Patchiness as a natural phenomenon in arid and semi-arid landscapes is now supported by field studies in semi-arid woodlands of eastern Australia [11, 12], in the chenopod shrublands of Western Australia [21], in the wet-dry savannas of the Serengeti, East Africa [22], in desert grasslands of Chihuahua, Mexico [23] and in the 'tiger bush' of West Africa [24].

To rehabilitate degraded areas, vital landscape patchiness and processes must be restored through appropriate land management practices or rehabilitation treatments. An effective treatment known to speed the restoration of landscape processes is to construct a surface obstruction to water flow (along contours) with tree and shrub branches [21]. This recreates patches and rebuilds the processes which function to capture limited water and nutrients, and patches also provide valuable habitats for plants and animals.

Further studies are needed to confirm these findings for the semi-arid Australian rangelands using other long-term rainfall records, where available. These results also need to be examined for other rangeland regions with different levels of degradation, and which have different climate change scenarios.

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