A PRELIMINARY MODEL TO PREDICT RAINFALL USE EFFICIENCY OF PASTURES ON OPEN-CUT COAL MINES IN CENTRAL QUEENSLAND, AUSTRALIA[1]

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Abstract. Cattle grazing is a potential post-mining land-use option for open-cut coal mines in the dry sub-tropical region of central Queensland, Australia, but no research has been conducted to determine the grazing capacity of these lands. A study was conducted to develop a model for estimating pasture productivity of rehabilitated mined lands, from which long-term sustainable stocking rates could be predicted. Rainfall-use efficiency (RUE), a reliable indicator of pasture productivity in this moisture-limited environment, was calculated for 17 plots across three minesites over a single growing season, and related by linear regression and stepwise multiple linear regression to several site and mine-soil properties. Plots were dominated by *Cenchrus ciliaris* (buffel grass), and ranged in age from 3 to 25 years since establishment. Slope (r^2=0.45) and surface cover (r^2=0.44) were most strongly correlated with RUE. These factors were interpreted as affecting surface retention of rainfall. The factors most correlated with RUE from multiple linear regression were slope (r^2 = 0.45), surface soil exchangeable Mg (cumulative r^2 = 0.71) and surface exchangeable sodium percentage (ESP) (cumulative r^2 = 0.77). ESP is a measure of soil dispersion and surface crusting, which when combined with slope (negative correlation), influenced the ability of incident rainfall to enter the soil profile. Mg was interpreted as a surrogate soil fertility factor, as Mg was strongly correlated with soil total N (r^2=0.53) and cation exchange capacity (r^2=0.74). Dry matter yield and RUE results are generally consistent with those observed on unmined pastoral lands in the region, but data from additional sites and over more seasons are required to fully develop and validate the model for minesite conditions.

Additional Key Words: pasture productivity, carrying capacity, rehabilitation, post-mining land-use, grazing.

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Introduction

Approximately 8000 ha of land disturbed by open-cut coal mining in the dry sub-tropical region of central Queensland, Australia, have been returned to pastures since major operations commenced in 1961. Cattle grazing is a potential post-mining land-use option, but investigations into the grazing capacity of these lands has only recently begun. Given the high cost of the rehabilitation process (US$12,500/ha), Grigg et al. (2000) suggested that grazing management should be directed at preventing degradation of the plant-soil system rather than achieving high production from cattle. Guidelines for sustainable grazing management are therefore required.

Through long-term experience and research in the region, safe stocking rates have been determined as using 30% of pasture yield in 80% of years (McKeon et al., 1990). This calculation requires the determination of net above-ground primary productivity (NPP) of pastures, a key measure of the potential productivity of a pasture system (Redmann, 1992). Given the stochastic climate (Willcocks, 1993), and the variable nature of rehabilitated pastures in central Queensland in terms of slope and aspect, and spoil chemical and physical properties (McLennan, 1994), considerable variation in pasture productivity is expected. Rainfall use efficiency (RUE), a measurement determined from seasonal NPP and rainfall, is valuable in predicting pasture yields as it accounts for variation in topography, substrate and rainfall (Grigg et al., 2000).

A study was initiated to determine the NPP and RUE of rehabilitated pastures at three mines in central Queensland over the 2000-2001 growing season. An empirical model to predict RUE, and ultimately NPP, was developed from site climatic and bio-physical characteristics.

Materials and Methods

Eighteen sites were selected for the measurement of NPP at Blackwater, Norwich Park and Goonyella Riverside mines in the Bowen Basin coalfields in central Queensland, Australia (20°-25°S; 148°-150°E). The Bowen Basin has a sub-humid environment with approximately 650mm annual rainfall, 70% of which falls over the summer (November to April). Mean monthly maximum/minimum temperatures range from 34°/21°C in January, down to 23°/7°C in July.

All sites were rehabilitated to pasture using *Cenchrus ciliaris* (buffel grass), *Chloris gayana* (Rhodes grass) and a range of legumes including *Macroptilium atropurpureum* (siratro). The Blackwater sites were rehabilitated to pasture sown directly onto spoil in the mid-1970's. The Norwich Park and Goonyella Riverside sites were top-soiled prior to rehabilitation in the mid-1990's.

Six exclosure plots (12m x 15m) were fenced to exclude grazing animals at each mine. Plots were selected to represent the range of variability of the rehabilitated pastures at each mine and to minimize variation within each exclosure. Consequently, the sites had a uniform cover of buffel grass, the dominant pasture species at the three mine sites. Daily rainfall and maximum and minimum temperatures were recorded at each mine over the experimental period.

Net primary productivity sampling and analysis

The NPP exclosures were slashed in late winter of 2000, prior to the commencement of the growing season. Slashed plant material was removed from the exclosures. At each sampling, pasture yield and cover were collected from 3 quadrats (1m x 1m) from within each exclosure. Dry matter (DM) yields were obtained by clipping all material within quadrats to a height of 5cm and weighing after oven-drying at 80°C for 48 hours. Green cover percentage was visually determined.

Peak DM yield, the highest yield recorded at each site over the growing season, was used to determine the primary productivity (Redmann, 1992). Peak green cover, the highest cover percentage recorded at each site over the growing season, was also determined. Differences in peak DM yield and peak green cover percentages among the sites at the three mines were investigated by analysis of variance.

Soil sampling and analysis

Two soil cores were collected from each exclosure at depth intervals of 0-15cm and 15-50cm at each pasture sampling for determination of physical and chemical properties. Bulked samples were air-dried and ground to pass through a 2mm sieve, and analysed for pH, electrical conductivity (EC), total soil nitrogen (N), total carbon (C), available phosphorous (Colwell-P) and exchangeable cations (Ca, K, Mg, Na). Cation exchange capacity (CEC) and exchangeable sodium percentage (ESP) were calculated from exchangeable cation analyses. Particle size distribution (proportion of clay, silt, fine sand and coarse sand) was determined using the pipette method on the <2 mm fraction. Water holding capacity (WHC) was determined at field capacity (P=10 kPa) and at permanent wilting point (P=1500 kPa) from three replicates for each sample at each depth using a pressure plate apparatus.

Determination of Rainfall Use Efficiency

Rainfall use efficiency (RUE) is the amount of DM biomass produced over one hectare per millimeter of rain (Le Houerou, 1984). RUE was calculated for each site using the peak DM yield for the season and cumulative rainfall over the period from slashing to achievement of peak yield.

RUE values were regressed against the range of measured site and soil physical and chemical parameters, in order to determine the factors most affecting RUE. Finally, an empirical model was developed, based on individually significant site parameters using multiple step-wise linear regression, to predict RUE.

Results

Weather

Blackwater mine received 458 mm of rainfall for the 12-month period from May 2000 to April 2001, well below the long-term average of 640 mm for the area. Goonyella-Riverside mine received 744 mm of rainfall, higher than the long-term average of 608 mm for the area. However, most of the rain fell at the beginning of the growing season between October and December 2000 in heavy, short-duration events. Norwich Park mine received 824 mm of rainfall for the 12-month period, higher than the long-term average of 723 mm. The July-September quarter was the driest period at all the three mines.

Pasture DM yield and surface cover

One of the 6 experimental exclosures at Norwich Park was grazed by cattle in November 2000 and was excluded from subsequent measurements and analyses. There was significant ($P<0.05$) variability in DM yields among the three mines. Mean peak DM yields at each mine were highest at Norwich Park (7550 kg/ha) followed by Goonyella Riverside (4380 kg/ha) and Blackwater (4130 kg/ha). Peak DM yield over the 2000-2001 growing season across the 17 sites varied significantly (P<0.05) from 3040 to 11080 kg/ha, with a mean peak yield of 5350 kg/ha (Table 1). The highest peak DM yield was recorded at Site 16 at Norwich Park mine (11080 kg/ha) while the lowest was recorded at Site 5 at Blackwater mine (3040 kg/ha). Peak green cover across the 17 sites varied significantly (P<0.05) from 45 to 100 % with a mean cover of 68 % (Table 1). The lowest peak green cover (45 %) was recorded at Blackwater mine and the highest was recorded at Norwich Park mine (100 %).

Table 1**.** Peak DM yield, peak green cover percentage, slope, cumulative rainfall and rainfall use efficiency at peak yield for the 17 sites in central Queensland.

Mine/Site	Peak DM (kg/ha)	Peak Green Cover (%)	Slope (%)	Cumulative Rainfall (mm)	RUE at Peak Yield (kg/ha/mm)
Blackwater					
1	4870	75	5	293	17
2	3260	63	11	361	9
3	3410	60	17	293	12
4	5670	87	12	316	18
5	3040	52	18	316	10
6	4550	45	9	316	14
Goonyella Riverside					
7	5390	75	13	716	8
8	5220	60	15	716	7
9	4130	73	18	716	6
10	3220	52	17	711	4
11	3770	63	17	711	5
12	4550	70	13	711	6
Norwich Park					
13	6850	92	14	582	12
14	7440	100	3	582	13
15	5670	85	4	502	11
16	11080	100	5	533	21
17	6700	72	9	453	15
Mean	5350	68			
LSD (P<0.05)	2630	27			

Soil chemical and physical characteristics

The greatest differences in soil chemical and physical characteristics occurred between mine sites, and mean data at two depths for each mine are presented in Table 2. Soil C and N concentrations were higher at Blackwater mine in comparison to Norwich Park and Goonyella Riverside mine. Similarly, CEC was comparatively higher at Blackwater mine, with the lowest exchangeable Mg, Ca and CEC observed at Goonyella Riverside mine. Sites at Goonyella Riverside mine also showed higher salinity (EC) and sodicity (ESP) in comparison to sites at Blackwater and Norwich Park mines. Total sand proportion at Norwich Park mine was higher than the other two mines, resulting in relatively lower water holding capacity. Clay proportion ranged from 42 to 57 %. There were no major differences in soil pH, or available P across the three mines (Table 2).

Table 2. Soil chemical and physical characteristics averaged for each mine.

Parameter	Blackwater		Goonyella Riverside		Norwich Park	
Depth Interval (cm)	0-15	15-50	0-15	15-50	0-15	15-50
Total C (%)	3.3	2.4	1.2	1.5	1.0	1.1
Total N (%)	0.16	0.14	0.07	0.07	0.07	0.07
Colwell-P (cmol/100g)	19.4	19.3	17.4	19.9	20.2	17.7
Ca (cmol/100g)	17.9	11.9	6.5	5.4	11.2	11.4
K (cmol/100g)	0.54	0.48	0.29	0.28	0.26	0.29
Mg (cmol/100g)	12.2	12.4	5.8	5.7	8.5	10.1
Na (cmol/100g)	1.4	1.0	3.1	3.2	1.2	2.0
CEC (cmol/100g)	32	26	16	15	21	24
ESP (%)	4	4	18	20	5	8
pH	8.8	9.0	8.5	8.6	8.7	8.7
EC (dS/m)	0.15	0.13	0.45	0.32	0.10	0.15
CCR*	0.62	0.61	0.33	0.31	0.37	0.42
Clay (%)	52	42	48	47	57	56
Silt (%)	25	31	21	30	11	12
Fine Sand (%)	23	27	31	23	33	32
Coarse Sand (%)	13	15	21	31	32	25
WHC** (%)	25	23	23	22	18	20

*CCR = cation exchange capacity : clay ratio, **WHC = water holding capacity

Rainfall Use Efficiency

Rainfall use efficiency (RUE) values ranged from 4 to 21 kg/ha/mm across the 17 sites with the lowest value (4 kg/ha/mm) recorded at Goonyella Riverside mine and the highest value (21 kg/ha/mm) at Norwich Park mine (Table 1). In initial regression analyses, 11 of the 38 measured parameters were significantly ($P<0.05$) correlated with RUE. Individually, slope and surface cover were the best predictors of RUE (Table 3). Slope, EC, and ESP were negatively correlated with RUE, whereas surface cover and Ca, Mg and clay content were positively correlated.

These 11 parameters were then used for multiple regression analysis. The regression model used three parameters to explain 77 % of the variation in RUE using the following equation:

$$\text{RUE (kg/ha/mm)} = 0.59*\text{Mg}_{(0\text{-}15)} - 0.49*\text{Slope} - 0.12*\text{ESP}_{(0\text{-}15)} + 12.8 \quad (1)$$

Table 3. Coefficients of determination and slopes for correlations between site parameters and RUE, and cumulative r^2 from multiple linear regression.

Parameter	r^2	Regression slope	Cumulative r^2 from multiple linear regression
Slope	0.45	-0.62	0.45
$Mg_{(0\text{-}15cm)}$	0.33	0.75	0.71
$ESP_{(0\text{-}15cm)}$	0.33	-0.26	0.77
Surface Cover	0.44	0.26	0.80
$ESP_{(15\text{-}50cm)}$	0.23	-0.22	0.83
Clay $_{(15\text{-}50cm)}$	0.25	0.32	0.85
$CEC_{(15\text{-}50cm)}$	0.32	0.44	0.85
$Ca_{(15\text{-}50cm)}$	0.37	0.81	0.86
$Mg_{(15\text{-}50cm)}$	0.33	0.81	0.86
$EC_{(15\text{-}50cm)}$	0.31	-23.5	0.87
$EC_{(0\text{-}15cm)}$	0.22	-9.91	0.87

Discussion

The mean peak DM yield recorded across the mines (5350 kg/ha) approximated the mean DM yield recorded for mined lands at central Queensland coal mines in other studies. Grigg et al. (2000) reported a mean total DM (including litter) of 5000 kg/ha for buffel grass dominant pastures at Moura, Blackwater, Gregory, and Goonyella Riverside mines. DM yields of 6610 and 6600 kg/ha have been reported for unmined buffel grass pastures in central Queensland (Willcocks and Filet, 1993) and in northern Kenya (Keya, 1998), respectively.

Not surprisingly RUE values were also similar to those reported in the literature. Many authors have reported water use efficiency (WUE) values for pastures by accounting for initial and final soil moisture and assuming negligible run-off and deep drainage. In these studies, WUE and RUE are generally very similar as differences between initial and final soil water are small in comparison to total seasonal rainfall. WUE values for unmined buffel grass pastures ranged from 6.7 kg/ha/mm in south-west Queensland (Johnston, 1996) up to 15 kg/ha/mm (RUE = 14.6 kg/ha/m) in central Queensland (Willcocks and Filet, 1993). These values are comparable to the mean RUE for Goonyella Riversde Mine (6.0 kg/ha/mm) and Blackwater and Norwich Park Mines (13.3 and 14.4 kg/ha/mm, respectively). Some caution is required when comparing RUE values, as the data in the current study were derived from ungrazed pastures. Heavy grazing reduces RUE by reducing photosynthetic area and ground cover, thereby reducing rainfall retention and infiltration (Grigg et al., 2000). Pearson (1965) reported lower RUE values for moderately grazed paddocks in comparison to ungrazed paddocks in Eastern Idaho. However, if paddocks are ungrazed for a long time, the problem of stand stagnation may arise leading to even lower RUE values mainly through decreased vigor of the pasture. Therefore, appropriate grazing management is necessary to maximize RUE in the long term.

Factors affecting growth and RUE

Plant growth is driven by solar radiation, water, and essential nutrients. Little variation existed in solar radiation levels among sites in the current study, and incident radiation was relatively high throughout the growing season (c. 19 MJ/m^2/day, data not presented). Solar radiation was therefore not included as a variable for prediction of RUE.

Water. An hierarchy of factors affects the ability of pasture to utilize rainfall: 1) incident rain must be retained within the landscape long enough for adequate infiltration to take place; 2) infiltration must be sufficient for water to penetrate into the root zone; and 3) losses from deep percolation must be minimized. The results of this preliminary study suggest that the ability of the rehabilitated landscape to trap or slow the passage of incident rain is the most significant factor influencing pasture productivity.

The predominance of slope in influencing RUE has important implications for mine practitioners considering grazing as a post-mining land-use, or indeed for the establishment and maintenance of a grass cover for surface stability only. Slopes on rehabilitated pastures on these mines are generally steep (>10 %), due to the considerable costs involved in regrading (up to US$12,500/ha). Although not measured, surface roughness created by deep ripping during the rehabilitation process is also likely to have influenced retention of rainfall at the study sites, notably at Norwich Park mine. Carroll et al. (2000) reported substantial reductions in runoff with increasing surface roughness for a given slope, as long as rills did not breach the ridge-furrow relief. It is interesting to note, however, that the effect of surface roughness was most pronounced early after establishment, following which vegetation cover became the predominant factor affecting runoff.

Vegetation cover, which was strongly related with RUE on an individual basis (Table 3), has consistently been the main factor affecting runoff and erosion in these landscapes (McIvor et al., 1995; Carroll et al., 2000; Loch, 2000). Cover has a twofold effect in reducing runoff by impeding overland flow and also by increasing infiltration via root macropores (Loch and Orange, 1997). In this study, cover was also negatively related to slope, evident in the small additional contribution of cover within the stepwise regression model. Lower cover was generally associated with steeper slopes, indicating a possible feedback effect on pasture productivity. Similar negative relationships with slope have been reported for rangeland environments elsewhere (Holecheck et al., 1995).

Factors affecting potential infiltration, as distinct from surface retention of water, were of lesser apparent importance in this study, although such an interpretation may change with data from a planned expanded set of sites. Shaw (1995) found that the resistance to water movement through a soil could be described by a combination of sodicity (ESP), clay content and clay mineralogy in terms of the reaction to the presence of sodium. These terms accounted for a soil's porosity and the effect of clay dispersion into the pore spaces reducing overall hydraulic conductivity. Soils with clay contents in the range 30-60% were at greatest risk of reduced hydraulic conductivity in the presence of sodium, a situation evident at the sites at Goonyella Riverside mine. The moderate clay content and high ESP at the Goonyella Riverside sites would reduce water infiltration. Of note is the stronger influence of surface ESP, as indicated by a larger individual correlation co-efficient and contribution to the overall model. Sodicity at the surface will be reflected in sealing and crusting behaviour which directly inhibits water penetration. Elevated salinity is a common feature of waste rock from these mines and the downward migration of salts within the soil profile beneath established rehabilitation pastures provides an indication of the ability of water to infiltrate. In this study, measured EC was positively related to ESP and so added little to the multiple regression. Its presence as a significant parameter influencing RUE at both depth classes (Table 3), suggests a direct constraint on pasture growth through osmotic stress at Goonyella Riverside (Table 2).

The climate of central Queensland imposes strong constraints on the availability of moisture for pasture growth. Annual evaporation exceeds rainfall by a factor of three and monthly totals are greater than rainfall throughout the year. The greatest deficit between evaporation and rainfall generally occurs between October and December (Willcocks, 1993), covering the first half of the main growing season. Approximately 60 % of the annual average rainfall is estimated to occur in events of less than 10 mm, the minimum considered necessary for adequate plant growth (Willcocks, 1993). In addition, larger falls frequently occur in short storms of high intensity, with concurrent low infiltration and high runoff. This explains the prominence in the RUE model of factors affecting the ability of the pasture to access incident rainfall, with far less emphasis on parameters of soil fertility. The results are also confirmation of the utility of RUE as a measure of pasture productivity for these lands.

Soil fertility. Once moisture requirements are met, N and P are generally the soil nutrients most limiting to plant growth in the region (Burgess and Barrett, 2000), with particular significance given to the availability of P (Jones, 1990; Ahern et al., 1994; Johnston, 1996). In this study, RUE was poorly related to P and most likely reflects the presence of P across all sites at levels considered not to be limiting for pasture growth (Moody and Bolland, 1999). Rehabilitation pastures are typically fertilised at establishment at rates of 30-60 kgP/ha (Roe et al., 1996).

Whilst exchangeable Mg is necessary for plant growth, its inclusion in this preliminary model was considered to be a surrogate for other soil factors. Absolute levels of Mg at all sites, and ratios with other exchangeable cations did not appear to pose any direct nutritional limitations on pasture growth (Aitken and Scott, 1999). Instead, Mg was strongly related to surface soil N (r^2=0.53) and surface soil CEC (r^2=0.74), a measure of a soil's ability to retain major plant cations (data not presented). Exchangeable Mg forms a major component of CEC, so that CEC made no significant additional contribution to predicting RUE in the multiple linear regression. The apparent importance of Mg may be a result of the small sample size to date and direct inclusion of N, P or CEC may feature in a final model incorporating data from an expanded set of sites.

Conclusions

The study showed that the primary productivity and RUE of rehabilitated pastures in the Bowen Basin of central Queensland are comparable to those of the surrounding unmined lands. RUE may decline to some extent as the grazing of pastures is commenced.

The study also showed that pasture DM yield could be predicted from a small number of site and soil characteristics, slope, surface soil exchangeable Mg and surface ESP. The model suggested that high pasture productivity was primarily dependant on the absence of factors that reduced rainfall retention and infiltration, and the presence of soil fertility factors, using Mg as a fertility indicator. The model will be improved through the incorporation of a broader range of sites, and validation using independent data.

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