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Title: “AJAE appendix for ‘A Bioeconomic Model of Cattle Stocking on Rangeland Threatened by Invasive Plants and Nitrogen Deposition’”

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Date: March 2008

“Note: The material contained herein is supplementary to the article named in the title and published in the American Journal of Agricultural Economics (AJAE).”

Table 1 presents the data used in the simulations. We will illustrate how the data were generated using native grass; data for cheatgrass and leafy spurge were similarly derived. At the top of the table notes are the values for I_0 and A that were used. The first five rows of the table show the population, biomass, SLA, non photosynthesis respiration parameter and extinction coefficient for native grass taken from the sources cited in the table notes. We assume the native grass is in steady-state at these data and that nitrogen is at its ideal level for the native grass ($N = N_i$). Then to calibrate the model these seven values are inserted into the below equations to solve for SEL , α_i , β_i , q_i and L_i , $i = g, c, s$, which occupy rows 6 – 10 of the table.

$$(A.1) \quad R_i = (I_0 - SEL)x_i s_i - \alpha_i x_i^{q_i} \left((N - N_i)^2 + 1 \right) - \beta_i = 0$$

$$(A.2) \quad (I_0 - SEL)s_i - q_i \alpha_i x_i^{q_i-1} \left((N - N_i)^2 + 1 \right) = 0$$

$$(A.3) \quad n_i x_i s_i - L_i A = 0$$

$$(A.4) \quad r_i (I_0 - SEL)x_i s_i - \beta_i = 0$$

$$(A.5) \quad I_0 - SEL - I_0 e^{-k_i L_i} = 0$$

(A.1) is the net energy objective function, (A.2) is the derivative of (A.1) or the first order condition for a maximum, and (A.3) is the biomass balance condition that sets the maximum leaf area index equal to the total plant biomass divided by the available area. (A.4) states that non green biomass respiration is r_i percent of total incoming energy as in the table notes. Finally, (A.5) is the light attenuation equation (Monsi and Saeki, 1953).

The three equations (A.1) – (A.3) are used in the simulations, with the calibrated parameters I_0 , A , α_i , β_i , q_i and L_i substituted into them. Steady-state values of x_i , n_i and SEL are derived from the simultaneous solution of (A.1) – (A.3). Out of steady state, there are two cases. In the first case, if the population is small and the leaf area index is below its maximum value, then competition for light is low and SEL will be small. However, SEL will not be zero because there still will be some shading. To determine this nonzero SEL we use (A.5) to calculate a low competition SEL^{lc} by assuming the leaf area index is half of its maximum steady-state value. In the simulations it is always the case that total shading energy loss is no less than SEL^{lc} by adjusting (A.1) to:

$$(A.6) \quad R_i = (I_0 - SEL^{lc} - SEL)x_i s_i - \alpha_i x_i^{q_i} \left((N - N_i)^2 + 1 \right) - \beta_i$$

where the SEL in (A.6) is the energy loss above the minimum value SEL^{lc} . (This change applies to (A.2) as well.) Given this modification to SEL , then in this first case, (A.2) is solved for x_i with $SEL = 0$. The population then is updated using (A.1) and (8), and because competition is low, $R_i > 0$ and population will increase. When the population gets large enough to satisfy (A.3) because the maximum leaf area index is reached, the simulations move into case 2. Now, (A.2) and (A.3) are used to solve for x_i and SEL which are then substituted into (A.1) to update the population using (8). The process of sequentially using (A.2) and (A.3) and then (A.1) and (8) is repeated until a steady state is reached.

If there are two or more species competing, then (A.1) and (A.2) and (8) are used for each individual population. However, (A.3) is modified. For example, with all three species competing, we get:

$$(A.7) \quad n_g x_g s_g / L_g + n_c x_c s_c / L_c + n_s x_s s_s / L_s - A = 0$$

Essentially (A.7) assures that it is the competition among all three species that is determining the community *SEL* and the three biomasses. Therefore, with all three species of plants in the simulations, each period four equations ((A.2) for each species and (A.7)) are solved for x_g , x_c , x_s and *SEL*. Then (A.1) and (8) for each species are used to update the populations between periods.

Cattle are added to the simulations using (13) and (14), but variable respiration parameters in $f_k(x_{kn}, x_{kc})$ and the d_i in (14) must be determined from further calibration.

For the respiration parameter a flexible functional form is used for variable respiration:

$$(A.8) \quad f_k(x_{kn}, x_{kc}) = \alpha_{kn} x_{kn} + \alpha_{kc} x_{kc} + 0.5\alpha_k (x_{kn} x_{kc} + x_{kn}^2 + x_{kc}^2)$$

Using (A.8) in equations (11) and (14) from the text, substituting values for x_{kg} , x_{kc} that reflect a hypothetical diet composition of 60% native grass and 40% cheatgrass, the values of e_n and e_c from Table 1 and assuming a (high) average daily gain of 1.5 kg day⁻¹, yields the values shown in the Table. To obtain the d_g and d_c , equation (13) from the text is solved twice after substituting in the native grass and cheatgrass populations and biomasses from the Table and assuming a diet composition of 60% native grass and 40% cheatgrass, and assuming high grazing in these steady state communities so $n_t = 45$ on 100 ha.

A simulation with cattle involves simultaneously solving eight equations: three first-order conditions for the plants from (A.2), but where the biomass supply term (12) is added to the conditions for native grass and cheatgrass; plant balance condition (A.7); the two first-order conditions for the cattle which are the derivatives of equation (11) from

the text with respect to x_{gc} and x_{cc} ; and the two plant-cattle balance conditions from equation (13). Then (A.1) and (8) for each species are used to update the plant populations between periods, while the cattle period-to-period populations are determined from the stocking decision.

Table 1 Variables and parameters in GEEM

Variable	Native Grass	Cheatgrass	Leafy Spurge	Cattle
Populations N_i ha ⁻¹	7.5x10 ⁶ a	1.5x10 ⁷ b	4.5x10 ⁵ c	as stocked d
Biomass-plant (kg) or biomass consumption- animal (kg t ⁻¹) x_{ij}	0.0002 e	0.00004 f	0.0035 g	1307 - 2818 h
Shaded leaf area s_i m ² kg ⁻¹	10 i	10 j	11.429 k	n.a.
Non photosynthesizing respiration r_i	0.39 l	0.40 m	0.45 n	n.a.
Extinction coefficient k_i	0.30 o	0.30 p	0.50 q	n.a.
Variable respiration α_i	5.7670x10 ⁵ r	3.7773x10 ⁶ s	24015 t	$\alpha_{kn}, \alpha_{kc} = 1$ u $\alpha_k = 1.139$
Respiration non green biomass or resting metabolism β_i kcal t ⁻¹	1799313 v	483495 w	26476080 x	857063 – 1532784 y
Leaf area index L_i	1.5 z	0.6 aa	1.8 ab	n.a.
Shaded energy loss in steady state SEL kcal m ⁻¹ t ⁻¹	1310989 ac	59596 ad	214696 ae	n.a.
Respiration power term q_i	2 af	2 ag	2 ah	n.a.
Gross energy content e_i kcal kg ⁻¹	4200 ai	3150 aj	n.a.	n.a.
Average longevity l_i	5 ak	2 al	10 am	n.a.
Weight w_i kg	0.0002 an	0.00004 ao	0.0035 ap	273–589 aq
Ideal nitrogen N_i	3 ar	4 as	4.675 at	n.a.
Herbivory d_i	1.257 au	1.054 av	n.a.	n.a.

Note: In the table n.a. refers to data that is not applicable or not needed. The grazing area employed in the simulations (A) was assumed to be 100 hectares or 1,000,000 m² and the

length of each period t taken to be one grazing season or 182 days. The total incoming solar energy (I_0) employed in the model was $400 \text{ W m}^{-2} = \text{kcal m}^{-2} \text{ season}^{-1}$. Of the total, 24% is assumed to be used for growth, metabolism and respiration, while the remainder is lost owing to nonabsorbed wavelengths, reflection, transmission and heat dissipation (Taiz and Zeiger, 2002, Chpt. 9). Therefore, $I_0 = (1.507 \cdot 10^6)(.24) = 3.6178 \cdot 10^5 \text{ kcal m}^{-2} \text{ t}^{-1}$.

(a) Beckstead and Augspurger (2004) find 100,000-50,000,000 cheatgrass tillers ha^{-1} for low-high density patches in Western Utah. We assume individual native grasses have half the density of cheatgrass and use the high end in the Table, but the population changes according to updating in the model. To scale to the forage production conditions of the central Great Plains, these values were scaled to those documented by Andales et. al. (2005) which found forage production of 424-1500 kg ha^{-1} . Under an assumption that forage production for native grass as the dominant plant was at the high end of this range (1500 kg ha^{-1}) then the native grass population is taken to be 30% of that inferred from Beckstead and Augspurger (2004). The same scaling factor is applied to cheatgrass populations and leafy spurge. Note that all populations change when updated in the dynamics.

(b) See (a).

(c) About 200 stems m^{-2} (www.nature.nps.gov/biology/ipm/manual/spurge.cfm, National Park Service) and 100 stems m^{-2} (Leitch *et al.* 1994). Using the scaling factor from (a) we

used 45 stems m^{-2} . This is consistent with observed leafy spurge kg ha^{-1} (Rinella and Sheley, 2005).

(d) Cattle stocking is a choice variable in the model.

(e) Average native grass, and particularly blue grama, biomass production in general is about 5000 kg ha^{-1} (Uresk *et al.*, 1979; Hart and Ashby, 1998; Bakker and Wilson, 2001).

Based on (a), this implies 0.0002 kg ind^{-1} . This value can change with competition and available nitrogen because it is the plant's choice variable.

(f) Average cheatgrass biomass production in general is about 2000 kg ha^{-1} (Hull, 1949; Uresk *et al.*, 1979; Beckstead and Augspurger, 2004). Based on (b), this implies 0.00004 kg ind^{-1} . This value can change with competition and available nitrogen because it is the plant's choice variable.

(g) Based on estimates from Lym and Messersmith (1994) of 4650 kg ha^{-1} and Morrow (1979) of 3.5 gm per plant for tops. Estimates from Ziska (2003) were as high as 6.5 gm for the entire plant. Since x_i is green biomass only, we chose 3.5 gm.

(h) One animal unit requires 11.8 kg of dry matter per day per 450 kg of body weight.

See <http://www.agr.gc.ca/pfra/land/fft1.htm>. This was adjusted for the different weights and summed over a 6 month season.

(i) An average of area/mass indices reported by Jurik and Kleibenstein (2000) for big bluestem (*Andropogon gerardii*). We assumed this to be a reasonable approximation for native grasses and cheatgrass.

(j). See (i).

(k) From Table 1 in Ziska (2003) leaf area is about 400 cm^2 per plant. We calculate $(400 \text{ cm}^2 / \text{ind})(\text{m}^2 / 10000 \text{ cm})(\text{ind} / .0035 \text{ kg}) = 11.429 \text{ m}^2 \text{ kg}^{-1}$.

(l) The percent of carbohydrates produced in photosynthesis consumed in respiration for slow-growing grass species is 16% by roots and 25% by shoots (Lambers *et al.*, 1998).

This yields $16 / (16 + 25) = 39\%$ for the non green biomass.

(m) The percent of carbohydrates produced in photosynthesis consumed in respiration for fast-growing grass species is 12% by roots and 18% by shoots (Lambers *et al.*, 1998).

This yields $12 / (12 + 18) = 40\%$ for the non green biomass.

(n) Based on (m), and given the fast growth and extensive root system of leafy spurge, we assumed 45%.

(o) The extinction coefficient is as low as 0.3 for vertically inclined leaves such as grasses (Lambers *et al.*, Chpt 2).

(p) The extinction coefficient is as low as 0.3 for vertically inclined leaves such as grasses (Lambers *et al.*, Chpt 2).

(q) The extinction coefficient for horizontal leaves is higher than for vertically inclined leaves (Lambers *et al.*, Chpt 2) and we assumed 0.5 for spurge.

(r) - (t), (v) - (x), (z) - (ab), (ac) - (ae), (af) - (ah) From equations (A.1) – (A.5), noting that in the simulation model plant populations were divided by 10,000 and plant biomass multiplied by 10,000 to reduce the computational task of the simulations, and that for (af)- (ah) the value of 2 chosen was an approximation that also allowed for more efficient numerical solutions.

(u) See equation (A.8) and the associated calibration section.

(y) For mammals, resting metabolic rate in kcal d⁻¹ (M) is related to body weight (W) in kg by the formula $M = 67.61W^{0.756} \pm 5\%$ (Kleiber 1975). Weights are given in (aq). Extrapolating to one 6 month season for both weights yields 857063-1532784 kcal season⁻¹. The value used in the simulations was 1250554 kcal season⁻¹.

(ai)- (aj) Gross energy as opposed to digestible energy is used because the variable respiration term for cattle includes feces. Blue grama contains 4200 kcal kg⁻¹ (Kelsey *et al.*, 1973). Cheatgrass has virtually the same gross energy; however, it is available for only about two months in the Spring before becoming unpalatable (Cook and Harris, 1952). Therefore, we reduce the gross energy of cheatgrass by 25%, and the embodied energy term can be thought of as available energy in a kg of biomass averaged over the season.

(ak) Perennials, assumed to have 5 year average longevity.

(al) An annual, but since cheatgrass new growth begins in autumn we added a year.

(am) Gylling and Arnold (1985).

(an)-(ap) Same as biomass for plants.

(aq) Weights of stocked cattle vary. We use typical weights of 273 kg per stocked feeder calf and 589 kg market weight at the end of the stocking season.

(<http://agalternatives.aers.psu.edu>)

(ar)-(at) See *Steady State and Coexistence* section in text. We could find no data that suggests what the ideal nitrogen levels are or how movements from those levels change respiration. There is evidence that non native annuals benefit from greater *N* relative to native perennial grasses (Wedin and Tilman, 1996), and that leafy spurge growth benefits

from higher N levels (McIntyre and Raju, 1967). Therefore, we set the native grass ideal N level at 3.0 and gave higher ideal levels to cheatgrass and spurge. Based on Figure 1 in the text, which species dominates is sensitive to where these ideal levels are set, and our numbers coincide with the relative advantages found by these and other authors.

(au)-(av) Determined from equation (13) in the text, noting again that in the simulation model plant populations were divided by 10,000 and plant biomass's multiplied by 10,000 to reduce the computational task of the simulations.

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